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**TRAFFIC SOLUTIONS FOR GREENER AND CLEANER
CITIES**

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EL PRESIENTE

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ABSTRACT

Cities world-wide suffer from serious air quality problems and are main contributors to climate change by consuming about two-thirds of the world's overall energy and emitting an estimated 70% of the world's Green House Gases (GHG). Road traffic is a major source of GHG emissions and the largest contributor to air pollutant emissions in urban environments. Transport emissions have a varying influence on the urban environment, as GHG and air pollutants have different spatial effects: GHG emissions have a global impact contributing to climate change while air pollutant emissions have a major local impact directly affecting human health.

Policy makers can make use of different actions to face these emission problems: implement mechanisms that diminish both the trip length and the need to travel (*avoid* strategies), promote the modal shift towards public-transport systems or non-motorized transport modes (*shift* strategies) and enhance the efficiency of the remaining travel activity through a more effective management of transport systems and networks or the improvement of vehicle design and fuel efficiency (*improve* strategies). While *avoid* and *shift* strategies may have a direct impact in reducing both air pollution and GHGs in urban areas, *improve* strategies could lead to important air pollution drawbacks due to e.g. the redistribution of the traffic activity to high-populated areas.

This thesis stresses the importance of evaluating transport emission reduction strategies by taking into account the different spatial impacts of emissions. To do so, this thesis evaluates climate change and air pollution co-benefits and trade-offs of two speed management strategies (speed reduction and variable speed limits), two eco-traffic strategies (eco-driving and eco-routing) and the combination of these measures (eco-routing combined first with variable speed limits and second with eco-driving).

Three types of methodological tools were applied to model, assess and map the impacts of the measures on traffic performance, traffic emissions and population exposure in Madrid Metropolitan area. A total of 61 scenarios were simulated for different traffic periods and different percentages of penetration of the eco-traffic measures. Results were obtained for six different indicators and up to four types of roads

The results show that a speed reduction strategy is efficient to reduce emissions in the section where the measure was implemented. The increase of the operational capacity of the variable speed limit measure led to an increase of emissions in the urban highway where it was applied but a decrease in the city center and in the whole network, showing climate change and air pollution co-benefits. On the other hand, the eco-routing strategy turned out to be positive for climate change mitigation but ineffective to reduce air pollutants in high populated areas. Finally, from the application of the combined measures, perfect environmental and traffic performance synergies were found for eco-routing and eco-driving penetration rates lower than 50% under free-flow traffic conditions.

The present study provides local policy makers and city managers with useful tools and insights to achieve *greener* and *cleaner* cities through selected traffic management policies.

RESUMEN

Las ciudades de todo el mundo sufren graves problemas de calidad del aire siendo además principales causantes del cambio climático al consumir alrededor de dos tercios de la energía total del planeta y emitir un 70% de los gases de efecto invernadero (GEI). El tráfico rodado es una fuente importante de emisiones de GEI y la mayor fuente de emisiones de contaminantes atmosféricos en entornos urbanos. Las emisiones del transporte presentan diferentes impactos en el ámbito urbano debido a que los GEI y los contaminantes atmosféricos tienen diferentes alcances: las emisiones de GEI tienen un impacto global que contribuye al cambio climático, mientras que las emisiones de contaminantes atmosféricos tienen un impacto local que afecta directamente a la salud humana.

Los responsables políticos tienen a su disposición diferentes medidas para hacer frente a los problemas de emisiones: implementar mecanismos que disminuyan tanto la duración del viaje como la necesidad de viajar, promover el cambio modal hacia sistemas de transporte público o modos de transporte no motorizados o mejorar la eficiencia de los viajes restantes mediante una mejor gestión de los sistemas transporte o un desarrollo más eficiente de vehículos y combustibles. Si bien los dos primeros tipos de estrategias pueden tener un impacto directo en la reducción tanto de la contaminación atmosférica como de los GEI en las zonas urbanas, el último, que incluye medidas como la gestión eficiente de la velocidad o las medidas de eco-tráfico, podría dar lugar a importantes problemas de contaminación atmosférica debido a la redistribución de los flujos de tráfico hacia zonas con alta densidad de población.

En esta tesis se destaca la importancia de evaluar las políticas de reducción de emisiones de transporte teniendo en cuenta los diferentes impactos espaciales y temporales de las emisiones. En la tesis se evalúan los posibles beneficios y conflictos sobre cambio climático y de la contaminación atmosférica de dos medidas de gestión de velocidad (reducción de la velocidad y límites de velocidad variables), dos estrategias de gestión eco-eficiente del tráfico (en concreto eco-conducción y eco-enrutamiento) y la combinación de estas (en primer lugar eco-enrutamiento combinado primero con límites de velocidad variables y segundo lugar con eco-conducción)

Se han aplicado tres tipos de herramientas metodológicas para simular, evaluar y representar en mapas los impactos de las medidas mencionadas sobre el tráfico, las emisiones y la exposición de la población a los contaminantes aéreos en el área Metropolitana de Madrid. Se simuló un total de 61 escenarios teniendo en cuenta diferentes períodos de tráfico y diferentes porcentajes de penetración de las medidas de gestión eco-eficiente del tráfico. Se han obtenido resultados para seis indicadores diferentes y hasta cuatro tipos de carreteras.

Los resultados muestran que las estrategias de reducción de velocidad son eficientes para reducir las emisiones en la sección donde se implementa la medida. El aumento de la capacidad operativa de los límites de velocidad variables produce un aumento de las emisiones en autopistas urbanas de circunvalación, pero a una disminución en el centro de la ciudad y en toda la red, mostrando beneficios conjuntos sobre el cambio climático y la contaminación del aire. Por otra parte, la estrategia de eco-enrutamiento resultó ser positiva para la mitigación del cambio climático, pero ineficaz para reducir los contaminantes aéreos en áreas con alta densidad de población. Por último, los resultados de las medidas combinadas, muestran sinergias relacionadas con la reducción de emisiones y la operación del tráfico para tasas de penetración del eco-enrutamiento y de la eco-conducción inferiores al 50% en condiciones de tráfico de flujo libre.

El presente estudio proporciona a los gestores de las ciudades herramientas y resultados útiles para lograr ciudades más verdes y más limpias a través de la gestión del tráfico urbano.

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GLOSSARY

AADT	Annual Average Daily Travel
AM	Morning peak hour
ASI	Avoid - Shift - Improve for emission reduction strategies
ASIF	Activity - modal Share- mode Intensity - Fuel carbon content for quantifying emissions
AVS	Average speed
BC	Base-case
BPR	Bureau of Public Roads
CBD	Central District
CO ₂	Carbon dioxide
E	East section of M30 ring-road
ED	Eco-driving
EF	Emission Factor
FC	Fuel consumption
FF	Free - Flow
GHG	Greenhouse Gas
GIS	Geographic Information SystemS
GN	Green Navigation
GN+ED	Green Navigation combined with Eco-driving
GN+VSL	Green Navigation combined with Variable Speed Limit
GPS	Global Positioning System
ICT	Information and Communication Technology
ITS	Intelligent Transport Systems
NO _x	Nitrogen oxides
NW	North West section of M30 ring-road
OD	Origin Destination
OP	Off peak hour
PEI	Population Exposure Indicator
PM	Particulate Matter
PM	Afternoon peak hour
RO	Research Objective
RO1	First specific Research Objective
RO2	Second specific Research Objective
S70	Scenario 70 km/h in the M30 South West section
S90	Scenario 90 km/h in the M30 South West section
SPR	Speed Reduction
SW	South West section of M30 ring-road
TEI	Traffic Emission Indicator
TPI	Traffic Performance Indicator
VDF	Volume Delay Function
VEH	Vehicles hour
VKM	Vehicles kilometer
VSL	Variable Speed Limit

1. INTRODUCTION

Cities worldwide suffer from serious air quality problems and are main contributors to climate change. During the past few decades, a rapid economic growth has led to a boost in transport activity, particularly in road traffic, and consequently an increase in energy consumption and air quality impacts.

On the one hand, research activity of road transport was concentrated on the analysis of emissions and the assessment of actions to mitigate them. However, emissions impacts on air pollution and climate change are usually tackled separately and when this occurs, it often results in undesirable side effects such as adverse health outcomes and ineffective policy interventions. A well-known example of this situation was *dieselization* of the European car fleet. At the beginning of the 80s diesel cars represented a minor part of the fleet; however, nowadays represent more than the 40% of the total EU car fleet (Rodríguez-Lopez et al. 2015). This was mainly due to the decision made by most European governments to base fuel tax only on carbon emissions efficiency without taking into account, for example, the harmful impact of pollutant emissions from diesel engines (actually, the carbon emissions efficiency of diesel cars has been already challenged by different authors e.g. Schipper and Fulton 2013; González and Marrero 2012).

On the other hand, recent technological developments have brought about new possibilities to improve traffic performance in urban environments while reducing their externalities. The emissions reduction potential of ICT-based solutions has traditionally been viewed as secondary to the impacts on traffic safety and congestion. Although recently different researchers have been studying the effects of these new technologies on emissions (Samaras et al. 2016; Garcia-Castro & Monzon 2014b; Baptista et al. 2012; Xia et al. 2013; Mastenbroek et al. 2012; Papageorgiou et al. 2007; Spence et al. 2009; Canaud & Faouzi 2015), more knowledge is needed on the assessment and impacts of this type of technologies before supporting the wider deployment of 'Green ITS' services. Since previous research works mainly focus on the impact on fuel consumption and CO₂ emissions without considering the effect of these measures on air pollutants nor on population exposure these type of emissions, further research is needed on their combined impact on GHGs and air pollutants in urban environments.

This research aims to bridge these topics providing methods and knowledge on the combined impacts of emissions reduction strategies (especially ICT-based) on climate change and air pollution.

1.1. Research context

This research has been developed under the frame of a 7FP project - ICT-Emissions- and a stay at the World Bank Transport& ICT Global Practice. The disruptive and innovative character of part of this research has already received international recognition through the "Lee Schipper Memorial Scholarship for Sustainable Transport and Energy Efficiency".

1.1.1 ICT-Emissions project

ICT-Emissions developed a novel methodology to evaluate the impact of ICT related measures on mobility, vehicle energy consumption and CO₂ emissions of vehicle fleets at the local scale, in order to promote the wider application of the most appropriate ICT measures. The methodology combined traffic and emission modelling at micro and macro scales and was tested and validated in the cities of Madrid, Turin and Roma.

The UPM team at the project had an active role on the development of the micro-macro links of the methodology and led the Madrid Case Study. In particular, my role in the project supervised by Andres Monzon and Cristina Valdes, was to develop the macro-scale simulation of the ICT selected measures. This duty included the calibration and validation of traffic model for the Madrid Case study, the simulation of the macro-scenarios and the analysis of results.

In this thesis the macro-scale ICT-emissions methodology has been extended to allow for

- (i) the assessment of air pollutant emissions and population exposure to these emissions and,
- (ii) the mapping of the results for a quick identification of network links with high emissions levels and population rates i.e. air pollution hotspots.

Besides, the impact evaluation of the policy measures has also been broadened including the analysis of

- (i) the implementation of combined ICT-based traffic management strategies and,
- (ii) the analysis of air pollution and climate change co-benefits and trade-offs.

1.1.2 World Bank stay at the Transport&ICT Global Practice

The World Bank Internship Program is opened to highly motivated and successful Master or PhD students. As a Bank intern, I have received professional coaching and hands-on training that have deepened my experience and exposed me first-hand to the challenges and rewards of international transport projects implementation and management.

The Transport & ICT Global Practice provides stakeholders with infrastructure and policies to improve connectivity and competitiveness, link people to markets and social services to stimulate social inclusion, productivity, increase climate resilience and reduce carbon footprint.

In my stay at the bank I've got a deeper understanding of:

- (i) the importance of urban transport emissions in the world but in particular in the Latin American region focusing in Mexico and Brazil
- (ii) the complexity of urban transport emissions assessment
- (iii) strategies to reduce urban transport emissions
- (iv) assessment methodologies for transport emissions in cities

In particular I applied a well-known bottom-up transport emissions assessment methodology based on transport activities, structure, energy intensity, and a carbon factor effect, which is related to the composition of fuels. This analytical methodology known as ASIF method (Schipper et al. 2000a), was the foundation of the *Avoid-Shift-Improve* (ASI) framework (Dalkmann & Brannigan 2007) used in this thesis to classify emission reduction strategies. Both concepts are further explained in the literature review

At the bank and based on the ASIF framework, I developed a model to evaluate the impacts on traffic volume, travel times and emissions of urban mitigation strategies that promote modal shift to more efficient transportation modes. The model has been used to evaluate a project financed by the World Bank which aims to improve the level-of-service provided to the urban

rail transport users in São Paulo. The model showed It has been prove that the project bring about reductions in transport emissions as well in traffic performance for the city of Sao Paulo.

1.1.3 Lee Schipper Memorial Scholarship

In 2016, I have been awarded with the “Lee Schipper Memorial Scholarship for Sustainable Transport and Energy Efficiency”. The Scholarship is aimed at expanding the contributions to research and policy dialogue in the field of sustainable transport and energy efficiency.

Part of the content of this thesis was submitted to the call of proposals. The research was selected out of more than 70 research applications due to its “iconoclastic” contributions (challenging conventional wisdom), its clear transformative outputs and its contribution to measurable changes.

The Scholarship is governed by an Advisory Board of selected experts in the field and managed under the umbrella of the World Resources Institute Foundation. The scholarship was awarded through a transparent process with strong governance procedures.

The Advisory Board was formed by

- Holger Dalkmann, Director, EMBARQ
- Judith Pollock, Deputy Director, Shell Foundation
- Nancy Kete, Managing Director, Rockefeller Foundation
- Ramon Munoz-Raskin, Urban Transport Specialist, World Bank Group
- Sanjivi Sundar, Professor, TERI University
- Sam Zimmerman, Urban Transport Advisor, World Bank
- David Jhirad, Former Director of the Energy, Resources and Environment Program, Johns Hopkins University

Results have been presented in a special session devoted to the Lee Schipper Scholars in the Transforming Transportation 2017 “Beyond Commitments: Sustainable Mobility for All”, at the World Bank Headquarters, Washington, DC. The winning candidate letter can be found in Annex IV.

Figure 1-1 summarizes the research context and its contribution to the thesis. The ICT-emissions project provided the methodological grounds, the policy portfolio and the city-wide approach to understand the impacts of site specific policies. Besides, results of this project showed benefits of the policies analysed regarding climate change but they also suggested potential air pollution drawbacks. The stay at the World Bank allowed me to deepen my knowledge on emissions assessment methodologies and the ASI framework for emissions reduction strategies. Besides, the opportunity to work with already implemented projects and to experience the difficulties to assess their impacts supported the idea to develop simple but effective indicators to measure exposure to air pollutants. Finally the Lee Schipper Memorial Scholarship encouraged me to question the positive impacts of *Improve* type of emissions reduction strategies on air pollution.

Figure 1-1 Research context and its contribution to the thesis

1.2. Thesis structure

This thesis is organized in six chapters each of them covering one research step as is shown in Figure 1-2

- **Chapter 2** covers the literature review. It is divided in three sections. The first poses the emissions problem in urban environments while the following sections identify the research gaps regarding assessment and policy.
- **Chapter 3** concludes the literature review establishing the overall research question and its specific research objectives and describes the research approach followed to achieve them.
- **Chapter 4** describes the specific methodology developed to analyse the impacts of the selected policy measures on traffic performance and emissions
- **Chapter 5** presents the Madrid case study where the methodology for policy analysis is applied
- **Chapter 6** introduces the measures selected for policy analysis, describes the scenarios chosen for simulation
- **Chapter 7** presents the results of this simulation
- Finally, based on the results of the literature review and the original research works, **chapter 8** summarizes the main conclusions and contributions of this dissertation. It also includes future research lines complementing and reinforcing this thesis

Figure 1-2 Thesis structure

2. CLIMATE CHANGE AND AIR POLLUTION IN URBAN AREAS: THE IMPACT OF TRAFFIC EMISSIONS

*“The ambition is clear: by mid-century, GHG emissions from transport will need to be at least 60% lower than in 1990 and be firmly **on the path towards zero**. Emissions of air pollutants from **transport** that harm our health need to be **drastically reduced** without delay”*

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

A European Strategy for Low-Emission Mobility. Brussels, 20 July 2016

This chapter delivers a literature review on traffic emissions in urban areas which is intended to:

- (i) provide information about the dimension and scope of the emissions problem in urban environments,
- (ii) understand the complexity of the emissions assessment and introduce the most popular methodologies used and,
- (iii) understand how transport policy intervention can contribute to climate change mitigation and air pollution reduction in urban environments.

The ultimate goal of this literature review is to identify the research gaps that the thesis should contribute and try to fill. These research gaps are summarized at the end of the chapter.

2.1 Exhaust Emissions from road traffic: a two-fold challenge.

Transportation is widely recognized to be a significant source of greenhouse gas (GHG) and air pollution. Globally, transportation is responsible for 23% of CO₂ emissions. The transport sector is also a key source of air pollutant emissions, and accounts for 58% of emissions of NO_x, 18% of NMVOC, 30% of CO, 21% of SO_x, 27% of PM_{2.5} and 22% of PM₁₀ (EEA 2012).

The transport sector has not seen the same gradual decline in emissions as other sectors: emissions only started to decrease in 2007 and still remain higher than in 1990. Emissions from the transport sector increased 56.9% from 1990 to 2012 and the growth rate of road transport emissions was even higher, 64.1% (IEA 2014).

Within the transport sector, road transport is a major source of GHG emissions and the largest contributor to air pollutant emissions in urban environments (EEA 2006). Road vehicles accounts for about three-quarters of CO₂ emissions, 53.5% of this share is attributable to light vehicles (car, motorbikes, light duty) and the remaining 46.5% to heavy vehicles (buses and trucks) (Miller & Façanha 2015; IEA 2014).

Road transport related emissions can be classified into: exhaust emissions and non-exhaust emissions. Exhaust emissions from road transport result from the incomplete combustion of fuels such as gasoline, diesel, liquefied petroleum gas, and natural gas in internal combustion engines (Samaras & Ntziachristos 2016). Non-exhaust emissions can be generated from: brakes, tyres, clutches and road surface wear; or emissions that already exist in the environment such as deposited material that become re-suspended due to traffic induced by turbulence (Grigoratos & Martini 2014). Recent research has highlighted increased contribution of non-exhaust emissions to air pollutants, especially PM, in urban areas (van der Gon et al. 2013). Among the transport exhaust emissions gases we find CO₂, CO, NO_x, NMVOC, CH₄, CO₂, N₂O, NH₃, SO_x, exhaust PM, PAHs and POPs, dioxins and furans, PCBs, HCB, and heavy metals contained in the fuel (lead, arsenic, cadmium, copper, chromium, mercury, nickel, selenium and zinc). Depending on the level of detailed data available there are different ways to estimate those emission gases e.g. Samaras & Ntziachristos (2016) developed a detailed methodology for estimating CO₂, NO_x, VOCs, CH₄, NH₃, NMVOCs, HC and PMs emissions.

Figure 2-1 Different type of emissions from road transport and main gases (Pastorello & Mellios 2016)

2.1.1 Scope: Diverse spatial and temporal environmental impacts of transport emissions

Transport emissions have a varying influence on the urban environment, given that GHG and air pollutants have different spatial and temporal effects.

On the one hand, most GHG emissions have minimal local effects. GHGs are a world-wide problem with large-scale impacts: no matter where these emissions are produced, all of them contribute to global figures and hence to global warming and climate change (HEI 2010). CO₂ is the primary GHGs emitted through human activities accounting for more than 75% of GHG emissions globally (Barrett et al. 2014). We can describe CO₂ effects as global and long-lasting. Atmospheric CO₂ is part of the global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Some of the excess carbon dioxide will be absorbed quickly (for example, by the ocean surface), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments (US-EPA 2016). Exhaust emissions from road transport also include other non-CO₂ emitters which are both air pollutants and climate forcers e.g. NO_x, methane, carbon monoxide, HC, Black Carbon and fluorinated gases (Sims et al. 2014).

On the other hand, air pollutant emissions have a major local impact since they tend to affect the area or street where they are emitted (Gauderman et al. 2005; HEI 2010). Their concentrations fall off rapidly with increasing distance from the road (e.g. Colville et al. 2001; Parra et al. 2009) and can be relatively short-lived. Since air pollutants concentrations fall off rapidly with increasing distance from the road (Rioux et al. 2010; HEI 2010; Han & Naeher 2005), people who live, work or frequent locations near major roads appear to have an increased incidence and severity of health problems associated with air pollution exposures (Parra et al. 2009). Several studies show a direct correlation between the increase in cardiac and respiratory morbidity and mortality and exposure to air pollution (Laumbach & Kipen 2012; Brunekreef et al. 2009; Schwela n.d.; Guo et al. 2015; WHO 2003). This represents an alarming health problem; in fact, a special report published by the Health Effects Institute in February 2017 have identified air pollution as the leading environmental cause of death world-wide (HEI 2017).

Figure 2-2 Spatial and durational effect of main road-transport emissions (adapted from Rodrigue et al. 2009)

Among the main air pollutants from road transport exhaust emissions we can find (Pastorello & Mellios 2016):

- Hydrocarbons (HCs), which are produced from either incomplete or partial combustion and which are toxic to human health. HCs, and particularly the volatile organic compounds (VOCs), contribute to the formation of ground-level ozone and photochemical smog in the atmosphere. Ozone irritates the eyes, damages the lungs and aggravates respiratory problems
- Carbon monoxide (CO), a product of incomplete combustion, which occurs when the carbon in the fuel is only partially oxidised, forming CO and not CO₂. It is colourless and odourless but highly toxic. Direct exposure to CO reduces the flow of oxygen in the bloodstream and is particularly dangerous to people with heart disease. Like HCs, CO also contributes to the formation of ground-level ozone and smog.
- Particulate matter (PM), which is a product of incomplete combustion and a complex mixture of both primary and secondary PM. 'Primary' PM is the fraction of PM that is emitted directly into the atmosphere, whereas 'secondary' PM forms in the atmosphere following the release of precursor gases mainly: sulphur dioxide (SO₂), nitrogen oxides (NO_x), ammonia (NH₃) and some VOCs. In terms of its potential to harm human health, PM is one of the most important pollutants, as it penetrates into sensitive regions of the respiratory system and can cause or aggravate cardiovascular and lung diseases and cancers.
- Nitrogen oxides (NO_x), comprises of a mixture of nitric oxide (NO) and nitrogen dioxide (NO₂). NO is not harmful to health at the concentrations typically found in the atmosphere. NO_x emissions also lead to the subsequent formation of 'secondary' PM and ground-level ozone in the atmosphere, and cause harm to the environment by contributing to the acidification and eutrophication of waters and soils. NO₂ is associated with respiratory and cardiac health problems

2.1.2 Dimension: Extent of the problem in urban areas

Currently over half of world's population lives in urban areas and this figure is expected to reach 70% by 2050. On the one hand, cities have the potential to produce synergies and increasing returns to scale, which makes them extremely efficient allowing great development opportunities to their inhabitants. But, on the other hand, cities cause a wide range of problems difficult to tackle such as pollution, climate change, traffic congestion, lack of affordable housing, urban sprawl, poverty, social tensions and high crime rates which leads to a reduction of the quality of life of their inhabitants (UN-HABITAT 2011).

Cities world-wide suffer from serious air quality problems and are main contributors to climate change consuming about two-thirds of the world's overall energy and emitting estimated 70% of the world's GHG (IEA 2014). Particularly, urban transport contribution to CO₂ emissions is estimated at around 25%. If just 100 of the world's largest cities follow low-carbon agendas, global greenhouse gas emissions could decrease by an estimated 10 percent a year (Aijun 2014). According to the European Environment Agency (EEA 2015), during the period 1997–2008 up to 62% of the European population living in cities (70% of the total population) may have been exposed to concentrations of particulate matter, ozone or nitrogen dioxide above European Union established air quality limits. Besides, road transport is the largest contributor

to NO_x emissions in urban environments (EEA 2006). The average contribution of urban and local traffic to NO₂, which is one of the components of NO_x concentration, is estimated at 64% (Sundvor et al. 2012).

Different forecasts e.g. (IEA 2014; OECD 2012; WORLD ENERGY COUNCIL 2011) expect around 2% yearly growth in world transport energy use over the next few decades, this figure would be even higher, above 3%, in emerging economies. Drivers that explain this trend are:

- (i) the economic growth (transport demand and economic activity are highly correlated),
- (ii) the predicted growth in urban population (over half the world population now lives in cities, and estimations indicate that over 70% will do so by 2050),
- (iii) the predicted growth in passenger vehicles and in car ownership particularly in developing countries. There are about 1.2 billion passenger vehicles today, a figure that is expected to reach 2.6 billion by 2050 (UN-HABITAT 2011), and
- (iv) the current trend of urban decentralization in virtually all metropolitan areas (Giuliano et al. 1999; Kahn Ribeiro et al. 2007).

2.2 Transport emissions

Transport emissions assessment becomes a complex task due to the diffused nature of emission sources and the unfeasibility of direct measurement due to cost and logistical issues. In order to estimate the impact of transport policies on emissions different factors need to be taken into account e.g. modal composition or policies rebound effects as well as estimating factors affecting fuel or electricity consumption such as vehicle kilometer travelled, load factors, public transport occupancy rates, network travel speeds, driving behavior, traffic composition, and technology change (Wright & Fulton 2005; Millard-Ball & Ortolano 2010; Wb 2012; Dalkmann & Brannigan 2007)

There are two main approaches evaluate the impact of transport emissions strategies (Sobrinho 2015): the top-down approach, where total annual road traffic emissions are assessed by means of statistical indicators (proxies of population, roads, land-use, total fuel sales, emissions per unit energy and emissions factors based on energy content), and the bottom-up approach, where emission are calculated on the basis of the available traffic data.

The bottom-up approach is more precise and accurate but at the same time requires more input data: traffic volumes, average speeds, fleet composition by fuel and technology for macroscopic assessment (metropolitan areas or cities) and specific driving behaviours and vehicle performance including acceleration and deceleration rates or idle time for microscopic assessment.

2.2.1 Transport emission drivers

Schipper et al. (Schipper et al. 2000b) developed a bottom-up comprehensive approach that describes the drivers of transport emissions: the ASIF equation. The authors considered carbon emissions of a particular transport sector (**G**) as a function of:

- the total travel activity in passenger-km (or tonne-km for freight) (**A**),
- the modal share in percentage of total passenger or tonne-km carried by each mode **k** (**S**), and
- the fuel (**j**) intensity of each mode (**I**) which depends on vehicle technology and driving cycles and the carbon content of fuels (**F**)

$$G = A \times S_k \times I_{k,j} \times F_{k,j}$$

This equation has been widely used to quantify the emissions of different transport projects and was the seed of a policy framework to reduce transport emissions. Martinez-Jaramillo et al. (2017) estimated the amount of emissions avoided by the implementation of Medellin's Master Plan in Colombia, the promotion of telecommuting, and the development of a transport energy model for Medellin between 2010 and 2040. Also, Zegras (2007) used it to evaluate three project proposals to be funded under the Clean Development Mechanism (CDM) in Santiago de Chile: bus technology switch, bicycle promotion, and location efficiency. Moreover, this bottom-up approach is used by different IFIs to measure emissions from transport around the world (BID 2013; Wb 2012; Leather 2009). On the other hand, the use of

decomposition techniques with this framework (ASIF decomposition) provide insights to identify the necessary policies to address transport emissions and can shed light on the effectiveness of transport policies (Schipper et al. 2011).

Wright and Fulton (2005) have also developed a similar framework where GHGs are a combination of behavior, design of the transport system and technology. The behavioral component includes the relative market share of a particular mode and the number of passenger carried by vehicle, the transport design takes into account the distance travelled which is a function of the land-use and transport network design, and finally the technology component which considers the type of fuel, the weight of the vehicle and the driver behavior among others.

2.2.2 Road traffic emissions assessment models

Following a bottom-up approach, transport demand models have been linked with emission models for emission inventory studies and analysis of the environmental impacts of transport initiatives in urban environments.

Emissions models designed specifically for calculating traffic emissions can be classified depending on how they obtain emissions factors (EFs). They estimate hot emissions from traffic multiplying emission factors by appropriate traffic activity data for different vehicle classes. EFs express the mass of pollutant emitted per unit distance (g/km), time (g/s) or mass of fuel burned (g kg⁻¹). The corresponding activity data follows from these units (i.e. vehicle kilometres travelled), total time spent in particular driving conditions (e.g. idling), or total fuel consumption. Start emissions and evaporation are seldom addressed using this method (Samaras et al. 2014).

The traffic activity data is provided by the traffic models. Particularly, traffic systems are very complex, nonlinear, and are affected by many external and internal factors: vehicle dynamics with respect to the infrastructure and driver's behaviour increase their complexity and stochasticity, thus making it difficult to capture all the traffic phenomena with a single model (Zegeye et al. 2013). There are three main types of traffic models: macroscopic, mesoscopic and microscopic models. The main difference among them is the trade-off between optimizing simulation speeds and estimating the traffic states accurately. For a recent review of traffic simulation models, see (Hoogendoorn & Bovy 2001; Barceló 2010).

Here we will focus on macroscopic transport models. Macroscopic traffic models are used to obtain traffic intensities and average speeds at link level. These models describe traffic at a high level of aggregation as a flow without distinguishing its constituent parts and using attributes as flow-rate, density, and velocity (Blewitt 2010). They represent the steady-state behaviour of network systems which is representative of average system conditions in the adopted simulation period. Despite being often computationally tractable and scalable; they fail to account for vehicle-specific attributes or detailed traffic dynamics (Hoogendoorn & Bovy 2001) This makes them suitable for large scale, network-wide applications, such as cities or metropolitan areas which are the focus of this research.

There are different types of emission models that can be used at the macro level: (a) average speed models like COPERT, MOBILE or EMFAC, where emission factors are function of mean average speed; (b) traffic situation models, like HBEFA or ARTEMIS, where EF are determined

by descriptions of particular traffic situations; (c) traffic variable models, TEE, NEMO or Matzoros, where EF are defined by traffic flow variables such as average speed or traffic density; (d) cycle variable models, like MEASURE or VERSIT+, where EF are function of different cycle variables such as idle time or positive kinetic energy and; (e) modal emissions models like MOVES, PHEM or CMEM, where EF are produced via engine or vehicle operating models at the highest resolution (Smit et al. 2010a; Grote et al. 2016). Both average speed and traffic situation models can be easily fed by macroscopic transport models. Inputs for traffic variable models can be provided by both macroscopic and microscopic transport modes. However, cycle variable and modal models can only be fed by microscopic transport models (Smit et al. 2010a)

Several examples of the joint application of traffic and emission models can be found in the literature e.g.: Zegeye et al. (2013) provide a general framework to integrate macroscopic transport models, specifically METANET1 with microscopic emissions models (VT-Micro), and present an empirical analysis of the error and the computation time based on calibrated models of the Dutch A12 freeway. Osorio & Nanduri (2015) combine a microsimulation traffic model with an emission model to evaluate traffic emissions and air quality in a dense neighborhood. Alam et al. (2014) investigate the effectiveness to reduce emissions of traffic signal control and variable message sign using a microscopic transport model and an emissions model. Mascia et al. (2016) uses both a macroscopic transport model and a macroscopic emission model to assess the environmental impact of speed limits changes in urban motorways. The same approach was used by Pu et al. (2015) to evaluate the impact of a plate restriction policy on emission reduction.

Most of the emissions assessment models reviewed are not customized for the specific city and fleet and therefore their results could present some bias for evaluation impacts at the local level. Besides, they analyse the sections directly affected by transport measure and do not take into account the wider effects on the rest of the urban network.

2.2.3 Indicators

As mentioned before, the effect of traffic emissions in the urban context is singular due to the fact that GHGs and air pollutants have different spatial impacts. Yet transport emissions are usually evaluated without taking into account where they are emitted or the amount of population affected by these emissions. Transport emissions assessment frameworks have been primarily developed to evaluate climate change mitigation strategies (Schipper et al. 2000b; Wright & Fulton 2005; Creutzig et al. 2011) and, therefore, transport planning has usually-been a means to tackle both types of emissions in similar ways considering that most of the strategies designed to reduce GHGs emissions also reduce air pollutants and not taking into account the local impacts of air pollutants.

Despite this fact, authors analysing environmental impacts of transport interventions usually report emission reductions without considering where they are achieved (see e.g. Shiftan et al. 2015; Liu et al. 2013; Doorley et al. 2015). The same occur with the indicators used in transport project appraisal methodologies (Shiftan et al. 2008) which do not take into account the amount of population exposed to air pollution emissions. To obtain these indicators e.g. tons or kg of CO₂ or NO_x reduced, we only need to take into account traffic activity attributes.

This is of particular importance when evaluating the impact of traffic management strategies at city level, since transport interventions in a delimited area of the city could affect other areas in different ways (Samaras et al. 2016). For example, Hoogendoorn et al. (2013) evaluate the air quality impact of a dynamic speed limit on a freeway near Rotterdam. Results showed that air quality deteriorate slightly along the stretch with a maximum increase of NO_x emissions of 3.7%. This increase would be more harmful if it was produced in an urban highway crossing a high populated area. However, using gross air quality indicators this nuance cannot be considered.

Very complex dispersion and chemical models are needed to model the contribution of traffic to urban air quality. Along with traffic activity variables, climatic and topographic variables need to be taken into account as well as road and building geometry. High resolution urban air quality modelling has limitations and uncertainties that remain unsolved (Gorham 2002; Laña et al. 2016).

One way to simplify this problem is to choose single variables to act as indicators for the exposure effects of the aggregate pollution. For example, Lipfert et al. (2006) found that traffic density, calculated as the annual average vehicle travel per unit of land area, can be used as county-wide surrogate exposure measure suitable for cohort and population-based epidemiology studies; Huang and Batterman (2017) reviewed 45 studies that used residence location as a measure of environmental exposure intended to reflect the portion of exposure received at home, which is generally the dominant share since most individuals spend the majority of their time at home. Residential proximity to high traffic roads and dense road networks have been linked to respiratory diseases (McConnell et al. 2006; Gauderman et al. 2005; Salam et al. 2008; Hamra et al. 2015) and increased risk of coronary heart disease or atherosclerosis (Kan et al. 2008; Medina-Ramón et al. 2008; Maté et al. 2010).

However, direct measurement of traffic-related air pollutant exposure is hardly achievable due to cost and logistical issues (Rioux et al. 2010). Besides, air quality monitoring networks do not provide the spatial coverage needed to estimate near-road exposures (Batterman 2013). This information, together with the amount of exposed population, would be of high importance to identify roads and areas in a city that urgently need traffic emissions reduction measures.

2.2.4 New technologies assessment challenges

Information and Communications Technologies (ICTs) have brought about new possibilities to improve traffic performance in urban environments while reducing their externalities, but significant results and quantitative data are still to come (ERTRAC 2011; Spence et al. 2009). So far, only a few Intelligent Transport Systems (ITS) – which are based on ICTs – have specifically addressed environmental aspects. The environmental effects of ITS strategies have generally been viewed as secondary to the effects on accidents, congestion and journey times. Tangible results are needed to support the wider deployment of ‘Green ITS’ services. In parallel there is an urgent need for more research in the area of optimal technological change and technological diffusion involving multi-disciplinary cooperation between engineers, social scientists and end users in order to detect the true potential and benefits of various forms of ICT driven innovations for a more energy efficient society. This will require extensive cross-disciplinary and cross-sectoral approach for an enhanced holistic view of ICTs. Nevertheless, recently different researchers are studying the effects of these new technologies on fuel

consumption and CO₂ emissions (Samaras et al. 2016; Garcia-Castro & Monzon 2014b; Baptista et al. 2012; Xia et al. 2013).

The European Research and Development project ECOSTAND has divided Intelligent Transport Systems applications into five categories: driver behavior change, navigation and travel information, traffic management and control, demand and access management and logistics and fleet management (Canaud & Faouzi 2015). Later and based on the ECOSTAND classification, the ICT-Emissions ¹ project provided a similar list of ITS with also with 5 categories, but excluding logistics and fleet management as they are outside the scope of the project and including Advanced Driver Assistance System (ADAS).

The ICT-Emissions project developed a methodology to assess emissions at microscopic and macroscopic level that takes into account these limitations. It has been used to quantify the impact of different ITS on CO₂ using different combinations of macroscopic and microscopic transport and emission models. The methodology developed within the project, as well as the results of ICT measures considered, can be found in (Garcia-Castro & Monzon 2014b; Garcia-Castro et al. 2016; Toffolo et al. 2015; Valdes Serrano et al. 2015; Valdes 2015; Samaras et al. 2016).

The macroscopic assessment in the ICT-Emissions project is based on the interaction of a macroscopic transport model with the macroscopic emissions model, COPERT. This method is a useful starting point to understand the impact of ICT- based strategies on emissions; however, it presents limitations for evaluating air pollution impacts at the local level, since they do not take into account population exposure levels.

Recently, a novel approach for modelling emissions in urban networks and motorways based on its spatiotemporal distribution is being developed (Csikás et al. 2015). The modelling framework is based on the Network Fundamental Diagram concept which aims at describing the vehicular traffic movement in cities on an aggregate level. Several works ((Keyvan-Ekbatani et al. 2012) have attempted to predict both the average and the distribution of speed in an urban area as a function of explanatory variables that characterize the demand and the network infrastructure. Results showed that large networks behave predictably and independently of their OD matrices.(Geroliminis & Sun 2011).The Network Fundamental Diagram concept applied to traffic emissions formalized emissions in finite spatiotemporal windows as function of total travel distances and network average speeds within the network. Further research is needed in this field, but it is already considered of great importance to plan and evaluate ICT-based traffic management policies without the uncertainty inherent in today's forecast-based approaches (Geroliminis & Sun 2011)

¹ <http://www.ict-emissions.eu/>

2.3 Strategies for reducing transport emissions

Based on Schipper's ASIF identity, Dalkmann and Brannigan (Dalkamann & Brannigan 2007) proposed a framework to identify transport strategies that reduce carbon emissions from the demand side: the *avoid-shift-improve-finance* framework or ASIF2 paradigm (Tiwari et al. 2011).

- *Avoid* refers to improve the efficiency of the transport system by implementing mechanisms that diminish both the trip length and the need to travel e.g. integrated land-use and transport planning or demand management initiatives as urban tolls, pay as you drive or the reduction of parking space in the city centers;
- *Shift* apply to measures that promote modal shift from high energy consuming transport modes i.e. cars towards public transport systems and non-motorized transport modes;
- *Finance* refers to investment in urban development and transport to achieve reduced CO₂ levels and sustainability; and
- *Improve* strategies concentrate on enhancing the efficiency of the remaining travel activity through the improvement of vehicle design and fuel efficiency or the more effective management of transport system operations and networks.

Focusing on the *Improve* type of strategies and in particular in traffic management measures, it is worth to notice that these type of strategies were primarily designed to improve network efficiency by reducing traffic congestion and travel times. Therefore, traditionally their role in controlling emissions has been considered as secondary. Nevertheless, since congestion has consistently been singled out as a major factor in road traffic emissions and air quality degradation in cities e.g. (Carr et al. 2002), these measures could also help decrease direct emissions of air pollutants and GHG from vehicle operations (Chiquetto 1997). Efforts worldwide have recently gone into studying the success of various congestion management strategies in reducing GHG and air pollutant emissions from road urban traffic transport.

The ASI framework has been developed to evaluate transport strategies to reduce GHG emissions and do not explicitly takes into account air pollutant emissions. However, air pollutants and GHGs arise from many of the same sources; therefore, there are potential co-benefits to reducing emissions related to both air quality and climate change (Williams 2012). Recent research (Nemet et al. 2010a) suggests that considering the potential additional benefit of reducing air pollutants may lead to a reduction in the cost of carbon reduction policies.

The challenge in addressing air pollution and climate change over the coming decades will be to maximize co-benefits among policies at international, national, regional and local level, while attempting to minimize trade-offs between policies and to manage any residual negative impacts (UK HEALTH 2016). Figure 2-3 shows a policy map already considered by the UK government (UK DEFRA 2010 and UK HEALTH 2016) displaying air quality and climate change interactions. We have highlighted those strategies related to the transport sector. The map shows that demand management strategies and hybrids vehicles are beneficial for both climate change and air pollution. However, it shows that diesels vehicles as well as some

biofuels produce air quality trade-offs while the use of particulate filters for diesel cars and three-way catalyst for petrol cars lead to climate change trade-offs.

Figure 2-3 Policy map displaying climate change and air pollution interactions (UK HEALTH 2016)

2.3.1 *Improve* strategies for emissions reduction: climate change and air pollution co-benefits and trade-offs

While the *Avoid* and *Shift* strategies may have a direct impact in reducing both air pollution and GHGs in urban environments, *Improve* strategies could lead to important drawbacks due to e.g. the redistribution of the traffic activity in densely populated areas or the implementation of fuel tax policies based only in carbon emission-efficiency i.e. the case of diesel. This does not mean that the *Avoid* and *Shift* strategies should not be evaluated from this combined point of view.

Among the *Improve* strategies we can find eco-driving, speed management measures, road capacity management, vehicle and fuel energy efficiency and ICT-based measures such as ramp metering, variable speed limits, real-time travel information, traffic signal synchronization and eco-routing or Green Navigation systems.

Improve transport policies designed to avert climate change show co-benefits on air pollution mitigation (Woodcock et al. 2009; Thambiran & Diab 2011; Oxley et al. 2012a; Mao et al. 2012; Geng et al. 2013; Xue et al. 2015; Dhar & Shukla 2015; Pathak & Shukla 2016); however, there are potential conflicts where climate policies could result in increased air pollution, and vice versa.

Focusing only on the *Improve* type of strategies, a well-known case is the shift to diesel cars which not only delivered less CO₂ savings than expected (Schipper & Fulton 2009; Schipper & Fulton 2013) but also increases air pollution. For example, a study in Ireland showed how a car taxation policy promoting the purchase of lower CO₂ emitting cars could lead to a higher share of fuel- efficient diesel vehicles with up to 7% of CO₂ savings but a 28% increase of NO_x emissions (Leinert et al. 2013). The use of biofuels has also potential trade-offs regarding air quality (Liaquat et al. 2010; Godiganur et al. 2010; Gumus & Kasifoglu 2010). Regarding electric vehicles, studies show that they have a direct positive impact on pollution in urban environments since exhaust emissions are not produced during the operation of the vehicle (Hooftman et al. 2016; Sioshansi et al. 2010). Further regulations will be needed in the future to address the non-exhaust emissions (Hooftman et al. 2016) of electric vehicles. Besides, gains in terms of GHGs will highly depend on the electricity mix of the countries (Lang et al. 2013).

Measures directly affecting traffic performance have also been analysed from the combined point of view of climate change and air quality. For example, it has been reported that traffic calming measures increases both types of emissions (Ghafghazi & Hatzopoulou 2015; Jazcilevich et al. 2015). Traffic calming can provide emissions savings only if they generate a reduction in traffic activity or a shift to more efficient transport modes. Garcia-Castro et al. (Garcia-Castro et al. 2016), showed that while in low and medium congested traffic conditions eco-driving generated savings up to 2.3% in CO₂ and up to 4.3% in NO_x emissions, during highly congested traffic conditions emissions increase up to 1.3% and 0.5% respectively. In Belgium, a study showed reductions of about 10% in NO_x and CO₂ from the implementation of a green-wave signal coordination scheme along an urban arterial road (Madireddy et al. 2011). Cohen et al. (Cohen et al. 2014) reported global environmental benefits of a speed reduction strategy in segments of different motorways in Lille. Regarding, road capacity increases Monzon et al., (2005) predicted a reduction of GHGs and air pollutants in Madrid after the renovation of its inner ring-road. An ex-post study (Perez-Prada & Monzon 2012) confirmed this trend after three years (short-term) of operation of the renovated beltway. However, other studies (BID 2013) suggest an increase in emissions in the long run after a road capacity increase.

Although these research papers take into account both types of emissions: GHGs and air pollutants they do not explicitly acknowledge the different spatial impact of the emissions. Results are presented in gross emissions reduced without considering the characteristics of the area where they are emitted.

2.3.2 Speed management strategies

In recent decades, higher speed transportation has fostered economic development by enhancing mobility, decreasing travel times and enabling access to goods, services and facilities. Higher speeds still enjoy significant rates of support from society and industry, although they imply major adverse impacts on safety, environment and quality of life in urban areas (OECD/ECMT 2007). The effects of speed on reducing travel times tend to be overestimated, especially in urban areas where time savings are often small or negligible due to short trip length and frequent stop-and-go cycles, usually caused by numerous intersections, traffic lights, shopping areas or heavy congestion rates (Archer et al. 2008).

From a macroscopic perspective, transport emissions are a function of driving conditions (average speed is the input for macroscopic emission models for traffic conditions, although traffic dynamics are also important), total travel activity (km travelled), vehicle technology and fuel efficiency. Traffic management strategies can affect the first two factors, which are indeed closely related.

Among all the traffic management strategies, one of the most cost-effective ways to reduce road transport emissions is by lowering speed limits (OECD/ECMT 2007; TRB 2012; OECD 2008). Speed limits have traditionally had a twofold function (Archer et al. 2008). On the one hand, they limit the maximum speed of a road for safety purposes, and on the other, they reduce dispersion in driving speeds, which not only increases safety but also improves traffic flow efficiency. Like Sweden Vision Zero, numerous other studies support the idea that lower speed limits lead to a significant reduction in traffic accidents (WOOLLEY 2005; Aarts & van Schagen 2006; De Pauw et al. 2014). New trends arising from global concern about climate change also ascribe an energy conservation function to speed limits. It is well known that during the 1970s oil crises, the US government applied a nationwide speed limit reduction of 90 km/h to save fuel, which remained in effect for almost 25 years. In several countries in Europe this measure was replicated by setting a range of speed limits. In Spain, it was again applied in 2011, when for energy saving reasons the Spanish government lowered the motorway speed limit—which had already been reduced in the 1970s— from 120 km/h to 110 km/h, although in this case the measure only lasted for 4 months. A number of authors have examined the relationship between lower speed limits and reduced emissions or fuel consumption. In Germany a 4.8% reduction in fuel consumption was achieved after lowering the speed limit to 100 km/h on motorways and 80 km/h on roads outside urban areas (GIER 1996). A recent study of Spanish highways concludes that the most effective traffic management strategy among those analysed is the reduction of motorway speeds for cars, a finding also borne out by the sensitivity analysis. The measure led to a 5.5% reduction in CO₂ emissions (Monzon et al. 2012). Most studies also show that a reduction in speed limits leads to lower air pollutant emissions. In Austria, lowering speed limits on highways from 130 km/h to 100 km/h led to a 17% reduction in NO_x and 25% in CO₂ emissions (ECMT 1996). A study conducted in Rotterdam, Netherlands, shows a 5-30% fall in NO_x emissions after reducing the speed limit from 100 km/h to 80 km/h on an urban ring road (Keuken et al. 2010). Transport policies should be designed to take into account both the major contribution of the transport sector to global emissions and the different spatial impacts of GHG and air pollutant transport emissions. Different type of strategies should be applied for urban and interurban areas.

Although lower and more strictly-enforced speed limits have proved to be a straightforward and efficient policy for reducing road transport externalities (accidents, emissions, noise and so on), community acceptance is still low due to its impact on average travel times at the individual level (Archer et al. 2008).

Variable Speed Limits (VSL) are being implemented worldwide; however, their effects on emissions and even on traffic operations are not yet clearly defined, and in some cases their benefit are not fully proven (Garcia-Castro 2016).

Garcia-Castro and Monzon (2014a) proposed a classification of VSL systems and conducted a review on the traffic, environmental and safety impacts of VSL implemented around the world. They identified two main types of VSL: scheduled variable speed limits, which operate following prefixed calendars or timetables based on historical data, and dynamic speed limits which produce changes in speed limits in response to accurate information regarding road, driving, weather and/or environmental conditions. The latest type of VSL system consists of a central processing unit which integrates traffic sensors and VSL signs. It uses real-time speed and traffic intensity information to determine time-varying speed limits and display them in a timely fashion (Wang & Cheng 2017).

VSL systems can be designed to harmonize speeds across lanes delaying the onset of traffic breakdown or reducing the probability of breakdown (Papageorgiou et al. 2008; Geistefeldt 2011) or, at active bottlenecks, to slow down traffic in a controlled manner to prevent traffic flow breakdown and avoid capacity drop (Hegyi et al. 2005; Carlson et al. 2010; Liu et al. 2015). Their effectiveness is based on the capacity increase resulting from the homogenization of traffic flows at high congested traffic conditions (van Nes et al. 2008). As it occurs with the speed limit reduction measure, enforcement of the VSL increases its effectiveness. However, not all the VSL systems implemented operate as mandatory speed limits but as recommended speed limit e.g. E4 in Stockholm (Nissan & Koutsopoulos 2011)

Very few examples have been reported on the impact of VSL on emissions. A case study in The Netherlands based on model predictive control, showed over 35% total emission reduction (Zegeye et al. 2013). An empirical estimation in Barcelona using the difference-in-differences method comparing the use of variable speed limits and a reduced fixed speed limit showed that reducing the speed limit to 80 km/h caused a 1.7-3.2% increase in NO_x (Bel & Rosell 2013). Nevertheless, other empirical research studies reported by (Garcia-Castro & Monzon 2014a) showed an emissions reduction e.g. on the M25 motorway in the U.K. after the implementation of VSL in a section of the motorway vehicle emissions have dropped between 2% and 8% as a result of improved traffic conditions (reduction of start-stop driving, reduction of the frequency and severity of shockwaves and traffic more evenly spread across all four lanes) (UK HIGHWAYS 2004); another example from the Inn Valley in Austria showed a 3.6% NO₂ emissions reduction after one year of VSL operation (Land Tirol 2012). Simulation studies on the effects of VSL on traffic performance are more common and typically show positive effects ranging from travel time reductions to increases in operational capacity of the road. Detailed information of these studies can be found in the already mentioned review conducted by Garcia-Castro and Monzon (2014a). More research is needed to understand the impact of VSL on traffic operation and on emissions.

2.3.3 Eco-traffic strategies

This section will explain first what is understood by eco-traffic strategies. Then, a literature review will be presented for the measures considered.

Sivak and Schoettle (2012) defined Eco-driving as “*those strategic decisions (vehicle selection and maintenance), tactical decisions (route selection and vehicle load), and operational decisions (driver behaviour) that improve vehicle fuel economy*”. Their results indicate that although vehicle selection has by far the most dominant effect, the remaining factors that a driver has control over can contribute, in total, to about a 45% reduction in the on-road fuel economy per driver. To avoid misunderstanding, henceforth the term *eco-driving* will be used to refer to operational eco-driving, the term *eco-routing* to refer to tactical eco-driving and the term *eco-traffic* to refer to both environment friendly driving techniques.

Recently numerous authors have analysed the impact on fuel consumption and emissions of operational eco-driving, i.e. driving behavior which involves “accelerating moderately (with shift ups between 2000 and 2500 revolutions for those with manual transmissions), anticipating traffic flow and signals, thereby avoiding sudden starts and stops; maintaining an even driving pace (using cruise control on the highway where appropriate), driving at or safely below the speed limit; and eliminating excessive idling” (Barkenbus 2010). A summary of behavioral eco-driving research studies by type, variables studied and effects can be found in (Garcia-Castro 2016).

Less attention has been paid to the tactical decisions, and particularly to the route selection choice i.e. eco-routing so called green-navigation systems. Navigation systems are on-board tools that use Global Positioning System (GPS) data to locate the user on a road map database. Navigation systems show different origin destination routes based on the optimization parameters selected e.g. distance, travel time, fuel consumed. Since navigation systems can influence the route chosen by the driver, they have impacts on fuel consumption and emissions. Green Navigation (GN) systems or the so called eco-routing systems aim to lower vehicle operating cost by providing routing recommendations based on information about real-time traffic situation and on calculation of fuel consumption. This means that GN systems plot a route that minimizes fuel consumption for a given origin and destination. Increased availability of information on topography, real time traffic and road signs make it possible to better predict fuel consumption over a pre-defined route (Kubicka et al. 2016). Although further research is being conducted in this regard, GN systems have already been implemented by passenger car manufacturers (ACEA 2016).

Although today it is unrealistic to expect a high use of this type of devices, in the near future with the increasing penetration of driverless cars, we will need to tell our car how we want to arrive at a destination: by following the fastest, the shortest or the most environmentally friendly route. Usually, the use of a time or distance-minimizing algorithm will also minimize fuel consumption and emissions. However, this is not always the case, e.g. in roads with high levels of congestion or high road grades (Barth et al. 2007).

There are very few studies evaluating the environmental and traffic impact of GN Systems. In general, research efforts have been concentrated in developing route-search algorithms to obtain the most fuel or emissions efficient itinerary (e.g. Rao et al. 2016; Kubicka et al. 2016;

Zeng et al. 2016) and applying them to a case study usually showing the effectiveness of the system to reduce fuel consumption and therefore CO₂ emissions. The effects of different type of algorithms on emissions have been analysed in different studies. The use of a shorter-route algorithm may have a vehicle travelling through heavily congested conditions, resulting in a higher fuel consumption, at the same time, the use of a shortest-time route could result in longer distances traveled, albeit on less congested roadway and/or higher speeds (Barth et al. 2007). A study in Lund showed that, for 46% of trips, drivers do not choose the most fuel-efficient route, and when they do, they save up to 8.2% on fuel consumption (Ericsson et al. 2006b). Ahn and Rakha (2008) reported a fuel consumption reduction of 14-18% and CO₂ emissions 17-25% through field trials and micro emissions simulation models for a shorter but slowly arterial route compared to a longer but faster highway corridor. Minett et al., (2011) reported a 17% reduction in fuel consumption between the cities Delft and Zoetermeer using the shortest local road instead of a faster motorway or a provincial roads. Regarding NO_x emissions Ahn and Rakha (2008) showed that up to 45% reduction in the arterial route. The focus of these studies was at corridor level, lacking interaction with other corridors in the context of a complete road network.

At the city-wide level, it is also interesting to understand the effect on traffic and emissions of different percentages of eco-routing drivers. In a later study, Ahn and Rakha (2013) quantified the impacts of implementing dynamic eco-routing in two American cities (Cleveland and Columbus) by considering various levels of market penetration and congestion. For a full level of market penetration results showed a reduction of travel distance by 5.11% and 5.46%, of NO_x by 8% and 9.5% and CO₂ by 3.3% and 5.2% in Cleveland and Columbus respectively. Results also showed an increase in travel times by 4.54% in Cleveland and 3.21% in Columbus. Their results led to the conclusion that eco-routing impacts are sensitive to the road network configuration. The eco-routing market penetration analysis showed further reduction as the percentage of eco-routing drivers increased; in particular, for Cleveland 0.23% and 3.85% of fuel savings were reported for a 10% and 90% of eco-routing market penetration while these figures were 4.97% and 6.12% in Columbus. The authors also reported increased fuel consumption and emission savings with increased congestion levels.

In 1998, Benedek & Rilett (1998) described how environmental objectives and environmental cost functions can be used within traditional macroscopic assignment models and applied a cost-function based on minimizing travel time and carbon monoxide (CO) in the city of Edmonton reporting very few benefits attributed to the selection of a high congested network without many alternative routes and an expected potential benefit of only 7%. Following this macroscopic assignment simulation approach, the ICT-Emissions project estimated fuel and CO₂ impacts of different percentages of eco-drivers at different traffic periods (Valdes 2015). The reported fuel and CO₂ reductions were consistent with the results of previous studies. In congested conditions results showed a reduction by 2.22%, 4.89%, 7.07%, 7.92% and 9.16% for a 10%, 25%, 50%, 75% and 90% of eco-routing drivers. For off-peak hours these figures ranged from 1.13% to 4.66% and for free-flow conditions from 5.91% to 9.47%. These reductions were attributed to a reduction of vehicle-km travelled (from 3.65% to 13.51% for congested conditions, from 1.61% to 8.53 for off-peak hours and 5.85% to 9.48% for free-flow conditions) and the relocation of traffic to shorter routes. They also reported an important increase of travel times, higher as the level of green drivers increased.

Emissions reduction from studies conducted at city wide-level have been largely attributable to the selection of shorter routes through the city center (Ahn & Rakha 2013; Samaras et al. 2016) instead of faster routes but longer routes using high capacity roads. This fact could have a negative impact on population exposure to air pollutants due to the potential reallocation of emissions to high-populated city centers. Further research is needed to understand this potential impact.

2.3.4 Combined strategies for emissions reduction

There is evidence that the combination and integration of policies can lead to positive side-effects and synergies (Santos et al. 2010). Although there is no clear evidence for cancelling or overlapping between the eco-ITS of interest.

The Working Group for Clean and Efficient Mobility (WGCEM) suggests such a potential may exist (Vreeswijk et al. 2014). Figure 2-4 displays the identified areas with possible overlapping effects. Highlighted in orange on the left side of the figure, we can find some of the *Improve* type of strategies analysed before: eco-driving, eco-information, navigation and guidance i.e. GN systems and eco-traffic management strategies which include VSL. The figure suggests possible overlapping effects using navigation systems that support eco-driving. It could also apply to eco-driving over eco-routing routes. Finally, it suggests some kind of complementarity between traffic management strategies and eco-routing navigation systems.

Figure 2-4: Areas of possible overlapping of ICT-based applications (Vreeswijk et al. 2014))

On the other hand, results from previous research may also suggest the possibility to balance the adverse effect of some ICT-measures e.g. on travel times if we can combined them with another measure that cancel it effect. For example, results of the ICT-emissions project in Madrid showed a reduction of 0.6% of CO₂ and 2.8% of travel times for a 25% market penetration rate of eco-drivers in high congested conditions for the same percentage of green navigation drivers a 2.5% reduction of CO₂ and 6.2% increase of travel times was obtained.

There is a need to analyse the possible synergies, complementarities or trade-offs of the combined application of these types of measures.

2.4 Summary of identified research gaps

From the literature review on methods to measure and estimate road transport emissions, we have identified a need to further develop comprehensive emissions assessment methodologies which

- (i) take into account the spatial and temporal scale of traffic emissions,
- (ii) overcome the assessment challenges of innovative emissions reduction strategies and can be adapted to analyse the impact of ICT-based transport policies,
- (iii) can be customizable for different fleet compositions,
- (iv) be able to evaluate policy impacts both in the area directly affected by the measure and at city level,
- (v) be able to identify areas in the city with high air pollutant emissions levels taking into account not only traffic activity but also the amount of people affected by the emissions.

From the literature review on strategies for reducing road transport emissions we have found a lack of research on the joint assessment of environmental and traffic performance impacts of the *Improve* type of strategies. In particular, more research is needed on:

- (i) the traffic and emissions redistribution of traffic management strategies, specially of policies that could lead to the reallocation of emissions to denser areas in cities and,
- (ii) the impacts on traffic and emissions of the combined application of traffic management strategies.

3. OBJECTIVES AND RESEARCH FRAMEWORK

This section is based on the literature review and it is aimed to establishing the research questions and the specific research objectives. It also includes the description of the overall research approach.

3.1 Overall objective

As a conclusion from the previous chapter we can state that cities world-wide suffer from serious air quality problems and that they are the main contributors to climate change. We can also affirm that road traffic is a major driver of this situation. Hence, the overall research question of this thesis is: how can we get *greener* and *cleaner* cities through transport measures?

But first, we should clarify what we understand by *green* and *clean*. The term *green city* was first used by Kahn (2006):

“Green cities have clean air and water and pleasant streets and parks. Green cities are resilient in the face of natural disasters, and the risk of major infectious disease outbreaks in such cities is low. Green cities also encourage green behavior, such as the use of public transit, and their ecological impact is relatively small”

After Kahn, other authors and institutions (UNEP 2011; ELCA 2011; Lewis 2015) recognized the descriptive *green* as a multidimensional concept involving economic, environmental and social aspects. Among the indicators used to quantify how green is a city we can find specific indicators related to air quality and climate change (Pace et al. 2016).

However, sometimes the term *green* is used for environmental aspects (e.g. Hysing 2009; Agrawal et al. 2010; Björklund 2011) and in particular to energy consumption, carbon footprint and its effect on global warming and climate change (e.g. Kim et al. 2012; Froehlich et al. 2009; Jabbarpour et al. 2015); apart from other dimensions of the concept. A low carbon footprint will be the connotation of the term *green* throughout the thesis while the term *clean* will imply low air pollution levels. Therefore, the explicit use of the two distinctive city qualities (*green* and *clean*) is to underline the fact that exhaust emissions from road traffic have a varying influence on the urban environment, since GHG and air pollutants have different spatial impacts.

A wide variety of strategies were considered to reduce both types of emissions. The *avoid* and *shift* strategies present strong reduction emission benefits as they promote the reduction of the total vehicles-km travelled in the system or the transference of passengers to more efficient transport modes. However, the *improve* strategies, which are employed with the aim to enhance the remaining travel activity, present potential conflicts for achieving greener and cleaner cities. In particular, *improve* strategies that change the distribution of traffic flows throughout the city e.g. eco-routing systems or speed reductions, may present air pollution trade-offs due to the spatial reallocation of traffic emissions.

There is a lack of studies and tools to evaluate traffic exhaust emissions impacts taking into account their different spatial impacts. Therefore, the aim of the present thesis is to provide *knowledge* and *tools* to design and evaluate transport policies that contribute to achieve both **greener** and **cleaner** cities.

Overall Research Question:

HOW CAN WE GET GREENER AND CLEANER CITIES THROUGH TRANSPORT POLICIES?

Overall Research Objective (RO):

PROVIDE KNOWLEDGE AND TOOLS TO DESIGN AND EVALUATE TRANSPORT POLICIES THAT CONTRIBUTE TO ACHIEVE BOTH GREENER AND CLEANER CITIES.

3.2 Specific Objectives

In order to comply with this central objective, a set of research gaps arose from the literature review need to be addressed. These research gaps were converted in specific research questions and properly justified in this subsection. Therefore, the specific objectives of this thesis are linked directly to give answers to the following research questions.

- I. Is there an emissions assessment model that could address both climate change and air quality impacts? How can we analyse the impact of ICT-based strategies in traffic emissions and traffic performance?

Addressing these questions should result in developing a modelling framework with which to assess GHGs and air pollutant emissions taking into account their different spatial impacts. The model should account for assessing and balancing traffic performance and environmental impacts for different policy scenarios. It also should be easily adapted to evaluate innovative ICT-based initiatives and understand their impact in different type of roads. Eventually, it should serve for policy design and management of large urban areas.

- II. How can transport emissions indicators be adapted or further developed to consider the varying spatial impacts of transport emissions? How we can consider population exposure to air pollutants?

The reason behind this question is that although the impact of traffic emissions in the urban context is singular since GHGs and air pollutants have different spatial impacts, transport planning has usually tackled them in similar way. In urban environments air pollution is of great importance; however usually the impact of transport policies on emissions are analysed in terms of gross emissions i.e. total of CO₂ tons reduced or total of NO_x and PM kilograms reduced. They only consider transport activity; nevertheless, when assessing air pollutants it is very important to take into account *how many people are exposed* to air pollution. The answer to this question involves the understanding of the variables affecting air pollution concentration and the development of an indicator that take into account population exposure to air pollution. Its ultimate objective is to provide policy makers with accessible and easy-to-implement resources to enhance their emissions evaluation without adding additional complexity to the assessment methodology.

- III. Where is more necessary to implement emission reduction measures? How to design effective traffic measures towards the reduction of air pollution emissions?

The aims of addressing this question are (i) to identify links in areas with high levels of population exposure to air pollution i.e. air pollution hotspots and, (ii) propose customized emissions reduction strategies to reduce them. To do this the impacts of the measures in the area directly affected by the measures and at a broader city level will be considered. To that end, there is a need for a comprehensive procedure that takes into account emissions from traffic activity and population exposure levels.

Although most researchers agree on the need to design holistic transport emissions reduction policies instead of applying individual measures (Banister et al. 2000; Schipper & Fulton 2003; Akerman et al. 2006; Hickman & Banister 2007; Chapman 2007; Bristow et al. 2008; Yang et al. 2009; Hickman et al. 2010), it is critical to understand the explicit impact and scope of each single measure. In particular we want to understand the co-benefits and conflicts of the policies under study regarding climate change and air quality.

IV. What are the impacts of speed strategies on emissions and on traffic performance? How does a speed reduction affect travel times? How do speed strategies implemented in an urban ring-road impact traffic performance and emissions in the city center? And in the periphery?

Speed management strategies have been selected because of their potential to reduce emissions. On the one hand, reducing speed limits is one of the most cost-effective ways of reducing road transport emissions (TRB 2012); however, its effects in travel times remain questionable and are usually overestimated. Regarding VSL, although these systems are being implemented worldwide; their effects on emissions are not yet clearly defined, and in some cases their benefit are not fully proven (Garcia-Castro 2016). In particular there is a lack of research on the effect of the measure on the areas adjoining the road where the measure was implemented.

V. What are the impacts on Green Navigation Systems emissions and traffic performance? Do more green drivers mean more benefits? Do Green Navigation systems contribute to greener and cleaner cities?

Eco-routing systems are one of the new technological developments that have brought about new possibilities to reduce energy consumption and transport emissions. This measure has been selected because despite some research has been conducted on the fields of eco-route algorithms development and assessment of the policy at corridor level (Ericsson et al. 2006a; Minett, A. M. Salomons, et al. 2011; Ahn & Rakha 2008b), scant attention has been paid to the impact of these systems on whole urban network.

VI. Does the combination of ICT –based measures provide more benefits in terms of emissions? And in terms of traffic?

On the one hand, the Working Group of Clean and Efficient Mobility (Vreeswijk et al. 2014) identified Green Navigation and Eco-driving together with Green Navigation and Variable Speed Limits as areas of possible overlapping of eco-ITS applications. On the other hand, previous research on ICT measures (Samaras et al. 2016; Valdes 2015) suggested a potential degree of complementarity among them. Therefore, it is interesting to evaluate whether the increases of travel times for low GN penetration rates could be offset with the travel times reduction produced by low penetration rates of ED.

Following the structure of the literature review, these research questions can be arranged by topic and classified in two groups: those which express the need on the development of assessment **tools** and provision of methodological insights (research questions from I to III)

and those which aim to provide scientific evidence and **knowledge**-sharing on the impacts of specific measures (research questions from IV to VI).

The specific objectives of this thesis descend from this classification and are expressed as follows:

RO1.

To develop modelling, assessment and mapping tools to (i) identify where is more necessary to implement emission reduction measures and, (ii) assess the impact of these measures on traffic and emissions.

RO2.

To provide city managers with scientific evidence on the impacts of speed and eco-traffic strategies on emissions and traffic performance for informed policy making.

3.3 Research Framework

Through the literature review, research gaps have been identified and research objectives proposed.

To achieve the first specific objective tools for modeling, assessing and mapping emissions were developed. As components of the methodology we include: (i) traffic, emissions and GIS models interaction, (ii) key performance indicators and (iii) the mapping of models output.

To achieve the second specific objective, these tools will be implemented to the Madrid case study to conduct an impact assessment of speed management (speed reduction –SPR- and variable speed limits –VSL-), eco-traffic strategies (eco-driving –ED- and green navigation –GN-) and their combination (GN+VSL and GN+ED) on both climate change and air pollution.

The case study method enables a researcher to closely examine the data within a specific context. It helps explain both the process and outcome of phenomena through complete observation, reconstruction and analysis of the case under investigation (Tellis 1997; Zainal 2007). Case studies are used for research purposes to develop a new theory through observation and testing, evaluating or improving existing theories through their implementation in practice. The method has been criticized for allowing wide generalization, subjectivity, and difficulties in documenting the acquired data in a unified manner. Nevertheless, in urban mobility planning, case studies are considered as an extremely useful tool to be used along with other research methods since the commons and similarities in relevant projects allow for transferability maintaining specific attributes of scheme proposals. A case study also provides a communicative platform for transferring knowledge from the experts to the public and can inform the general public on complex features of scientific attributes (Bakogiannis et al. 2014).

Results of the policy impact analysis will allow us to understand how the selected emission reduction strategies contribute to achieve *greener* and *cleaner* cities. Finally, this research will provide methodological and policy recommendations to effectively reduce mobile source emissions in urban environments.

Figure 3-1 is a summary of the research approach followed in this thesis.

Figure 3-1 Overall research framework

4. TOOLS FOR MODELLING, ASSESSING AND MAPPING ROAD EXHAUST EMISSIONS

This section describes the methodological tools developed to evaluate emission reduction measures.

As explained before, the methodology is based on the one developed by the ICT-Emissions project. It combines traffic and emission modelling at micro and macro scales and offers the necessary interface to shift from one scale to the other (Toffolo et al. 2015) to evaluate the impact of ICT measures on fuel consumption and CO₂ emissions.

In order to achieve the first specific objective (RO1) and to answer research questions I-III, the methodology:

- (i) extends the ICT-emissions project macroscopic assessment framework with a GIS tool to have the capability of producing GHGs and air pollutants emissions indicators taking into account the spatial varying impacts of transport emissions.
- (ii) produces traffic performance and emissions indicators including a population-weighted air pollution indicator to evaluate exposure of people to traffic emissions.
- (iii) uses the GIS mapping capability to identify where is more necessary to apply emissions reduction strategies i.e. identify priority urban roads for the implementation of emissions reduction measures.

These tools will be used to evaluate the impact of two speed management (SPR and VSL), two eco-traffic strategies (GN and ED) and the combined GN+VSL and GN+ED measures on traffic operation and GHGs and air pollutant emissions.

Figure 4-1 shows the relationship among the methodological tools which include:

- *Modelling tools* i.e. interaction of traffic, emissions and GIS models (section 4.1) and the development of traffic simulation techniques to model ICT-based strategies (section 4.1.1).
- *Assessment tools* i.e. the development of indicators to measure traffic performance, traffic emissions and population exposure (section 4.2).
- the development of a *mapping tool* to identify roads with high levels of population exposure to air pollution i.e. air pollution hotspots in urban areas (section 4.3).

Figure 4-1 Tools for modelling, assessing and mapping road transport emissions

4.1 Modelling traffic and emissions

At macroscopic scale, the ICT-Emissions methodology links the widespread macroscopic emissions model COPERT to a macroscopic traffic model to evaluate fuel consumption and CO₂ emissions. Two more attributes were then added to the assessment interface:

- (i) the interaction of the traffic and emissions model with a GIS model
- (ii) the capability of simulate air pollutant emissions

For large urban road networks, macroscopic traffic models generate traffic data for each road link in the network. They provide information on length (km), traffic intensity (vehicles/hour), capacity (vehicles/hour), average speed (km/h) and travel times for each network link.

The interaction between the macroscopic transport model and the emission model occurs in two ways. First, emission factors (EFs), which express the mass of pollutant emitted per unit distance (g km⁻¹), are calculated using the average speed provided by the traffic model for each vehicle category (fleet composition) considered in the network. Second, traffic emissions are finally calculated using the EFs provided by the emissions model and traffic activity information provided by the traffic model.

Usually emissions models are fed with information about the existing fleet that considers that all vehicle categories distribute equally throughout the network. However, for this research we will consider the circulating fleet which allows for more accurate emissions estimations since it considers a different fleet distribution by road type in the traffic model.

This methodology is designed to evaluate two types of emitters: CO₂ and NO_x. The selection of the emitters was for the following reasons. First, EFs for both types of emissions can be obtained from COPERT. Second, both types of emitters can be considered a proxy to evaluate the impact of the emission reduction strategies on climate change (CO₂) and air pollution (NO_x). On the one hand, CO₂ is the largest anthropogenic emission among the GHGs. And on the other hand, quantifying the amount of NO_x emitted into the atmosphere is essential to reliably predict air pollutants (Tong et al. 2015), since NO_x are key precursors to tropospheric ambient ozone (O₃) and fine particulate matter (PM_{2.5}) (Crutzen & Gidel 1983; Spicer 1983). Besides, the term NO_x includes NO and NO₂ emissions and the emission inventory guidebook (Ntziachristos, Leonidas; Samaras 2012) considers NO₂ as an equivalent term for NO_x. Finally, previous studies concluded that traffic-related pollutants are described well by NO₂ (Beckerman et al. 2008), which is therefore used as a common marker for traffic-related air pollution (Han & Naeher 2005)

Macroscopic transport models usually consider population density at the model zone level. For large metropolitan areas, these zones usually include various administrative districts hence the population density resolution of the macroscopic model is not enough to evaluate population exposure at link level nor to identify priority links for emission reduction interventions. This is why we have added the interaction of previous models with a GIS.

The GIS model loads (a) the road network provided by the traffic model, (b) the emissions provided by the emissions model and, (c) information regarding population near the links to calculate population exposure to air pollution.

Figure 4-2 Traffic, emissions and GIS models' interaction

The GIS adds the population density of the administrative area crossed by the link as a new link characteristic. When a link crosses more than one administrative area, the average population density of these areas will be considered. The level of disaggregation of these areas will depend on the information available for the city under study.

Figure 4-2 is a summary of the interaction among the traffic, emissions and GIS models. Green-dotted boxes detail the inputs of the models while the black arrows indicate the relationship among the models attributes. Information regarding specific models attributes, calibration and validation for the Madrid case study are detailed in section 5.4 and ANNEX I

4.1.1 Traffic simulation techniques for modelling ICT-based strategies

This subsection explains the general attributes of the traffic simulation for the ICT- measures variable speed limits, eco-driving and green navigation (VSL, ED and GN respectively) while the particular specifications of each scenario simulated are detailed in the corresponding sections of Chapter 6. The simulation of the speed reduction (SPR) measure is quite straightforward and do not need further explanation in this subsection.

Emission reduction measures selected are simulated in two different ways:

- GN produces changes in route choice. These modifications affect the whole network system and therefore the simulation should be directly done at macroscopic level.
- VSL and ED produce changes at driver level as they modify speed and acceleration profiles. These modifications at driver level can influence the relation between intensity and speed of the corridor, and consequently affect the performance of a wider network. Therefore, the simulation of these measures needs to be conducted at two levels: at the micro level to evaluate changes in speed and intensity at corridor where they are applied and at the macro level to understand their effect in the whole network. In order to simulate these measures, we used the ICT-Emissions project guidelines related to the interaction between the microscopic and macroscopic

transport models. Since this research aims to understand the impacts of these measures at city-wide level, we refer to the ICT-Emissions deliverables 6.2 (Valdes Serrano et al. 2015) and 6.3 (Valdes 2015) for further information on the micro-simulation of the VSL and ED measures.

To simulate these measures at macro level we need to vary either the impedance function of the traffic model (GN) or the cost-function of the links (VSL and ED). Besides, the simulation of the GN function requires the development of a specific assignment process that captures the changing traffic conditions in the network during the assignment (see Figure 4-3).

Figure 4-3 Traffic simulation attributes at macro scale

4.1.1.1. Green Navigation

To simulate the GN measure we need to vary the traffic model impedance function. The model impedance function, also known as model objective function, is the key factor of driver's route choices. It assigns the effort connected to each route or path. Usually this effort is measured in terms of travel time. Additional properties such as travel expenses can be converted into travel time units and considered within the travel impedance function (PTV 2014). The traffic assignment selects the routes that minimize the impedance function

The green-navigation (GN) scenario assigns an impedance function defined in terms of fuel consumption, which is directly related to CO₂ emissions i.e. the assignment will seek results that minimize fuel consumption and therefore also CO₂ emissions. The ICT-Emissions project tested five different fuel consumption functions from different studies and the one which better performed at congested traffic conditions was selected, i.e. the default fuel consumption function of COPERT (g/km) expressed as a function of time (g/s) (Samaras et al. 2016)

$$I_{GN} = FC(v_{Cur}) \times t_{Cur} \quad (1)$$

Where:

I_{GN} is the GN impedance function expressed in seconds

FC is the COPERT default fuel consumption function expressed in g/s expressed as:

$$FC = av_{Cur}^5 + bv_{Cur}^4 + cv_{Cur}^3 + dv_{Cur}^2 + ev_{Cur} + f; \quad (2)$$

$a = -3.29612 \times 10^{-10}$; $b = 1.097 \times 10^{-7}$; $c = -1.1893 \times 10^{-5}$; $d = 5.30345 \times 10^{-4}$,
 $e = -1.56253 \times 10^{-3}$ and $f = 0.256344$,

v_{Cur} is the link average speed calculated in the traffic model in km/h

t_{Cur} is the link travel time calculated by the traffic model in seconds

It is not realistic to assume that all the vehicles in the network will be equipped with GN systems; therefore, different percentages of green drivers will be considered. To simulate the different penetration rates of the measure, a new demand segment, which represents the GN drivers, needs to be created in the model. Different impedance functions can be defined at the assignment per demand segment.

Therefore, GN scenarios will consist on a combination of GN drivers following the fuel consumption impedance function defined above and conventional drivers following the conventional impedance function based on travel times and monetary cost. A percentage of the origin-destination (OD) matrices will be assigned to each demand segment. For example, for a scenario with a 25% of green drivers and 75% of conventional drivers, the 25% of the OD matrix will be assigned under the fuel consumption impedance function while the 75% of the OD matrix will be assigned to the network under the conventional impedance function.

Finally, since navigation systems provide eco-routing recommendations based on real-time traffic situation; their assignment process has been designed to continuously capture the new traffic conditions and then, to allow for different route alternatives taking into account this new traffic situation. The assignment process follows the sequence summarized in Figure 4-4.

Figure 4-4 Green Navigation assignment process

First, heavy vehicles and conventional car drivers are assigned to the network and subsequently the impedance function of green drivers is calculated for the new traffic levels and average speeds. Next, green drivers are assigned to the network in 10 steps and after each of the stages the impedance function is calculated again to reflect the new traffic conditions. This implies that in every step of the GN demand segment assignment, the impedance function is updated with the new traffic situation and henceforth routing recommendations will be modified consequently. In each stage 10% of the OD matrix corresponding to green drivers is assigned

4.1.1.2. Variable Speed Limits and Eco-driving

As explained before, VSL and ED change the vehicle operation which, under fixed capacity and traffic flow, leads to modifications in the links cost-functions (Valdes et al., 2015a). The cost-function of a link, or the so-called Volume Delay Functions (VDFs), represents the relationship among capacity, traffic intensity and level of congestion.

Usually traffic model defines BPR functions from the Traffic Assignment Manual of the United States Bureau of Public Roads for each link type:

$$t_{cur} = t_0 \times \left(1 + a \times \left(\frac{Volume}{Q_{max} \times c} \right)^b \right) \quad (3)$$

Where t_{cur} is the time in current traffic conditions, t_0 is the time in free flow conditions, volume is the number of veh/hour circulating in each link, Q_{max} is the maximum capacity of each link, and a , b and c are the estimated parameters.

The ICT-Emissions project, through field trials and micro-simulation, revealed changes in capacity and free-flow speeds in the roads where the measures were implemented. These changes were implemented at macro-scale changing the VDFs parameters of the corresponding road links in the macroscopic traffic model. The specific parameters of the VDFs for each scenario considered are specified in section 6.4.

4.2 Assessment Indicators

This section introduces the indicators used for the policy assessment. Three types of indicators were developed using the outputs of the models (see Figure 4-5): traffic performance indicators, traffic emissions indicators and population exposure indicators.

Figure 4-5 Key performance indicators as outputs of the assessment models

4.2.1 Traffic Performance Indicators (TPIs)

VKT (Vehicle Kilometers Travelled) represents traffic volume as a product of traffic intensity (number of vehicles crossing a specific section in an hour) and section length. It is often described as an indicator of traffic demand. It characterizes the traffic flow over a road link on an average hour in a day. The model gives three different values of traffic intensity, one for each average hour in the three defined periods: morning peak hour (AM), afternoon peak hour (PM) and off-peak hours (OP). In view of the fact that the test measure in this study –lowering the speed limit from 90 km/h to 70 km/h– changes neither the length or the capacity of the links, both saturation (traffic intensity divided by section capacity) and traffic volume are synonyms of traffic intensity in relative terms.

$$VKT = \sum_i^N I_{i,p} l_i \quad (4)$$

Where:

$I_{i,p}$ is the traffic intensity (vehicles/hour) in a specific link of the network for an average hour in the time period considered

l_i is the length (km) of the link

i represents the links of the network

p is the time period or the traffic condition considered

VEH (vehicles per hour): the total travel time of all vehicles on a link or segment of the road for an average hour of the three defined periods. The average daily travel times were calculated using a similar formulation as for average daily traffic.

$$VEH = \sum_i^N I_{i,p} t_{i,p} \quad (5)$$

Where:

I_i is the traffic intensity (vehicles/ hour) on a specific link of the network

t_i is the travel time (hours) on a specific link of the network for an average hour in the time period considered

i is the links of the network

p is the time period or the traffic condition considered

AVS (Average speed): the average speed of the vehicles in a link or a segment of the road for an average hour of the three defined periods. The daily average speed was calculated using the same formula as for average daily traffic.

$$AVS = \frac{\sum_i^N v_{i,p} l_i}{\sum_i^N l_i} \quad (6)$$

Where:

$v_{i,p}$ is the speed (km/hours) on a specific link of the network for an average hour in the time period considered

l_i is the length (km) of the link

i is the links of the network,

p is the time period or the traffic condition considered

When needed, the daily values of the traffic performance indicators were calculated by multiplying the result for each time period by the length of the period. Traffic periods are described in section 0.

4.2.2 Traffic Emissions Indicators (TEIs)

The TEIs were calculated using EFs provided by the emission model and activity information provided by the traffic model. COPERT provides a straightforward expression for hot EFs based on two or three speed ranges by vehicle category and uses for the calculation average speeds provided by the traffic model. Each vehicle category is also classified according to fuel, engine type, and the associated emissions reduction technology (from Conventional to Euro IV). Traffic emissions are the result of multiplying VKT, which are function of traffic intensity and link length also provided by the traffic model, with the corresponding emission factors. The daily values of the emissions indicators, when needed, are calculated by multiplying the result for each time period by the length of the period. The basic formula for estimating traffic exhaust emissions (in grams) for the whole study network and a given time period:

$$TEI_{k,p} = \sum_i^N EF(v)_{m,i,p,k} I_{i,p} l_i \quad (7)$$

Where

$EF(v)$ represents the emission factor (g/km) provided by COPERT which is directly related to the speed in the link and to the fleet composition

m represents vehicle classes (fleet composition) depending on technologies vehicle fuel, engine type and technology

k is the type of emission considered

I is the traffic intensity (vehicles/ hour) in a specific link of the network for an average hour of the time period considered

l is the length (km) of the link

i is the links of the network

p is the time period or the traffic condition considered

4.2.3 Population Exposure Indicators (PEIs)

Traditionally, traffic emissions indicators take into account only transport activity; however, as explained before there is a need of indicators that also reflect population exposure to air pollution.

Atmosphere and climate, together with urban form and population and street densities, influence the extent to which citizens are exposed to air pollutants. Therefore, very complex dispersion models are needed to develop accurate population exposure indicators that take all the variables affecting concentration levels into account, e.g., precipitation, wind speed and direction, atmospheric pressure, temperature, topography and urban street disposition, as well as the type and height of buildings. These complex high resolution urban air quality modelling have limitations and uncertainties that remain unsolved (Gorham 2002; Laña et al. 2016). Population density by itself could be deemed as a relevant proxy to consider population exposure levels, since:

- (i) exposure to local emissions from transport is largely a function not only of the amount of traffic activity, but also of population densities near large transportation corridors and the number of people who regularly work along these roadsides (Gorham 2002),
- (ii) numerous authors analyse air pollutants exposure levels at certain distance from a high traffic road (Brown et al. 2012; Porebski et al. 2014),
- (iv) health effects and residential proximity to high traffic roads show correlation associations between health effects and residential proximity to high traffic roads (Han & Naeher 2005) have usually been reported.

Bearing in mind these considerations, PEIs are calculated by weighting transport exhaust emissions with population density as follows. PEIs will be only calculated for air pollutants, in particular for NO_x :

$$PEI_{k,p} = \sum_i^N TEI_{i,p,k} D_{i,p} \quad (8)$$

Where:

TEI is the Traffic Emission Indicator by link

i is the links of the network

p is an average hour of the time period considered (in this case will be peak hours and off-peak hours)

k is the type of emission considered

D is the population density of the area the link crosses over

4.3 Mapping the outputs of the models

The identification of links with high levels of air pollutant emissions and high levels of population exposure to air pollution is crucial for designing effective future air pollution reduction interventions. Therefore, on top of the emissions assessment purpose, the methodology developed aims to identify these types of roads for emission reduction

interventions. The interaction of the elements described in previous sections along with the use of the GIS mapping tools result in an insightful and ready-to-use tool for identifying what we have called urban air pollution traffic hotspots i.e. roads with high levels of NO_x emissions and high levels of NO_x (TEI_NO_x) population exposure to NO_x (PEI_NO_x). (see Figure 4-6).

Figure 4-6 Mapping tool to identify air pollution hotspots to implement emission reduction measures

In order to determine what we consider high levels, TEI_NO_x and PEI_NO_x have obtained at link level will be mapped using a geometrical interval classification scheme provided by the GIS tool. It creates class breaks based on class intervals that have a geometric series, to create the red to green colour scale. The algorithm creates geometric intervals by minimizing the sum of squares of the number of elements in each class in order to ensure that class ranges have approximately the same number of values and that the change between intervals is fairly consistent. The use of this algorithm produces cartographically comprehensive maps balancing the stress of changes in middle and extreme values (ArcGIS 2016).

The main purpose of this mapping tool is to provide information about the relative variation of air pollution exposure across the network. Nevertheless, it can also be used to:

- to quickly identify road links with the highest carbon footprint,
- to easily understand the redistribution of emissions after the implementation of traffic reduction strategies.

4.4 Assumptions and limitations

The use of a macroscopic static traffic and an average speed emissions models brings about some limitations: On the one hand, for large urban road networks the outputs of traffic models are usually limited to data for the traffic on each link, rather than for individual vehicles (Smit et al. 2008), therefore macroscopic traffic models are commonly used although it leads to less detailed output data (Grote et al. 2016). Besides, for static macroscopic traffic models, both demand, and the resulting intensity and speed values for each link, are assumed to be constant for the entire modelled period which is not a very realistic assumption for congested networks (Ortúzar & Willumsen 2011), particularly over longer time periods (e.g. a peak hour). On the other hand, some authors questioned the appropriateness of average speed models to assess emissions at a city level (Int Panis et al. 2011; Grote et al. 2016) since similar average speeds can be reached with different speed patterns in each link. Notwithstanding this, COPERT was further developed within the ICT-emissions project to be able to calculate emissions at a link level in urban environments (Toffolo et al. 2015), including (i) algorithms suitable for working with hourly time periods and for links that are hundreds of meters long, (ii) a subroutine to distribute the data among the hundreds of types of vehicles, subdivided by fuel type, emissions technology, age, etc. Further limitations may appear for high saturation levels (e.g. >80%) and/or for very short road segments (e.g. <400 m). Moreover, as is customary, start emissions and evaporation emissions are not considered.

Circulating fleet will be considered instead of the existing fleet for more accurate emissions estimation; however, we will assume that the penetration of in-vehicle emissions reduction measures such as GN and ED is equally distributed by all type of vehicles. This assumption could lead to an overestimation of the results, since these types of devices are mostly available in newer and cleaner vehicles.

Due to the use of population density, PEIs are mainly residential focused and only partially reflects exposure to air pollution excluding the effect on working areas and, on tourist and commercial areas that frequently exhibit higher number of pedestrians. Besides, PEIs do not completely captures the fact that pollution decreases quickly when moving away from the roadside. The model assumes that the population distributes equally through the administrative area considered.

The ICT-Emissions project also pointed out limitations on the assessment of ED emissions at macro-level (Valdes 2015). In eco-driving scenarios speed reduction is caused by different driving style characterized by lower accelerations and not by the effect of congestion, hence specific emission factors (EFs) must be used to estimate eco-drivers emissions. The use of non-eco drivers EFs for both conventional and eco-drivers would present quite significant errors. However, further research is needed to develop new emissions factors for eco-drivers. Since the information is not available at the moment, we have used conventional driver emission factors to calculate fuel consumption and CO₂ emissions. Being aware of the anticipated errors, results for ED scenarios will present additional emphasis on the analysis of traffic indicators.

5. MADRID CASE STUDY

This section provides relevant information about the Madrid case study including its population distribution, which is key for the calculation of the PEIs, modal split, road network characteristics, and GHGs and air pollutant emission levels.

In the final section of this chapter, the tools developed in the previous chapter are applied to Madrid CBD in order to identify links with high levels of NO_x population exposure and to propose emissions reduction strategies to reduce them. To do so, first we specify the inputs that feed the macroscopic transport, emissions and GIS models for the Madrid context. After, we compare the results provided by the Traffic Emissions Indicators (TEIs) with those provided by the Population Exposure Indicators (PEIs).

5.1 Population and road network distribution in Madrid

The Madrid Region is the capital of Spain and the country's most populated region. Policy analyses not only covers Madrid City itself but all the municipalities of Madrid Region with a high degree of interaction between its urban centers in terms of trips, relationships and economic activity.

Madrid region is spread over an 8,030 km² surface while Madrid city covers 604.3 km². The population of Madrid Region is about 6.5 million inhabitants, half of which live in the main city. Population density is high in the central city, 5,232 inhab./km², and rather low in the whole region, 605 inhab./km² (Monzon et al. 2016). Figure 5-1 shows the distribution of population within the Madrid Region.

Figure 5-1 Population density by municipality in Madrid Region

The Madrid road network has a radio-centric structure, with eight main free-radial highways linking central Madrid to all of Spain's coastal regions (A1, A2, A3, A4, A5, A6) and four ring-roads (two of them unfinished) encircling it: the first is the M-30, which divides the city into two parts, the inner part -Central District- and the peripheral districts, and it acts as a local distributor road; the second is the M-40, which encompasses most of the city of Madrid, and is the most congested road in the Madrid metropolitan area; and the M-45 and M-50, both yet incomplete rings. Four toll-ways run in parallel to four of the main highways (see Figure 5-2).

Figure 5-2: Madrid's network structure

The densest area in Madrid City is its Central District (CBD) (Figure 5-3) which is encircled by Madrid inner ring-road, the M30. The north-west zone, which is home of the main green areas in Madrid (El Pardo), and Castellana (the city's north-south main avenue) adjacent areas are the ones with less population density in the Central District due to its predominantly business and tourist orientation. The north area is less populated than the city center and the south except for the area next to the M30-Ilustracion. The road network in the historic city center is dense with fairly high traffic volumes while in the northern and southern areas the network is lighter but with several high traffic volume roads; the ones connecting the city center and the metropolitan area.

Figure 5-3 shows the distribution of population densities across the CBD (left side) next to its road network structure (right side) classified by traffic volumes

Figure 5-3 Madrid CBD population densities and traffic volumes

The M30 has particular importance in this research since some of the policy measures have been specifically applied to this urban highway. The M30 was renovated in 2004 to solve environmental and safety problems. It had a heterogeneous design through consolidated built-up areas, and ran very close to the city center –less than 1.5 km in the west section– consequently causing substantial problems with noise, air pollution and accidents. In broad terms, renovation consisted of a more uniform layout and better integration with urban arteries, intended to improve the level of service, reduce congestion rates and diminish accidents. It included the construction of 12 km of tunnels in the South-West section and, in the East section, the improvement of the transfers between side and central lanes, eliminating all the left side exits, as well as the renovation of all the links in this section. This project was supported by a socioeconomic study to assess the environmental and operational benefits of the remodeled layout. Savings in time and CO₂ emissions accounted for 75% of the socioeconomic benefits of the program. After three years of construction work, the new M30 was fully operative in 2007.

Today the M30 is a 32.5 km long urban motorway (see Figure 5-4), except for about 1.5 km in the northern area –Ilustracion– where it becomes a signalized urban boulevard. Its Annual Average Daily Traffic (AADT) varies widely throughout its layout, but is about 200,000 vehicles on average. The west section has the highest traffic volumes. The south-west section of the M30 is a tunnel section with a speed limit of 70km/h while the rest of the ring-road has a

speed limit of 90km/h (except for the Ilustracion area which is 50km/h).The main features of the M30 are summarized in Table 5-1

Table 5-1 M30 ring road main features

M30 Traffic Features	DL ¹	SL ²	NC ³	AADT ⁴
La Paloma	0.57	90		
Costa Rica	2.88	90		
Avda. America	4.02	90		
O'Donnel	3.15	90		
Mediterraneo	2.54	90		
EAST	13.17		6,300	270,000
Bypass	4.00	70		
Pte. Toledo	3.10	70		
Pte. Rey	2.30	70		
SOUTH-WEST	8.80		6,800	110,000
El Pardo	3.59	90		
North	2.95	90		
Ilustracion	1.68	50		
North Link	2.40	90		
NORTH-WEST	10.62		6,000	95,000
TOTAL M30	32.59		6,350	

¹DL (Driving Length in km)
²SL (Speed Limit in km/h)
³NC (Network Capacity in vehicles/h)
⁴AADT (Annual Average Daily Traffic in vehicles)

Table 1- M30 ring-road main features

Figure 5-4 Madrid's inner ring-road -M30- layout and division by sections and subsections

The specific renovation works carried out in each section consisted on:

- **South-West (SW) section:** This section was completely rebuilt. The South and South-West of M30 is a highly populated area located very close to the city center and the main river in the city. This was built underground to reduce the environmental pressure and congestion problems also to recover the livability on the river banks eliminating the barrier effect of the former road. The planned speed limit for the tunnel sections was 90 km/h –the same speed as for open air sections; however, for safety reasons the speed limit was finally set at 70 km/h.
- **East (E) section:** This section was renewed. The enhancement plan of the East section of the M30 ring-road comprised the improvement of the transfers between side and central lanes eliminating all the left side exits as well as the renovation of all the links of this section.
- **North-West (NW) section:** This section did not change. It comprises four subsections; the closest to the tunnel entrance is El Pardo.

5.2 Modal split

As occurs in other European cities, car ownership for the whole Madrid Region is higher than for Madrid City itself, 0.505 and 0.455 respectively. Dispersed areas are characterized by car dependency, as the car is frequently the only practical alternative to typically inadequate, relatively and increasingly expensive public transportation systems (EEA 2006).

According to the 2004 Household Mobility Survey carried out in Madrid almost 13 million trips were made per day in the whole region. Therefore, each person made on average 2.5 trips per day. The trips lasted on average 29 minutes and have a length of 6 km. The modal split was dominated by car use since 40% of these trips were done by car, 30% walking and 28% by public transport (Monzon et al. 2016).

These figures present considerable variations depending on the purpose or the area of the trip. Commuting trips are more based on motorized modes while people travelling for other purposes prefer to walk or cycle. On the other hand, trips done within Madrid City are based on public transport, walking and cycling, however trips made between the City and the rest of Madrid Region (i.e. Metropolitan Area) and among the different districts of the Metropolitan Area are basically made by motorized modes, especially by car (see Figure 5-5 and Figure 5-6). Nevertheless, a considerable percentage of these trips were also made on foot and cycling. Public transportation within the municipalities of the Metropolitan Area is the less preferred option due to the operational difficulties and lack of economic viability of quality public transport services to segregated areas (EEA 2006).

Figure 5-5: Modal split by trip purpose (Monzon et al. 2016)

Figure 5-6: Modal split in trips between the different zones of Madrid Region (Monzon et al. 2016)

Finally, from the latest Simplified Household Mobility Survey conducted in 2014, mode split in the Central District is dominated by soft modes, in particular by walking achieving 57.7% of the trips. Cars are only chosen to make 10.1% of the trips within the CBD.

5.3 Transport emissions in Madrid

Transport in Madrid City accounts for 47.3% of total CO₂ emissions and 82% of NO_x emissions, of which 85% and 83%, respectively, come from road transport (Madrid City Council 2011). Road traffic is the main factor responsible for NO_x emissions exceeding all the other sectors put together (Borge et al. 2012). As a whole, the M30 contributes to 9.4% of the metropolitan area daily traffic and to 24.2% of Madrid. At the same time, its contribution to CO₂ emissions is 8.2% for Metropolitan Area and 21.9% for Madrid. Finally, it contributes 8.6% to NO_x emissions of metropolitan area and 23.1% of Madrid.

Despite the variety of strategies considered to reduce emissions, including promoting the use of less polluting cars and fuels, public transportation, walking and cycling, the implementation of parking restrictions, the pedestrianization of historic zones, the restriction of private vehicles in densely populated areas and, the renovation of the inner ring-road completed in 2007 (Monzon et al. 2005); the suburbanization process, which implies longer trips and greater car dependency led to exceeding the air pollutant limits set by the European Legislation (Madrid City Council 2011).

In 2016, the city of Madrid approved a new Protocol for high nitrogen dioxide pollution levels (Madrid City Council 2016). Four scenarios were considered depending on the pollution concentration of different measurement stations within the city. The scenarios added new traffic restriction measures as the level of alert increases. The traffic restriction measures range from a speed limit reduction in the M30 and the road accesses to the city to a complete traffic restriction in the city center. Intermediate scenarios also consider parking restrictions in the city center and a partial restriction of the traffic depending on the license plate. The protocol also considers measures to foster public transportation. Due to the traffic distribution function, the M30 has an important potential for reducing urban transport emissions, and especially air pollutants in the highly-populated surrounded area. In fact, the new Protocol for

High Nitrogen Dioxide Pollution Levels (Madrid City Council 2011), force a 70km/h speed reduction on the M30 and some arterial roads after one day of NO₂ concentration levels over 180 mg/m³ in two measurement stations of the same area. The protocol, approved in 2016, consider four scenarios of pollution concentration levels. These scenarios added new traffic restriction measures as the level of alert increases. The traffic restriction measures range from speed reduction to banning traffic in the city center

5.4 Methodological tools applied to the Madrid case study.

This section is divided in two main subsections:

- First we introduce a summary of the modelling attributes particularized for the Madrid case study.
- Finally we apply the methodology to identify road links in Madrid CBD with high levels of population exposure to NO_x and propose traffic management strategies to solve this problem.

5.4.1 Modelling attributes for the Madrid case study

5.4.1.1. Traffic model attributes

The traffic model is based on the one developed by Valdes (2012) which considers the whole Madrid road network with a higher level of detail in the city of Madrid and particular for the city center i.e. road network inside the M30 ring-road.

The model consists of 636 Traffic Analysis Zones (TAZ) of which 355 corresponds to Madrid City, 144 to the city center, 130 to the remaining 130 municipalities of Madrid region and 7 zones that represent the road connections of Madrid with neighboring regions.

Road network

The 6,350km of the Madrid's regional network is represented by 15,712 road links. This road links are classified as follows (see Figure Figure 5-7)

- **CBD NETWORK** represents 1670 km of streets and avenues inside the M30 and accounts for 28% of the whole network.
- **HIGHWAYS** represent 1647 km of urban ring-roads, highways, and motorways and also account for 28% of the whole road network. The **M30** will be considered a specific study class for this research due to the fact that some of the policies have been directly applied to this road.
- **OTHER ROADS** aggregate 2560 km of conventional roads, junctions, and service lanes belonging to the peripheral, metropolitan, and regional areas, and account for 44% of the

Figure 5-7 Madrid's model road network. Adapted from Valdes (2012) and (Valdes et al, 2015)

The model used the BPR volume delay functions to estimate travel times of the different types of roads depending on traffic intensities. BPR functions from the Traffic Assignment Manual of the United States Bureau of Public Roads are defined as follows:

$$t_{cur} = t_0 \times \left(1 + a \times \left(\frac{Volume}{Q_{max} \times c} \right)^b \right) \quad (3) \text{ already shown in page 37}$$

Where t_{cur} is the time in current traffic conditions, t_0 is the time in free flow conditions, volume is the number of veh/hour circulating in each link, Q_{max} is the maximum capacity of each link, and a , b and c are the estimated parameters

Table 5-2 show the parameters of these function for each of the road types defined in the model. These parameters are based on the ones used by Valdes (2012) and ones used by the ICT-emissions project (Valdes et al., 2015)

Table 5-2 BPR attributes by road type

Road type	BPR Parameters		
	a	b	c
CBD: Streets	3.92	2.45	0.5
CBD: Avenues	3.92	2.45	0.6
HIGHWAYS (except M30)	1.68	9.64	0.96
M-30 west	12.84	10	0.85
M-30 east	0.38	1.89	0.9
OTHER ROADS	2.27	7.66	0.88

Determination of traffic periods

Four different **traffic periods** were determined based on the traffic hourly distribution for the Madrid region. Since the M30 is considered a specific study class in the Madrid case study, its traffic hourly distribution was also considered.

The traffic hourly distribution was obtained using data from 343 traffic counts: 126 from highways not including the M30 (30 from M40, 4 from M11 and 92 from the corridors entering the city), 217 from the M30 (50 from tunnel sections, 75 from central open-air sections, 35 from service lanes, 55 from junctions).

The specific traffic periods considered were:

- **Peak hours:** Traffic period with high congested conditions accounting for more than 6% of the daily traffic considering the whole Madrid region. For the M30 this peak of traffic is even sharper accounting up to 7% of the daily traffic. Peak hours have been differentiated in morning peak hours (AM) and afternoon peak hours (PM). AM peak hours correspond to the 8-10am period while PM peak hours correspond to the 3-5 pm and 6-9 pm period. (see Figure 5-8).
- **Off-Peak hour (OP):** Traffic period with normal traffic conditions corresponding to the off-peak hours in Madrid Region i.e. from 7-8 am, 10 am-1 pm, 5-6 pm and 9-11 pm
- **Free-flow (FF):** Traffic period with low congested traffic conditions corresponding to night hours in Madrid Region i.e. from 24-6 am

Figure 5-8 Traffic hourly distribution for the whole Madrid region and the M30 based on traffic counts information

Model calibration and validation

The traffic assignment model for Madrid Region used the 2012 origin-destination (OD) matrices, updating the 2004 OD matrices, based on the 2004 Madrid Household Mobility Survey with data from traffic flow counters, as input: 325 for the peak period (89 from urban roads, 193 highways and 43 from extra-urban roads) and 277 for the off-peak period (32 from urban roads, 192 from highways and 43 from extra-urban roads). The model assigns the OD matrices on the road network, using the equilibrium assignment in the VISUM platform. The model assigns the OD matrices corresponding to the average hour in the period simulated. Therefore, to simulate the traffic conditions in the morning peak scenario assigns the AM-OD matrix, the same reasoning applies to the remaining traffic periods. The free-flow matrix was obtained by multiplying the off-peak OD matrix by 0.5. The validation exercise for the base-case scenarios, comparing link volumes based on the assignment outputs with the observed link volume data for the different traffic periods, provided satisfactory results. The fit obtained in the calibration process of the new peak and off-peak hour matrices shows a good convergence, with a corresponding R2 of 0.73 and 0.71 respectively.

More information about the model calibration process followed, in particular about (i) the analysis of traffic to select traffic periods for modelling, (ii) the extraction and calibration of OD matrices and (iii) the assignment process followed can be found in ANNEX I

5.4.4.2. Emissions model attributes

In order to provide accurate emissions estimations, the emissions model (COPERT) need to be fed with Madrid fleet composition. The emissions model provides a straightforward expression for hot emissions factors, based on two or three speed ranges by vehicle category. Each vehicle category is also classified according to fuel and engine type, and the associated emissions reduction technology. In total, COPERT considers 292 vehicle categories.

As an innovative approach to customized urban emission assessment, the emissions model used the circulating fleet, instead of the existing fleet, to estimate emissions more accurately. The **existing fleet** considers that all the vehicles are equally distributed through all type of road while the **circulating fleet** considers a different fleet composition depending on the road type considered.

Table 5-3 Madrid's circulating fleet by category and fuel and zone distribution

VEHICLE CATEGORY & FUEL	CBD NETWORK	RING-ROADS	OTHER ROADS& REST OF HIGHWAYS
Passenger Cars	83.5%	88.0%	86.1%
Gasoline	25.2%	25.8%	25.1%
Diesel	55.8%	61.4%	60.0%
Others	2.5%	0.8%	1.0%
Light Duty Vehicles	4.7%	8.5%	8.6%
Gasoline	0.1%	0.3%	0.2%
Diesel	4.6%	8.2%	8.4%
Heavy Duty Vehicles	1.0%	2.0%	1.8%
Bus	2.0%	1.0%	1.6%
Diesel	1.1%	1.0%	1.3%
Others	0.8%	0.0%	0.3%
Mopeds and Motorcycles	8.9%	0.5%	1.8%

The circulating fleet is distributed through the Madrid network as follows (See Table 5-3 based on (Madrid City Council 2013):

Passenger cars represent more than the 80% of all the vehicles in the considered zones. The share of light-duty vehicles (LDV) on urban roads is almost half that on highways and other roads. Other roads include the extra-urban network of the model, and all the highways except ring-roads. The share of two-wheel vehicles is only relevant at an urban level, where it represents almost 9%, while on ring-roads, its share is almost negligible (0.5%). Finally, heavy-duty vehicles (HDV) in urban areas only account for 1%, while this figure is double on ring-roads (2%) and almost double on other roads (1.8%). The share of buses at an urban level (2%)

doubles the bus portion on ring-roads (1%), and is also higher than the bus segment on other roads (1.6%).

Regarding fuel types, the highest share of gasoline cars appears at an urban level (34.2%), which is more than 25% higher than the gasoline vehicle share on orbital highways (26.6%) and extra-urban roads (27.1%). Therefore, the share of diesel vehicles is higher on orbital motorways and other roads. It accounts for 72.5% and 71.5%, versus a 62.4% share in urban areas. The share of other types of fuels is trivial for other roads and highways, and very small for the urban network (3.3%).

Newest passenger vehicle technologies (EURO 4 and 5) have a higher share on urban roads, while the incidence of pre-EURO 2 vehicles (both diesel and gasoline) is higher on other roads. The share of gasoline pre-EURO 2 vehicles is more than 4 times the share of diesel pre-EURO 2 vehicles, higher on urban and orbital-highways: 17.5% and 26.5%, versus 4% and 6.6%, respectively. On other roads, its share is also high, at 23.5%, versus 7.1%.

The complete information about the distribution of the 292 different COPERT categories for macro emission estimations in the selected zones can be found in ANNEX II.

5.4.4.3. GIS attributes

Finally, using a GIS tool, population maps provided by the National Statistical Institute (<http://www.ine.es/>) were combined with the model network to assign a new link characteristic: population density. We have used information from 4,341 census sections in Madrid Region. These sections are an official geographical reference of statistical character. Since they have basically an operational character and therefore always have to be defined by more or less fixed sizes: to be accessible to an interviewing agent for the purpose of population counts or statistical surveys, it is recommended that the size of a section does not exceed 2,500 legal residents (Madrid Region Gov. 2017).

For links crossing more than one census section, the density was calculated as follows:

$$Link\ Density = \frac{\sum_i^N A_i P_i}{\sum A_i} \quad (9)$$

Where A is the area of the census section, P is the population in the census section and N is the total number of census sections crossed by the link.

The emissions assessment methodology particularized for the Madrid case study will be used to evaluate the traffic performance and environmental impacts of the policy measures described in next section.

5.4.2 Pre-policy analysis: Identifying roads with high levels of NO_x exposure for emission reduction interventions in Madrid CBD.

The purpose of this analysis is identify links with high levels of NO_x population exposure to air pollution i.e. air pollution hotspots, further understand the differences provided between NO_x traffic emissions and population exposure indicators (TEI and PEI) and propose emissions reduction strategies to reduce them. To do so we have applied the methodological tools already particularized to the Madrid case study as a self-assessment tool to obtain NO_x traffic emissions and population exposure indicators (TEI and PEI respectively). The area of the analysis will be Madrid City Center (CBD)

Results will be presented in a coloured scale using a geometrical interval classification scheme based on all the values of the indicators obtained for the CBD, instead of providing detailed values of the indicators. Red links represent the interval with the highest values of the indicators while green links represent the intervals with the lowest values. Three intermediate intervals are also considered: orange for high, yellow for moderate and light green for low values. The PEI is the indicator used for the identification of hotspots; nevertheless, the information provided by the TEI is also valuable and used to complete the analysis.

Results are presented in two maps for an average hour of the morning peak (Figure 5-9) and off-peak (Figure 5-10) traffic periods. TEI and PEI have been compared at link level for the two traffic periods under study.

Consistency in the results of the peak and off-peak scenarios emphasizes the impact of air pollution, especially for the links with high values of the PEI, since it means more hours of high exposure levels. The results for the two traffic scenarios are not directly comparable because of the classification used for mapping the indicators; the highest and lowest value of the indicators for the two scenarios are different, and therefore, same colors represent different indicator values in the two scenarios. For example, we cannot state that a red link for the PEI off-peak scenario is more polluted than the same yellow link for the peak scenario. Nevertheless, we can maintain that the same red link in the two mentioned scenarios is subject of an urgent intervention, since it means that this link has the highest levels of the indicator in the two scenarios. Independently of the specific values of the indicator, this implies that the exposure levels next to this road link are at its highest levels during the whole day.

At first sight, results for the TEI and PEI are quite different which is especially notorious for the peak hour scenario. In the TEI map, red and orange are the predominant color for the M30 (except for the south west area which is orange), its access roads and the Castellana while in the historic City Center (see Figure 5.3 to identify the different areas in Madrid CBD) green colored links are the most comment ones. This means that from the point of view of exhaust emissions, not exposure, the whole ring-road and Castellana should be considered air quality hotspots.

Figure 5-9 TEI and PEI values for the morning peak scenario

Figure 5-10 TEI and PEI values for the off-peak scenario

At first sight, results for the TEI and PEI are quite different which is especially notorious for the peak hour scenario. In the TEI map, the red is the predominant color for the M30 (except for the south west area which is orange), its access roads and the Castellana while in historic City Center green colored links are the most comment ones. This means that from the point of view of exhaust emissions, not exposure, the whole ring-road and Castellana should be considered air quality hotspots.

Nevertheless, analysing the PEI results different conclusions arise which changes potential intervention priorities. M30 ring-road exposure levels range from low values in the north-west section to high values in the Ilustración Avenue and the east section. Exposure values along the Castellana are predominant moderate due to the residential focus of the current state of the tool. Western accesses to the M30 present low exposure values compared to TEI results; while southern and eastern accesses maintain high values in both indicators. Finally, historic City Center's turn its low TEI values to moderate PEI values.

The comparison of the two indicators allows for identification of air quality particularities:

- **Road links with high values of TEI and moderate or low values of PEI**

These areas highlight the relevance of the PEI indicator, since it reduces the weight of high congested links in low populated areas. For example, the north-west area of the CBD shows very high levels of TEI both for peak and off-peak hours. Nevertheless, since this is a low populated area, PEI values are definitively lower. Using the TEI for the air quality diagnosis could lead to a misinterpretation of the relative importance of these links in Madrid's CBD network air quality and impact on population wellbeing. These should not been considered as air quality hotspots, i.e. they do not need urgent intervention.

- **Road links with low values of TEI and moderate to high values of PEI**

A good example of these areas is the historic City Center, especially at the west side of Castellana. This high populated residential area shows low values of TEI which are consequence of moderate to low traffic intensities and low speed ranges. However, the PEI map shows moderate values, reflecting higher levels of exposure. Results are consistent for the two traffic periods analysed. Exposure levels show that this area would need an early intervention. Taking into account its urban form and traffic conditions (high density, predominant narrow roads and low speed limits), traffic restriction policies, such as the extension of the residential priority areas that include traffic calming measures, would be recommended.

- **Road links with high values of TEI and PEI**

This means that exhaust emissions are very high and occurs in high populated zones. This condition makes these areas subject of urgent action. This is the case of the east section of the M30 ring road. Results maps show a red color for TEI and PEI in both traffic scenarios, meaning that high levels of air pollution emission and exposure occurs for the most part of the day. This section has the highest traffic volumes in the city center and belongs to the part of the M30 with a 90km/h speed limit. A straightforward reduction strategy could be lowering the speed limit in the section to 70km/h, as it is in the south-west section which presents slightly lower TEI values. Since the M30 structures the traffic from the periphery towards the CBD, traffic

restriction policies are not recommended. Nevertheless, other traffic management strategies could be also considered such as variable speed limits.

This analysis has been part of the work conducted for the **Lee Schipper Memorial Scholarship**. Beside, these results have already been presented as:

Perez-Prada, F., & Monzon, A. (2017). *Identifying Traffic Emission Hotspots for Urban Air Quality Interventions: Case of Madrid City, Spain*. In 96Th Annual Meeting Transportation Research Meeting. Washington, D.C.

6. POLICY ANALYSIS: SCIENTIFIC EVIDENCE FOR KNOWLEDGE-SHARING

“To achieve the positive and lasting results on the ground, policy makers need to be able to make informed decisions, after assessing the benefits and costs of each available option.

An effective policy almost always relies on science”

Hans Bruyninckx. EEA Executive Director, March 2017

This chapter applies the methodology developed in chapter 4 and particularized for the Madrid Case study in Chapter 5 to evaluate the impact on climate change and air pollution of the following speed management and eco-traffic emissions reduction policies: speed reduction (SPR), variable speed limits (VSL), green navigation systems (GN) and eco-driving (ED), and the combination of green navigation systems with variable speed limits (GN+VSL) and with eco-driving (GN+ED)

This Chapter describes the policy measures applied to the case study as well as the scenarios used for the simulation. The aim of the analysis will be to understand how the selected policy measures contribute towards *greener* and *cleaner* cities and to identify possible co-benefits and trade-offs in this respect. Results will be presented in next chapter.

Figure 6-1 illustrates this objective. It is a summary of the effect of the Improve type of measures analysed in the literature review (see section 2.3.1) on climate change and air pollution from a qualitative perspective. The top-right shows strategies that are positive for both climate change and air pollution i.e. initiatives that contribute towards achieving *greener* and *cleaner* (**Green + Clean +**) cities while the bottom-left present initiatives with negative consequences for both climate change and air pollution (i.e. **Green - Clean -**). The remaining quadrants show initiatives that presents climate change or air quality trade-offs (i.e. **Green + Clean -** are initiatives that contributes towards greener cities but present trade-offs regarding air pollution and **Green - Clean +** are initiatives that contributes toward cleaner cities but present trade-offs regarding climate change). The figure also highlights the lack of information about the impact of the ICT and speed strategies under study to achieving *greener* and *cleaner* cities.

Figure 6-1 Summary of the IMPROVE strategies' impacts on climate change and air quality based on literature review and research gaps regarding the ICT-based and speed strategies under study

Since it would be unrealistic to adopt emissions reduction strategies that lead to a significant deterioration of traffic conditions, the impact of the measures on traffic performance will be also assessed.

Besides, the use of a macroscopic traffic model will make it possible to evaluate the interventions not only in the area directly affected by the measure but also at a broader city level.

Table 6-1 summarizes the impacts assessed for each policy measure (traffic performance and emissions) as well as the scope of the analysis conducted. For the impact assessment it specifies the indicators used in the analysis. The scope of the analysis comprises the area directly affected by the measure and the whole metropolitan area considered.

Table 6-1 Impacts and scope of the policy measures analysed

			IMPACTS ASSESSED			SCOPE OF THE ASSESSMENT	
			Traffic performance	Climate change	Air pollution	Area affected	Metropolitan area
EMISSION REDUCTION STRATEGIES	Speed Management	SPR	✓	✓	✓	✓	
		VSL	✓	✓	✓	✓	✓
	Eco-traffic	ED	✓			✓	✓
		GN	✓	✓	✓	N/A	✓
	Combined ICT	GN-ED	✓			N/A	✓
		GN-VSL	✓	✓	✓	✓	✓

Scenario building

To analyse the impacts of the emission reduction measure, all the policy scenarios will be compared with their corresponding base-case (BC) scenario.

BC scenarios represent Madrid traffic situation in 2012 for each of the traffic periods considered: peak hours, off-peak hours and free-flow conditions.

Scenarios for policy analysis were built for:

- Different traffic periods
- Different percentages of green navigation drivers and eco-drivers i.e. different penetration rates of the eco-traffic measures.

As a result of these considerations, **a total of 61 scenarios were simulated.**

6.1 Speed management strategies

Impacts on traffic performance and emissions of two speed management strategies will be evaluated. The selected measures are the implementation of a speed limit reduction (SPR) and a variable speed limit (VSL) in a section of an urban ring-road.

Madrid's inner ring-road, M30, was selected to implement the speed management measures. In general, orbital motorways bring about major environmental problems: barrier effects, noise, air pollution and GHGs emissions due to their high annual average daily traffic (AADT), high average speeds during off-peak hours, and high congestion rates during peak hours. There

are a number of studies assessing their impact on transport, accessibility and land use (e.g. Gutiérrez & Gómez 1999); however, we can find few examples analysing their environmental impacts (Monzon et al. 2005) and even fewer of how implementing speed management strategies in orbital motorways can reduce traffic emissions (Keuken et al. 2010). Environmental issues are crucial in cities where urban ring-roads run through dense built up areas, which is the case of M30 (Monzon & Villanueva 1996).

The following subsections describe the implementation context and the measure itself for the Madrid case study.

6.1.1 Speed Reduction (SPR).

In 2004, the Madrid City Council launched a plan to re-design its inner ring-road to move traffic out of the city center. The renovated M30 was again in operation in 2007 and for safety reasons the planned 90km/h speed limit of the full-renovated South-West section was finally reduced to 70 km/h.

Besides contributing to traffic safety, this strategy could also be seen as positive to the environment due to the associated reduced fuel consumption and lower emissions. However, lower speed limits have lower rates of community acceptance.

We applied the modelling and assessment tools described in section 4.1 and 4.2 to conduct an ex-post evaluation of this speed reduction strategy and to explore its environmental and traffic performance impacts.

We have analysed this policy for the year 2010, therefore the inputs of the traffic model are not exactly the same as the ones used for the rest of the policy analysis which reference year is 2012. In this case the OD matrices have been updated to 2010 using traffic information from 2008 and 2009 from 491 traffic loops with a higher level of detail for the M30. Results have been calculated for morning and afternoon peak hours and off-peak hours in order to obtain an average result of the indicators under study for the whole day. Besides, we have fed the emissions model with the existing fleet instead of the circulating fleet as we have done for the remaining policies. Additional (cell, row and column) deviation restrictions were imposed to prevent an uncontrolled distortion between the original OD matrix and the adjusted matrix

Scenarios

Two scenarios were designed to simulate the SPR measure: S90 and S70 scenarios. Both scenarios use the BPRs corresponding to the BC scenario specified in section 5.4.1.1. and assign a conventional impedance function based on travel times and monetary costs. The scenarios have the following specific characteristics:

- S90 (Base) – SW section at 90 km/h.

This simulates the Madrid traffic situation in 2010, but with the speed limit on the M30 motorway sections set at 90 km/h (except for the Ilustración subsection, which is an urban boulevard with traffic lights and a 50 km/h speed limit), including the 8.8 km of South-West tunnel section.

- S70- SW section at 70 km/h

This simulates the current traffic situation in Madrid in 2010: reduced speed limit in the South-

West tunnel section to 70 km/h. The speed limit in the rest of the sections of the M30 remains at 90 km/h.

The traffic and emissions joint assessment allowed by the methodology will provide insights on the environmental benefits of speed reduction policies as well as on their potential trade-offs regarding urban mobility.

6.1.2 Variable Speed Limit (VSL)

This measure has been simulated for the M30 west and south west sections (see Figure 6-2). To simulate the measure at macroscopic level we have used the inputs of the ICT-emissions field trials and microsimulations, more information regarding these processes and results can be found in Valdes Serrano et al. (2015); Valdes (2015); Garcia-Castro & Monzon (2014b) and Garcia-Castro (2016). The analysis of the volume-delay function (VDF) of the section of the road where the measure was implemented in the context of the ICT-emissions showed a 16% capacity increase

The ICT-emissions project already conducted the analysis at macro level for CO₂ emissions and traffic performance indicators; nevertheless, this thesis extends this analysis in two ways:

- (i) it evaluates NO_x emissions and population exposure to NO_x and,
- (ii) it uses the circulating fleet instead the existing fleet to feed the emissions model.

Scenarios

One scenario has been simulated to evaluate this measure. The increase in capacity reflected by the measure was simulated using the BPR parameters of the VDF function showed in table 6-2 for the M30 west section. The remaining link cost-functions were the same of table 5-2. Table 6-2 only shows the BPR parameters with an actual change.

Table 6-2 BPR parameters for the M30 west section before and after the implementation of the VSL

Scenario	Road type	BPR Parameters		
		a	b	c
BC	URBAN HIGHWAY: M30 west	12.84	10	0.85
VSL	URBAN HIGHWAY: M30 west	12.84	10	0.99

Since the VSL system only works when the road reaches certain levels of congestion, only the congested traffic conditions were considered. This scenario assigned the typical impedance function for conventional drivers based on time and monetary costs.

Figure 6-2: West section of the Madrid ring motorway where the VSL measure was applied

6.2 Eco-traffic strategies

Impacts on traffic performance and emissions of two eco-traffic strategies were evaluated: eco-driving (ED) and eco-routing or green navigation systems (GN). This section describes the implementation context and the measure itself for the Madrid case study. Both measures were analysed in the context of the ICT-emissions project; nevertheless, here the previous assessment is expanded in three ways:

- using the circulating fleet instead of the existing fleet
- including the evaluation of air pollutants emissions and its impact on population i.e. measuring population exposure to NO_x , for the GN measure and,
- evaluating the impacts ED on traffic redistribution throughout the whole network. Estimations of NO_x emissions were obtained, however it won't be presented in the results section due to the limitations regarding EFs acknowledged in section 4.4 . Besides, the aim of this thesis is not the evaluation of the measure applied in isolation, but the analysis of the potential impacts of this measure applied in combination with GN. Therefore, results will focus on the combined assessment of the measure instead on ED applied in isolation.

The following subsections include a description of the implementation context and the measure itself for the Madrid case study.

6.2.1 Eco-driving (ED)

As explained in the literature review (section 2.3.3), eco-driving is a driving style aimed at lowering fuel consumption and producing a proportional decrease in CO_2 emissions. The measure was applied to highways and urban roads and it was simulated considering three different ED penetration rates.

To see how the measure changes the volume delay function (in the Madrid case the VDFs used are BPRs) of the roads where it was applied, the ICT-emissions project conducted a data campaign and a microsimulation of the measure in Madrid for highways and in Turin for urban roads. Results showed a reduction in capacity for highways and a reduction of capacity together with a reduction of free flow speeds for increasing eco-drivers penetration rates.

Figure 6-3 and Figure 6-4 show the fundamental diagram of highways and urban roads for different ED penetration levels respectively. Detailed information about the data campaign and microsimulations conducted to obtain the new VDF can be found in Valdes Serrano et al. (2015) and (Valdes 2015)

Figure 6-3: Changes in the fundamental diagram with different penetration levels of ED in urban highways (Valdes 2015)

Figure 6-4: Changes in the fundamental diagram with different penetration levels of ED in urban roads (Valdes 2015)

Scenarios

ED scenarios simulate the eco-driving measure applied to highways and urban roads. A total of 6 scenarios were considered for morning peak hours and free-flow conditions (AM and FF) and three penetration rates (25%, 50% and 75%). Morning peak hours were selected to understand the impact of the measure in congested conditions while free-flow conditions were selected to understand the effect of the measure without congestion constraints.

Table 6-3 lists the new BPR parameters of the link cost-functions which include the capacity and free flow speed reduction explained before. BPR parameters are different for each ED penetration rate considered and the road types affected by the measure. The BPR parameters of the OTHER road class, which is not affected by the measure, were the same considered in Table 5-2

Through the text, these scenarios will be referred by the initials of the applied measure ED followed by the penetration rate of the measure considered in the simulation e.g. ED25 will refer to scenario with a 25% of eco-drivers

Table 6-3 BPR parameters before and after the implementation of the ED scenarios

Scenario	Road type	BPR Parameters		
		a	b	c
BC	URBAN: Streets	3.92	2.45	0.8
	URBAN: Avenues	3.92	2.45	0.825
	MOTORWAYS: Highways and toll motorways	1.68	9.64	0.96
	URBAN HIGHWAY: M30 west	12.84	10	0.85
	URBAN HIGHWAY: M30 east	0.38	1.89	0.9
ED25	URBAN: Streets	4.2	3.98	0.8
	URBAN: Avenues	4.2	3.98	0.825
	MOTORWAYS: Highways and toll motorways	1.68	9.64	0.936
	URBAN HIGHWAY: M30 west	12.84	10	0.829
	URBAN HIGHWAY: M30 east	0.38	1.89	0.877
ED50	URBAN: Streets	4.3	3.53	0.8
	URBAN: Avenues	4.3	3.53	0.825
	HIGHWAYS: Highways and toll motorways	1.68	9.64	0.909
	URBAN HIGHWAY: M30 west	12.84	10	0.803
	URBAN HIGHWAY: M30 east	0.38	1.89	0.85
ED75	URBAN: Streets	4.09	3.53	0.8
	URBAN: Avenues	4.09	3.53	0.825
	HIGHWAYS: Highways and toll motorways	1.68	9.64	0.9
	URBAN HIGHWAY: M30 west	12.84	10	0.797
	URBAN HIGHWAY: M30 east	0.38	1.89	0.844

6.2.2 Green Navigation (GN)

As detailed in section 2.3.3, GN systems provide routing recommendations based on calculation of environmental impact and real-time traffic situation. The ICT- emissions project analysed the impact of different GN penetration rates on CO₂ emissions. Results showed that up to 8% fuel consumption reductions for a 75% penetration level in congested and low congested scenarios. This benefit concentrates in motorways and highways while urban streets and peripheral roads had an increase in emissions due to traffic transfer to shorter routes. Results also suggested that, since length has an important effect in fuel consumption, green drivers choose routes similar to the minimum length although this may imply crossing the city center or selecting a road with lower speed than a highway.

Taking these results as the starting point for this policy analysis and recognizing the different spatial impacts of GHG and air pollutant emissions, we argue that GN systems present clear benefits for combating climate change but they could be inefficient to reduce air pollution in urban environments. Therefore, this research will expand the ICT-Emissions assessment applying the comprehensive methodology developed to analyse the potential of GN to achieve not only *greener* but also *cleaner* cities. To do this we analysed the impacts of GN on CO₂ and NO_x emissions as well as the effect of NO_x emissions on population exposure levels. The impact of this measure on traffic operations will be also analysed

Scenarios

GN: These scenarios simulate the eco-routing measure applied to the whole Madrid Region. A total of 10 scenarios have been considered, including two different traffic periods (morning peak –AM- and free-flow conditions –FF-) and five market penetration rates (10%, 25%, 50%, 75% and 90%). Morning peak hours were selected to understand the impact of the measure in congested conditions while free-flow conditions were selected to understand the effect of the measure without congestion constraints

For green drivers the model assigned the fuel consumption impedance function (see eq 1 and 2 in page 36) while for the rest of the drivers the model assigned the conventional function defined in the BC scenario based on travel times and monetary costs.

This measure does not affect the cost-function of the links, therefore BPRs were the same used in the BC scenario. Through the text, these scenarios will be referred by the initials of the applied measure GN followed by penetration rate of the measure considered in the simulation e.g. GN25 will refer to scenario with a 25% of green or eco-routing drivers.

6.3 Combined ICT-based strategies

Previous research suggested that ICT-based traffic measures are effective to reduce fuel consumption and CO₂ emissions (Samaras et al. 2016); however, they present conflicts regarding traffic performance. Previous research results also suggest complementarity among ICT measures e.g. the increases of travel times showed by the ICT-Emissions project for low GN penetration rates could be offset with the travel times reduction produced by low penetration rates of ED. However, there is a lack of studies evaluating the impact of combined ICT-measures in urban areas. Besides, the Working Group for Clean and Efficient Mobility identified GN+ED and GN+VSL as measures with a potential overlapping of impacts.

This research builds on the results of the GN measure applied in isolation and analyses the environmental and traffic performance overlaps, complementarities and synergies of its combination with VSL and GN to Madrid Metropolitan area.

When implementing different measures at the same time and location, special care needs to be given to the question whether the total effects are the sum of the separate effects, higher or lower. Adapted from (May et al. 2006; Mayeres et al. 2003; Mastenbroek et al. 2012), the following interactions between two measures are possible:

- Synergy: when the combined measure gives a greater benefit than the sum of the benefits of applying either one of them in isolation ($A+B > A + B$ being $A+B > A$ and $A+B > B$).

- Additivity: when the gain combined measure is equal to the sum of benefits of using each in isolation ($(A+B) = A+B$).
- Complementarity: when the combined measure gives a greater total benefit than either application in isolation (with $A+B > A$ and $A+B > B$, $(A+B) < A+B$).
- Perfect substitutability: when the application of one measure eliminates entirely the gain from applying another measure ($A+B = A = B$).

Following the above approach we have added two more possible types of interaction. The first one explains the situations when one single measure provides a benefit and the other provide a loss and hence the effect of the combined measure could be greater than the sum of the single measures benefits but still lower than the benefit of one of them applied in isolation. The second one explains the situation when the combined measure provides lower benefits than both single measures in isolation.

- Partial compensation: When the combined measure gives a greater benefit than one of the measures in isolation but lower than the other; when $A < 0$ or $B < 0$ with $(A+B) < A$ or $(A+B) < B$ even if $(A+B) > A + B$.
- Perfect conflict: The combined measure gives lower benefits than the use of either measure in isolation $(A+B) < A$ and $(A+B) < B$.

Scenarios

Green Navigation combined with Variable Speed Limits (GN+VSL): These scenarios simulate the VSL applied to one section of M-30 combined with the GN applied to the whole Madrid region. A total of 5 scenarios were simulated for morning peak hours (the VSL only works in congested conditions) considering the five eco-routing penetration rates already described.

For green drivers the model assigned the fuel consumption impedance function (see section 4.1.1) while for the rest of the drivers the model assigned the conventional function defined in the BC scenario.

Since the VSL measure modifies the link cost-function of the section where it was applied, BPRs for the west section of the M30 will be the same used for the VSL scenario (Table 6-3).

Throughout the text, these scenarios will be referred by the initials of the applied measures GN+VSL followed by the GN penetration rate considered in the simulation e.g. GN25VSL will refer to combined GN+VSL scenario with a 25% of green drivers

Green Navigation combined with Eco-driving (GN+ED): This scenario simulates the ED measure applied to highways and urban roads combined with the eco-routing measure applied to the whole Madrid region. A total of 30 scenarios were simulated, including two traffic periods (morning peak –AM- and free-flow –FF-), five GN penetration rates and three ED penetration rates. Morning peak hours were selected to understand the impact of the measure in congested conditions while free-flow conditions were selected to understand the effect of the measure without congestion constraints

Again, for drivers following the eco-routing recommendations the model assigned the fuel consumption impedance function (see section 4.1.1) while for the rest of the drivers

(conventional and eco-driving) de model assigned the conventional function defined in the BC scenario.

Changes in capacity and free-flow speeds due to the effect of eco-driving are reflected in the BPRs used in the simulation (see Table 6-3 for the ED scenario).

Throughout the text, these scenarios will be referred by the initials of the applied measures GN+ED followed by the GN and ED penetration rates considered in the simulation e.g. GN25ED50 will refer to combined GN+ED scenario with a 25% of green drivers and a 50% of eco-drivers.

6.4 Summary of the scenarios for policy analysis

This section summarizes the modelling attributes used to simulate each of **61 the scenarios**.

Since the selected measures modified either the model impedance function or the links cost-function, Table 6-4 provides explicit information about these parameters. It also provides information regarding the traffic periods and the number of scenarios simulated for each policy measure.

Table 6-4 Summary of the modelling attributes of the different scenarios considered

SCENARIO	TRAFFIC PERIOD	PARTICULAR MODELLING ATTRIBUTES			NUMBER SCENARIOS
		Imp. Function	BPRs	Pen. rate	TP. x Pen. rate
BC	peak hours, off-peak hours and Free flow	Conventional	Table 5.2	N/A	3x1 = 3
SPR ¹	Moning and afternoon peak, Off-peak	Conventional	Table 5.2	N/A	3 x (S90) and 3 x (S70) = 6
VSL	Peak hours	Conventional	Table 6.2	N/A	1 x 1 = 1
ED	Peak hours and Free-flow	Conventional	Table 6.3	ED25, ED50,ED75	2 x 3 = 6
GN	Peak hours and Free-flow	FC green drivers & conventional (for the remaining)	Table 5.2	GN10,GN25,GN50, GN75, GN90	2 x 5 = 10
VSL+GN	Peak hours	FC green drivers & conventional (for the remaining)	Table 6.2	GN10, GN25, GN50, GN75,GN90	1 x (5 x 1) = 5
GN+ED	Peak hours and Free-flow	FC green drivers & conventional (for the remaining))	Table 6.3	GN10, GN25,GN50, GN75 GN90&ED25, ED50, ED75	2 x (5 x 3) = 30

NOTE1 In order to simulate the SPR scenarios we have modified the free-flow speed of the M30 links affected by the speed reduction i.e. the tunnel section in the west area using 2010 OD matrices. S90 describes the 90km/h in the tunnels while the S70 simulates the 70km/h in the tunnels.

NOTE2 Imp. Function stands for Impedance function, Pen. Rate stands for penetration rate T.P stands for traffic periods, FC stands for fuel consumption, N/A stands for not applicable

Finally, Table 6-5 summarizes the specific modelling, assessing and mapping tools used for the analysis of each of the measures.

Table 6-5 Summary of the modelling components used in the pre-policy and policy analysis

	Model's interaction	ICT-simulation	Indicators						Mapping
			VKM	VEH	AVS	TEI CO ₂	TEI NO _x	PEI NO _x	
Pre-policy	✓						✓	✓	✓
SPR	✓		✓	✓	✓	✓	✓		
VSL	✓	✓	✓	✓		✓			✓
ED	✓	✓	✓	✓					
GN	✓	✓	✓	✓		✓	✓	✓	
GN-ED	✓	✓	✓	✓		✓			
GN-VSL	✓	✓	✓	✓		✓			

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7. RESULTS AND DISCUSSION

This chapter presents the results and discussion of the policy analysis. Results have been already published in indexed scientific journals or presented in international conferences. At the end of each subsection a note will specify the details of the publication.

In order to achieve the second specific objective (RO2) and to answer research questions IV-VI, this section will provide local decision-makers and city managers with useful insights regarding the emissions reduction initiatives under study. The aim of the analysis is to understand how the selected policy measures contribute towards *greener* and *cleaner* cities and to identify possible co-benefits and trade-offs in this respect.

7.1 Speed management strategies

Results of the SPR will be introduced and discussed in subsection 7.1.1. Results for the VSL will be introduced in subsection 7.1.2 and further discussed in the context of the combined ICT-measures in subsection 7.3

7.1.1 Speed reduction strategy (SPR)

This section delivers the results of the scenario modelling for an average working day, and then the daily variations in the traffic performance and emissions indicators by period (peak –AM and PM- and off-peak –OP-).

Results express the differences between the two scenarios considered for this measure (S90 and S70) in terms of traffic volume (VKM), travel times (VEH), average speeds (AVS), CO₂ emissions and NO_x emissions (kg/km). Results reflect the effect of the speed limit reduction from 90 to 70 km/hour; therefore, variations in the indicators will take the S90 as the base scenario.

Finally, results are provided for the M30 sections and areas described in section 5.1 (Figure 5-3 and Table 5-1)

Average Daily results

Daily results are presented in a homogeneous manner for traffic volumes, average speeds, aggregated travel times and vehicle emissions. The effect of the speed limit reduction is calculated by section and subsection. While the analysis of the sections offers a comprehensive picture of the situation along the road as a whole, the analysis of the smaller subsections explains the impacts of the measure in transition segments; i.e. the subsections closer to the section where the speed reduction measure was implemented. Values are presented in absolute and relative terms, which is particularly relevant in the results for CO₂ emissions due to their global impact; a 1% reduction in CO₂ emissions in one section with high emission levels is more important than a 5% reduction in an section with low emission levels in aggregate terms. The number of tons of CO₂ reduced is therefore more important than the relative reduction in a specific section. Finally, the dispersion among the parameters studied is especially important when studying average speeds.

Figure 7-1 shows daily traffic volumes by section (table above) and subsection (graph below) for each scenario, and their absolute and relative variation after the implementation of the 70 km/h speed limit along the SW section. As explained in the Impact Assessment Methodology, the variation in traffic volumes and saturation rates for this speed reduction measure is the same.

As expected, the measure generates a major reduction of almost 13% in traffic volume in S-W section. Traffic volume variation in open-air sections (E and NW) is marginal. There is a 3.5% reduction in traffic volume and saturation rates for the whole M30.

Subsections further away from the where the measure was applied –La Paloma and North Link– have a minor increase in traffic volume, and transition subsections (Mediterraneo and El Pardo) indicate a decrease, as shown in the graph The SW section is the most homogeneous

stretch of the ring road in terms of traffic volume, which is explained by the fact that this road section has fewer exits and entrances. Traffic volume dispersion in this section is even lower after the speed limit reduction. The open-air sections present high levels of traffic volume dispersion both before and after the implementation of the speed measure.

Figure 7-2 shows the daily average speed by section and subsection. The results show that a 22.2% reduction in the speed limit in the SW section (from 90 km/h to 70 km/h) leads to a smaller reduction of 17.8% in the daily average speeds in this section. The speed reduction also causes less speed dispersion between the sections. The S90 scenario has a maximum average speed variation of over 13.4 km/h between the E and the SW sections; however, the S70 scenario has a maximum variation of 5.1 km/h between the SW and the N-West sections. Considering the ring-road as a whole, the 22.2% speed reduction over less than a third of its length leads to a 4.76% reduction in average speeds. This reduction is mainly due to the reduction in average speeds in the SW section, and directly affects individual travel times.

It is worth noting that the subsections closest to the section where the measure was applied (Mediterraneo and El Pardo) undergo a slight increase in average speed due mainly to the effect of the transition from a 70 km/h section to a 90 km/h section. The results are aggregated for both driving directions. In these segments the total average speed variation is positive means that the 'measure effect' is more powerful when emerging from the section than when entering. Aggregate travel times remain virtually unchanged when considering the M30 as a whole. In the SW Section they increase 3.3%, but this rise is offset by the 3.0% decline in the N Section. Figure 7-3 shows daily travel times by section and subsection. Subsections results show that the road segments closest to the zone of implementation of the measure undergo a reduction in travel times (O'Donnell: -1.4%; Mediterraneo: -1.8%; El Pardo: -11.2% and North : -0.9%) due to the decrease in traffic volume and speed in these subsections. SW sections show an increase in travel time, which is not matched by all the subsections in the section, i.e. the Pte. Toledo subsection has a slight decrease in travel times as the reduction in average speed (14.1%) is offset by the lower traffic volume (13.6%). This is not the case for the other two subsections of the tunnel section, where the reduction in average speed is too high (over 19%) to be compensated by the fall in traffic volume.

Figure 7-4 and Figure 7-5 show a 16.4% reduction in NO_x emissions and a 14.4% reduction in CO₂ emissions in the SW section. The variation in the other sections of the M30 is almost negligible, and therefore the 4.1% and 4.6% reduction in CO₂ and NO_x emissions respectively for the whole of the M30 is mainly due to their variation in the tunnel sector.

These figures also show that the subsections closest to the tunnel section undergo a slight reduction in emissions after the implementation of the new speed limit, while the road segments furthest away see an increase in vehicle emissions.

Figure 7-1 Variation in daily traffic volumes in the M30 by section and subsection after the implementation of the SPR

Figure 7-2 Variation in daily average speeds in the M30 by section and subsection after the implementation of the SPR

Figure 7-3 Variation in daily travel times in the M30 by section and subsection after the implementation of the SPR

Figure 7-4 Variation in daily CO₂ emissions in the M30 by section and subsection after the implementation of the SPR

Figure 7-5 Variation in daily NO_x emissions in the M30 by section and subsection after the implementation of the SPR

Daily variation in results

The model also allows to analyse the variation in the study parameters throughout the day – morning peak period (AM), afternoon peak period (PM) and off-peak period (OP)– which provides a deeper understanding on how this measure performs at different levels of urban congestion.

Table 7-1 Relative hourly variation in traffic performance and emissions indicators after lowering the speed limit in the South-West section from 90 km/h to 70 km/h on the M-30

RELATIVE HOURLY VARIATION IN TRAFFIC PERFORMANCE AND EMISSIONS INDICATORS						
			North-West	South-West	East	M30
Traffic performance indicators	VKM(%)	AM	0.1	-10.2	-1.8	-3.4
		PM	-0.1	-11.4	0.1	-3
		OP	-1.7	-14.1	0.5	-4
	VEH(%)	AM	-2.8	7.7	-3.7	-1.2
		PM	-2	4.2	0.4	0.6
		OP	-3.8	1.6	1	-0.1
	AVS(%)	AM	1.2	-18.5	1.6	-4.4
		PM	0.1	-17.4	-0.2	-4.8
		OP	0.9	-17.8	-0.6	-4.8
Emission indicators	CO ₂ (%)	AM	-0.5	-12.1	-2.2	-4.1
		PM	-0.6	-12.6	0.2	-3.3
		OP	-2	-16.3	0.5	-4.6
	NO _x (%)	AM	-0.1	-14.2	-1.8	-4.5
		PM	-0.3	-14.6	0.2	-3.8
		OP	-1.7	-18.1	0.4	-5.2

Table 7-1 shows the hourly variation in the traffic performance and emissions indicators after the implementation of the 70 km/h speed limit in the tunnel sector. In tunnels, the variation in average speed and traffic volume among periods is less than 10%, except during off-peak hours when traffic volume is considerably lower than in peak hours. However, travel times in the South-West section differ substantially from one period to another. Differences between AM and PM are explained by the cumulative effect of these minor variations in average speed and traffic volume. During the morning period, traffic volume is about 10% greater than during

the afternoon, and average speed is about 10% slower; travel times during morning peak hours are therefore longer (7.7%) than in afternoon peak hours (4.2%).

Travel times during off-peak hours in tunnels rise only 1.6%, as although average speed declines by 17.8%, there is also a substantial reduction in traffic volume (14.1%), which offsets the effect of the average speed reduction.

There are two main reasons why daily variations in travel times remain practically unchanged. On the one hand, the rise in the South-West section travel times is offset by the decrease in travel times in the North-West section; and on the other, although travel times increase considerably during peak hours, these only represent 5 of the 15 hours considered in the model.

The model shows that the most important CO₂ and NO_x emission reductions occur during off-peak hours. This was expected, as the lower saturation rates during these periods make it possible to drive at free-flow speeds most of the time. 22.2% lower free flow speeds can be achieved by lowering speed limits to 70 km/h.

The effect of the measure during peak hours is also important. Vehicles usually fail to attain free-flow speed at these times, and yet lower speed limits generate less changing friction, less speed dispersion and greater headways, which lead to fewer shock waves (Noland, R.B. and Quddus 2005) and a reduction in both CO₂ and NO_x emissions.

These results have already been published as:

Perez-Prada, F., & Monzon, A. (2017). *Ex-post environmental and traffic assessment of a speed reduction strategy in Madrid's inner ring-road*. **Journal of Transport Geography**, 58, 256–268. <http://doi.org/10.1016/j.jtrangeo.2016.12.018>

7.1.2 Variable Speed Limits (VSL)

The VSL measure has been only simulated for the morning peak (AM) traffic period i.e. congested conditions. Since the measure has been only applied in a section of the M30, the impact of the measure on traffic and emissions indicators is minimal for the whole region (see Table 7-2). Therefore, we have analysed what happened in the areas affected by the measure.

As expected the operational capacity increase produced by the measure in the M30 urban ring road returned an increase of traffic volumes of 4.9% followed by an increase of both CO₂ and NO_x gross emissions, specifically the measure produced an increase of 4.3% and 4.7% of TEI_CO2 and TEI_NOx respectively. PEI indicators have also increased but in a lower percentage, 3.9%. The measure also led to a minor increase in travel times. On the other hand, focusing on the urban network we can observe a slightly reduction in all the traffic and emissions indicators considered. This means that some of the trips that were previously done through the CBD, have been redistributed to the M30 after the implementation of the measure.

Table 7-2 Impact of the VSL measure on traffic performance and emissions by road type (CBD, M30 and whole network)

		Type of road		
		CBD	M30	WHOLE NETWORK
Assessment Indicators	VKM	-0.6%	4.9%	0.0%
	VEH	-0.9%	0.6%	-0.3%
	TEI_CO2	-0.7%	4.3%	0.0%
	TEI_NOX	-0.6%	4.7%	-0.1%
	PEI_NOX	-0.8%	3.9%	-0.1%

To better understand how air pollutant emissions have been redistributed through the road network we have mapped their variation in Figure 7-6. It shows how NO_x emissions in the M30 increase significantly west section as well as in the main roads connecting the M30 with the CBD. The remaining urban network showed a decrease in NO_x emissions (most of the links are either in light or dark green).

We can also observe a slight increase of NO_x emissions in the road links between the M40 and the M30. In fact, we also notice that most of the links in the west section of the M40 reduced their NO_x impact meaning that some trips with origin or destination the M30-M40 strip were attracted by the M30 after the implementation of the VSL measure.

Some of these results have already been presented at the 2016-ANT conference:

Valdés, C., Garcia-Castro, A., Monzon, A., Garcia-Martinez, A., Perez-Prada, F., (2016). Modelling Variable Speed Limits: a double scale approach. Presented at the 7th International Conference on Ambient Systems, Networks and Technologies, 23-26 May, Madrid, Spain

Figure 7-6 Redistribution of PEI_NO_x after the implementation of the VSL measure in the west section of the M30

7.2 Eco-traffic strategies

Results of the GN will be introduced and discussed in this section; however results for the ED will be introduced and further discussed in the context of the combined measures application.

7.2.1 Green Navigation (GN)

Results are consistent with prior research (see section 2.3.3. for more information)

Whole region

Eco-routing systems generated important reductions at a regional level in terms of CO₂ emissions, up to 10.4% in reductions under highly-congested traffic conditions (i.e. AM traffic period. For the whole discussion of the GN results we will used congested conditions and AM traffic period as synonyms), and up to 7.1% under free-flow traffic conditions (FF traffic period) (Table 7-3). When considering gross NO_x emissions (TEI_NO_x indicator), similar benefits were also shown.

Table 7-3 Variation of indicators for the whole regional network for each GN penetration rate

Penetration rates	VKM (veh x km)	VEH (veh x h)	TEI_CO2 (kg)	TEI_NO_x (kg)	PEI_NO_x (kg x hab./km²)
BC_AM	5,884,915	96,541	904,802	3,009	10,277,277
GN10	-3.7%	6.8%	-3.3%	-3.3%	6.4%
GN25	-7.7%	14.1%	-6.3%	-7.5%	9.4%
GN50	-11.3%	21.3%	-8.9%	-11.2%	14.0%
GN75	-12.9%	25.7%	-9.9%	-12.9%	17.9%
GN90	-13.5%	28.7%	-10.4%	-13.8%	20.2%
BC_FF	2,170,829	25,623	333,790	1,164	3,779,809
GN10	-5.8%	-3.6%	-1.7%	-1.6%	1.2%
GN25	-6.8%	0.2%	-3.0%	-3.8%	4.5%
GN50	-7.8%	7.2%	-4.8%	-7.2%	9.6%
GN75	-8.9%	13.2%	-6.4%	-10.2%	14.0%
GN90	-9.5%	16.8%	-7.1%	-11.8%	16.3%

Notes: BC_AM stands for BC scenario under congested conditions i.e. simulated for the morning peak hour (AM), BC_FF stands for the BC scenario under free-flow conditions i.e. simulated for the FF traffic period, VKM stands for vehicles-km travelled i.e. traffic volume, VEH stands for vehicles-hour travelled i.e. travel times, TEI_CO2 stands for CO₂ traffic emission indicator, TEI_NO_x stand f or NO_x traffic emission indicator, PEI_NO_x stands for population-weighted NO_x indicator

Reductions in traffic volumes were in line with the reduction in traffic emissions. However, two indicators considerably increased with the GN penetration rate. On the one hand, travel times increased for all GN penetration rates, except for the GN10 under free-flow conditions. This increase was greater for lower penetration rates (from 6.8% to 14.1% and to 21.3% for GN10, GN25 and GN50, respectively) and it moderated at the highest penetration levels (GN75 and GN90). Analysing the PEI for NO_x , we find the first evidence that GN systems could be ineffective regarding air pollution in dense urban environments. At high levels of congestion, even the lower penetration rates produced an increase of 6.4% in the PEI_{NO_x} indicator, reaching 20.2% in the GN90 scenario. For free-flow conditions, this increase was more moderate, ranging from 1.2 % to 16.3% for GN10 and GN90, respectively.

Since previous research showed that green-drivers tend to choose the shorter route, we have simulated five extra scenarios in AM modelling “shortest route drivers (**SR**)” i.e. we have assigned to these types of drivers and impedance model impedance function based only on length. We wanted to probe that the fuel impedance function chosen for the simulations takes into account distance and speeds. Results showed in Table 7-4 confirmed that the fuel-consumption impedance function used for the simulation of the eco-routing measure took average speeds and traffic intensities into account, and not only trip distance.

Table 7-4 Changes in traffic volumes and averages speeds between the SR and the GN for peak hours and different penetration rates of the measure

		Traffic volume (veh-km)		Average speed (veh-km/veh-hour)	
		SR	GN	SR	GN
BC		5,884,915	5,884,915	61.0	61.0
Penetration rate (%)	10	-6.9%	-3.7%	7.40%	-9.8%
	25	-17.7%	-7.7%	6.80%	-19.1%
	50	-26.0%	-11.3%	-14.50%	-26.9%
	75	-22.8%	-12.9%	-43.40%	-30.7%
	90	-15.6%	-13.5%	-56.20%	-32.8%
Notes: BC_ is Basecase scenario, SR is Shortest Route scenario, GN is Green Navigation Scenario					

Results by road type

Figure 7-7 shows the share by road type of each of the indicators assessed for the base scenarios for congested and free-flow traffic conditions. While the CBD network only carried 14.8% of vehicle-km driven in Madrid and generated 15.7% of the CO₂ emissions, it represented 63.8% of the air pollution exposure levels in the highly-congested scenario. This is due to the fact that population density in the CBD is higher than in peripheral areas. For the free-flow scenario, similar levels of traffic flow (14.5%) led to a lower share of the PEI_NO_x indicator, 54.6%. This is due to the fact that the gross traffic NO_x emission share was higher under congested conditions than under free-flow conditions, 13.3% vs. 10.7%, respectively, in CBD.

Figure 7-7 Indicators' share of the total road network by road type in the base congested and free-flow scenarios.

Notes: CBD NET. stands for Central Business District Network, HIGHWAY. stands for Highways, and OTHER R. stands for Other Roads. Length is the percentage of km of road for each type of road considered, VKM stands for vehicles-km travelled i.e. traffic volume, TEI_CO2 stands for CO₂ traffic emission indicator, TEI_NOx stands for NO_x traffic emission indicator, PEI_NOx stands for population-weighted NO_x indicator

Figure 7-8 shows the evolution of the PEI_NO_x share by road type for the different GN penetration levels considered (rows in the tables below, the sum of the columns add up to 100%). Although for the free-flow base scenario the CBD share of PEI_NO_x was lower than for the congested scenario, it increased with the penetration rate. Hence, for the highest GN penetration rates (GN75 and GN90), the share of air pollution exposure was similar. This noticeable evolution under free-flow condition was due to the fact that, while NO_x gross traffic emissions increased in similar proportion to the congested condition, traffic flows in CBD grew faster as the GN penetration rate increased. Traffic flows rose from 14.5% for the free base-case scenario to 22.5%, while NO_x gross traffic emissions increased from 11% to 18%. For

the congested situation, this growth ranged from 15% to 20% for traffic volumes, and from 13% to 20% for NO_x emissions.

Evolution of the network share of the population-weighted NO_x exposure indicator increasing GN penetration rate

Figure 7-8 Evolution of the population exposure to NO_x indicator for different GN penetration rates and road types

Table 7-5 shows the variation of traffic performance and environmental indicators by road type (i.e. CBD highway and other roads) for each of the GN penetration rates considered. The impedance function looked for the traffic assignment that minimizes fuel consumption for the entire network. Traffic volumes increased considerably, especially under low-congestion conditions. At the CBD level, all the indicators worsened with the adoption of eco-routing choices, regardless of the traffic condition considered. Under free-flow conditions, shorter urban routes became even more attractive for green drivers, since road saturation levels were low. Traffic volumes also increased on OTHER roads. However, these growths were compensated by reductions on highways to obtain a global decrease (Table 7-3) in total VKM driven.

Table 7-5 Variation of traffic and environmental indicators by road type for each GN penetration rate

VKM (veh x km)			VEH (veh x h)		TEI_CO ₂ (kg)		TEI_NO _x (kg)		PEI_NO _x (kg x hab/km ²)	
CBD NET.	AM	FF	AM	FF	AM	FF	AM	FF	AM	FF
BC	870,955	314,411	29,662	7,016	141,633	44,528	405	125	6,553,843	2,064,349
GN10	0.1%	0.3%	10.6%	0.6%	2.5%	4.4%	2.0%	4.0%	1.0%	3.3%
GN25	2.8%	7.8%	25.9%	10.6%	8.7%	13.2%	7.8%	13.1%	5.3%	11.7%
GN50	8.2%	20.2%	47.1%	28.1%	18.7%	27.7%	17.2%	28.2%	13.2%	25.2%
GN75	13.5%	31.6%	62.2%	44.9%	27.2%	41.5%	25.3%	42.4%	21.0%	38.1%
GN90	16.4%	37.8%	71.0%	54.5%	31.8%	49.2%	29.6%	50.4%	25.4%	45.2%
HIGHWAY.	AM	FF	AM	FF	AM	FF	AM	FF	AM	FF
BC	3,545,963	1,412,048	45,751	13,622	541,775	222,941	1,891	819	3,192,085	1,552,678
GN10	-5.0%	-9.3%	2.9%	-9.1%	-4.1%	-5.5%	-4.4%	-5.6%	-1.6%	-4.2%
GN25	-11.8%	-15.7%	3.4%	-14.9%	-10.5%	-12.3%	-11.5%	-12.7%	-3.0%	-10.4%
GN50	-20.9%	-25.0%	-3.5%	-22.3%	-19.6%	-22.5%	-20.8%	-23.3%	-7.4%	-20.8%
GN75	-27.4%	-33.4%	-11.1%	-29.6%	-26.4%	-31.6%	-27.4%	-32.8%	-13.6%	-30.3%
GN90	-30.4%	-38.1%	-14.5%	-34.0%	-29.7%	-36.7%	-30.9%	-38.2%	-16.7%	-35.7%
OTHER R	AM	FF	AM	FF	AM	FF	AM	FF	AM	FF
BC	1,467,996	444,370	21,127	4,985	221,394	66,321	751	230	531,349	162,782
GN10	-2.6%	0.7%	9.8%	5.5%	-1.7%	6.8%	-3.1%	5.4%	6.4%	18.9%
GN25	-4.1%	11.4%	20.6%	26.9%	-2.5%	17.7%	-5.4%	14.6%	16.4%	47.6%
GN50	0.3%	26.7%	38.6%	58.3%	2.9%	33.1%	-1.8%	27.2%	33.2%	87.1%
GN75	6.2%	40.1%	53.9%	85.3%	9.6%	46.7%	3.7%	38.1%	47.6%	115.8%
GN90	9.7%	48.1%	62.9%	102.4%	13.3%	54.9%	6.3%	44.7%	56.4%	131.5%

Notes: CBD NET. stands for Central Business District Network, HIGHWAY. stands for Highways, and OTHER R. stands for Other Roads. BC for Basecase scenario, VKM stands for vehicles-km travelled i.e. traffic volume, VEH stands for vehicles-hour travelled i.e. travel times, TEI_CO₂ stands for CO₂ traffic emission indicator, TEI_NO_x stands for NO_x traffic emission indicator, PEI_NO_x stands for population-weighted NO_x indicator

Travel times increased noticeably on CBD and OTHER roads. While on CBD roads, there was an increase under highly-congested traffic conditions, on OTHER peripheral roads, there was a greater increase under free-flow traffic conditions. Nevertheless, travel times on highways significantly decreased as GN penetration rates increases.

In general, GN systems reduced congestion on faster roads (highways) by distributing traffic to shorter, but slower, routes, where saturation rates increase significantly. Therefore, global travel times (Table 7-3) for the whole region increased. Then GN systems resulted ineffective to improve traffic performance since congestion was transferred to other areas and situations in the city.

As expected, CO₂ emissions also increased at a CBD level and OTHER roads, although this increase was compensated by the CO₂ emission reduction on HIGHWAYS.

Although gross NO_x (TEI_NOx) emissions are reduced at a regional level, population exposure levels increased (Table 7-3). Furthermore, population exposure to NO_x (PEI_NOx) increased more quickly on CBD roads than it did for the entire region. For low GN penetration rates (GN10 to GN50), they increased in similar proportion, yet for GN10, the increase for the entire region is 6.4%, while for CBD roads, it was only 2%. However, for higher GN penetration rates (GN75 and GN90), CBD increased almost double the increases in the entire region. Population exposure to air pollution decreased in highways under free-flow traffic and congested conditions for all penetration rates considered.

To better understand the impact of this measure on the spatial redistribution of the emissions, Figure 7-9 plots TEI_CO2 reductions against PEI_NO_x reductions by road type. The penetration rate of green drivers is represented by dots, triangles, squares or addition signs depending on the type of road representing. Types of roads are also assigned different colours. Analysing the results for the WHOLE network (black line) we see how GN systems increasingly reduce CO₂ emissions as the percentage of GN drivers augments; however the NO_x population weighted exposure indicator raises for increasing percentages of GN. The relative increases in CO₂ emissions in the CBD (blue line) were offset by the greater relative decreases in the highways (red line). The relocation of NO_x emissions towards the densely populated CBD does not compensate their reduction in highways.

Figure 7-9 Impacts of the different levels of GN drivers on the spatial allocation of emissions by road type and traffic situation considered

This analysis has been part of the work conducted for the **Lee Schipper Memorial Scholarship**. Besides, these results have already been published as:

Valdes Serrano, C., Perez-Prada, F., Monzon, A. *Eco-Routing: More Green Drivers Means More Benefits?* Proceedings of the XII Conference on Transport Engineering (CIT 2016). Valencia (Spain), from 7-9 June 2016 ISBN: 978-84-608-9960-0

Perez-Prada, F. Monzon, A., Valdes, C. *ACHIEVING GREENER AND CLEANER CITIES: The role of Green-Navigation Systems*. **Energies**. 10(6), 791; doi:10.3390/en1006079. IP 2.077 – Q2.

7.3 Combined ICT strategies.

This section shows the results for the combined application of GN-VSL and GN-ED. Results of the combined measures will be compared first with the results of the corresponding base-case scenario and second with the results of the single measures.

7.3.1 Green Navigation combined with Variable Speed Limits (GN+VSL)

Results have been obtained for traffic volumes, travel times and CO₂ emissions and analysed for the WHOLE network, the CBD network and the M30. The analysis of CO₂ emissions for the whole region will allow us to understand the impact of the measure towards *greener* cities. The analysis of NO_x population weighted indicator for the whole region along with the impact of the measure on the CBD and the M30 will allow us to understand the impact of the measure towards *cleaner* cities.

Figure 7-10 shows how to interpret the results of the 5 scenarios summarized in Figure 7-11

Figure 7-10 Interpretation of results of the GN+VSL measure

Results compared with the congested base case scenarios

For the whole region the measure showed CO₂ and VKM reductions for all the GN penetration rates considered. These reductions were higher as the level of green drivers increased: CO₂ reductions range from 3.2% of the GN10VSL scenario to 10.4% of the GN90VSL scenario while VKM reductions range from 3.6% of the GN10VSL scenario to 13.5% of the GN90VSL scenario. Population exposure (PEI_NOx) and travel times (VEH) showed the opposite trend, they increase as the percentage of green drivers does: PEI_NOx increases ranged from 0.5% of the GN10VSL to 13.9% of the GN90VSL while VEH increases ranged from 6.4% of the GN10VSL scenario to 28.6% of the GN90VSL scenario.

For the CBD network the combined measure showed CO₂ emissions, population exposure to NO_x, traffic volumes and travel times increase for all the scenarios considered except for VKM of the GN10VSL scenario that showed a 0.2% reduction. Traffic volumes increases for the

remaining scenarios range from 2.4% of the GN25VSL to the 16.2% of the GN90VSL. The increase of VKM brought about a higher increase in CO₂ emissions and population exposure to NO_x emissions and an even higher increase in VEH. Increases in these indicators range from 0.9% of the GN10VSL scenario to the 30.2% of the GN90VSL scenario for CO₂, from 0.5% of the GN10VSL scenario to the 25.3% of the GN90VSL for PEI_NOx and from 9.6% of the GN10VSL to 70:9% of the GN90VSL for VEH.

Finally, for the M30 ring-road the combined measure produced increases for the scenario GN10VSL for all the indicators analysed. In particular it showed 1.7%, 1.5% 1.3% and 3.6% increase of CO₂, PEI_NOx, VKM and VEH respectively. For the remaining scenarios the measure produced a reduction in all the indicators ranging from 0.4% of the GN25VSL scenario to 18.0% of the GN90VSL for CO₂ emissions, from 0.8% of the GN25VSL scenario to 17.8% of the GN90VSL for PEI_NOx, and from 1.1% of the GN25VSL scenario to 17.5% of the GN90VSL scenario for VKM. The scenario GN25VSL stills showed an increase of travel times while the remaining scenarios showed VEH reductions up to 17.3% of the GN90VSL scenario.

Results of the combined measure compared with single measures

First we will provide a brief overview of the results of the single measures. The simulation of the VSL to the west section of the M30 resulted in a redistribution of traffic from the city center to the M30 which lead to a reduction of CO₂ emissions and population exposure to NO_x in the urban network and an increase in the M30. The simulation of the GN showed exactly the contrary effect: traffic volumes, travel times and CO₂ emissions increased in the urban network as the level of green drivers augmented while traffic volumes and CO₂ emissions diminished in the M30.

At first sight, results of the combined measure are very similar to the ones produced by the GN alone. Results of CO₂ and VKM for the whole region followed exactly the same pattern: the GN10VSL and the GN50VSL scenarios showed a VSL partial compensation meaning that the results are better than the ones produced by the VSL alone but worse than the ones produced by the GN alone. The GN25VSL showed complementarity compared with the measures applied in isolation meaning that the results of the combined measure is greater than the results of each of the measures applied alone. Finally the results of the remaining scenarios showed a GN substitution effect i.e. is exactly the same than the GN alone. PEI_NOx and travel times showed more homogeneous results, all the scenarios provided a GN compensation. PEI_NOx results differed substantially from the ones showed by the GN alone; nevertheless, travel times results were again very similar to the ones produced by the GN alone. Taking into account that the measure VSL has been applied to a section of the M30 ring-road in a network of more than 6,500 km this little variation from the results of the GN was expected.

Since the results of the majority of the indicators for the whole region are virtually the same than the ones produced by the GN alone, we are narrowing the scope of the analysis to the road links next implementation of the VSL to better understand the impact of the combined measure.

For the CBD network, the combined measure showed a GN partial compensation of CO₂, PEI_NOx, VKM and VEH for all the scenarios under study. The combination of the GN for the whole region and the VSL in a section of the M30, mitigated the emissions, population exposure to NO_x, traffic volumes and travel times increases of the GN applied in isolation,

however the benefit provided by the VSL was not enough to counterweigh the overall worsening of the indicators. For the lower GN penetration rates (in particular for the GN10VSL, GN25VSL AND GN50VSL scenarios), results of the combined measure showed bigger differences compared the ones produced by the GN alone. However, as the level of GN drivers increases, the effect tend of the VSL in the combined measure tended to disappear and results closer to the ones produced by the GN alone.

Traffic volumes were redistributed to the M30 hence it showed a lower decrease of CO₂ emissions and population exposure to NO_x compared to the GN applied in isolation. Results for the M30 show the biggest differences compared to the ones provided by the GN, which is expected since the VSL was directly implemented in this road. In this case, results of CO₂ emissions, population exposure to NO_x and traffic volumes showed a VSL partial compensation i.e. the increases provided by the VSL alone have been compensated by the reduction effect of the GN. Results for travel times were more heterogeneous, while for the GN10VSL scenario provided a GN partial compensation , the GN25VSL scenario provided a conflict i.e. results of the combined measure were worse than the ones provided by each of the measures alone. However, for the remaining scenarios the combined measure produced synergies i.e. results of the combined measure were better than the sum of the results of the single measures. While results of VKM, CO₂ and PEI_NOx for the combined measure in the M30 noticeably differ from the ones of the GN alone, results of travel times are again similar to the ones produced by the GN alone in particular for the GN10VSL, the GN50VSL and the GN90VSL scenarios

Figure 7-11 GN+VSL results and their comparison with the single measures

7.3.2 Green Navigation combined with Eco-driving (GN+ED)

Due to the already acknowledge limitations regarding ED emission factors, results will be focused on traffic performance indicators. Results have been obtained for traffic volumes, travel times and analysed for the WHOLE network and the CBD network. The analysis of traffic volumes for the WHOLE network will be used as a proxy to understand the contribution of the measure towards *greener* cities while the analysis of traffic volumes in the CBD will be used to understand the impact of the measure towards *cleaner* cities. The measure has been simulated for morning peak hours and free flow conditions. As done with the GN+VSL measure, results of the combined GN+ED measures will be first compared with the basecase scenario of the traffic period under analysis and second with the results of the single measure for the traffic period under analysis.

Figure 7-12 shows how to interpret the results of the 30 scenarios summarized in Figure 7-13 and Figure 7-14

Figure 7-12 Interpretation of results of the GN+ED measure

Results compared with the base case scenarios

For the whole region and free-flow conditions the combined measure showed traffic volume reductions for all the scenarios under analysis. VKM reduction increased as the percentage of GN drivers did; however, VKM remain virtually the same for all ED drivers' penetration rates.

For the whole region and congested conditions the combined measure showed traffic volume reductions for all the scenarios under analysis. For high levels of GN drivers i.e. GN75 and G90 results are virtually the same when combined with all the ED penetration rates under study i.e. results for GN75ED25, GN75ED50 AND GN75ED75 barely varied. For GN penetration rates of 50% or lower, VKM reductions decrease with higher ED penetration rates up to 50% when they reached an asymptote i.e. the GN25ED25 brought about higher VKM reductions than the GN25ED50 and the GN25ED75; however the difference between the GN25ED50 and the GN25ED75 is negligible. Finally, for GN10 and GN25 combined with all the ED penetration rates considered results reductions for congested conditions are lower than the ones obtained for

free-flow conditions. However, this trend is exactly the opposite for GN penetration rates of 50% or higher.

Regarding travel times, the CBD free-flow scenarios showed travel times reductions for scenarios with a 25% or less of green drivers and all the ED penetration rates while they showed increases for all the remaining combinations i.e. GN penetration rates of 50% or higher with all the ED penetration rates considered. The highest VEH reductions occurred for the GN10ED25 scenario while the highest increases occurred for the GN90ED50. When we consider an specific GN penetration rate, results are very similar when combined with the ED scenarios considered. For example, the GN25ED25 scenario provided a 2.2% travel time reduction while the GN25ED50 a 2% and the GN25ED75 a 2.1%. For congested conditions results showed travel time increases for all the scenarios considered, these raises in travel times are higher as the percentage of both GN and ED drivers increases. VEH ranged from an increase of 1.6% of the GN10ED25 scenario towards the 29.4% increase of the GN90ED50 scenario.

For the CBD region results showed a traffic flow increased for both congested and free-flow conditions. In general traffic volumes increased with GN penetration rates, while decreased until reach an asymptote at ED50 as the percentage of ED drivers increased. The lower traffic increases are given by the GN10 scenario combined with all the ED scenarios considered in free-flow conditions, while the higher traffic increases are given by the GN90 scenario combined with all the ED scenarios considered also in free-flow conditions. In congested conditions traffic increases ranged from around 5.1% for the GN10ED50 scenario to the 26.4% of the GN90ED25 scenario.

Regarding travel times results showed decreases for the GN25 scenario combined with all the ED scenarios in free-flow conditions and the GN10ED25 scenario in congested conditions. Travel times increase progressively as the level of GN drivers increase for all the ED scenarios reaching up to 63.1% increases in congested conditions and 43.1% increases in free-flow conditions for the GN90ED50 scenario.

Results of the combined measure compared with single measures

First we will provide a brief overview of the results of the single measures. All GN penetration rates applied in isolation led to traffic volume reductions, which become higher as the level of green drivers raised while ED applied in isolation produced the opposite for both congested and free-flow conditions. In general, travel times increased with the percentage of both eco and green drivers except for ED25 and GN10 applied alone that resulted in a 2.8% and 3.6% network travel time reduction.

For the whole region and free-flow conditions the GN+ED combined measure provided a synergy regarding traffic volumes even offsetting the VKM increases of the ED applied alone, i.e. VKM reductions for the combined measure are bigger than the sum of the ones provided by the single measures. However, for congested conditions, the measure provided a ED partial compensation i.e. results of the combined measure a greater in terms of traffic volumes reduction than the ones provided by the ED alone but worse than the ones provided by the GN alone for each of the combined scenarios considered.

Regarding travel times, the whole network presented more heterogeneity. For free-flow conditions travel times present synergies for lower GN penetration rates (specifically for GN10

and GN25) combined with all the ED scenarios. The GN50ED75 also presented synergies, in this case the travel times increase of the combined measure is lower than the sum of travel times increases of the GN50 and ED75 alone. For the remaining combined scenarios, the measure present a GN partial compensation i.e. VEH increases obtained from the combined measure are lower than the ones obtained for the different GN scenarios applied in isolation. For congested conditions results are even more heterogeneous. The combination of the ED25 scenario with all the GN scenarios brought about a GN partial compensation as well as the combination of the ED50 scenario with the GN10 and the GN25. However the combination of the ED50 and ED75 scenarios with the GN50, GN75 and GN90 brought about a perfect conflict i.e. the increase in travel times of the combined measure are greater than the ones showed by each of the single measures. The GN10ED75 scenario showed a complementarity i.e. the combined measure brought about better results than each of the measures alone while the GN25ED75 showed a substitution of the effects of the GN25 applied alone.

For the urban network the measure showed a perfect conflict both in free-flow and congested conditions regarding traffic volumes. Results for all the scenarios considered are worse than the ones provided by the measure alone.

Regarding travel times results were again more heterogeneous. In free flow conditions, we found synergies for the GN10 scenarios combined with all the ED scenarios considered. On the other hand, we found a GN partial compensation for all the remaining scenarios except for the GN25ED75 where we obtained a complementarity effect. Finally, for congested conditions we found a GN partial compensation for all the scenarios considered except for the GN10ED25 where we got a synergy.

Results of the GN-ED combined measure for the whole Madrid network

CONGESTED					FREE FLOW				
VKM	ED	-0.3	-1.2	-1.5	VKM	ED	-0.2	-1.0	-1.4
GN	GN/ED	ED25	ED50	ED75	GN	GN/ED	ED25	ED50	ED75
3.7	GN10	3.3	2.6	2.6	5.8	GN10	6.4	6.5	6.4
7.7	GN25	7.3	6.6	6.5	6.8	GN25	7.4	7.3	7.4
11.3	GN50	10.1	9.6	9.6	7.8	GN50	8.3	8.5	8.5
12.9	GN75	11	11	11.1	8.9	GN75	9.4	9.4	9.5
13.5	GN90	11.3	11.3	11.4	9.5	GN90	9.9	10	10.1
VEH	ED	2.8	-3.6	-6.4	VEH	ED	-0.6	-3.8	-6.0
GN	GN/ED	ED25	ED50	ED75	GN	GN/ED	ED25	ED50	ED75
-6.8	GN10	-1.6	-5.0	-5.1	3.6	GN10	5.8	5.5	5.6
-14.1	GN25	-9.8	-13.7	-14.1	-0.2	GN25	2.2	2	2.1
-21.3	GN50	-17.8	-21.8	-21.9	-7.2	GN50	-3.3	-3.9	-3.7
-25.7	GN75	-22.3	-26.2	-26	-13.2	GN75	-8.7	-9.4	-9.1
-28.7	GN90	-25.8	-29.4	-29.1	-16.8	GN90	-12.2	-13	-12.6

KEY:

- Synergy
- Additivity
- Complementarity
- Perfect Substitutability
- EC partial compensation
- GN partial compensation
- Perfect conflict

NOTE:

Figures show VKM and VEH reductions for the whole network and congested and free flow traffic conditions

Figure 7-13: GN-ED results and their comparison with the single for the whole Madrid Region

Results of the GN-ED combined measure for the urban network

CONGESTED					FREE FLOW				
VKM	ED	-1.0	0.6	1.9	VKM	ED	3.7	7.1	9.2
GN	GN/ED	ED25	ED50	ED75	GN	GN/ED	ED25	ED50	ED75
-0.1	GN10	-5.2	-5.1	-5.4	-0.3	GN10	-1.4	-1.1	-1.1
-2.8	GN25	-8.5	-8	-8.2	-7.8	GN25	-9.5	-9.3	-9.3
-8.2	GN50	-15.1	-14.8	-14.8	-20.2	GN50	-22.3	-21.8	-21.7
-13.5	GN75	-22.6	-21.5	-21.5	-31.6	GN75	-34.2	-33.5	-33.7
-16.4	GN90	-26.4	-25	-24.9	-37.8	GN90	-41.2	-40.3	-40.3
VEH	ED	-8.3	2.2	6.7	VEH	ED	0.3	-5.6	-10.3
GN	GN/ED	ED25	ED50	ED75	GN	GN/ED	ED25	ED50	ED75
-10.6	GN10	2.9	-1.8	-1.2	-0.6	GN10	4.4	3.3	3.7
-25.9	GN25	-12.3	-17.0	-17.2	-10.6	GN25	-4.9	-6.3	-6.2
-47.1	GN50	-33.8	-39.7	-39.0	-28.1	GN50	-19.7	-21.5	-21.5
-67.2	GN75	-49.4	-53.2	-54.9	-44.9	GN75	-34.5	-36.5	-35.9
-71	GN90	57.8	-63.1	-62.3	-54.5	GN90	-43.8	-46.1	-45.6

KEY:

Synergy
 Additivity
 Complementarity
 Perfect Substitutability
 EC partial compensation
 GN partial compensation
 Perfect conflict

NOTE:

Figures show VKM and VEH reductions for the whole network and congested and free flow traffic conditions

Figure 7-14 GN-ED results and their comparison with the single measures for Madrid CBD

Some of these results have already been presented as:

Perez-Prada, F., Wang, Y., Monzon, A. *Analysing the impact of urban traffic measures to reduce GHGs emissions*. 2017 NECTAR Conference. May, June Madrid Spain

8. CONCLUSIONS AND FUTURE RESEARCH:

Chapter 8 includes the conclusions of this research. It starts with a review of the objectives presented in Chapter 3 and the thesis contributions towards their accomplishment. This is followed by a set of policy recommendations to achieve *greener* and *cleaner* cities based on the main findings of this thesis. Finally, an outline of future research lines is presented

8.1 Fulfilment of research objectives and summary of main findings

The main objective of this thesis is **to provide knowledge and tools to design and evaluate transport policies that contribute towards achieving both *greener* and *cleaner cities***. This thesis has contributed to accomplish this goal from two approaches corresponding to the specific research objectives described in Chapter 3; i.e. by providing

- (i) modelling, assessing and mapping tools to identify where is more necessary to implement emission reduction measures and to assess the impact of these measures on traffic performance and emissions,
- (ii) scientific evidence on the impacts of a number of traffic management strategies on climate change and air pollution.

These research objectives are derived from the research questions proposed in the same chapter, which also include both methodology and policy questions. These questions have been addressed through this thesis.

In particular, the ***methodological contributions*** of the thesis towards objectives and research questions are listed below:

- The ***tools*** developed allow for a quick identification of air pollution hotspots to implement emissions reduction traffic management strategies (addressing research questions II and III)
They provide city managers and policy-makers with a comprehensive traffic-related air pollution diagnosis tool that takes into account not only emissions from traffic activity but also population exposure levels. This methodology is easy-to-implement when limited information is available since the additional population density data points are easily accessible and in most cases off-the-shelf. Besides, the use of population-weighted indicators for air pollutants allows for a quick identification of priority roads, i.e. links with the highest levels of emissions and population in urban areas, to implement emission reduction strategies.
- The ***tools*** developed allow for the joint assessment of climate and air pollution impacts city-wide (addressing research questions I and II).

This research is aimed to stress the importance of evaluating transport emission reduction strategies taking into account different spatial effects of emissions. The use of traffic emission indicators together with population exposure indicators make it possible to assess climate change and air pollution policies co-benefits and trade-offs. Besides, the use of traffic indicators enables a comprehensive assessment of transport policies that take into account both environmental and mobility impacts. Finally, the macroscopic character of the methodology allows analysing the impacts of transport policies at city level and not just in the area directly affected by the measure.

The methodology was applied to the Madrid case study to assess the impacts of different emission reduction strategies: speed management strategies, eco-traffic strategies and their combination.

The main findings of *the policy analysis* are explained below:

Speed management

We have simulated two speed management strategies implemented in a section of an orbital highway: speed reduction strategy (SPR) and variable speed limits (VSL). They showed divergent impacts on traffic volumes and emissions. While the SPR diminishes traffic volumes and emissions in the ring road, the VSL led to an increase in vehicle-km and emissions. However, this rise is balanced with a decrease in both emissions and traffic flows in the city center. Further, research is needed to understand the redistribution of traffic flows due to the SPR.

Speed Reduction (SPR): Results of this policy analysis showed that lowering speed limits on an urban highway can provide significant benefits in terms of reducing CO₂ and NO_x emissions, which are consistent with the findings by other researchers e.g. Dijkema et al., 2008 and Farzaneh et al., 2010, without substantially adding to travel times. The measure therefore offers clear environmental benefits with very little impact on traffic performance. NO_x reductions are higher than CO₂ reductions for the range of speeds considered, which is explained by the fact that NO_x emissions are directly linked to engine temperature and thus increase at high speeds and loads (ECMT 2004). The highest reductions in vehicle emissions occur during off-peak hours.

We have analysed the impacts on the area directly affected by the measure, on the speed reduction adjoining sections of the ring-road and on the whole ring-road. The results of the study reveal differing impacts along the road layout and for different congestion levels. The section affected by the SPR showed a slight increase in aggregate (3.27%) travel times. The daily average speed reduction (17.8%) in this section is lower than the speed limit reduction (22.2%), and directly affects individual travel times. As expected, the measure produces a significant reduction in traffic volume of almost 13% that led to a reduction of both CO₂ and NO_x emissions of 14.4% and 16.4% respectively. The effects in the sections not directly affected by the measure can be considered negligible. The subsections adjacent to the speed limit reduction undergo variations in traffic performance indices and emission rates of the same sign as in area directly affected by the measure, and show a reduction in traffic volume, average speed and emissions. Aggregate travel times increase, although usually at a considerably lower rate than in the section directly affected by the speed reduction. Finally, the impact of the measure on emissions and traffic performance is less noticeable for the whole M30. It produces an average speed reduction of 4.76% and a 3.56% reduction in traffic volume. Aggregate travel times remain virtually unchanged. CO₂ and NO_x emissions undergo a 4% and 4.6% decrease.

As a conclusion, the results of the study showed how selected actions in specific sections could produce good enough results without affecting global mobility. The direct effect of lowering speed limits in reducing air pollutant emissions makes it especially interesting for highway sections passing through highly populated areas.

Variable Speed Limit (VSL): Results of this policy analysis showed that variable speed limits applied to an urban ring-road can provide benefits in terms of reducing emissions and population exposure in the nearby areas to the road highway were the measure was applied contributing towards *greener* and *cleaner* cities.

In this case we have analysed the impacts on the M30, on the city center and on the whole Madrid network for congested traffic conditions. The analysis revealed different impacts along the studied network. Results showed the deterioration of traffic performance and emissions indicators in the M30 resulting from the increase of the operational capacity. Nevertheless, the measure led to an improvement of those parameters in the urban network, while its impact on the whole urban network can be considered negligible. Indicators that measure population exposure to NO_x showed a decrease for both the whole network and the CBD.

As a conclusion, the impact analysis showed how improving the operational capacity of an urban-ring road we can reduce traffic pressure in the city center diminishing population exposure to air pollution.

Eco-traffic

We have simulated two speed eco-traffic strategies implemented throughout the whole Madrid network considering different market penetration rates: eco-driving (ED) and eco-routing also called green navigation systems (GN). Due to the limitations of the methodology regarding ED emissions factors (see section 4.4), we have focused on understanding the climate and air pollution impacts of GN. Although the results for ED have also been obtained, its findings are discussed in the context of combined policy applications (next listed element).

Green Navigation (GN): Results of this policy analysis showed that eco-routing systems can provide significant benefits in reducing emissions as well as critical detriments regarding population exposure and traffic performance. Therefore, this measure contributes towards *greener* cities but not towards *cleaner* cities. These results are consistent under both congested and free-flow traffic conditions and their magnitude increases with the level of penetration of GN drivers. Considering the whole Madrid network, results show up to 10.4% CO₂ reductions in congested traffic conditions for a 90% penetration of green drivers. Traffic volumes decrease by 13.5% for the entire region although they increase by up to 16.4% downtown. The greatest emission reductions occur in highly-congested scenarios. Although NO_x emissions at regional level showed a reduction, their spatial reallocation toward the CBD areas led to an upsurge in the exposure of the population to NO_x. This increase is greater in congested situations than in free-flow situations, and it rises along with the percentage of green drivers.

Traffic performance worsens considerably as eco-routing drivers increase due to the reallocation of traffic to shorter routes. On the one hand, considering the entire network, travel times increase for all GN penetration levels in highly-congested scenarios, and for penetration levels higher than 25% for free-flow situations. On the other hand, although global traffic volumes diminish, congestion increases on urban and peripheral roads.

As a conclusion, the impact analysis revealed GN systems as an effective tool for fighting climate change, but ineffective at reducing local air pollution, since the traffic redistribution derived from the measure increases emissions in highly-populated areas.

Combined ICT-measures

We have simulated two combined ICT-based traffic management strategies considering different market penetration rates and different traffic periods. The measures analysed were green navigation systems combined with variable speed limits (GN+VSL) and green navigation systems combined with eco-driving (GN+ED). In this case we analysed two types of results. On the one hand, as with the single measures we evaluated the impact of the combined measures on climate change and air pollution and on the other hand we have analysed the effect of the combined measures on the results of the single measures. Due to the limitations regarding the lack of specific ED emissions factors, the combined GN+ED was only analysed in terms of traffic performance.

Green Navigation combined with Variable Speed Limit (GN+VSL): Results of this policy analysis showed that GN+VSL can provide significant benefits in reducing emissions for the whole network contributing towards greener cities however it can also provide critical detriments regarding population exposure and traffic performance. Results follow a similar pattern as the ones for the GN applied in isolation but of lower magnitude. The increases showed by the measure regarding population exposure together with the emissions increases for the CBD inform this measure as ineffective to achieve *cleaner* cities.

In general, all the parameters analysed presented a partial compensation of the GN effects. We can find a synergetic effect on M30 travel times for GN penetration rates greater than 50% while for a 25% penetration rate the combined measure showed a travel time perfect conflict in the same road.

As a conclusion, the impact analysis revealed the implementation of the combined measure as a promising initiative to diminish the negative effects of the GN systems alone without compromising its benefits on climate change mitigation.

Further research is needed to analyse the extent of this compensation if the VSL measure were applied to the whole M30 and to other high congested highways in the network.

Green Navigation combined with Eco-driving (GN+ED): Results of this policy analysis showed that GN+ED reduced traffic volumes for the whole region although this reduction is lower than the one showed by the GN. From this point of view and using traffic volumes as a proxy for emissions, we can say that the measure contribute towards *greener* cities. However, the application of the combined measure resulted in traffic flows reallocated to the urban network which values were higher than the ones produced by the single measures. Therefore, the measure does not contribute towards *cleaner* cities

As a conclusion, the impact analysis showed that the GN+ED diminish the impact of GN on global traffic volumes reduction while increases their impact on high-populated areas.

Further research is needed to develop emission factor for eco-driving conditions and evaluate the effect of this changes on traffic volumes on emissions

Figure 8-1 is a summary of the contribution of the thesis at achieving research objectives.

The accomplishment of **RO1** implied the development of an assessment methodology that allow for the quick identification of air pollution hotspots and the co-joint assessment of climate and air pollution impacts of emissions reduction strategies.

The achievement of **RO2** involved a policy impact analysis of selected traffic management measures. Following the scheme developed in Figure 6-1, the bottom left illustration shows the contribution of the measures at achieving *greener* and *cleaner* cities. This qualitative analysis reveals that variable speed limits – **VSL** - (applied to highways taking into account the effect of the measure in the adjoining areas of the city) and the speed reduction strategy –**SPR**- (only taking into account the effect of the measure on the road where the speed reduction was applied) are beneficial towards the achievement of *greener* and *cleaner* cities while, green navigation –**GN**- and green navigation combined with variable speed limits -**GN+VSL**- and with eco-driving -**GN+ED**- (applied to a whole regional network) present increasing air pollution conflicts as the penetration rate of eco and green drivers increases.

The position of the combined measures' arrows show the extent of the effects of these measures compared with the GN alone. For example, the GN+ED arrow is located lower and to the left compared with the GN arrow, this means that the impact of the GN+ED on clean cities is more negative than the GN while its impact on green cities is less positive. The GN+VSL is located lower and to the right compared with the GN; therefore, the impact of this measure on clean cities is less negative than the GN while its impact on green cities is less positive.

NOTES:

* Not taking into account the effect of the measure in the whole city (future research)

** For congested traffic conditions and based on the redistribution of traffic volumes (the arrow for the free-flow conditions should be higher than the GN arrow since it produces more CO₂ reductions)

Figure 8-1 Summary of thesis contributions to research objectives

8.1.1 Original scientific publications and their contribution to research questions and objectives

This thesis includes contributions to scientific knowledge-sharing since most of the results have already been published, are forthcoming or have been submitted to a scientific peer-reviewed journal or in conference proceedings.

The list of original publications is presented below and followed by (i) the authors' contribution to each of them (ii) the contribution of the publication to the research questions introduced in chapter 3.

- A) **Perez-Prada, F.**, & Monzon, A. (2017). Identifying Traffic Emission Hotspots for Urban Air Quality Interventions: Case of Madrid City, Spain. In 96Th Annual Meeting Transportation Research Meeting. Washington, D.C.
- B) **Perez-Prada, F.**, & Monzon, A. (2017). *Ex-post environmental and traffic assessment of a speed reduction strategy in Madrid's inner ring-road*. Journal of Transport Geography, 58, 256–268. <http://doi.org/10.1016/j.jtrangeo.2016.12.018> **IP: 2.090 - Q1**
- C) Valdes Serrano, C., **Perez-Prada, F.**, Monzon, A. *Eco-Routing: More Green Drivers Means More Benefits?*. Proceedings of the XII Conference on Transport Engineering (CIT 2016). Valencia (Spain), from 7-9 June 2016 ISBN: 978-84-608-9960-0
- D) **Perez-Prada, F.** Monzon, A. Valdes, C. **ACHIEVING GREENER AND CLEANER CITIES: The role of Green-Navigation Systems**. Energies. 10(6), 791; doi:10.3390/en1006079 **IP: 2.077 – Q2**
- E) **Perez-Prada, F.**, Wang, Y., Monzon, A., Analysing the impact of urban traffic measures to reduce GHGs emissions. 2017 NECTAR Conference. May, June Madrid Spain.
- F) Valdés, C., Garcia-Castro, A., Monzon, A., Garcia-Martinez, A., **Perez-Prada, F.**, (2016). Modelling Variable Speed Limits: a double scale approach. Presented at the 7th International Conference on Ambient Systems, Networks and Technologies, 23-26 May, Madrid, Spain.

We can classify the published research works in two main groups. This classification is delivered from the research framework (Figure 3-1):

- Methodological developments i.e. tools for modelling, assessing and mapping the impacts of emission reduction strategies (paper A)
- Policy analysis:
 - Speed management strategies: Speed reduction (paper B) and Variable Speed Limits(paper F)
 - Eco-traffic strategies: Green Navigation (papers C, D)
 - Combined ICT-based strategies (paper E)

Each of the papers addresses more than one of the research questions as summarized in Table 8-2. As a result there is some overlap in the content of the publications. All of them develop or apply at least one of the research questions regarding methodological developments.

Paper A: the air quality diagnosis tool was developed and used to identify air quality hotspots in Madrid CBD. We address all the methodological questions regarding modeling, assessing and mapping emissions in urban areas.

This research work introduces (i) the emissions assessment methodology based on the interaction of different types of models, (ii) the indicators to measure traffic performance, traffic emissions and population exposure, and (iii) the mapping tools to identify network air quality hotspots.

Finally in this paper we apply the methodology to Madrid CBD, identifying air pollution hotspots in the network and providing customized emission reduction interventions. The paper validate the use of the PEI indicator comparing the results of standard traffic emission indicator that only takes into account the exhaust emissions produced by transport activity. The results provided a population exposure indicator (PEI) that measures the population exposure levels to pollutants.

The contribution of the authors to the paper was as follows: Fiamma Perez-Prada designed the simulations, developed the indicators, analysed the data and wrote the manuscript. Andres Monzon supervised the research and reviewed the manuscript.

Paper B is a combined assessment on the environmental and traffic performance impacts of a speed reduction strategy in the Madrid M30. We address policy questions regarding speed management strategies using a macroscopic transport model and macroscopic emissions model for the joint evaluation on traffic operation and emissions.

The contribution of the authors to the paper was as follows: Fiamma Perez-Prada, developed the indicators, analysed the data and wrote the manuscript. Andres Monzon supervised the research and reviewed the manuscript.

Papers C and D are an analysis of the impacts of Green-Navigation systems on emissions, traffic performance and population exposure. Regarding emissions, the first paper focus on the impacts on fuel consumption and climate change of an increasing share of green drivers while, the second one extends the analysis to air pollutants. Here, we developed simulation techniques for ICT-based strategies, in particular how to simulate GN systems, is finally addressed.

The contribution of the authors to the paper was as follows: Fiamma Perez-Prada calibrated the traffic model, designed and conducted the simulations, developed the air pollution and population exposure indicators, analysed the data traffic and emissions data, and wrote the manuscript. D; Cristina Valdes designed and supervised the simulations, analysed the data and wrote manuscript C; Andres Monzon directed the research, reviewed the manuscripts and proposed changes and improvements to its structure.

Paper E provides scientific evidence regarding the potential synergies or conflicts of the combined application of different ICT-based emissions reduction strategies. It addresses research questions on the combined impact of ICT-based traffic management strategies.

The contribution of the authors to the paper was as follows: Fiamma Perez-Prada designed the simulations, analysed the data, organized the results, and wrote the manuscript. Yang Wang conducted the simulations and analysed the data. Andres Monzon directed the research.

Paper F is an explanation of the interaction between the microscopic transport models and the macroscopic transport models to simulate variable speed limits at city-wide level. It includes an application of the methodology to Madrid case study and a presentation of the results of the impacts of the measure traffic performance and CO₂ emissions.

The contribution of the authors to the paper was as follows: Alvaro Garcia-Castro and Andres Garcia conducted the field campaign and developed the microsimulation and analysed its results; Fiamma Perez-Prada and Cristina Valdes conducted the macrosimulation and analysed the results; all the authors contribute to the analysis of the micro-macro interaction. Cristina Valdes wrote the paper and Andres Monzon directed the research and reviewed the findings.

Finally, Table 8-1 which research works addresses each of the policies considered for analysis

Table 8-1 Policies assessed by applied research works

			IMPACTS ASSESSED			SCIENTIFIC PUBLICATION
			Traffic performance	Climate change	Air pollution	
EMISSION REDUCTION STRATEGIES	Speed Management	SPR	✓	✓	✓	B
		VSL	✓	✓		E,F
	Eco-traffic	ED	✓	✓		E
		GN	✓	✓	✓	C,D,E
	Combined ICT	GN+ED	✓	✓		E
		GN+VSL	✓	✓		E

		A) Identifying Traffic Emission Hotspots for Urban Air Quality Interventions: Case of Madrid City, Spain	B) Ex-post environmental and traffic assessment of a speed reduction strategy in Madrid's inner ring-road	D) Eco-Routing: More Green Drivers Means More Benefits?	C) ACHIEVING GREENER AND CLEANER CITIES: The role of Green-Navigation Systems	D) Analyzing the impact of urban traffic measures to reduce GHGs emissions	E) Modelling Variable Speed Limits: a double scale approach
Methodology development RO1	ASSESSMENT	Emissions modelling	Emissions assessment model to evaluate ICT taking into account both CC and AQ	✓	✓	✓	✓
		KPIs	KPIs that take into account the different spatial impacts of emissions	✓	✓	✓	✓
		Mapping	Identification of priority urban roads for emission reduction interventions	✓			
Scientific evidence RO2	POLICY ANALYSIS	Speed management	Impacts of speed strategies on emissions and on traffic performance	✓			
		Eco-traffic	Impacts of GN systems on emissions and traffic performance		✓	✓	
		Combined ICT-measures	Impacts of combined ICT measures on emissions and traffic performance			✓	✓

KEY: Green tick (✓) implies that the paper directly addresses the research question while the pink key (✓) implies the use of the different components of the methodology developed for policy analysis

Table 8-2 Original contribution by publication to research questions and thesis objectives

8.2 Policy recommendations for *greener* and *cleaner* cities

The shift towards low-emission mobility has already started globally and its pace is accelerating. It offers stakeholders in the transport industry major opportunities to contribute to sustainable growth and provide new jobs while modernizing, embrace new technologies more strongly and regain the trust of consumers (EC 2016). In order to achieve greener and cleaner cities in the most cost-effective way, we need to develop strong linkages between climate change and air pollution management frameworks (UK DEFRA 2010). Therefore, a proper environmental assessment of low-emission policies should take climate change and air pollution co-benefits and conflicts into account (Oxley et al. 2012b; Puppim de Oliveira et al. 2013; Nemet et al. 2010b; Bollen et al. 2009; West et al. 2013; Apsimon et al. 2009; Puppim de Oliveira 2013). Besides, in order to attain public engagement, the local public health benefits resulting from low-emissions mobility actions should inform future communications activities at national and local level (UK HEALTH 2016).

The aim of this thesis was to provide insights towards achieving greener and cleaner cities through transport interventions. The following policy recommendations deliver from the main findings of this research.

- Spatial effects of transport emissions should be taken into account to assess emission-reduction transport policies.

Several ICT-measures can be implemented to address total CO₂ emissions of the existing road fleet. As a result, they should be seen as a pragmatic option for road transport carbon emissions mitigation and should be further advanced in the relevant policy and environmental context ((Samaras et al. 2016; Canaud & Faouzi 2015; Nasir et al. 2014). However, some of them present air pollutant emissions conflicts and therefore a comprehensive assessment of transport emissions should acknowledge the dissimilar spatial impacts of GHGs and air pollutants.

This is of particular relevance for traffic management strategies that lead to a redistribution of traffic flows. This research showed the example of GN systems which provide significant benefits in terms of CO₂ reductions but resulted in increased NO_x exposure levels due to the reallocation of traffic flows to denser areas.

The use of population-weighted indicators (PEIs) for the assessment of air pollution exposures has revealed important insights. Although these indicators do not take in account all the drivers to evaluate population exposure to air pollution, PEIs make emissions produced in dense areas more significant than those produced in less dense areas, and allows for an easy and quick identification of air pollution exposure hotspots.

- The impacts of emission reduction transport policies should be analysed both in the area directly affected by the measure and city-wide.

The main difference among macro and micro traffic and emissions models is the trade-off between optimizing simulation speeds and input data and estimating the traffic states and emissions accurately (Hoogendoorn & Bovy 2001; Barceló 2010; Smit 2006; Smit et al. 2010b). Macroscopic emissions take into account different driving patterns and more explicitly different congestion levels (R. Smit et al. 2008; Grote et al. 2016). However, several authors advise the use of micro-simulation tools to accurately estimate transport emissions taking into account vehicle dynamics (Boutler et al. 2006; Ahn & Rakha 2008c; Zegeye et al. 2013). Nevertheless, this research has shown two examples of traffic management strategies that

recommend a macroscopic evaluation due to the redistribution of traffic flows and its impact on the reallocation of emissions. ED and VSL were applied in a section of the Madrid inner urban ring-road. While ED reduced the trip attraction of the M30 with a result of reduced traffic volumes and emissions, the VSL augmented the operational capacity of the road thus increasing both traffic volumes and emissions. However, since the M30 is a high-capacity road planned to allocate high traffic volumes between Madrid CBD and the peripheral areas, we can consider the VSL measure also beneficial for air pollution exposure if, as is the case, traffic and emissions diminished in denser areas. Such an evaluation can only be conducted using macro-simulation tools.

- Orbital highways present a great potential to reduce the environmental pressure of traffic in urban environments through traffic management measures.

Urban ring-roads have been constructed in cities all over the world turning into major structuring elements in metropolitan areas (Martin et al. 2010) to manage the increasing flows between central cities and suburbs and among suburbs themselves.

In order to diminish the environmental impact of orbital motorways, especially of those running closer to the city center, different strategies can be followed. Tunnels, as the one constructed in Madrid, diminish air pollutants and noise (Monzon et al. 2005). Nevertheless, congestion reduction strategies (e.g. real time travel information, ramp metering or speed management) have been advanced as cost-efficient solution to reduce traffic emissions (Chiquetto 1997; TRB 2012).

This research has shown how the implementation of speed management strategies in a section of a ring-road brought about different impacts on traffic performance and emissions. In particular, variable speed limits (VSL) which aim to increase the operational capacity of the ring-road and to attract traffic from the city center have shown co-benefits regarding climate change and air pollution considering the whole network, while speed reduction strategies (SPR) have revealed as an effective measure to reduce the impact of air pollutants in belt-ways crossing high-populated areas.

- ICT-based emissions reduction approaches, in particular in-vehicle applications, should be system oriented and not only individual oriented.

Current GN navigation systems are designed to reduce the operation costs of vehicles individually. Results of the impact analysis of GN systems showed an increasing reallocation of NO_x towards high-populated areas as the share of green drivers rose in the network. This is due to the fact that in order for an individual to minimize fuel consumption; he/she tends to choose shorter routes through the city center.

In order to achieve *greener* and *cleaner* cities, green navigation systems should be designed to provide routing recommendations taking into account the impacts on the whole network systems and not only the individual operation costs.

This will be of greatest importance with the increasing penetration of autonomous cars, whose potential environmental benefits will be determined by our ability to design navigation algorithms that take into account different sustainability parameters.

- The implementation of integrated policy measures need the perfect understanding of the impacts of the measures applied in isolation.

Most researchers agree on the need of designing holistic transport emissions reduction in order to deliver policy goals in the most cost-effective way (e.g. Hickman et al. 2013; Holden et al. 2013; Banister 2011; Schipper & Fulton 2003; Tiwari et al. 2011). The *avoid-shift-improve* framework introduced in the literature review is a useful tool to identify policy measures that reduce transport emissions on the demand side (Dalkamann & Brannigan 2007).

However, this research has shown that before implementing comprehensive policy plans, it is critical to understand the explicit impact and scope of each single measure in order to:

- (i) better understand potential co-benefits and conflicts among strategies,
- (ii) look for the most effective synergies, and
- (iii) select the most appropriate geographic area to apply them.

8.3 Future research

The results of this thesis have shed light on the climate and air pollution co-benefits and trade-offs of selected traffic management interventions.

Besides, traffic performance and emissions assessment tools have been developed and oriented to policy-makers and city-managers to identify areas with high levels of traffic activity, emissions and population where to implement emissions reduction interventions.

However, the results also raise new questions that future research can answer.

- New technologies assessment challenges

Traffic and emission simulation is a powerful tool to predict the impacts of new technological developments such as autonomous car and new ICT-based policy measures (urban tolls, variable speed limits, eco-traffic management). However, there are many aspects that need to be further developed in this regard. In particular, from the limitations found in this thesis we can highlight the following.

New technologies extensively use sensing and detection technologies to provide real-time operation of transportation networks. An efficient operation and an accurate evaluation of these tools inform the use of Dynamic Traffic Assignment (DTA) models. DTA models have the ability to account for time-varying properties of traffic flow (dynamic link travel cost, travel times and flows) and to capture travellers' behaviour (Mahmassani 2001). These types of models need very detailed data inputs for example, in order to apply these models for larger networks; a proper description of flow propagation under time varying loading patterns is required. Besides, these formulations generally lead to extremely complicated solution procedures (Ziliaskopoulos et al. 2004). Nevertheless, progress has been made using new computational techniques for solving large networks (Boyles et al. 2006). It could be interesting to develop a model to assess the impacts of the policies analysed in this thesis from a dynamic assignment perspective.

Macro-emission modelling requires improvements in two aspects: (i) to take account the impacts of different traffic situations on a link by link level and (ii) to development emissions factors (EFs) taking into account eco-driving behaviours

- Development of eco-routing navigation systems that take into account climate change, air pollution and traffic performance

On-board navigation systems need to be enhanced to take into account both traffic performance and traffic emissions. There are some advances in this regard, e.g., Jimenez et al. (Jiménez et al. 2014) have developed an objective function that optimizes the energy used on the trip, while observing the time schedule.

However, the different spatial impact of transport emissions should also be considered in order to efficiently achieve not only *greener*, but also *cleaner* cities. Therefore, there is a need to develop navigation algorithms that balance traffic performance, air pollution and climate change impacts to obtain the optimal route, taking the impacts on the entire network into account, instead of focusing on individual fuel consumption reductions

- Impacts of traffic management strategies

This research has shown the potential of orbital motorways to reduce road transport emissions through the implementation of speed management strategies. However, further research is needed fully understand the impacts of in such measures at city level. In particular, further research is required to understand the impact of the speed reduction strategy on the CBD network as well as to analyse the impact of such a measure applied to the whole ring-road as well as on road sections with above-average traffic volumes where a reduction in emissions will have a greater impact.

Besides, further research is needed to fully understand the whether city size, density and network structure could have an impact on the redistribution of traffic flows and emissions in urban areas due to the implementation of a traffic management strategy. For example, (Ahn & Rakha 2013) demonstrate that the configuration of the transportation network is a significant factor in defining the benefits of eco-routing systems. Specifically, eco-routing systems appear to produce larger fuel savings on grid networks compared to freeway corridor networks.

- Population exposure indicators

PEIs developed for this research are mainly residential focused and only partially reflects exposure to air pollution excluding the effect on working areas and, on tourist and commercial areas that frequently exhibit higher number of pedestrians. This type of indicators could be further developed to incorporate this attributes.

Besides for the identification of priority areas for air quality interventions, this tool could be used for the selection of cleaner paths for cyclist and pedestrians and the allocation of green areas, schools, hospitals, and green business in the cleanest areas of a city

- Environmental equity.

This research focused on how much GHG and air pollutants urban traffic emits and on to what extent these emissions are reduced through emissions reduction policies. Nevertheless, the emissions reallocation problem highlighted in this thesis suggests another research line regarding environmental equity (Joumard & Nicolas 2010; Feitelson 2002; Carrier et al. 2016): who pollutes and who is affected by this pollution

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ANNEX I:
TRAFFIC MODEL
CHARACTERIZATION AND CALIBRATION
FOR THE MADRID CASE STUDY

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The ICT-Emissions developed a novel methodology to evaluate the impact of ICT related measures on mobility, vehicle energy consumption and CO₂ emissions of vehicle fleets at the local scale, in order to promote the wider application of the most appropriate ICT measures. The methodology combined traffic and emission modelling at micro and macro scales and was tested and validated in the cities of Madrid, Turin and Roma.

The UPM team at the project had an active role on the development of the micro-macro links of the methodology and led the Madrid Case Study. In particular, my role in the project supervised by Andres Monzon and Cristina Valdes, was to develop the macro-scale simulation of the ICT selected measures. **This duty included the calibration and validation of traffic model for the Madrid Case study**, the simulation of the macro-scenarios and the analysis of results.

In this thesis the macro-scale ICT-emissions methodology has been extended to allow for (i) the assessment of air pollutant emissions and population exposure to these emissions and (ii) the mapping of the results for a quick identification of network hotspots. Besides, the impact evaluation of the policy measures has also been broadened including the analysis of (i) the implementation of combined ICT-based traffic management strategies and, (ii) air pollution and climate change co-benefits and trade-offs

This annex explains the model calibration and validation for the Madrid case study. Much of this information is already published in the ICT-Emissions Deliverable 6.3. Here, I have updated the work I had done for the ICT-emissions project to the context of this thesis.

The structure of this Annex is divided in the following subsections:

- Description of the model: Zoning and Network characterization
- Traffic analysis and period selection for modelling
- Extraction and calibration of OD matrices
- Assignment process

1. MODEL CHARACTERIZATION

The tool used for macro scale simulations is an assignment model developed using the PTV-VISUM software and the model was based on the one developed by Valdes (2012)

The macro traffic model covers the whole region of Madrid - an area of 8,026 square km and home to 6 million inhabitants. The city of Madrid – with a population density of 5,208.6 inhabitants/square km - is located in the center of the region (in orange in Figure 1). The rest of the region is formed by other 179 municipalities. The affection of the traffic from border regions is negligible compared with the internal traffic of the region.

Figure 1. Madrid's network structure

The road network has a radio centric structure with eight main free radial highways linking central Madrid and all the Spain's coastal regions and four ring-roads (two of them unfinished) encircling it: the first one is the M-30, which divides the city into two parts, the inner part -Central Area - and the peripheral districts, and it functions as a local distributor road; the second is the M-40, which encompasses most of the city of Madrid, and is the most congested road in the Madrid metropolitan area; and the M-45 and M-50, both yet incomplete rings. Running in parallel to four of the main highways, are four toll highways (R-2, R-3, R-4 and R-5), which end in the surrounding rings M-40 (R-2, R-3 and R-5) and M-50 (R-4).

The territory is divided into 638 different zones distributed as follows (for a summary see Table 1):

- 355 correspond to Madrid City, where each of the neighbourhoods of the city of Madrid comprises at least two zones, in some cases three or more. Among all of them, 144 belong to the Central Area while the other 244 correspond to the peripheral districts.

- 144 zones correspond to the 49 municipalities of the metropolitan area. In this case, each of the municipalities of the metropolitan and regional area is disaggregated into census sections, though in some cases more than one census section is included in each zone.
- 130 zones correspond to the 130 municipalities of the regional ring. In this case, each municipality is represented by one zone.
- 7 zones represent the road connections of Madrid with the rest of the regions bordering the region.

Table 1 show the different levels of aggregation will be used to analyse the results of the different measures. Basically those areas corresponding to Madrid Central Area will be considered as URBAN areas and the rest will be considered as PERIURBAN areas. Zones in the model are connected to the road network by 7,716 links-connectors. The model has a higher level of detail in for URBAN areas (see Figure 2)

Table 1: Number of zones in the region of Madrid (Valdes, 2012)

Area		Nº zones	Higher level of aggregation used in case studies
Madrid	Central Area	111	Urban areas
	Peripheral districts	244	Periurban areas
Other municipalities	Metropolitan area	144	Periurban areas
	Regional area	130	Periurban areas
Outside the region		9	Periurban areas
Total		638	Periurban areas

Figure 2. Model zones showing the higher level of detail in URBAN areas

1.1. ROAD NETWORK IN THE MODEL

The model includes a network model of the main roads of the region with a higher level of detail in Madrid City, and in particular for the city center. The 6,350km of the Madrid's regional network is represented by 15,712 road links. This road links are classified as follows (see Figure 3)

- **CBD NETWORK** represents 1670 km of streets and avenues inside the M30 and accounts for 28% of the whole network.
- **HIGHWAYS** represent 1647 km of urban ring-roads, highways, and motorways and also account for 28% of the whole road network. The **M30** will be considered a specific study class for this research due to the fact that some of the policies have been directly applied to this road.
- **OTHER ROADS** aggregate 2560 km of conventional roads, junctions, and service lanes belonging to the peripheral, metropolitan, and regional areas, and account for 44% of the entire network

Figure 3: Madrid's model road network. Adapted from Valdes (2012) and (Valdes et al, 2015)

Each link has its own capacity, free flow speed and length. Therefore, each link type is assigned a capacity restraint function or Volume Delay Function. The model used the BPR Volume Delay functions to estimate travel times of the different types of roads depending on traffic intensities. BPR functions from the Traffic Assignment Manual of the United States Bureau of Public Roads are defined as follows:

$$t_{cur} = t_0 \times \left(1 + a \times \left(\frac{Volume}{Q_{max} \times c} \right)^b \right) \quad (1)$$

Where t_{cur} is the time in current traffic conditions, t_0 is the time in free flow conditions, volume is the number of veh/hour circulating in each link, Q_{max} is the maximum capacity of each link, and a , b and c are the estimated parameters

Table 2 show the parameters of these function for each of the road types defined in the model. Volume Delay Functions of the M30 links that have been matter of the field surveys in the ICT-Emissions project (east and west area), were updated with real data obtained in the surveys. These parameters are based on the ones used by Valdes (2012) and ones used by the ICT-emissions project (Valdes et al., 2015).

Table 2: Road type distribution of the network

Road type	Parameters		
	a	b	c
Streets	3.92	2.45	0.5
Avenues	3.92	2.45	0.6
Roads	2.27	7.66	0.88
Highways and toll motorways	1.68	9.64	0.96
M-30 west	12.84	10	0.85
M-30 east	0.38	1.89	0.9

2. MACRO TRAFFIC MODEL CALIBRATION

This section will explain the model calibration process following the next steps:

- Traffic analysis and period selection for modelling
- Extraction and calibration of OD matrices
- Assignment process

2.1. TRAFFIC ANALYSIS AND PERIOD SELECTION:

The model has been developed for three different traffic situations: free flow, normal traffic and congestion. Time periods corresponding to normal and congested situation have been determined after a detailed traffic analysis of the city of Madrid, while free flow corresponds to either very early in the morning or close to midnight. For this purpose different traffic data sources have been analysed.

A) Traffic data: Sources and features

Different traffic data sources were used for the traffic periods selection and the calibration of the traffic model (see 3):

Table 3: Traffic data sources, coverage and features

Authorities	Type of roads	Roads	Main Features
Ministry of Transport and Infrastructure	Highways and toll motorways	A1,A2, A3, A4, A5,A6,A42,M40,M11, M607 and Radial Roads ²	Count locations with different level of reliability. Availability of hourly traffic information for labor days
National Traffic Authority	Highways	M-40, M-45, M-50, M-501, M-503 and M-607	Availability of hourly traffic information for labor days
Road Department of the Regional Government of Madrid	Others	Regional highways(M607, M503, M501..) and conventional roads	Count locations with different level of reliability. Traffic information only available on a daily basis (AADT)
Mobility Department of the Madrid City Council	CBDnetwork, highways and Others	Main urban avenues. M30 ring-road open air sections (M30 central section and M30 junctions and service lanes)	Information about reliability of count locations not available. Traffic data available only for peak hours (intensity and percentage of the total daily traffic that it represents)

² Ministry of Transport and Infrastructure provides information of all the roads in Spain under their management. However, the only considered are the primary stations from Madrid Region

Madrid Calle30	M30	M30 ring-road tunnel sections (M30 central section and M30 junctions and service lanes)	Permanent stations. Availability of hourly traffic information for labor days Traffic data available
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The count locations of the Ministry of Transport and Infrastructures have a different level of reliability, depending on the number of days traffic was measured: permanent stations measure every day, primary stations do it one week every two months, secondary stations once a month and tertiary ones only 2 days a year, providing for the latter the daily traffic but not hourly distribution or month, weekend or night correcting factors. For the calibration stage, only primary stations were used (more than 150 traffic counts). These stations provide the hourly distribution of traffic for labour days. Primary stations were found in all the corridors entering the city.

In the case of the M-40, M-45, M-50, M-501, M-503 and M-607 hourly distribution was obtained from data provided by the National Traffic Authority, with the daily traffic provided by the secondary or tertiary count location of the Ministry of Transport and Infrastructure.

Count locations of the regional government do not provide the traffic hourly distribution therefore there were only used to check AADT (Average Annual Daily Trips).

City Council traffic counts for urban locations only provide information about the traffic intensity (vehicles/hour) and the percentage that this represents over the daily traffic intensity of the peak hour in the section. Therefore, the number of traffic counts from the city council used in the calibration stage will be highly different among modelling periods.

Nevertheless, the information provided by the Mobility Department and by Madrid Calle30 for the M30 ring-road (both for its open-air and tunnel sections) is available from primary stations in an hourly basis and for labour days.

Since data sources present high variability on the data available, we had to select the most appropriate data sources and traffic counts locations for the calibration stage; therefore, not all the data sources nor count locations were used for the calibration of OD matrices explained in section.

B) Traffic analysis: Methodology and results

Traffic analysis in the Madrid Region is a key step to establish time periods for the modelling stage. Modelling periods must be relevant for the whole Madrid region.

The traffic hourly distribution has been obtained using data from 343 traffic counts: 126 from highways not counting M30 (30 from M40, 4 from M11 and 92 from the corridors entering the city), 217 from M30 (50 from tunnel sections, 75 from central open-air sections, 35 from service lanes, 55 from junctions).

As explained before, urban traffic counts from the Mobility Department of Madrid City Council only provide information about the peak hour in each station. Figure shows that 45% of the 453 traffic counts analysed have 8 am as peak-hour³, 20% have 2 pm and more than 10% 6 pm.

Figure 4: Percentage of urban traffic counts per peak -hours

Figure 4 shows the traffic hourly distribution for the whole Madrid Region and more specifically for the M30 ring-road. For both, cases 3 different peaks can be easily observed being sharper in the case of the M30 ring-road. This information is coherent with Figure 5 which also shows 3 well defined different peaks.

Figure 5: Madrid's traffic hourly distribution

C) Selection of time periods for modelling

As a result of the traffic assessment in Madrid Region we have established the following time periods:

Table 4: Description of the traffic periods used in the model

Description	Traffic situation	Hours
Peak hours	Congestion	AM from 8 am to 10 am, PM from 3-5 pm and 6-9 pm period
Off-peak hours	Normal	7-8 am, 10 am-1 pm, 5-6 pm and 9-11 pm
Night	Free flow	From 11pm to 7 am (7 hours)

2.2. O-D MATRICES

The OD-matrices represent the number of people who move from one zone to another at a specific time. They play a key role in travel analysis and transport planning and operations. This section explains how OD matrices for the model of Madrid have been obtained and calibrated.

A) General Extraction Process of Origin Destination Matrices

Three different periods have been considered, according to the traffic level: peak hour (morning -AM- and afternoon -PM- representing congested flow), off-peak hour (HV- medium flow) and free flow. OD matrices used in the model for congested and medium flow are based on the 2004 Madrid's Household Mobility Survey (HMS, the latest available at the moment). These matrices were updated in 2010 by the Mobility Department of Madrid City Council using 491 traffic counts from 2008 and 2009 for same demand periods defined in 2004 (see Figure 7 for a summary of the OD generation process and Figure 6 for the location of the traffic counts used for the calibration of the model)

Figure 6: Traffic counts location used for the calibration of the model

Finally, the 2012 OD matrices were obtained updating the 2010 OD matrices with data from more than 300 traffic counts by TRANSYT-UPM.

Figure 7: Generation of OD matrices flow chart

Apart from cars, heavy vehicles have been considered (TRUCK mode). OD matrices for the TRUCK mode were calculated as a percentage of the 2010 OD matrices, according to the percentage heavy vehicles represented in each of the time periods previously defined (8.6% for morning peak hour and 8% for Off peak hour). Besides, there were multiplied for the adjustment factor for heavy vehicles in urban environments specified in the Highway Capacity Manual (see Figure 8). This factor, which is, calculates passenger-car equivalents for trucks and is the same for all the periods: 1.5.

Figure 8: Extraction process of OD matrices for the TRUCK mode

These matrices were calibrated using those 2012 traffic counts with heavy vehicles traffic information for the traffic periods considered.

B) Calibration process

The 2012 O-D matrices were calibrated for each of the defined periods using traffic flow counters from the Ministry of Transport and Infrastructure, the Road Department of the Regional Government of Madrid and the Mobility Department of the Madrid City Council. Since data sources presented high variability on the data available, the most appropriate data sources for the calibration stage were selected.

Table 5 shows the number of traffic counts used by period and the distribution of the traffic counts in the network. This calibration process has been done only in normal or congested traffic situations, but not for free flow, as it is not needed.

Table 3 shows the number of traffic counts used by period and the distribution of the traffic counts in the network.

		Road distribution of traffic counts		
Period	Number of traffic counts in the whole network	Urban Roads	Highways and toll motorways	Other roads (conventional, junctions, service roads)
AM	325	89	193 [60 for M30]	43
PM1	274	40	190 [65 for M30]	44
HV	277	32	192 [61 for M30]	23

Table 3- Number and distribution of traffic counts in the model network

The adjustment to traffic counters was carried out with the adjustment procedure for O-D matrices “Lohse Matrix Calibration”, with a tolerance of 20% of the values of count locations.

The calibration process consisted of the following steps for each traffic situation. We are showing the results for (normal i.e. off peak and congested in this case morning peak):

1. Calibration of 2010-OD matrices (for all private vehicles trips i.e. both cars and trucks) with aggregated traffic data for cars and trucks in 2012. The matrices obtained after the calibration are 2012-OD-EQ matrices.
2. Calibration of 2010-OD for trucks (the extraction of these matrices have been explained in previous section “Extraction of OD matrices for the TRUCK mode”) with traffic data for trucks in 2012. The matrices obtained after the calibration are the 2012-OD-TRUCK matrices.
3. OD matrices for the CAR mode i.e. 2012-OD-CAR matrices have been obtained by subtracting 2012-OD-TRUCK matrices to 2012-OD-EQ matrices

C) Calibration results and comparison with traffic data

In this section we will present the results of the calibration process comparing firstly traffic flows in the model with real traffic flows (traffic adjustment) and finally 2012 matrices with 2010 matrices (matrices adjustment).

As seen in Figure 46 and Figure 47, the fit obtained for the two periods considered shows a good convergence between the real data of traffic flow and the results obtained from assigning new matrices for 2012.

Figure 9: Traffic count versus modelled traffic. Congested situation (morning peak hours)

Figure 10: Traffic count versus modelled traffic. Normal traffic situation i.e. off peak hours

Disaggregating these data into different road types (CBD, highways and other roads) a high correlation is also shown in Figure 50 and Figure 51. Since M30 ring-road will be the principal setting of most of our research case studies and also where the field surveys were conducted; a perfect calibration of this road is mandatory. This is reflected by the high number of traffic loops considered for this road if compared with the rest of the roads, around 32% of traffic counts considered for highways are located in the M30.

Figures 48 and 49 show a high correlation between the observed and modelled traffic intensities at these points.

[Error! No se encuentra el origen de la referencia.11 Traffic count versus modelled traffic disaggregated by road types for congested traffic conditions (i.e. morning peak hours)

Figure 12: Traffic count versus modelled traffic disaggregated by road types for normal traffic conditions i.e. off-peak hours

Comparing the new matrices adjusted to count locations with the previous 2010 matrices calibrated by the Mobility Department of Madrid City Council, the curve fit yields a R^2 coefficients of 0.997, for both traffic situations. The adjustment function is shown in Figures 50 and 51, where the horizontal axis stands for estimated car trips for 2012 and vertical axis for the estimated car trips in 2010.

Figure 13: Post-adjustment correlation between Origin Destination matrices. Morning peak hour: congested situation

Figure 14: Post-adjustment correlation between Origin Destination matrices. Average non-peak hour: normal traffic situation

Total number of trips of matrices 2012 compared to 2012 decrease in around 8%, which is explained by the traffic decrease due to the economic crisis.

3. ASSIGNMENT PROCESS

The assignment process consists in the distribution of the trips, which are stored in the OD matrices, throughout the model network taking into account the overall travel costs and the specific characteristics of network objects.

Description of the assignment process

The assignment process runs for the TRUCK mode first and subsequently it runs for the CONVENTIONAL CAR mode. This derives from the decision of assigning heavy vehicles and light vehicles independently as ICT-based traffic management strategies will be applied to the CONVENTIONAL CAR mode. The logic of the assignment process is the following:

- **TRUCK mode assignment**

Most of the traffic management strategies will not affect this mode so the assignment will have the same features (cost function and characteristic of network objects) as in the base case scenario. During the assignment process is important to save TRUCK intensities in a separated field. Since 2012-OD-TRUCK matrices are equivalent matrices (they were obtained using the adjustment factor for heavy vehicles in urban environments) to obtain the real flow of heavy vehicles it would be necessary to divide the link flow in the assignment by the adjustment factor i.e. 1.5.

- **CAR mode assignment**

The model network is already loaded with heavy traffic. Without initialize the process the CAR mode is assigned to the network thus adding car flows to the network already loaded with trucks.

ANNEX II
MADRID CIRCULATING FLEET

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In order to provide accurate emissions estimations, the emissions model (COPERT) need to be fed with Madrid fleet composition. The emissions model provides a straightforward expression for hot emissions factors, based on two or three speed ranges by vehicle category. Each vehicle category is also classified according to fuel and engine type, and the associated emissions reduction technology. In total, COPERT considers 292 vehicle categories.

As an innovative approach to customized urban emission assessment, the emissions model used the circulating fleet, instead of the existing fleet, to estimate emissions more accurately. The **existing fleet** considers that all the vehicles are equally distributed through all type of road while the **circulating fleet** considers a different fleet composition depending on the road type considered.

This Annex specifies the distribution of the 292 COPERT vehicle categories for the CBD network, Madrid ring-roads and OTHER roads based on the information provided by the Madrid City Council (2013) for Madrid's circulating fleet.

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Passenger Cars_Gasoline <0,8 l_PC Euro 4 - 98/69/EC Stage2005	0.285%	0.272%	0.227%
Passenger Cars_Gasoline <0,8 l_PC Euro 5 - EC 715/2007	0.001%	0.000%	0.002%
Passenger Cars_Gasoline <0,8 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline <0,8 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 0,8 - 1,4 l_PRE ECE	0.003%	0.006%	0.006%
Passenger Cars_Gasoline 0,8 - 1,4 l_ECE 15/00-01	0.128%	0.636%	0.355%
Passenger Cars_Gasoline 0,8 - 1,4 l_ECE 15/02	0.010%	0.244%	0.025%
Passenger Cars_Gasoline 0,8 - 1,4 l_ECE 15/03	0.019%	0.333%	0.043%
Passenger Cars_Gasoline 0,8 - 1,4 l_ECE 15/04	0.106%	0.462%	0.203%
Passenger Cars_Gasoline 0,8 - 1,4 l_Improved Conventional	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 0,8 - 1,4 l_Open Loop	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 1 - 91/441/EEC	0.260%	0.463%	0.451%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 2 - 94/12/EEC	0.662%	0.860%	0.977%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 3 - 98/69/EC Stage2000	2.259%	2.639%	2.824%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 4 - 98/69/EC Stage2005	3.662%	3.722%	3.737%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 5 - EC 715/2007	1.632%	1.535%	1.450%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 0,8 - 1,4 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 1,4 - 2,0 l_PRE ECE	0.000%	0.001%	0.002%
Passenger Cars_Gasoline 1,4 - 2,0 l_ECE 15/00-01	0.027%	0.118%	0.068%
Passenger Cars_Gasoline 1,4 - 2,0 l_ECE 15/02	0.003%	0.076%	0.011%
Passenger Cars_Gasoline 1,4 - 2,0 l_ECE 15/03	0.007%	0.120%	0.018%
Passenger Cars_Gasoline 1,4 - 2,0 l_ECE 15/04	0.261%	0.549%	0.393%
Passenger Cars_Gasoline 1,4 - 2,0 l_Improved Conventional	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 1,4 - 2,0 l_Open Loop	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 1 - 91/441/EEC	0.661%	0.815%	0.868%
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 2 - 94/12/EEC	1.434%	1.577%	1.927%
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 3 - 98/69/EC Stage2000	4.043%	4.307%	4.541%
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 4 - 98/69/EC Stage2005	4.512%	4.005%	4.010%
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 5 - EC 715/2007	1.188%	0.947%	0.914%
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline 1,4 - 2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline >2,0 l_PRE ECE	0.001%	0.001%	0.000%
Passenger Cars_Gasoline >2,0 l_ECE 15/00-01	0.003%	0.006%	0.006%
Passenger Cars_Gasoline >2,0 l_ECE 15/02	0.000%	0.003%	0.000%
Passenger Cars_Gasoline >2,0 l_ECE 15/03	0.006%	0.014%	0.002%
Passenger Cars_Gasoline >2,0 l_ECE 15/04	0.028%	0.034%	0.016%
Passenger Cars_Gasoline >2,0 l_PC Euro 1 - 91/441/EEC	0.313%	0.225%	0.206%
Passenger Cars_Gasoline >2,0 l_PC Euro 2 - 94/12/EEC	0.465%	0.284%	0.317%
Passenger Cars_Gasoline >2,0 l_PC Euro 3 - 98/69/EC Stage2000	1.447%	0.820%	0.787%
Passenger Cars_Gasoline >2,0 l_PC Euro 4 - 98/69/EC Stage2005	1.549%	0.647%	0.641%
Passenger Cars_Gasoline >2,0 l_PC Euro 5 - EC 715/2007	0.236%	0.067%	0.071%
Passenger Cars_Gasoline >2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Gasoline >2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Diesel <1,4 l_PC Euro 4 - 98/69/EC Stage2005	2.438%	3.317%	3.387%
Passenger Cars_Diesel <1,4 l_PC Euro 5 - EC 715/2007	0.581%	0.799%	0.735%
Passenger Cars_Diesel <1,4 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Diesel <1,4 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Diesel 1,4 - 2,0 l_Conventional	0.036%	0.181%	0.064%
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 1 - 91/441/EEC	0.254%	0.532%	0.546%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 2 - 94/12/EEC	1.527%	2.736%	3.052%
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 3 - 98/69/EC Stage2000	9.137%	13.429%	13.593%
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 4 - 98/69/EC Stage2005	23.917%	24.635%	24.293%
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 5 - EC 715/2007	8.703%	8.204%	7.505%
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Diesel 1,4 - 2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Diesel >2,0 l_Conventional	0.035%	0.103%	0.053%
Passenger Cars_Diesel >2,0 l_PC Euro 1 - 91/441/EEC	0.094%	0.139%	0.128%
Passenger Cars_Diesel >2,0 l_PC Euro 2 - 94/12/EEC	0.307%	0.358%	0.411%
Passenger Cars_Diesel >2,0 l_PC Euro 3 - 98/69/EC Stage2000	1.894%	2.032%	1.845%
Passenger Cars_Diesel >2,0 l_PC Euro 4 - 98/69/EC Stage2005	5.097%	3.938%	3.573%
Passenger Cars_Diesel >2,0 l_PC Euro 5 - EC 715/2007	1.748%	1.006%	0.852%
Passenger Cars_Diesel >2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_Diesel >2,0 l_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_LPG_Conventional	0.000%	0.000%	0.000%
Passenger Cars_LPG_PC Euro 1 - 91/441/EEC	0.000%	0.000%	0.000%
Passenger Cars_LPG_PC Euro 2 - 94/12/EEC	0.000%	0.000%	0.000%
Passenger Cars_LPG_PC Euro 3 - 98/69/EC Stage2000	0.005%	0.003%	0.004%
Passenger Cars_LPG_PC Euro 4 - 98/69/EC Stage2005	0.351%	0.132%	0.126%
Passenger Cars_LPG_PC Euro 5 - EC 715/2007	0.342%	0.136%	0.134%
Passenger Cars_LPG_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_E85_PC Euro 4 - 98/69/EC Stage2005	0.000%	0.000%	0.000%
Passenger Cars_E85_PC Euro 5 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_E85_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_CNG_PC Euro 4 - 98/69/EC Stage2005	0.008%	0.004%	0.003%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Passenger Cars_CNG_PC Euro 5 - EC 715/2007	0.000%	0.001%	0.001%
Passenger Cars_CNG_PC Euro 6 - EC 715/2007	0.000%	0.000%	0.000%
Passenger Cars_2-Stroke_Conventional	0.000%	0.000%	0.000%
Passenger Cars_Hybrid Gasoline <1,4 l_PC Euro 4 - 98/69/EC Stage2005	0.011%	0.014%	0.013%
Passenger Cars_Hybrid Gasoline 1,4 - 2,0 l_PC Euro 4 - 98/69/EC Stage2005	1.784%	0.499%	0.714%
Passenger Cars_Hybrid Gasoline >2,0 l_PC Euro 4 - 98/69/EC Stage2005	0.006%	0.002%	0.002%
Passenger Cars_electric	0.015%	0.008%	0.004%
Passenger Cars_solar	0.000%	0.000%	0.000%
Light Commercial Vehicles_Gasoline <3,5t_Conventional	0.023%	0.175%	0.057%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 1 - 93/59/EEC	0.008%	0.013%	0.010%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 2 - 96/69/EEC	0.006%	0.012%	0.012%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 3 - 98/69/EC Stage2000	0.049%	0.064%	0.073%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 4 - 98/69/EC Stage2005	0.055%	0.064%	0.074%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 5 - 2008 Standards	0.007%	0.006%	0.004%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 6	0.000%	0.000%	0.000%
Light Commercial Vehicles_Gasoline <3,5t_LD Euro 6	0.000%	0.000%	0.000%
Light Commercial Vehicles_Diesel <3,5 t_Conventional	0.035%	0.232%	0.079%
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 1 - 93/59/EEC	0.048%	0.137%	0.137%
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 2 - 96/69/EEC	0.176%	0.382%	0.446%
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 3 - 98/69/EC Stage2000	1.056%	2.046%	2.240%
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 4 - 98/69/EC Stage2005	2.527%	4.141%	4.313%
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 5 - 2008 Standards	0.736%	1.216%	1.186%
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 6	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Light Commercial Vehicles_Diesel <3,5 t_LD Euro 6	0.000%	0.000%	0.000%
Light Commercial Vehicles_electric	0.002%	0.001%	0.000%
Heavy Duty Trucks_Gasoline >3,5 t_Conventional	0.007%	0.011%	0.010%
Heavy Duty Trucks_Rigid <=7,5 t_Conventional	0.008%	0.062%	0.019%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro I - 91/542/EEC Stage I	0.004%	0.016%	0.011%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro II - 91/542/EEC Stage II	0.029%	0.101%	0.084%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro III - 2000 Standards	0.192%	0.460%	0.413%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro IV - 2005 Standards	0.243%	0.482%	0.465%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro V - EGR	0.310%	0.568%	0.482%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid <=7,5 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 7,5 - 12 t_Conventional	0.002%	0.014%	0.008%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro I - 91/542/EEC Stage I	0.001%	0.002%	0.004%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro II - 91/542/EEC Stage II	0.004%	0.010%	0.014%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro III - 2000 Standards	0.012%	0.027%	0.040%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro IV - 2005 Standards	0.014%	0.023%	0.022%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro V - EGR	0.019%	0.029%	0.041%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 7,5 - 12 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 12 - 14 t_Conventional	0.000%	0.003%	0.002%
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro II - 91/542/EEC Stage II	0.001%	0.001%	0.000%
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro III - 2000 Standards	0.001%	0.002%	0.002%
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro IV - 2005 Standards	0.001%	0.003%	0.005%
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro V - EGR	0.002%	0.001%	0.002%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 12 - 14 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 14 - 20 t_Conventional	0.003%	0.022%	0.007%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.002%	0.000%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro II - 91/542/EEC Stage II	0.005%	0.011%	0.007%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro III - 2000 Standards	0.015%	0.033%	0.032%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro IV - 2005 Standards	0.021%	0.032%	0.021%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro V - EGR	0.017%	0.027%	0.022%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 14 - 20 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 20 - 26 t_Conventional	0.002%	0.010%	0.003%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.001%	0.000%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro II - 91/542/EEC Stage II	0.001%	0.003%	0.001%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro III - 2000 Standards	0.007%	0.009%	0.012%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro IV - 2005 Standards	0.008%	0.009%	0.006%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro V - EGR	0.007%	0.005%	0.008%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 20 - 26 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_Conventional	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro V - SCR	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Heavy Duty Trucks_Rigid 26 - 28 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_Conventional	0.000%	0.001%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro III - 2000 Standards	0.000%	0.001%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro IV - 2005 Standards	0.001%	0.002%	0.002%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro V - EGR	0.001%	0.001%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid 28 - 32 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid >32 t_Conventional	0.001%	0.016%	0.004%
Heavy Duty Trucks_Rigid >32 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid >32 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid >32 t_HD Euro III - 2000 Standards	0.000%	0.001%	0.000%
Heavy Duty Trucks_Rigid >32 t_HD Euro IV - 2005 Standards	0.000%	0.001%	0.001%
Heavy Duty Trucks_Rigid >32 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid >32 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Rigid >32 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 14 - 20 t_Conventional	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro II - 91/542/EEC Stage II	0.001%	0.002%	0.001%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro III - 2000 Standards	0.002%	0.005%	0.002%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro IV - 2005 Standards	0.002%	0.006%	0.007%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro V - EGR	0.004%	0.005%	0.003%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 14 - 20 t_HD Euro VI	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Heavy Duty Trucks_Articulated 20 - 28 t_Conventional	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro V - EGR	0.000%	0.000%	0.001%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 20 - 28 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_Conventional	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro IV - 2005 Standards	0.001%	0.001%	0.001%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 28 - 34 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_Conventional	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 34 - 40 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_Conventional	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 40 - 50 t_HD Euro VI	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_Conventional	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Heavy Duty Trucks_Articulated 50 - 60 t_HD Euro VI	0.000%	0.000%	0.000%
Buses_Urban Buses Midi <=15 t_Conventional	0.000%	0.003%	0.003%
Buses_Urban Buses Midi <=15 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.001%	0.001%
Buses_Urban Buses Midi <=15 t_HD Euro II - 91/542/EEC Stage II	0.006%	0.010%	0.016%
Buses_Urban Buses Midi <=15 t_HD Euro III - 2000 Standards	0.017%	0.027%	0.039%
Buses_Urban Buses Midi <=15 t_HD Euro IV - 2005 Standards	0.018%	0.034%	0.042%
Buses_Urban Buses Midi <=15 t_HD Euro V - 2008 Standards	0.032%	0.066%	0.065%
Buses_Urban Buses Midi <=15 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Buses_Urban Buses Midi <=15 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Buses_Urban Buses Midi <=15 t_HD Euro VI	0.000%	0.000%	0.000%
Buses_Urban Buses Standard 15 - 18 t_Conventional	0.000%	0.005%	0.002%

Buses_Urban Buses Standard 15 - 18 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Buses_Urban Buses Standard 15 - 18 t_HD Euro II - 91/542/EEC Stage II	0.009%	0.020%	0.012%
Buses_Urban Buses Standard 15 - 18 t_HD Euro III - 2000 Standards	0.026%	0.062%	0.057%
Buses_Urban Buses Standard 15 - 18 t_HD Euro IV - 2005 Standards	0.030%	0.087%	0.065%
Buses_Urban Buses Standard 15 - 18 t_HD Euro V - 2008 Standards	0.019%	0.193%	0.026%
Buses_Urban Buses Standard 15 - 18 t_HD Euro V - EGR	0.000%	0.000%	0.000%
yBuses_Urban Buses Standard 15 - 18 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Buses_Urban Buses Standard 15 - 18 t_HD Euro VI	0.000%	0.000%	0.000%
Buses_Urban Buses Articulated >18 t_Conventional	0.000%	0.001%	0.001%
Buses_Urban Buses Articulated >18 t_HD Euro I - 91/542/EEC Stage I	0.001%	0.000%	0.001%
Buses_Urban Buses Articulated >18 t_HD Euro II - 91/542/EEC Stage II	0.005%	0.001%	0.005%
Buses_Urban Buses Articulated >18 t_HD Euro III - 2000 Standards	0.433%	0.079%	0.400%
Buses_Urban Buses Articulated >18 t_HD Euro IV - 2005 Standards	0.230%	0.092%	0.315%
Buses_Urban Buses Articulated >18 t_HD Euro V - 2008 Standards	0.316%	0.276%	0.259%
Buses_Urban Buses Articulated >18 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Buses_Urban Buses Articulated >18 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Buses_Urban Buses Articulated >18 t_HD Euro VI	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_Conventional	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro V - 2008 Standards	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Buses_Coaches Standard <=18 t_HD Euro VI	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Buses_Coaches Articulated >18 t_Conventional	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro V - 2008 Standards	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro V - EGR	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro V - SCR	0.000%	0.000%	0.000%
Buses_Coaches Articulated >18 t_HD Euro VI	0.000%	0.000%	0.000%
Buses_Urban CNG Buses_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Buses_Urban CNG Buses_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Buses_Urban CNG Buses_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Buses_Urban CNG Buses_EEV	0.818%	0.008%	0.331%
Buses_Urban Biodiesel Buses_Conventional	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro I - 91/542/EEC Stage I	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro II - 91/542/EEC Stage II	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro III - 2000 Standards	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro IV - 2005 Standards	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro V - 2008 Standards	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro V - EGR	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro V - SCR	0.000%	0.000%	0.000%
Buses_Urban Biodiesel Buses_HD Euro VI	0.000%	0.000%	0.000%
Buses_Electric	0.000%	0.003%	0.005%
Mopeds_2-stroke <50 cm ³ _Conventional	0.000%	0.000%	0.000%
Mopeds_2-stroke <50 cm ³ _Mop - Euro I	0.000%	0.000%	0.000%

COPERT_CATEGORY	CBD network	Ring Roads	OTHER roads
Mopeds_2-stroke <50 cm ³ _Mop - Euro II	0.000%	0.000%	0.000%
Mopeds_2-stroke <50 cm ³ _Mop - Euro III	0.522%	0.000%	0.668%
Mopeds_4-stroke <50 cm ³ _Conventional	0.000%	0.000%	0.000%
Mopeds_4-stroke <50 cm ³ _Mop - Euro I	0.000%	0.000%	0.000%
Mopeds_4-stroke <50 cm ³ _Mop - Euro II	0.000%	0.000%	0.000%
Mopeds_4-stroke <50 cm ³ _Mop - Euro III	0.000%	0.000%	0.000%
Motorcycles_2-stroke >50 cm ³ _Conventional	0.000%	0.000%	0.000%
Motorcycles_2-stroke >50 cm ³ _Mot - Euro I	0.000%	0.000%	0.000%
Motorcycles_2-stroke >50 cm ³ _Mot - Euro II	0.000%	0.000%	0.000%
Motorcycles_2-stroke >50 cm ³ _Mot - Euro III	0.000%	0.000%	0.000%
Motorcycles_4-stroke <250 cm ³ _Conventional	0.105%	0.098%	0.032%
Motorcycles_4-stroke <250 cm ³ _Mot - Euro I	0.198%	0.016%	0.026%
Motorcycles_4-stroke <250 cm ³ _Mot - Euro II	0.649%	0.043%	0.093%
Motorcycles_4-stroke <250 cm ³ _Mot - Euro III	3.614%	0.160%	0.425%
Motorcycles_4-stroke 250 - 750 cm ³ _Conventional	0.087%	0.044%	0.017%
Motorcycles_4-stroke 250 - 750 cm ³ _Mot - Euro I	0.131%	0.009%	0.020%
Motorcycles_4-stroke 250 - 750 cm ³ _Mot - Euro II	0.333%	0.019%	0.056%
Motorcycles_4-stroke 250 - 750 cm ³ _Mot - Euro III	1.974%	0.074%	0.309%
Motorcycles_4-stroke >750 cm ³ _Conventional	0.031%	0.009%	0.009%
Motorcycles_4-stroke >750 cm ³ _Mot - Euro I	0.049%	0.005%	0.012%
Motorcycles_4-stroke >750 cm ³ _Mot - Euro II	0.114%	0.008%	0.014%
Motorcycles_4-stroke >750 cm ³ _Mot - Euro III	1.040%	0.032%	0.138%
Motorcycles electric	0.009%	0.001%	0.000%

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ANNEX III

LEE SCHIPPER MEMORIAL SCHOLARSHIP FOR SUSTAINABLE TRANSPORT AND ENERGY EFFICIENCY

10 G Street NE, Suite 800 - Washington, DC, 20002 USA +1 (202) 729-7600

May 19, 2016

Dear Ms. Perez,

On behalf of The Lee Schipper Memorial Scholarship Committee, we are delighted to announce that you have been selected to receive our scholarship for the year 2016-2017. Congratulations! Your selection was unanimous by all board members.

You will receive \$3,235 to help cover the expenses with your research, as specified by your research proposal. We are very excited to see the results of your outstanding proposal come to fruition. It truly captures the spirit of the scholarship and is a tribute to Lee Schipper's legacy.

The Lee Schipper Memorial Scholarship has been made possible by generous contributions from Shell Foundation, and numerous individual gifts in memory of Lee's work. The scholarship is aimed at supporting outstanding young individual researchers and students, like you, in reaching educational goals, while enriching the international dialogue in the fields of sustainable transport and energy efficiency.

Over the next few weeks, you will be contacted by Vanessa Nwankwo (vnwankwo@wri.org) who will provide you information about the contract agreement and other logistics. Also, Caitlin Drown (CDrown@wri.org) from Communications will be gathering your quotes and statements in order to develop the official announcement.

The Lee Schipper Memorial Scholarship is enriching the international policy dialogue in the fields of sustainable transport and energy efficiency. More information [here](#).

10 G Street NE, Suite 800 - Washington, DC, 20002 USA +1 (202) 729-7600

Lastly, the Scholarship Board, through Ramon Munoz-Raskin, Holger Dalkmann or Sam Zimmerman, will be in touch with you and your academic adviser soon to discuss the next steps. In your case, the Board would like to explore discussing areas for potential scaling up of your proposed research.

We would like to thank you for taking the time to apply to the Lee Schipper Memorial Scholarship and on behalf of the Lee Schipper Memorial Scholarship Advisory board, congratulations once again on your selection.

Sincerely,

Holger Dalkmann
Director
EMBARQ

Ramon Munoz-Raskin
On behalf of the Schipper Family

The Lee Schipper Memorial Scholarship is enriching the international policy dialogue in the fields of sustainable transport and energy efficiency. More information [here](#).