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Development of a microscale traffic emission simulation system.
Application to Madrid for the definition of air quality
improvement measures

*Desarrollo de un sistema de simulación de emisiones del tráfico
rodado a microescala. Aplicación a Madrid para la definición de
medidas de mejora de la calidad del aire*

Tesis Doctoral

Christina Quaassdorff, MSc.

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Departamento de Ingeniería Química Industrial y del Medio Ambiente

Escuela Técnica Superior de Ingenieros Industriales

UNIVERSIDAD POLITÉCNICA DE MADRID

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calidad del aire***

Memoria de tesis presentada para obtener el título de Doctor por la Universidad Politécnica de
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Los vocales

*Abuelo, sé que esto te hubiera gustado,
por eso es para ti.*

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The value of a person is defined by $V = (K + S) \times A$. Knowledge and Skills add up but, Attitude multiplies.

Víctor Küppers

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El valor de una persona se define por $V = (C + H) \times A$. El Conocimiento y las Habilidades suman pero la Actitud multiplica.

Víctor Küppers

hotspot
abatement resolution
copert exhaust composition
air congestion
factor vehicle power local networks
fleet urban mode kilometers driving diesel
speed phemlight petrol cycle value madrid
profile accuracy microsimulation travelled
volume pdp traffic limit nox
model versitmicro vissim pm10 acceleration
emissions road
instantaneous gradient
pollution measures
secondbysecond

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ABSTRACT / RESUMEN / ZUSAMMENFASSUNG

ABSTRACT

Road transport is often the main source of air pollution in urban areas, significantly affecting air quality in cities such as Madrid (Spain). Due to the adverse effects of atmospheric pollution, the European Union has established legislation to improve air quality and reduce air pollution. Although Madrid is expected to satisfy air quality limit values at a mesoscale level, pollutant concentrations are influenced by very local phenomena, and exceedances or non-compliance situations at some specific points are assumed for much larger areas. In this sense, macroscale models have been successfully applied to Madrid. Nevertheless, they do not adequately reflect the driving effects, simplifying acceleration-deceleration processes that significantly influence emissions at a finer scale and do not allow their calculation in short periods of time. It is essential to develop emission reduction measures that focus on hot-spots and highly polluted micro-environments. On these specific points, finer-scale tools are needed due to the complexity of the processes that determine emissions from mobile sources and also to estimate the contribution of traffic to atmospheric emissions at local level.

For those cases, a microscale emission estimation methodology has been developed and the performance of a suitable combination of traffic and emissions micro-simulation models that accurately define the emissions in a specific area has been tested. These models do not only describe the behaviour of the single entities which define the traffic such as individual vehicles and their interactions, but they also take into account traffic signs and lane changes for each vehicle. This results in stop & go cycles that produce braking-acceleration patterns with a huge influence on emissions. So that, in order to obtain detailed traffic emission results a modelling system based on a microscale traffic flow simulation model (VISSIM) fed with real-measured data collected by measurement campaigns that serves inputs for a microscale emission model (VERSIT+_{micro} through the ENVIVER interface) was implemented.

Several microscale traffic simulations representative for different types of urban hot-spots (roundabout, signalized intersections, combination of urban roads) and for different daily and weekly traffic conditions were carried out. Speed management influences in a complex way vehicle emissions so that differentiating between congested and non-congested scenarios is useful to suggest control strategies. Traffic results were used as input for the microscale emission simulation model to obtain detailed estimations of NO_x and PM₁₀ emissions related to different vehicle types with five meters resolution.

This modelling system provides detailed traffic emissions for complex urban hot-spots locations. Nevertheless, as an evaluation test, NO_x results for passenger cars were compared with those obtained from the well-known mesoscale emission model COPERT 4. Also, modal emission models PΔP and PHEM-light have been successfully applied, analysed and compared to VERSIT+_{micro} for two case studies. Results points out the relevance of congestion and a detailed vehicle composition definition for accurate emission estimations. In the case of very detailed modal models implementation also engine power is a very important parameter. In turn, these parameters relay on an accurate estimation of the speed-acceleration pattern, road gradient and vehicle loading. So that, larger number of vehicle classes included in a particular model implies a better chance to provide representative emissions estimates.

These detailed emission results from VERSIT+_{micro} has been successfully coupled to stationary simulations from highly detailed air quality models based on CFD-RANS. Nevertheless, non-stationary simulations with CFD in urban areas needs second-by-second resolved emissions that can be provided by modal emission models.

However, real-world emission measurements are essential towards the validation of emission factors and total emissions computed by these modelling techniques. In this sense, a first approach to the validation of the high resolution emission estimation modelling system VISSIM-VERSIT+_{micro}/ENVIVER on a real hot-spot using mobile laboratory data has been performed.

KEY WORDS

Road traffic, microsimulation, emission modelling

RESUMEN

El transporte por carretera suele ser la principal fuente de contaminación del aire en zonas urbanas, lo que afecta significativamente la calidad del aire en ciudades como Madrid (España). Debido a los efectos adversos de la contaminación atmosférica, la Unión Europea ha establecido legislación para mejorar la calidad del aire y reducir la contaminación del aire. Aunque en líneas generales Madrid se espera que satisfaga los valores límite de calidad del aire a un nivel de mesoescala, las concentraciones de contaminantes están influenciadas por fenómenos muy locales y excedencias o situaciones de incumplimiento en algunos puntos específicos se asumen para áreas mucho más grandes. En este sentido, los modelos de macroescala se han aplicado con éxito en Madrid. Sin embargo, no reflejan adecuadamente los efectos de conducción, simplificando los procesos de aceleración-desaceleración que influyen significativamente en las emisiones a una escala más fina y no permiten su cálculo en cortos períodos de tiempo. Por ello, es esencial desarrollar medidas de reducción de emisiones que se centren en microambientes urbanos altamente contaminados. En estos puntos específicos, se necesitan herramientas de escala más fina debido a la complejidad de los procesos que determinan las emisiones de fuentes móviles y también para estimar la contribución del tráfico a las emisiones atmosféricas a nivel local.

Para esos casos, se ha desarrollado una metodología de estimación de emisiones a microescala y se ha comprobado su funcionamiento mediante una combinación adecuada de modelos de microsimulación de tráfico y emisiones que definen con precisión las emisiones en un área específica. Estos modelos no solo describen el comportamiento de las entidades individuales que definen el tráfico, como los vehículos individuales y sus interacciones, sino que también tienen en cuenta las señales de tráfico y los cambios de carril para cada vehículo. Esto da como resultado ciclos de detención y arranque que producen patrones de frenado-aceleración que tienen una gran influencia en las emisiones. De modo que para obtener resultados detallados de emisiones del tráfico se ha implementado un sistema de simulación basado en un modelo de simulación de flujo de tráfico a microescala (VISSIM) alimentado con datos reales recopilados en campañas de medición cuyos resultados se utilizan como entrada para un modelo de emisión a microescala (VERSIT_{micro} a través de la interfaz ENVIVER).

Se llevaron a cabo varias simulaciones de tráfico a microescala representativas de diferentes tipos de microambientes urbanos (rotonda, intersecciones señalizadas, combinación de vías urbanas) y para diferentes condiciones de tráfico diario y semanal. No obstante, la velocidad influye de manera compleja en las emisiones de los vehículos, por lo que diferenciar entre escenarios congestionados y no congestionados es útil para sugerir estrategias de control.

Los resultados de tráfico se utilizaron como entrada para el modelo de simulación de emisiones a microescala para obtener estimaciones detalladas de las emisiones de NO_x y PM_{10} relativas a diferentes tipos de vehículos con una resolución espacial de cinco metros.

Este sistema de simulación proporciona emisiones de tráfico detalladas para ubicaciones urbanas complejas. Sin embargo, para evaluar el sistema se compararon los resultados de NO_x obtenidos para automóviles con los obtenidos con un modelo de emisiones a mesoescala (COPERT 4) de referencia a nivel europeo. Además, los modelos de emisión modal PΔP y PHEM-light se han aplicado, analizado y comparado exitosamente con $\text{VERSIT}^{+}_{\text{micro}}$ para dos caso de estudio. Los resultados señalan la importancia de la congestión y de la definición detallada de la composición de la flota de vehículos para conseguir estimaciones de emisiones precisas. En el caso de la implementación de modelos modales muy detallados, otro parámetro importante es la potencia del motor. A su vez, estos parámetros se basan en una estimación precisa del patrón de velocidad-aceleración, la pendiente de la carretera y el peso del vehículo. De modo que, un mayor número de clases de vehículos incluidas en un modelo implica una mejor oportunidad de proporcionar estimaciones de emisiones representativas.

Estos resultados de emisiones con alto grado de detalle obtenidas con $\text{VERSIT}^{+}_{\text{micro}}$ se han acoplado con éxito a simulaciones estacionarias de modelos de calidad del aire altamente detallados basados en CFD-RANS. Sin embargo, para las simulaciones no estacionarias con CFD en áreas urbanas se necesitan emisiones resueltas en base a segundos, las cuales pueden ser obtenidas de modelos modales.

Sin embargo, es esencial la validación de los factores de emisión y las emisiones totales calculadas mediante estas técnicas de modelado con mediciones de emisiones en el mundo real. En este sentido, se ha realizado una primera aproximación a la validación del sistema $\text{VISSIM-VERSIT}^{+}_{\text{micro}}/\text{ENVIVER}$ en un entorno urbano real utilizando datos de un laboratorio móvil.

PALABRAS CLAVE

Tráfico por carretera, microsimulación, modelado de emisiones

ZUSAMMENFASSUNG

Der Straßenverkehr ist meist die Hauptquelle der Luftverschmutzung in städtischen Gebieten, was die Luftqualität in Städten wie Madrid (Spanien) erheblich beeinträchtigt. Aufgrund der negativen Auswirkungen der Luftverschmutzung hat die Europäische Union Rechtsvorschriften erlassen, um die Luftqualität zu verbessern und die Luftverschmutzung zu verringern. Obwohl erwartet wird, dass Madrid die Grenzwerte für die Luftqualität auf mesoskaliger Ebene erfüllt, werden die Schadstoffkonzentrationen durch sehr lokale Phänomene beeinflusst. Diese Überschreitungen oder Nichteinhaltungssituationen werden für sehr viel größere Gebiete übernommen. In diesem Sinne wurden Makro-Modelle erfolgreich in Madrid angewendet. Sie spiegeln jedoch nicht adäquat die Auswirkungen des Fahrverhaltens wider und simplifizieren Brems-Beschleunigungs-Prozesse. Beide beeinflussen signifikant die Emissionen in einem feineren Maßstab und ihre Berechnung nicht für kurze Zeiträume erlauben. Es ist wichtig, emissionsmindernde Maßnahmen zu entwickeln, die sich auf Hot-spots und stark verschmutzte Mikroumgebungen konzentrieren. In Bezug auf diese spezifischen Punkte werden aufgrund der Komplexität der Prozesse, die die Emissionen aus mobilen Quellen bestimmen, feiner messende Werkzeuge benötigt. Ebenso, um den Beitrag des Verkehrs auf die atmosphärischen Emissionen auf lokaler Ebene abschätzen zu können.

Für diese Fälle wurde eine mikroskalige Emissionsschätzungsmethodik entwickelt und die Leistungsfähigkeit einer geeigneten Kombination von Verkehrs- und Emissions-Mikrosimulationsmodellen getestet, die die Emissionen in einem bestimmten Gebiet genau definieren. Diese Modelle beschreiben nicht nur das Verhalten der einzelnen Einheiten, die den Verkehr definieren, z. B. einzelne Fahrzeuge und ihre Interaktionen, sondern sie berücksichtigen auch Verkehrszeichen und Spurwechsel für jedes Fahrzeug. Dies führt zu Stop & Go-Zyklen, die Brems-Beschleunigungs-Muster mit einem großen Einfluss auf die Emissionen erzeugen. Um detaillierte Verkehrs-Emissions-Ergebnisse zu erhalten, wurde ein Simulationssystem eingesetzt, basierend auf einem mikroskaligen Verkehrsströmungs-Simulationsmodell (VISSIM), das mit gemessenen Daten aus Messkampagnen gespeist wurde und dessen Resultate wiederum als Eingangsdaten, für den Mikro-Skala Emissionsmodell (VERSIT_{micro} über die ENVIVER- Benutzeroberfläche) gebraucht werden.

Es wurden mehrere Verkehrssimulationen im Mikromaßstab durchgeführt, die repräsentativ für verschiedene Arten von städtischen Hot-spots (Kreisverkehr, signalisierte Kreuzungen, Kombination von städtischen Straßen) und für verschiedene tägliche und wöchentliche Verkehrsbedingungen waren. Geschwindigkeitsmanagement beeinflusst jedoch

auf komplexe Weise die Fahrzeugemissionen, so dass die Unterscheidung zwischen überlasteten und nicht überlasteten Szenarien nützlich ist, um Steuerungsstrategien vorzuschlagen. Die Verkehrsergebnisse wurden als Eingabe für ein Emissions- Simulationsmodell auf Mikroskala verwendet, um detaillierte Schätzungen der NO_x- und PM₁₀-Emissionen verschiedener Fahrzeugtypen mit einer Auflösung von fünf Metern zu erhalten.

Dieses Modellierungssystem liefert detaillierte Verkehrsemissionen für komplexe urbane Hotspot-Standorte. Als Bewertungstest wurden NO_x-Ergebnisse für Personenkraftwagen mit denen des bekannten Emissionsmodells COPERT 4 verglichen. Auch die modalen Emissionsmodelle PΔP und PHEM-light wurden erfolgreich in zwei Fallstudien angewendet, analysiert und mit VERSIT+_{micro} verglichen. Die Ergebnisse zeigen die Relevanz von Staus, einer detaillierten Definition der Fahrzeugzusammensetzung und die Motorleistung der Fahrzeuge für genaue Emissionseinschätzungen bei sehr detaillierten Modalmodellen. Diese Parameter beziehen sich wiederum auf eine genaue Schätzung des Geschwindigkeits-Beschleunigungs-Musters, des Straßengefälles und der Fahrzeugbelastung. Daher bedeutet eine größere Anzahl von Fahrzeugklassen, die in einem bestimmten Modell enthalten sind, eine bessere Chance, repräsentative Emissionsschätzungen bereitzustellen.

Diese detaillierten Emissionsergebnisse von VERSIT+_{micro} wurden erfolgreich mit stationären Simulationen aus hoch detaillierten Luftqualitätsmodellen auf CFD-RANS-Basis gekoppelt. Für nichtstationäre Simulationen mit CFD in urbanen Gebieten sind jedoch sekundenweise aufgelöste Emissionen erforderlich, die durch modale Emissionsmodelle bereitgestellt werden können.

Für die Validierung von Emissionsfaktoren und Gesamtemissionen, die mit diesen Modellierungstechniken berechnet werden, sind jedoch reale Emissionsmessungen unerlässlich. In diesem Sinne wurde ein erster Ansatz zur Validierung des hochauflösenden Emissionsschätzmodellsystems VISSIM-VERSIT+_{micro}/ENVIVER an einem realen Hot-Spot unter Verwendung mobiler Labordaten durchgeführt.

SCHLÜSSELWÖRTER

Straßenverkehr, Mikrosimulation, Emissionsmodellierung

GRAPHICAL ABSTRACT

Nomenclature

AQ	Air Quality
AIMSUN	Integrated transport modelling software
BC	Black Carbon
CADC	Common Artemis Driving Cycle
CEP	Characteristic Emission curves over Power
CD-Adapco	Computational Dynamics-Analysis & Design Application Company Ltd
CFD	Computational Fluid Dynamics
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
COPERT	Computer Programme to calculate Emissions from Road Transport
CUEDC	Composite Urban Emissions Drive Cycles
EA	Escuelas Aguirre area
EEA	European Economic Area/European Environment Agency
EEC	European Economic Community
EF	Emission factor
EIA	Environmental Impact Assessment
EMEP	European Monitoring and Evaluation Programme
EMT	Municipal Transport Company of Madrid
ENVIVER	ENVironmental Vlsim-VERsit
EQUA	Air Quality Index
EU	European Union
FL	Fernández Ladreda square
FTP	Federal Test Procedure
Gabba	Woolloongabba intersections area
GDP	Gross Domestic Product
GEH	Geoffrey E. Havers statistic
GMCA	Atmospheric Pollution Modelling Group
GPS	Global Position System
GVM	Gross Vehicle Mass
HBEFA	Handbook of Emission Factors for Road Transport
HC	Hydrocarbon
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
KNU	Kangwon National University
LDV	Light-duty vehicle
LPG	Liquefied Petroleum Gas
MICROMET	Micro Meteorology group
ML	Mobile Laboratory
MODEM	Modelling of emissions and consumption in urban areas
NAEI	National Atmospheric Emission Inventory
NEDC	New European Driving Cycle
NG	Natural gas
NH ₃	Ammonia
NMVOC	Non-Methane Volatile Organic Compound
N ₂	Nitrogen gas
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides
N ₂ O	Nitrous oxide

PΔP	Power-delta-Power emission model
PDT	Palmes-type passive diffusion tubes
PEMS	Portable Emissions Measurement System
PHEM	Passenger car and Heavy duty Emission Model
PM	Particulate matter
PM ₁₀	Particulate matter with aerodynamic diameter less than 10 micrometers
PM _{2.5}	Particulate matter with aerodynamic diameter less than 2.5 micrometers
Posco	Posco intersection
PTV	Plannung und Transport Vehrkehr
RANS	Reynolds-Averaged Navier-Stokes
RDE	Real Driving Emissions
RSD	Remote Sensing Device
SCATS	Adaptive urban traffic management system
SEA	Strategic Environmental Assessment
SLCP	Short-lived climate pollutant
SO ₂	Sulphur dioxide
SO _x	Sulphur oxides
STARCCM+	Computational fluid dynamics model based on computational continuum mechanics
TE	Total Exposure
TEA	Triethanolamine
TECNAIRE-CM	Técnicas Innovadoras para la Evaluación y Mejora de la Calidad del Aire Urbano
TEE	Traffic Energy and Emissions
TTE	Total Theoretical Exposure
TNO	Netherlands Organisation for applied scientific research
TRANSMAX	Public traffic data interface specification
TSC	Traffic Signal Controller
UCM	Complutense University of Madrid
UFP	Ultrafine Particles up to 0.1 micrometers
UPM	Universidad Politécnica de Madrid
UQ	The University of Queensland
UROPOL	Urban Road Pollution
USA	United States of America
VCE	Vehicle Chasing Experiment
VERSIT+	TNO state-of-the-art traffic emission model
VISSIM	Vehrkehr In Stätten SIMulation
VKT	Vehicle Kilometres Travelled
VOC	Volatile Organic Compound
VSP	Vehicle Specific Power
WHO	World Health Organisation
WLTP	Worldwide harmonized Light vehicles Test Procedure
WLTC	Worldwide harmonized Light vehicles Test Cycle

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CHAPTER 1

INTRODUCTION

In this chapter the background of this work is provided. The relevance of traffic emissions on air quality is discussed focusing on the case of a large European city (Madrid, Spain). A compilation of the relevant air quality legislation in Europe is presented and the main policy actions are overviewed.

After that, the main road traffic air pollutants and their emission sources are explained. Finally, the main goals of this thesis are presented in relation to the objectives of the TECNAIRE-CM (S2013/MAE-2972) research project in which this work is framed.

1.1 Air quality

Atmospheric pollution is one of the main public health concerns nowadays. According to the World Health Organisation – WHO – ([WHO, 2016](#)) around 7 million premature deaths occur every year around the world due to air pollution. This represent about 11.6 % of the deceases which is roughly one of each 9 deaths. From these, 4.3 million deceases are related to household/indoor air pollution (mainly wood and coal cook-stoves and heating systems) and around 3 million are related to ambient/outdoor air pollution ([Lelieveld et al., 2015](#)) due to a variety of emissions from agriculture, industry and road transport (Figure 1.1). Pollutants are dispersed into the atmosphere influenced by meteorological conditions (weather, sunlight, temperature, humidity, wind), advection and diffusion processes that affect the chemical reactions. These processes are very important at microscale level in urban areas, where also morphological aspects such as topography, vegetation and/or urban geometry affects the spatio-temporal distribution of pollutants. These show strong concentration gradients along the day and in short distances (meters) that must be captured accurately in order to define population exposure to ambient air quality at microscale level ([EEA, 2015](#)). These pollutant distributions are directly influenced to emission generation that reflect the importance of an accurate definition of them. This is a particularly relevant issue in urban environments where more than 80 % of people are exposed to air quality levels that exceed WHO guideline limits. This exposure produces serious diseases such as ischaemic heart disease, stroke and chronic obstructive pulmonary disease ([WHO, 2016](#)). In Europe (EU-28), around 400,000 people are affected every year due to the exposure to polluted air ([EEA, 2017a](#)). The health-related external costs represent to the European Union (EU) an economic impact of around €330 billion to €940 billion every year which is 3 to 9 % of Europe’s Gross Domestic Product (GDP) ([EC, 2013](#)).

Figure 1.1. Air pollution from emissions to immission concentration (EEA, 2016b).

The [Directive 2015/1480](#) is the reference norm at European level. It introduces several modifications to the previous [Directive 2008/50/EC](#) of the European parliament and of the Council on ambient air quality and cleaner air for Europe. This directive establishes objectives for ambient air quality designed to avoid, prevent or reduce harmful effects on human health and the environment since air pollutants such as NO₂ and PM are still a concern in European cities which are struggling to meet air quality standards (Figure 1.2). These exceedances and non-compliance situations are associated in most of the cases to road transport which is the main source of air pollution in urban areas.

Figure 1.2. NO₂ annual mean concentrations in 2015 (EEA, 2017b). Red and brown dots exceed air quality standards for this pollutant.

In Spain, air quality and atmospheric pollution are regulated by [Ley 34/2007](#) that defines environmental politics and atmospheric protection according to the European Union standards established by the European Directives above mentioned. This norm establishes the bases on prevention, monitoring and reduction of air pollution in order to avoid and when this is not possible, reduce the damage that may result for people, the environment and other goods of any nature. These objectives are detailed the [Spanish Real Decreto R.D. 102/2011](#) (modified in [R.D. 39/2017](#)) that establishes air quality limit values for the main atmospheric pollutants. Table 1.1 summarizes those standards for the most relevant pollutants for road transport along with those corresponding to the WHO guidelines. In the case of NO₂ both values agree but in the case of PM the WHO guideline is more restrictive than the EU limit value. For this reason, many European cities are struggling to fulfil these limit values mainly for NO₂. If the EU limit value was reduced to match WHO guidelines too, many more cities would have difficulties to achieve legal limits as well. According to [EEA \(2016a\)](#) the percentage of population in the EU-28 exposed to air pollutant concentrations above reference concentrations would increase to more than 75 % of population exposed to PM_{2.5}, between 50 and 75 % of population exposed for PM₁₀ and for NO₂ it would remain between 5 – 10 %.

Table 1.1. Limit values for NO₂ and PM (RD 102/2011; WHO, 2005). Volumes referred to 293 K and 101,3 kPa.

Pollutant	Goal	Averaging period	EU Limit value	WHO guidelines
NO ₂	Hourly limit value	1 hour	200 µg/m ³ (max. 18 times per year)	200 µg/m ³
	Annual limit value	1 year	40 µg/m ³	40 µg/m ³
PM ₁₀	Hourly limit value	24 hours	50 µg/m ³ (max. 35 times per year)	50 µg/m ³
	Annual limit value	1 year	40 µg/m ³	20 µg/m ³
PM _{2.5}	Annual limit value	1 year	25 µg/m ³	10 µg/m ³

1.2 Traffic emissions

Road transport is often the main source of air pollution in urban areas, significantly affecting air quality in cities ([Degraeuwe et al., 2017](#); [HEI, 2010](#)). In Europe, the transport sector is responsible for more than half of nitrogen oxides (NO_x) total emissions, and contributes with more than 15 % to the total emissions of the other main air pollutants, such as CO, NMVOC, PM₁₀, PM_{2.5} and SO_x. Many efforts have been aimed at reducing emissions from this sector so that between 1990 and 2015, as achieving significant abatements: 41 %, 42 % and 35 % for NO_x, PM_{2.5} and PM₁₀ respectively. Nevertheless, emission reductions from road transport have been lower than expected due to the heavy growth of transport in the last two decades ([EEA, 2017b](#)) (Figure 1.3).

Figure 1.3. Development in EU-28 emissions from road transport sector of several pollutants, 2000-2015 (% of 2000 levels) related to exhaust emissions (left) and non-exhaust (right) (EEA, 2017b).

1.2.1 Main air pollutants from road traffic

A number of different air pollutants are emitted by road vehicles with potential effects on health (HEI, 2010). The most relevant air pollutants related to road traffic include:

1.2.1.1 Hydrocarbons

Hydrocarbons (HCs) include all organic compounds which are produced from either incomplete or partial combustion and are toxic to human health. HCs reactivity varies a lot but they are important precursors of photochemical smog, acidic and oxidising compounds. They contribute directly and indirectly to the greenhouse effect (Seinfeld & Pandis, 2016). Particularly, volatile organic compounds (VOCs) are associated to adverse respiratory effects (Arif & Shah, 2007) and contribute to the formation of ground-level ozone and photochemical smog in the atmosphere. Ozone irritates the eyes, damages the lungs and generates cardiopulmonary problems (Smith et al., 2009). The composition of HC emissions is strongly influenced by the composition of the fuel, so changes in fuel specifications can modify their effects.

1.2.1.2 Carbon monoxide

Carbon monoxide (CO) is 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. It is rapidly absorbed by the blood, reducing its oxygen carrying capacity and is particularly dangerous to people with heart disease (Lee et al., 2015). CO also contributes to the formation of ground-level ozone, smog and to the greenhouse effect reducing the destruction of methane depleting hydroxyl radicals from the atmosphere (Seinfeld & Pandis, 2016).

1.2.1.3 Particulate matter

Particulate matter (PM) 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 from the release of precursor

gases (mainly sulphur dioxide (SO₂), nitrogen oxides (NO_x), ammonia (NH₃) and some VOCs). Also, depending on the size of the particles, there are subdivided into PM₁₀ (referring to particulate matter with aerodynamic size up to 10 µm), PM_{2.5} (up to 2.5 µm and related to road traffic emissions) and UFP (ultrafine particles up to 0.1 µm) (EEA, 2016b). In terms of its potential to harm human health, the smaller the particles are higher is the penetration into the respiratory system and higher the effects on health (Atkinson et al., 2015; Perez et al., 2009). PM penetrates into sensitive regions of the respiratory system and people with existing heart or respiratory problems are in particular risk of aggravate cardiovascular and lung diseases (McCreanor et al., 2007; Mills et al., 2007). But also, it can affect the central nervous system, the reproductive system and produce cancer causing premature deaths (de Kok et al., 2006). Nevertheless, it also acts as a greenhouse gas and affects to the surface albedo (Horvath, 1993). This is the case of black carbon (BC) which is a so called short-lived climate pollutant – SLCP – generated as a by-product from fuel burning (diesel, coal, etc.). BC is very relevant in tailpipe emissions and extremely important for health and climate due to its small diameter (penetration in respiratory system) and dark colour (increase ice melting and reduces albedo effect).

1.2.1.4 Nitrogen oxides

NO_x constitute a group of different chemicals that are all formed by the reaction of nitrogen — the most abundant gas in air — with oxygen. NO_x comprises a mixture of nitric oxide (NO) and nitrogen dioxide (NO₂) very toxic and reactive and with harmful environmental effects and health problems mainly for the respiratory system (Spiric et al., 2012). The proportion of NO₂ in the NO_x emissions of diesel vehicles is higher than the proportion in petrol-fuelled vehicles and much more in new diesel vehicles were engine size (Chen & Borken-Kleefeld, 2016) and exhaust after-treatments affect significantly this ratio that varies from 12 % to 70 %. NO_x has an important atmospheric chemistry contributing to photochemical smog formation and acid deposition. Some of the products from these reactions such as nitrous oxide (N₂O) are powerful greenhouse gases. 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 (Jonson et al., 2017).

1.2.2 Road traffic emissions processes

Road traffic is an especially complex emission source since pollutants are originated by very diverse processes. Traffic emissions can be classified according to their generation process (Smit et al., 2009):

1.2.2.1 Exhaust emissions

These refer to the emissions produced from the combustion of different petroleum products such as petrol, diesel, natural gas (NG) and liquefied petroleum gas (LPG). These fuels are mixtures of different hydrocarbons. In a perfect engine, oxygen in the air would react in a combustion process with all of the hydrogen and carbon in the fuel to form water and CO₂, and the nitrogen in the fuel would remain unaffected. In reality, no combustion process is perfect so that vehicle engines emit many different pollutants in addition to water and CO₂ or CO on incomplete combustions. In the case of PM exhaust emissions these are directly related to unburned particulates from an incomplete combustion process (Reşitoiu et al., 2015). The amount of each pollutant emitted is very dependent on the type of fuel used and the engine technology (EMEP/EEA, 2016). This is the case of NO_x and SO₂ emissions whose formation is extremely dependant on the fuel type burned in the combustion chamber and the oxygen, temperature and pressure conditions reached in there. Due to the importance of the temperature on the exhaust emission formation, this parameter is specially taken into account in the emission formation:

- **Hot running emissions:** exhaust tailpipe emissions from a vehicle that occur under “hot stabilized” conditions, which means that the engine and the emission control system have reached their typical operating temperature.
- **Start “cold” emissions:** additional exhaust tailpipe emissions for vehicles that are starting a journey because engine is cold and catalysts are not warmed up so that there are operating in a non-optimal manner.

1.2.2.2 Evaporative emissions

Evaporative emissions are the result of non-exhaust volatile organic components (VOCs) losses by evaporation of hydrocarbons or by escaping through the vehicle’s fuel system. They are mostly related to petrol vehicles since diesel fuel is less volatile. These emissions comes from different processes such as the expansion of the fuel vapour in the petrol tanks as temperature rises each day, from the fuel system when the engine is turned off at the end of a trip and evaporative loses while a vehicle is in motion (Amodio et al., 2011).

1.2.2.3 Non-exhaust PM emissions

Non-exhaust PM emissions are produced from the mechanical abrasion and corrosion of vehicle tyres, brakes and clutch, the road surface wear or the corrosion of the chassis, bodywork and other vehicle components and significantly contribute to the coarse mode of PM emissions (PM_{2.5-10}) and to some heavy metals. Besides direct emissions, resuspension of PM from the road is a major contributor to PM ambient concentration in urban environments being comparable

to tailpipe emissions in Europe ([Amato et al., 2014](#)) where about 50 to 85 % of total traffic PM₁₀ emissions are related to non-exhaust sources. These type of emissions are gaining importance since cleaner engine technologies are been introduced in the vehicle fleets (e.g. increasing electric vehicles share).

Despite the contribution of non-exhaust emissions to exceedances of air quality guidelines and standards ([Amato et al., 2011](#); [Denier van der Gon et al., 2013](#)) traffic-related emission control regulation are typically focused on exhaust emissions. Difficulties are related to the high influence they shown to external factors such as tyre type, vehicle-induced turbulence, road and weather conditions which place a major challenge for the estimation of this type of emissions ([Ketzel et al., 2007](#)). Non-exhaust emissions can be classified into:

- **Brake and tyre wear:** these emissions are a result of frictional contact between different elements of vehicles and road. Brake wear emissions are generated by the frictional contact between brake system components during forced deceleration. The action of breaking results in wear of the brake lining materials that is a major source of traffic-related PM emissions. On the other hand, tyre wear emissions are produced by the frictional contact between the road surface and tyre tread. This friction results in the abrasion of the tyre tread that emits particles into the atmosphere ([Thorpe & Harrison, 2008](#)).
- **Road dust resuspension:** These emissions are related road surface deposited material (road dust) that is resuspended to the air after a crossing vehicle as a result of vehicle-generated turbulence. This occur when air is squeezed from beneath the tyre, by tyre shear caused by rotation and by the action of the wind ([Warner et al., 2000](#)). This emission source together with tailpipe emissions are the major contributors to PM emission factors ([Abu-Allaban et al., 2003](#); [Lawrence et al., 2013](#)) and is one of the main challenges for a sustainable transport in Europe ([Amato et al., 2012](#)).

1.2.3 Policy options and legal mechanisms

Due to the adverse effects of atmospheric pollution, over recent years the number of policy actions undertaken in Europe to specifically address transport-related air pollution have increased. To address this problem, a broad range of policy options are available to implement emission reduction strategies that should be combined to achieve emission reduction targets. These options can be grouped into two major categories ([Litman, 2013](#)):

- Cleaner vehicles strategies that reduce emission rates per vehicle-mile. These include more efficient and alternative fuel vehicles such as efficient vehicle technology

development, fuel efficiency standards or alternative fuel requirements and initiatives. Local and regional air quality management plans — including initiatives such as low-emission zones in cities — are now undertaken in many areas (Holman et al., 2015; Miranda et al., 2015; Obrecht et al., 2017).

- Mobility management strategies that reduce total vehicle travel. These include improved transport options (such as transit, walking and cycling improvements or High Occupancy Vehicle –HOV– priority lanes), incentives to choose efficient options (such as parking pricing, transit encouragement, fuel tax increases or congestion charges) and land use management (such as location-efficient development, parking management or traffic calming measures).

In this sense, different legal mechanisms has been introduced such as setting limit values for ambient concentrations of pollutants and also regulating emissions from the traffic sector by introducing more restraining emissions standards or setting requirements for fuel quality.

The legal framework that sets up emission standards from vehicles consists in a series of directives, each of them amendments to the 1970 Directive 70/220/EEC. A summary list of the standards for vehicle type passenger cars is shown in Table 1.2.

Table 1.2. EU emission standards for passenger cars (category M1).

Fuel	Stage	EU legislation	Date	CO	HC	NO _x	PM	NMHC
				g/km				
Positive Ignition (Petrol)	Euro 1	D.91/441/EEC & D.93/59/EEC	1992.07	2.72	-	-	-	-
	Euro 2	D.94/12/EC & D.96/69/EC	1996.01	2.2	-	-	-	-
	Euro 3	D.98/69/EC	2000.01	2.30	0.20	0.15	-	-
	Euro 4	D.98/69/EC & D.2002/80/EC	2005.01	1.0	0.10	0.08	-	-
	Euro 5	715/2007/EC	2009.09	1.0	0.10	0.06	0.005	0.068
	Euro 6	459/2012/EC	2014.09	1.0	0.10	0.06	0.005	0.068
Compression Ignition (Diesel)	Euro 1	D.91/441/EEC & D.93/59/EEC	1992.07	2.72	-	-	0.14	-
	Euro 2	D.94/12/EC & D.96/69/EC	1996.01	1.0	-	-	0.08	-
	Euro 3	D.98/69/EC	2000.01	0.64	-	0.50	0.05	-
	Euro 4	D.98/69/EC & D.2002/80/EC	2005.01	0.50	-	0.25	0.025	-
	Euro 5	715/2007/EC	2009.09	0.50	-	0.18	0.005	-
	Euro 6	459/2012/EC	2014.09	0.50	-	0.08	0.005	-

These standards, known as Euro norms, define the acceptable limits for exhaust emissions (pollutant mass by km driven) of new vehicles sold in the EU Member States according to standardised measurements in laboratories for standardized predefined driving cycles. However the official procedures currently used in Europe are not representative of real-world driving conditions. This problem has led to the development of new measurement procedures as well

as portable emission measurement systems to obtain better information on real-driving emissions (EEA, 2016b).

1.2.3.1 Driving cycles

Driving cycles are speed-time profiles that are assumed representative of certain traffic and road conditions in a particular geographic area. These cycles are used in order to determine pollutant emissions and fuel consumption. Around the world several driving cycles exist (Barlow et al., 2009). The United States Environmental Protection Agency uses the Federal Test Procedure (FTP)-75 (Bartley et al., 2007) for the emission certification of light-duty vehicles in the USA. In the case of Australia the Composite Urban Emissions Drive Cycles (CUEDCs) (Vehicle Standards ADR, 2012) were created to closely replicate actual Australian on-road urban driving and is composed of four drive cycle segments (congested, minor roads, arterial and highway).

1.2.3.2 Current European Union type approval driving cycle

In the European Union, type approval emission tests are required by law for all new light-duty vehicle models and for engines used in heavy-duty vehicles. New European Driving Cycle (NEDC) has been used under EU legislation since 1970 (updated in 1990) for assessing the emissions and fuel consumption of light-duty vehicles during type approval. This cycle was originally developed when vehicles were lighter and less powerful than those available today. So that the test involves simple speed patterns with low accelerations, constant speed and many idling events that under-load modern engines and underestimate vehicles actual emissions.

For this reason, a number of alternative cycles have been developed in Europe to provide information on real-world driving emissions. An example is the Common Artemis Driving Cycle (CADC) (Andre, 2004). This cycle is based on a large database of European real-world driving patterns and include three driving schedules: urban, rural and motorway. It is more dynamic than NEDC with higher average and maximum speeds, more accelerations and braking and less idling and constant speeds. As a result, both cycles produce significantly different emission values as shown in Figure 1.4. For the case of diesel vehicles, the ratio has greatly increased over time as the different Euro technologies have been implemented (EEA, 2016b). Also, these emission measurements tested over CADC cycle are incorporated in transport models. To obtain continuous speed data for detailed traffic situations different projects such as ARTEMIS (Boulter & McCrae, 2007) and COST346 (Andre et al., 1999) have initiated data collection process, as required for the emission estimation approach at this level. Although speed data have been obtained for hundreds of traffic situations, this still remains a weak point for the emission estimation due to missing data and poor representativeness.

Figure 1.4. Ratio of NO_x emissions measured on the NEDC and CADC cycles for different Euro categories and engine technologies.

Due to this deficiencies, the Worldwide harmonized Light vehicles Test Procedure (WLTP) and the corresponding Test Cycle (WLTC) replaced the NEDC procedure (Marotta et al., 2015). The main parameters of both cycles are presented in Figure 1.5 and show the main differences from WLTC to NEDC. They include longer testing distance and duration, higher average speed, higher maximum speed, fewer stops, less driving at constant speed, more acceleration and braking and less idling. This type of approval testing was introduced in September 2017 for new car types. Starting in September 2018 all new vehicles must be certified according to the WLTP and from January 2019 dealerships should have WLTP-CO₂ values for all cars. In 2020 the European Commission will convert NEDC targets to WLTP targets of comparable stringency. Hence, during the transition period, compliance with the existing NEDC-based targets will be determined with a correlation tool. Nevertheless, the WLTP include Real Driving Emissions (RDE) testing requirements that has been also introduced from 2017 to control vehicle emissions in real operation, outside of the laboratory emission test.

Figure 1.5. Speed-time profiles of NEDC (left above) and WLTC (left below) and key parameters of both driving cycles.

1.2.3.3 *Real-world exhaust emissions*

Despite test-center or laboratory emission testing over these predetermined cycles, it is widely accepted from the scientific community that emissions values and fuel consumption measured in laboratory underestimate actual emission levels obtained under real-world driving conditions (Kadijk et al., 2015, 2016; Ligterink & Smokers, 2016; Ligterink et al., 2013; Mock et al., 2012, 2013, 2014; Smokers et al., 2016; Tietge et al., 2016, 2015).

For this reason, RDE testing requirements have been introduced through several regulatory amends in the European legislation to measure real-world exhaust emissions (Regulation 2016/427; Regulation 2016/646; Regulation 692/2008). RDE testing conditions are designed to be representative of driving conditions from European roads (Mock, 2017). There are several techniques to directly measure these emissions from vehicles as they are driven on roads: Portable Emissions Measurement System (PEMS), Remote Sensing Device (RSD) and Vehicle Chasing Experiment (VCE).

PEMS is a transportable measurement system that can be carried on board a vehicle to monitor real-world in-use emissions. It is used in Europe for type-approval purposes and the test procedure is regulated in Appendix 1 of Regulation 582/2011. The system allows a complete and very accurate real-time monitoring of emissions of selected pollutants from combustion engines (most common HC, CO, CO₂, NO_x, PM) together with the associated engine, vehicle and ambient parameters (Perujo et al., 2015). This technology is also simpler to maintain and cheaper than laboratory measurements with chassis dynamometer. The main limitations of PEMS is the reduced range of pollutants that can be measured during a test in comparison to a laboratory as well as the mass (30-150 kg) it adds to the vehicle. Furthermore, the lower repeatability of the measurements in real-world driving patterns can be a challenge to ensure consistency between different vehicles tested (EEA, 2016b).

Remote sensing with RSD is the measurement of individual vehicles passing an optical sensor. It is a non-intrusive technique to determine the concentration of certain pollutants in situ. This devices routinely measure CO₂, CO, HC, NO and opacity and could be expanded also to NO₂, NH₃ and SO₂. The exhaust plume is measured by the light attenuation that is produced when a vehicle crosses the beam. This method covers different fleet scenarios so that individual vehicles are identified by plate reading and the main driving parameters (speed and acceleration) are stored (Borken-Kleefeld, 2013). The main drawback of this kind of technology is the limited number of sites and driving conditions (road gradient, vehicle speed and acceleration peers) that can be covered. This technology capture a snapshot of a crossing vehicle covering a limited number of vehicle specific power (VSP) values. So that it cannot reflect continuous emissions of individual vehicles in different operating modes.

VCE consists on a mobile laboratory (ML) vehicle that follows target vehicles sampling their exhaust plume (Tang & Wang, 2006). High resolution (seconds and meters) measurements of gaseous and particulate pollutants can be measured through an inlet system located in the front part of the ML (Kwak et al., 2014). Nevertheless, the main difficulty is to keep a constant distance between the chased vehicle and the MEL due to the important variations that it can produce on the pollutant measurements (Woo et al., 2016). Furthermore, as for PEMS measurements, to ensure consistency between different vehicles tested in real-world driving patterns can be a challenge.

Measurements from these RDE techniques have reveal in recent years that real-world measured emissions of NO_x , particularly from diesel passenger cars and vans, generally exceed the permitted European emission standards for the latest Euro norms (Euro 5 and Euro 6) (Fontaras et al., 2014; Kadijk et al., 2015). The magnitude of the discrepancy between measurements and laboratory tests varies depending on vehicle type, operation model, route characteristics and ambient conditions (Heijne et al., 2016; Kadijk et al., 2016). Recent studies on diesel Euro 6 cars have found that, on average, real-world NO_x emissions were seven times higher than the limit set by Euro 6 standard (Franco et al., 2014; TNO, 2015). This kind of results have generate controversy and some initiatives have arisen in recent years. An example is the EQUA Air Quality Index (EQUA, 2018) that makes a comparison between different cars in real on-road driving conditions. They are sorted using an index that clearly identifies vehicles emitting the lowest quantities of NO_x on a scale from A (meets Euro 6 limit for diesel cars) to H (more than 12 times Euro 6 limit) showing Euro 6 cars also in this lower category.

1.3 The case of Madrid

Madrid is a clear example of the traffic-related air quality issues discussed in previous sections. In the Madrid Greater Region, the main air quality problems are related to nitrogen dioxide (NO_2) and particulate matter (PM), mainly due to emissions from the road traffic sector dominated by diesel vehicles. Traffic is the major source of NO_x emissions in Madrid city, with a contribution to total emissions of up to 55 % in 2013 that represents 59.1 % of the Madrid's NO_2 annual average concentration (Madrid Emissions Inventory, 2015; Vehicle fleet characterization study, 2014).

These contribution of road traffic to the NO_2 concentrations is higher in the city centre and near to the main roads where the NO_2 annual average concentration contribution increase up to 90 % (Figure 1.6) (Borge et al., 2014).

Figure 1.6. Result of the source apportionment analysis for the road traffic sector.

Following legal requirements, the Madrid City and Greater Region have developed a series of plans and measures that are increasing in importance in recent years to improve air quality and meet the European standards. As regional strategy, [Plan Azul+ \(2013\)](#) include the air quality and climate change strategy for the Madrid Greater Region for the timeframe 2013-2020. In there, improvement objectives and considered measures are included. The most important example is the implementation of “Plan A” (Madrid’s Air Quality and Climate Change Plan) on September 2017. The main goals from this [Plan A \(2017\)](#) are to comply with European air quality legislation, achieve air quality levels for PM in accordance with the guidelines from the WHO and to develop a strategy for the adaptation to climate change effects and global warming. To achieve these goals the plan include a total of 30 measures following four action lines: sustainable mobility (21 measures), urban regeneration (7 measures), climate change adaptation (1 measure) and awareness raising and communication (1 measure).

Moreover, the Madrid City Council approved the actuation protocol during high pollution episodes of nitrogen dioxide (NO₂) in February 2016. Later, in November 2017 the Madrid Greater Region developed the legal framework for the whole Madrid region through the [Decree 140/2017](#). This protocol divides the region in seven areas (one is Madrid city that is subdivided into 5 subareas) (Figure 1.7) and establishes 3 levels of actuation: 1-information and notice, 2-warning and 3-alert. These levels of actuation come into force depending on the NO₂ concentration measured on the air quality (AQ) monitoring stations (from 200 µg/m³ to more than 400 µg/m³), the number of hours with these high concentrations and the number AQ stations affected inside an area. Stage 3 of this protocol was implemented in Madrid city for the first time on December 2016 ([Borge et al., 2018](#)).

Figure 1.7. Pollution protocol areas division for the Madrid Greater Region (left) and Madrid City subdivision (right).

Depending on the level of actuation and the number of days that it has been activated, there are different scenarios and measures to adopt. These scenarios are cumulative and include measures such as speed reduction for the main access roads to Madrid city and the nearest ring-road (M-30) for the less restrictive scenario. Scenarios 2 and 3 include banning parking, 50 % (even or odds license plate number) of vehicles in the city centre and in the most restrictive (scenario 4) also 50 % of the vehicles in the M-30. A summary of these restrictions is presented in Figure 1.8.

Figure 1.8. Traffic restriction scenarios from the Madrid NO₂ pollution protocol. Ayuntamiento de Madrid (2017).

In Madrid city, these high pollution concentrations are mainly linked to specific traffic-related urban locations. In Figure 1.9 the NO₂ annual mean concentration measured by the traffic stations from the Madrid air quality monitoring network in 2014 are shown. Five out of nine stations exceed the legal limit of 40 µg/m³ presenting the maximums in Fernández Ladreda and Escuelas Aguirre.

Figure 1.9. NO₂ annual mean values from the traffic AQ Stations in Madrid city.

On these highly polluted microenvironments (hot-spots) more detailed studies are necessary in order to explain these elevated concentrations profiles. Important efforts have been made to improve monitoring and modelling techniques to provide a better understanding of air quality problems and the ultimate causes for high ambient concentration levels. This understanding is necessary to design additional emission abatement measures that can effectively diminish the negative effects that air pollution on traffic hot-spots exerts on urban population (Thunis et al., 2016).

1.3.1 Previous studies in Madrid

Several studies have been carried out trying to get information about traffic emissions and their relationship to Madrid's air quality. In this sense extensively evaluated regional traffic emission models such as COPERT (based on average speed) and HBEFA (based on traffic situations) have been compared for Madrid at mesoscale level (Figure 1.10). These models show higher emission intensity at the city centre and main access roads, being currently the most detailed data available for the city (Borge et al., 2012). Nevertheless, this level of detail is not enough to understand the high pollutant concentrations that occur in specific points of the city.

Figure 1.10. Spatial distribution of NO_x emissions generated by a) COPERT and b) HBEFA calculation approach.

There have been also several studies dealing with specific characteristics of Madrid city traffic. In this sense, a detailed analysis of the actual vehicle fleet from Madrid city ([Vehicle fleet characterization study, 2014](#)) has been performed to obtain a detailed database of Madrid's actual circulating fleet composition. In order to obtain real-driving emissions from the vehicle fleet, several techniques have been applied to measure emissions on-road. RSD technology has been employed in Madrid to obtain real emission measurements representative for the Spanish circulating fleet ([Pujadas et al., 2017](#)) in the framework of [CORETRA project \(2015\)](#). The main aim of this project is to identify high emitter vehicles in order to reduce their emissions by removing them from the actual vehicle fleet. Currently, these measurements continue in the [Life GySTRA project \(2018\)](#) to control and quantify real driving emissions. Also PEMS technology has been applied to Madrid to analyse exhaust emissions. One example is their implementation on the urban bus fleet from the Municipal Transport Company (EMT) to obtain a methodology that helps to assess the effect of changing vehicle propulsion technologies in different renewal situations ([López-Martínez et al., 2017](#)). Other studies have investigated the specific driving conditions of the city. [Ariztegui et al. \(2004\)](#) proposed a driving cycle (speed-time profile) that represents the typical driving pattern in Madrid based on circulation data (Figure 1.11).

Figure 1.11. Madrid cycle speed-time profile.

Emission results over the Madrid cycle were compared to NEDC results ([Ariztegui et al., 2004](#)) confirming significant differences for real-world measurements. The same study analysed emission results also over chassis dynamometer using two speed approximations (instantaneous or average speed). These analysis remarks the importance of a detailed definition of traffic conditions for a specific area and points out that the speed approximation used and the driving cycle (representative for actual driving conditions) are fundamental factors for an accurate emission calculation. Consequently, site and scenario-specific cycles should be taken into account to support local policies and measures.

There is still a lack of monitoring and modelling technologies detailed enough to assess emission abatement policies and measures taking into account all the relevant atmospheric processes and multi-scale phenomena involved traffic-related in urban air quality and to support population exposure studies ([Borge et al., 2016a](#)). This is more evident in particular urban micro-environments (squares, junctions, etc.) with high ambient air concentrations (hot-spots), generally associated to high traffic intensity. In this sense there is a pressing need to estimate

the contribution of road traffic to atmospheric emissions at local level and with great detail. For this reason, contributing on the knowledge in this area is of great interest.

1.3.2 The TECNAIRE-CM Project (S2013/MAE-2972)

The characterization of pollution dynamics in such hot-spots poses a major scientific challenge. Buildings and other obstacles of the urban landscape and the movement of vehicles bring about very complex dispersion patterns that generate strong concentration gradients in time and space that are very hard to depict with the current monitoring and modelling techniques.

The main aim of the TECNAIRE-CM project (2014 - 2018) is the development and test of new technologies capable of describing urban air quality issues comprehensively and therefore useful for the assessment of improvement strategies. The activities to achieve this general aim are distributed in seven working areas or Objectives. Firstly, a series of experimental field campaigns were carried out (Objective 1) in several places of Madrid city, representative of different types of urban hot-spot. Observational data from these campaigns are used to feed and validate the modelling techniques developed in TECNAIRE-CM. Conventional monitoring techniques are unable to provide the information requirements of these models, so alternative measurement methods, including microsensor networks, are developed under Objective 2. Transport patterns were reproduced by the application of microscale air quality models based on Computational Fluid Dynamics (CFD) methods (Objective 5). Besides high temporal and spatial resolution observations, the development and application of CFD models for urban hot-spots require equally resolved (meters, seconds) microscale emission inventories. So that, microscale emission models has been coupled to microscale traffic simulation models for this purpose (Objective 4). The development of such emission systems constitutes the primary aim of this PhD thesis. Boundary conditions constitute another crucial input for air quality microscale modelling. An effective linkage between microscale and mesoscale, urban level air quality processes must be made by generating dynamic boundary conditions, both for the chemical composition of the atmosphere and the relevant meteorological parameters. Therefore, a highly-detailed and specific mesoscale air quality modelling system was applied (Objective 3). The mesoscale system includes updated, high-resolution emission inventories for the Madrid urban areas and optimized meteorological setup (boundary layer scheme, urban parameterizations) for this region. Besides these activities, monitoring of urban background concentration levels has been made (Objective 6) to identify relative contributions of the main emission sources and influences from different scales so the results from experimental campaigns can be better understood and to validate the different models involved in this research (Objective 7) (Borge et al., 2016a; Borge et al., 2016b). More information about the project is available on the website www.tecnaire-cm.org

1.4 Thesis objectives

The main goal of this thesis is to improve the existing simulation techniques to estimate microscale traffic emissions and to generate the necessary methodologies for their application to Madrid. The ultimate target of this research is to develop a useful instrument for decision makers to alleviate the negative impacts of air pollution in urban micro-environments.

The specific goals associated are as follows:

1. Development of experimental campaigns in selected places in Madrid city, representative of diverse types of hot-spots. The campaigns intend to compile the necessary data to feed and validate the modelling techniques developed.
2. Implement a traffic microsimulation model adapted to the characteristics of these selected areas in Madrid city.
3. Adapt and adjust the emission calculation model for Madrid coupled with the traffic microsimulation model.
4. Validate the modelling approach by comparing it with alternative models and applications in other urban areas in collaboration with international investigation centres and companies.
5. Apply this methodology to assess the effect of specific emission reduction measures in the hot-spots.
6. Adapt the emission outputs to be coupled with an Air Quality Model based on CFD (Computational Fluid Dynamics) techniques and test their compatibility.

CHAPTER 2

ROAD TRAFFIC EMISSION MODELLING

Due to the complex relationships between road traffic and air pollution, models are commonly used to predict and evaluate impacts and determine solutions. This occurs at different scales, ranging from a single road segment (hot-spot) to an entire urban or regional transport network or even at national or global level for emission inventories purposes. Consequently, the model fundamentals, variables involved and implementation options vary widely depending on the scale of application and the purpose of the study. This chapter discusses the different traffic and emission model approaches used for different types of studies in the past. Section 2.1 provides an overview of the modelling approaches and variables involved and section 2.2 presents and justifies the modelling approach proposed to achieve the objectives set for this Ph.D. Thesis.

2.1 Modelling approaches

Modelling techniques are usually divided into three scales depending on the level of detail they include: macroscopic (regional), mesoscopic (local) and microscopic (street level) (Figure 2.1).

Figure 2.1. Different scales in modelling techniques (*Aimsun next*, 2018).

The inputs required by macroscopic models are time and space aggregated variables such as average speed and travelled kilometres. These variables describe the traffic on a high level of aggregation without taking into account individual vehicles. Macroscopic models are commonly used for compiling regional or national emission inventories for annual periods. Mesoscopic models (between macro and micro) obtain aggregated performance results at link level. Due to this characteristics they are useful to describe individual vehicles (but not their interactions), approximate traffic dynamics and queue estimations ([Burghout, 2004](#)).

On the other hand, microscopic models describe individual vehicles behaviour, network performance and their interactions in full detail. Behaviour refers to the explicit description of vehicle acceleration patterns, lane changes, and also the definition of their routes to reach their

destination. For that, very short time steps are used (as much as 0.1 seconds) along with driver reaction times, route selection logics (define how drivers establish the route, how they react to traffic and the route information), car following logics (define braking-acceleration patterns as a result of the interaction from the driver with other elements, such as vehicles or objects in front, speed limits, etc.) and lane change logics (describe the decisions for a lane change taking into account driver preferences, lane situation, vehicle speed, lateral spacing with the next lane, etc.). They also use explicit models for traffic control and intersection geometry to obtain detailed vehicle trajectories. This type of models can be used to generate emission estimations with very high temporal, and thus spatial resolution (Den Braven et al., 2012). So that the use of microscale models can be a solution to model emissions with higher level of detail (Borge et al., 2014).

Another important factor is the consideration of congestion. Simulation tools are effective in evaluating the dynamic evolution of traffic congestion problems on transportation systems. By dividing the analysis period into time slices, a simulation model can evaluate the build-up, dissipation, and duration of traffic congestion. Emission models that need as input the quantification of the particular traffic situation defined as a speed-time profile (driving pattern data provided by a traffic microsimulation model) or models that generate these data during the emissions' modelling process are used for microscale applications. On the other hand, for mesoscale applications, models that incorporate the driving pattern data in the emission model are adequate (Smit et al., 2008).

Also, traffic simulators can model the variability in driver/vehicle characteristics. However, they require numerous input data, considerable error checking and manipulation of a large amount of potential calibration parameters to replicate the actual conditions in the field. These process can be complex and time consuming (Alexiadis et al., 2004). So that in general, one of the main limitations of the simulation models are the calibration requirements depending on the scale used. Macro- and mesoscale models need less detailed data and they can be used to study general traffic dynamics. However, their application is limited to cases where vehicle interaction is not a decisive parameter. Therefore, this kind of models can be used to obtain traffic fluxes and average speeds. So that they are typically applied to large scale networks and long time periods where these limitations have no significant effect. This is related to the simplifications that macro- and mesoscale models include for braking-acceleration patterns which have a crucial effect on emissions.

For applications where these limitations are crucial such as hot-spot analysis in cities, microscale models must be used (Burghout, 2004). Despite that more data are needed to feed microscale models and that they are more complex, this type of models have increase in recent years. These

highly detailed traffic simulation is very important for an accurate emission estimation with very high spatial and temporal resolution.

Due to the elevated economic and social costs that are related to emission reduction strategies, their implementation must be based on estimations with very low uncertainty ([Lumbreras et al., 2008](#)). For these reasons, on urban hot-spots high resolution tools that can accurately reproduce real-world conditions are required to propose and analyse the effect of detailed plans and programmes in these specific areas ([Borge et al., 2014](#)).

2.1.1 Variables involved in traffic emission calculation

The generic computation procedure of the traffic emission models takes into account a limited number of factors. Basically, the emission computation is based on the emission factor (amount of pollutant emitted per distance unit (g/km), per time unit (g/s) or consumed fuel (g/kg)) multiplied by the number of different vehicle types. Nevertheless, the level of detail of the models greatly influences these calculations ([Smit et al., 2008](#)). Usually the main vehicle type (passenger car, light commercial vehicle, motorcycle, articulated truck, bus, etc.), fuel type (diesel, petrol, LPG, etc.) and emission standard are factors that have a great effect on the emission calculations. However, more detailed vehicle classification schemes implies more detailed input traffic data that are often not available ([Smit et al., 2009](#)).

The estimation of detailed and accurate exhaust emissions from road transport for real-driving conditions present several difficulties. The difficulties are related to the limited amount of direct measurements of exhaust emissions that cannot cover a full vehicle fleet. For instance, in Europe light-duty vehicles have to be tested on a chassis dynamometer (Figure 2.2) and heavy-duty vehicles on engine test bed. In the case of chassis dynamometer system it is designed to operate a vehicle indoors on a stationary platform to simulate real-world vehicle operation. This system recirculates the emitted gases to a dilution tube where they are analysed. To determine the emissions and fuel consumption, vehicles follow a predefined driving-cycle of accelerations, gear changes, steady speeds, decelerations and idling within defined tolerances so that the type of standardized driving cycle used for testing is an important factor in determining vehicle emissions ([EEA, 2016b](#)). These cycles along with several traffic-related parameters ([André et al., 2006](#); [Boulter & McCrae, 2007](#)) such as vehicle characteristics (model, weight, size, power, fuel type, technology level, mileage, exhaust after-treatment or vehicle emission standard), driving mode (cold, hot, running, idling or parked), engine and emission control components deterioration (ageing effects) influence and determine exhaust emissions ([McCrae et al, 2006](#); [Smit et al., 2009](#)).

Figure 2.2. Chassis dynamometer test procedure.

These emissions, in turn, constitute the starting point for the modelling of road transport impacts on air quality. The magnitude of emission and its spatial and temporal distribution are determined by fleet characteristics and traffic conditions.

2.1.1.1 Vehicle characteristics

Emissions from a vehicle are influenced by the vehicle design and manufacturing technology. One of the most important parameters is the engine type since vehicles are still powered predominantly by combustion of fossil fuels in the form of petroleum products. Despite the promotion of electric and natural gas powered vehicles ([Directive 2014/23/UE](#)), petrol and diesel continue to be the most popular types. A diesel engine produces less CO and HC than petrol engines. However, diesel engines produce far more particulates and NO_x than petrol vehicles fitted with a catalyst. This is directly related to the fuel characteristics such as the content in sulphur (S) and the vapour pressure that have a direct effect on emissions. Also, large heavy vehicles require more power to propel them than small light vehicles which also has an effect on fuel consumption and the emissions from those vehicles. So that load factors and empty running rates should be also considered as functions of vehicle type and size. Empty running corresponds to the mileage driven without load and the load factor depends on the vehicle type and weight. Nevertheless, the distance travelled by a vehicle increases the deterioration of a vehicle including the engine performance so that emissions increase. Analysis of on road vehicles reveal that large variations in emission levels appear for badly maintained vehicles which generate significantly higher emissions. Vehicles with high mileages and the ones driven at high speeds present higher emission rates mainly for CO. However, deteriorating rates of the actual vehicles are still data that cannot be easily collected because they are highly dependent on driving conditions and maintenance levels. Nonetheless, an accurate description of the fleet composition and its evolution with the time is necessary for emission calculations. On the basis of vehicle registration data, the fleet evolution can be estimated using the number of vehicle scrapped each period (scrapage rate), or the proportion of vehicles surviving each period (survival rate). These rates are important, as they determine the longevity of vehicles within the fleet and influence the number of new vehicles entering the fleet each year. For that

reason it is an important criterion in the calculation of pollutant emissions so that specific rates should be defined for the emission calculation.

Nevertheless, to meet certain standards vehicles may be equipped with emission exhaust after-treatment control systems to meet the corresponding emissions requirements. These systems allow to eliminate pollutants from the vehicle exhaust after it leaves the engine, just before it is emitted into the air. The most common after-treatments to control NO_x emissions are Exhaust Gas Recirculation (EGR), Lean NO_x trap (LNT) and Selective Catalytic Reduction (SCR) and the 3-way catalyst. To control PM emissions the most used one is the Diesel Particulate Filter (DPF) for PM (Reşitoğlu et al., 2015). Newer emission standards include different exhaust after-treatments. EGR system is used in large diesel engines. CO_2 -rich exhaust gases are recirculated back into the combustion chamber and mixed with fresh air. This turns out in lower combustion temperatures that reduce the thermal production of NO_x , although it may increase HC and CO emissions. LNT is also called NO_x Storage Reduction (NSR) or NO_x Adsorber Catalyst (NAC). This system stores NO_x on the catalyst under engine lean conditions. Then, under fuel-rich engine conditions it releases the trapped NO_x . SCR is reduction technology improved for heavy-duty vehicles and more and more common on light-duty vehicles (e.g. Euro 6 passenger cars). In this case NO_x emission in the exhaust gas are minimized by a selective catalytic reduction in post-combustion reactor where ammonia (NH_3) or urea is used as a reductor agent. This system reduces NO_x on a continuous way and with high efficiency. Nevertheless, the sulphur content of the fuel may limit the applicability of this technology since it may degrade active sites within the catalytic converter, lowering the catalytic activity. The 3-way catalyst is used in petrol fuelled vehicles to convert NO_x , CO and HC into less harmful substances (N_2 , CO_2 and H_2O) by using a reduction catalyst (platinum and rhodium) and an oxidation catalyst (platinum and palladium) both with ceramic honeycomb structure. DPF are used for the reduction of PM. In this technology emissions from the exhaust gas are removed by physical filtration. The plugged channels at each end of the device force the diesel particulates through the porous substrate walls. These walls act as very efficient mechanical filters and when the particles pass through it, they are transported into the pore walls by diffusion. As the filter becomes increasingly saturated, a layer of soot is formed on the surface of the channels walls. Nevertheless, excessive saturation must be prevented by regenerating the filter through pyrolysis of trapped PM.

2.1.1.2 Driving conditions

A particular vehicle type can produce very different emissions depending on the way it is used. Detailed and accurate knowledge of actual driving speeds is fundamental for emission estimations and inventories. However, the data are often limited to average speed values for a unit of travel time or trip length. Speed distributions and speed profiles (or speed-acceleration matrices) can be obtained from instrumented vehicles, but the data are often incompatible with

the degree of detail that would be needed. Journeys with frequent stops and starts operations, accelerations and decelerations in response to traffic congestion are inefficient in fuel usage and present higher emissions. These patterns produce changes in speed (low average speed) that requires changes in engine conditions so that engine deviates from the optimum performance increasing emissions. Nevertheless, other related factors such as the driver (e.g. age, income), the trip (e.g. trip purpose, trip type, type of use), the vehicle (e.g. vehicle type, size, load), the local context (e.g. residential area, city size, origin and destination, etc.) and the time (e.g. season, day of the week, time period) play also an important role on emissions. The inclusion of such correction factors improve emission estimates.

2.1.2 Traffic simulation approaches

Traffic simulation modelling techniques are essential to produce the information needed by traffic emission models. Detailed information on operational profiles from vehicles are expensive to collect and rarely available for users. In addition, the output of traffic management measures or policies has to be necessarily simulated and traffic models become the only feasible methodology to produce the information needed to estimate emissions. To date, numerous traffic analysis methodologies and tools have been developed ([Alexiadis et al., 2004](#); [Balakrishna et al., 2013](#)). Traffic models include different characteristics and applications depending on the scale they consider:

2.1.2.1 *Macroscopic simulation models*

Macroscopic simulation models are based on the deterministic relationships of the flow, speed and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic models have considerably fewer computer demanding requirements than microscopic models. However, they do not have the ability to analyse transportation improvements in as much detail as the microscopic models. An example is VISUM which is a macroscopic simulation tool that models interactions between roads and users. It is used for transportation planning for transport networks, travel demand, transit changes and public transport services among others ([PTVGroup, 2018b](#)). VISUM is used to calculate general vehicle fluxes due to the scale that it uses.

2.1.2.2 *Mesoscopic simulation models*

Mesoscopic simulation models combine the properties of both microscopic (discussed below) and macroscopic simulation models. As in microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. Their movement, however, follows the approach of the macroscopic models and is governed by the average speed on the travel link. Mesoscopic model

travel simulation takes place on an aggregate level and does not consider dynamic speed/volume relationships. So that, mesoscopic models provide less fidelity than the microsimulation tools but have higher detail than the typical planning analysis techniques.

2.1.2.3 Microscopic simulation models

Microscopic models simulate the movement of individual vehicles based on car-following and lane-changing theories. Typically, vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process) and are tracked through the network over small time intervals (e.g., 1 second or a fraction of a second). Typically, upon entry, each vehicle is assigned a destination, a vehicle type and a driver type. Computer time and storage requirements for microscopic models are large, usually limiting the network size and the number of simulation runs that can be completed. Some examples are:

CORSIM is a microscopic simulation software, designed for the analysis of motorways, urban roads and networks. The combination of a freeway simulation model (FRESIM) and the traffic network model (TRAF-NetSim) allows to analyse all the individual components as a whole system including specific properties for each vehicle (length, acceleration, driver aggressiveness, minimum acceptable distance, etc.) and actualising for each simulation second the vehicle following logic and lateral movements ([McTrans, 2018](#)).

VISSIM is a tool for microscale traffic simulation. This model allows to generate different detailed scenarios for complex urban network geometries using the link-connector system. It also includes a signal state software to define traffic lights and allows to simulate the interaction with pedestrians with the VISWALK simulation software ([PTVGroup, 2018a](#)).

PARAMICS ([Cameron et al., 1994](#)) is a set of unified models in a single microscopic traffic simulation software that integrates all the different networks sizes. It also allows to control traffic and information systems ([PARAMICS, 2018](#)).

AIMSUN ([Barceló et al., 1998](#)) integrates also the three types of transport models (macroscopic, mesoscopic and microscopic simulator) in one application. The microscopic model was developed on the basis of algorithms for space detection, vehicle following and lane change logics as CORSIM. Nevertheless, AIMSUN present options to model dynamic aspects for large networks and reduces the calibration process. Also, it can be used to generate large urban and regional networks ([AIMSUN next, 2018](#)).

For congested road networks and interaction between urban streets and motorways the most useful simulation models are AIMSUN, CORSIM and VISSIM. On the other hand, AIMSUN,

PARAMICS and CORSIM are potentially useful for Intelligent Transportation Systems (ITS) analysis (Ratroun & Rahman, 2009).

Even inside a given category a variety of models with different characteristics exists. Each software or modelling approach presents specific features that differentiate it from the rest, presenting it as suitable for certain uses. Also, some of them include a distributed computing technique that allows the integration of different scales in the same model. A summary of some of the most used models and their main characteristics and features are shown in Table 2.1.

Table 2.1. A comparative analysis of currently used microscopic and macroscopic traffic simulation software (Adapted from Ratroun & Rahman, 2009).

Name	Characteristics	Main Features/Capabilities
CORSIM	Microscopic	Surface streets, freeways, actuated signals, weaving sections, incidents, variable message signs, 2-D animation.
SATURN	Microscopic	Individual junctions, traffic assignment
SUMO	Microscopic	Large road networks
VISSIM	Microscopic	Surface streets, freeways, ramp metering, pedestrians, transit operations, 3-D animation
PARAMICS	Microscopic, distributed computing technique	Surface streets, freeways, transit operations, 3-D animation, roundabouts, congested networks
AIMSUN	Microscopic, distributed computing technique	Surface streets, freeways, actuated signals, dynamic traffic assignment, variable message signs, 3-D animation, telematics
INTEGRATION	Mesoscopic	Surface streets, freeways, traffic assignment, intelligent transportation system, toll plaza, vehicle emissions, HOV
VISUM	Macroscopic	Node calculation, signal control, public transport schedule

2.1.3 Emission modelling approaches

Models for estimating emissions from road vehicles can be classified on the scale of application (macro-, meso- or microscale), emission calculation approach, type of input data or the generic type of model as shown in Table 2.2 (McCrae et al., 2006).

Table 2.2. Classification Systems for vehicle emission models.

Scale of application	Generic type	Emission calculation approach	Type of input data
Macroscale (country, region, city)	Aggregate emission factors	Discrete	Trip-based
Mesoscale (district)	Average speed	Continuous	Link-based
Microscale (road link, road subsection)	Adjusted average speed Traffic situation Multiple linear regression Instantaneous Modal	Discrete/Continuous mix	Continuous by operational mode

So that, model classification systems tend to be based upon a combination of geographical scale of application, the generic model type and the nature of the emission calculation approach. However, the choice of the modelling approach will depend on the purpose of the emission calculation, the level of detail needed or the scale of interest (Figure 2.3).

Figure 2.3. Emission modelling approaches schema from macroscale (above) to microscale (below).

2.1.3.1 Aggregate emission factor models

These models rely on constant emission factors representative of a particular type of vehicle and a very general type of driving (urban, rural or motorway), as is the case for area-wide and fuel-based models. They combine data on total vehicle kilometre travelled (VKT) and single distance-based emission factors to compute total area emissions by a top-down approach so that they are applied at a low spatial and temporal resolution.

An example is the NAEI (National Atmospheric Emissions Inventory) (NAEI, 2018) that provide annual estimates of emissions for a large number of the greenhouse gases and air pollutants using international agreed and recognised methods.

2.1.3.2 Average speed models

In this type of models emission factors are a function of average speed. Average speed is defined as the overall speed on a section of road or for an entire journey (with stops, starts, accelerations and decelerations). The most relevant model within this type is COPERT (Computer Programme to calculate Emissions from Road Transport) (Gkatzoflias et al., 2012, Ntziachristos et al., 2009) where emissions factors as a function of average speed (Figure 2.4) are available for a large array of vehicle types. This model is integrated in the EMEP/EEA methodology for emission computation (Ntziachristos & Samaras, 2017) and is the reference method for emission computation in European national emission inventories.

Figure 2.4. NO_x emission factor curves as function of average speed for 6 different PC emission standard implemented in COPERT 4.

In this kind of models the treatment of driving behaviour effects are not explicitly modelled. That may introduce substantial errors in emission predictions at local scale because driving cycle emission factors are derived from average speeds so that they are useful for large-scale applications if trip data are available. Nowadays this is a widespread approach because average speed modelling is a long-established method relatively easy to use and the required inputs are in close correspondence to those data available to users. However, the average speed of a trip may be obtained in different ways. So that all type of operation associated to a given average speed cannot be represented by a single emission factor especially at low average speeds associated with congestion (Borge et al., 2012). The variability of vehicle operation at low average speeds is partly responsible for a poor reliability of the corresponding emission factors.

2.1.3.3 Traffic situation models

In these models cycle average emission rates are not correlated to average speed but specifically to various driving cycle parameters. These cycle parameters are referenced to pre-defined traffic situations which are known by the user. They tend to be best suited to mesoscale applications, in which emission estimates are required for individual road links, but can also be used for macroscale regional and national inventories. These models use discrete emission factors for certain “traffic situations” defined quantitatively or qualitatively also for specific vehicle categories. These models require information on VKT and determination of the particular traffic situation that applies to the specific road link(s). An example of these kind of models is the HBEFA (Handbook of Emission Factors for Road Transport) (Hausberger et al., 2009). This model uses a qualitative description of speed variation (dynamics) to identify the traffic situation (e.g. free-flow, heavy, saturated, stop & go) for which and emission factor is applicable based on reference emission functions for a representative sample of cars, light-duty vehicles, diesel engines from HGVs and motorcycles. Correction factors are used to take into account the effects

of cold starting, gradient, altitude, special driving conditions and degradation of emission control systems. The different correction factors, which relate to the particular traffic situations the user is interested in, are applied to the reference emission functions in order to generate appropriate emission estimates. These traffic situations are characterised by the features of the section of road concerned and the driving patterns are defined in terms of average speed and accelerations (Figure 2.5). The main limitations of this approach are related to the definition of the traffic situation which include a subjective interpretation of the traffic definition and also the universal applicability of the traffic situations with significant differences among cities in not resolved (Borge et al., 2012; McCrae et al., 2006).

Figure 2.5. HBEFA emission factors result matrix as factor of average cycle speed for different vehicle and road types.

2.1.3.4 Traffic variable models

These models generate simplified driving pattern data as a function of a number of traffic variables relating to traffic characteristics (traffic volume, average speed, traffic density, queue length) and road infrastructure characteristics (link length, number of lanes, free-flow speed, type of intersection, signal settings). These simplified driving patterns are combined with emission rates derived from other emission models. An example of those type of models is the Traffic Energy and Emissions – TEE – model that incorporates a “corrected average speed” modelling approach (Negrenti, 1999). The model assumes that the effect of congestion on emissions at a certain average speed can be expressed by means of “congestion correction factor” derived from average speed, green time percentage, link length and traffic density. The emission factor for the average speed is then adjusted using the correction factor. The congestion level is used to calculate the fractions of time spent during cruising, acceleration,

deceleration and idling and the result is a reconstructed speed profile produced by the model itself.

2.1.3.5 Cycle variable models

Emission factors are a function of specific driving patterns variables at high resolution. They require driving pattern data to quantify selected cycle variables and to estimate emission factors or emission rates for different vehicle classes. The temporal resolution depends on the length of the driving patterns on which the model is based.

VERSIT+ ([Smit et al., 2007](#)) is a representative model within this class. It computes emission factors using multivariate regression functions based on a large number of vehicles in different driving cycles. Each driving cycle used is characterised by a large number of descriptive parameters (e.g. speed, acceleration and deceleration) and their derivatives (e.g. mean and maximum speed, acceleration and deceleration). The model incorporates a statistical optimisation software to predict for each pollutant and vehicle category the average emission values over the various driving cycles resulting in the determination of the descriptive variables which best predict the emissions. The main limitation for the user is the need of a detailed driving cycle which can be obtained only by microscale traffic simulation models.

2.1.3.6 Modal models

Modal modelling is designed to relate the modes of vehicle operation on a given trip (in terms of phases of steady speed, acceleration, deceleration and idling) to the emissions produced during these modes. A complex extension are the instantaneous emission models which aim to provide a more precise description of vehicle's operation. In this model types, emission rates are defined as a function of specific engine or vehicle operating modes at the highest resolution. Instantaneous emissions are modelled as a function of the engine power needed to propel a vehicle so that it is possible to calculate continuous emissions and fuel consumption for a particular vehicle type from a given driving cycle. Model variables include instantaneous speed and acceleration and vehicle variables such as engine capacity, vehicle mass, road gradient, aerodynamic drag coefficient and frontal area. More advanced instantaneous models take also into account transient driving cycle where engine load varies every second ([Barlow et al., 2007a, 2007b](#)). The fundamental limitation is that this kind of models require a substantial amount of input data (vehicle specific parameters) which is very expensive to collect and also very detailed information on the operational profiles of vehicles (instantaneous second-by-second speed-time).

PΔP ([Smit, 2013](#)) is an Australian modal emission model that uses the engine power and the change in engine power as main variables to simulate vehicle fuel consumption and CO₂ and NO_x

emissions. The model requires at least information of speed-time data (1 Hz) and also road gradient, vehicle loading and use of air conditioning in the vehicle. The model is based on a mathematical relationship between emission measurements during tests and the engine power of the vehicle. This model uses a vehicle classification scheme based on the main vehicle types considered by COPERT-Australia (Smit & Ntziachristos, 2013), that takes into account fuel type (petrol and diesel) and Australian Design Rule - ADR - category (emission standard) considering a total of 73 vehicle classes.

PHEM-light (Hausberger & Krajzewicz, 2014), is a simplification of the European modal emission model PHEM (Hausberger et al., 2009) that is based in the European fleet for the vehicle classification. PHEM-light retain relevant information of vehicle parameters and emission behaviour in Characteristic Emission curves over Power (CEP). These CEP curves define the emission amount (g/h) as function of the actual engine power. As a result, PHEM-light compute instantaneous fuel consumption and CO₂, NO_x, CO, HC and PM emission quantities for given speed and acceleration demands.

A summary of the most commonly adopted approaches are described in Table 2.3 (McCrae et al., 2006).

Table 2.3. Models for estimating emissions from road vehicles.

Generic type	Scale of application	Example	Type of EF	Level of input data	Type of input data	Typical application
Aggregated EFs	Macro	NAEI	Discrete	Trip-based	Road type	Emission inventories, EIA, SEA
Average speed	Macro - Meso	COPERT	Continuous	Trip- or link- based	Average trip speed	Emission inventories, dispersion modelling
Traffic situation	Macro - Meso	HBEFA	Discrete	Discrete	Road type, speed limit, level of congestion	Emission inventories, EIA, SEA, area-wide assessment of urban traffic management schemes, dispersion modelling
Adjusted average speed / Traffic variable	Meso	TEE	Continuous	Link-based	Average speed, level of congestion	Emission inventories, dispersion modelling
Multiple linear regression	Meso - Micro	VERSIT+	Discrete	Link-based	Driving cycle	Emission inventories, dispersion modelling
Modal Accel/ decel/ cruise/ idle	Micro	UROPOL	Discrete	Link-based	Distribution of driving modes	Detailed temporal and spatial analysis of emissions, dispersion modelling
Modal Instantaneous – “simple”	Micro	MODEM	Discrete	Continuous	Driving cycle	Detailed temporal and spatial analysis of emissions, dispersion modelling
Modal Instantaneous – “advanced”	Micro	PHEM	Discrete	Continuous	Driving cycle, gradient, vehicle data	Detailed temporal and spatial analysis of emissions, dispersion modelling

2.2 Model selection

The linkage between traffic and emissions models has been previously used in several cities to define emission sources. In the case of Madrid, as mentioned before, COPERT and HBEFA has been applied using traffic data from a mesoscale traffic model (TRANSCAT) concluding that these modelling approaches present the main differences between them on stop & go traffic situations, most common in city centres but there are the most detailed data now available for Madrid (Borge et al., 2012). For traffic situations with different dynamics but similar average speeds composite emission factors predicted by average speed models (such as COPERT) are always the same for all the situations whereas a cycle variable model (e.g. VERSIT+) predicts different emission factors. So that for particular average speed situation the first type of model would always predict the same emission factor in contrast to the cycle-variable model whose prediction would depend on the input driving pattern data (Figure 2.6). For these reasons the choice for a specific model clearly affects prediction accuracy.

Figure 2.6. NO_x emission factors for an average Euro 3 petrol car as predicted by COPERT 4 and VERSIT+ (Smit et al., 2009).

Macroscopic approaches work well for city-scale analysis (Borge et al., 2014). But a higher detail is needed for hot-spot investigation since the average speed or traffic conditions do not provide the necessary information to calculate emissions with the necessary spatial and temporal resolution to understand the processes that occur at the microscale level. For these cases microscale models are needed such cycle-variable or more complex modal models.

Microscale traffic models have been coupled to instantaneous emission models to estimate emissions for a highway (Abou-Senna et al., 2013) concluding that better emission estimates are possible with high detailed traffic data. Also and despite their complexity, there have been some relevant efforts to apply modal models to real traffic situations. For instance, the instantaneous

emission model PHEM was coupled to the traffic simulation model SUMO ([Hausberger & Krajewicz, 2014](#)) in the COLOMBO project ([Krajewicz et al., 2013](#)) and the impact of urban driving behaviour on fuel consumption was analysed in an Australian context with PΔP emission model coupled to AIMSUN traffic model ([Smit et al., 2013](#)).

Since emission reduction strategies imply several associated costs, these kind of decisions should be based on low uncertainty methods. So that for policy makers and transport planners, the correct effect on emissions is vital information for imposing the right measures in order to improve local air quality. Microscale traffic models linked to detailed emission models are useful in order to quantify the emissions from individual vehicles and the impact of traffic fluxes on air quality. In this sense, most detailed and complex emission models would lead to more detailed emission predictions but the sensitivity towards many factors would also create uncertainty due to the detailed input data required.

So that, the selected method must be able to estimate and quantify individual vehicle emissions at street level in different typologies of complex urban hot-spots and the impact of varying traffic fluxes on air quality but with limited data availability.

For these reasons in this thesis a microscale traffic emission model is used. This model is adequate to be applied to different types of complex urban configurations and changing traffic conditions and it also takes into account realistic interactions between traffic and pedestrians. The traffic model feeds a high resolution cycle-variable emission model with data of the individual vehicles in the network. These models have been found useful to provide very fine spatial and temporal resolution, suitable for microscale studies in local hot-spots ([Bigazzi et al., 2010](#); [Csikós & Varga, 2012](#)) including pedestrian analysis. These results can be used in a chemical transport model to obtain air quality for the studied area. These estimations can also be used to calculate pollutant concentrations to which pedestrians from a specific area are exposed. These exposition can vary in a range of meters in areas that requires very local control measures.

CHAPTER 3

**METHODOLOGY FOR URBAN HOT-SPOT
EMISSION CALCULATION**

In this chapter the methodology developed to model microscale emission from road traffic is presented. Firstly the overall flowchart of the proposed modelling system is shown. After that, the capabilities and operation principles of the selected models are explained along with the main inputs and outputs of the model suite.

3.1 Urban hot-spot types

Following the Highway functional classification from the U.S. Department of Transportation (USDOT, 2013) there are three types of roads (Arterial, collector and local) classified by the length of the route, number of access points, speed limit or number of travel lines, among others. These are broadened in the ARTEMIS classification for road networks (Boulter & McCrae, 2007) which includes 7 road types depending on their main function and speed limit (Table 3.1).

Table 3.1. ARTEMIS classification for urban roads.

Main function	Comments	Code	Speed limit (km/h)
National and regional network	High-speed or major roads carrying regional or national traffic through urban areas	5a: Motorway 5b: Non-motorway	80 – 130 70 – 100
Agglomeration, primary network	High-speed or major roads in urban areas, with rapid exchanges at city level	4a: Motorway 4b: Non-motorway	60 – 110 50 – 90
District distributor roads	Connections between districts and access to and from primary distributors	3: Road	50 – 80
Local distributor roads	Connections between communities and within districts. Access to and from district distributors, inner exchange roads and local roads	2: Road	50 – 60
Access roads	Local roads which provide access to residential and commercial areas	1: Road, side road	30 – 50

In this work combinations of these road types are analysed at microscale in complex urban configurations with high traffic volumes and high pollution concentrations.

3.2 Modelling system

As, discussed in Chapter 2, the selected modelling system for this work consists of two components: i) PTV VISSIM v. 6.22, that is one of the most used traffic microsimulation models for research purposes (Fontes et al., 2015) and ii) TNO ENVIVER Enterprise interface, a high-resolution post-processor that includes the microscale emissions model VERSIT+_{micro} (based on VERSIT+ models for emission calculations of simulated traffic streams). Figure 3.1 presents the general flowchart of the proposed methodology and in Annex 1 a summary of the software used in this Thesis is summarized.

Figure 3.1. General flowchart of the modelling system including inputs, outputs and model interconnection parameters.

3.2.1 Microscale traffic simulation model VISSIM

The traffic microsimulation model PTV VISSIM v6.22. estimates vehicles transit under the effects of traffic restrictions like traffic lights, traffic composition and public transport stops taking into account the interaction between private traffic and public transport. Moreover, it does not follow the traditional link-node system but it uses link-connector system facilitating the creation of complex geometries (Fellendorf & Vortisch, 2010). Two different programs are used in VISSIM to generate the simulations, one for the traffic flow and another for the state of the traffic lights. The first contains functions of movement patterns, traffic and transport management and considers the driver-vehicle units as unitary entities that take into account the car-following logic (Wiedemann & Reiter, 1992), the driver behaviour and an algorithm for lateral movements. This component has been recently optimized for emission estimation (Song et al., 2015). The second component, the signal control, described in Fellendorf (1994), was used to control the traffic lights. The signal control determine the signalling status of all signals for the next time increment and deliver it back to the traffic flow simulation.

3.2.1.1 Operating principles of car-following model

VISSIM uses the psycho-physical perception model developed by [Wiedemann \(1974\)](#). This model is based on the assumption that there are basically four different driving states:

- **Free-flow driving:** no influence of preceding vehicles exists so that the driver seeks to reach and maintain his desired speed (speed reached without impediments to the flow).
- **Approaching:** where the driver is adapting his speed to the lower speed of a preceding vehicle decelerating until the desired safety distance is reached.
- **Following:** when the driver follows the preceding vehicle without consciously decelerating or accelerating in order to keep a constant safety distance.
- **Braking:** when the driver applies high deceleration rates because the distance to the preceding vehicle falls below the desired safety distance.

The basic concept of the car-following model is that the driver of a faster moving vehicle starts to decelerate as he reaches a slower moving vehicle. Since he cannot exactly determine the speed of that vehicle, his speed will fall below that vehicle's speed until he starts to slightly accelerate again after reaching another perception threshold. Figure 3.2 shows a faster vehicle approaching a slower leading vehicle.

The gap distance between both vehicles (DX) decreases due to the higher vehicle's speed shown by a positive speed difference (DV). So that the vehicle enters a perception threshold (SDV) where the driver consciously observes that he approaches a slower leading car. This is the point when the driver will begin to adjust to the leading vehicle. Then, the vehicle reaches another threshold that implies the effect of braking ($CLDV$) where the speed reduction is even further. This reaction remains until the driver reaches a threshold ($OPDV$) where he noticed that he is slower than the preceding vehicle and starts to accelerate again. So that the different behaviour options from a driver are taken into consideration with distribution functions of the speed and distance ([Fellendorf, 1994](#)).

Figure 3.2. Car-following model by Wiedemann 1974 adapted from VISSIM 6 manual (PTV Group, 2013).

The main variables involved in car-following shown in Figure 3.2 are:

- DV: difference of velocity (m/s).
- DX: gap distance (m).
- BX: Desired minimum following distance.
- AX: Standstill distance between two vehicles in a queue.
- SDX: Car-following drift-off upper limit.
- OPDV: Perception threshold for low-speed differences with decreasing gap distances.
- SDV: Perception threshold for speed differences with high gap distance.
- CLDV: Perception threshold for low-speed differences with increasing gap distances.

3.2.1.2 Driving behaviour

The driving behaviour in VISSIM is defined by two different approaches proposed by Wiedemann, one to model urban traffic (Wiedemann 74) and the other one for freeway traffic (Wiedemann 99). Also, a no interaction approach is included in the case that vehicle's do not distinguish other vehicles in the simulation.

The Wiedemann 74 approach takes into consideration four main parameters in order to model driving behaviour for urban traffic characteristics:

- Following parameter include quantitative variables that takes into account minimum and maximum distance (in meters) that a driver in a vehicle see forward (look ahead distance) and backwards (look back distance) to react to other vehicles. Also, a variable defines the minimum standstill distance together with the safety distance (both in meters).
- Lane change is a fundamental parameter for vehicles in order to reach the next connector to finish properly the defined routes or to reach lanes with more space and higher speeds. For that, a general behaviour is selected between a free lane selection logic where vehicles overtake on each lane or a right side rule where vehicles overtake only on the left side. Nevertheless, fine-tuning variables for necessary lane changes and cooperative lane change (lateral movements inside the same road) for successful route accomplishment are included.
- Lateral parameter includes variables for the consideration of adjacent vehicles to perform lateral movements for a lively lateral behaviour or the minimum distance between overtaking vehicles.
- Signal control parameter main functionality is to define the reaction of vehicles to an amber signal by considering to stop or to go ahead by this light.

In this driving behaviour theory congestion is defined through the saturation flow rate by the calculation of the desired safety distance (in the following parameters) that is defined by the variables presented in Eq. 1.

$$d = ax + (bx_add + bx_mult \cdot z) \cdot \sqrt{v} \quad (\text{Eq. 1})$$

Where:

ax	average standstill distance between two cars (m)
bx_add	additive part of safety distance
bx_mult	multiplicative part of safety distance
z	value of range [0.1] which is normally around 0.5 with standard deviation of 0.15
v	vehicle speed (m/s)

These parameters can be modified inside the driving behaviour data (Table 3.2) to adjust it to local driving conditions.

Table 3.2. Default driving behaviour parameters for urban traffic conditions (Wiedemann 74).

Model parameters	Main variable	Specific variable	Value	Unit
Following	Look ahead	Min	0	m
		Max	250	m
		Observed vehicles	4	vehicles
	Look back	Min	0	m
		Max	150	m
		Average standstill distance	2	m
	Car following model Wiedemann 74 parameters	Additive part of safety distance	2	-
Multiplic. part of safety distance		3	-	
Lane change		General behaviour		Free lane selection
	Max. deceleration Own		-4	m/s ²
	Max. deceleration Trailing vehicle		-3	m/s ²
	Necessary lane change (route)	-1 m/s ² per distance Own	100	m
		-1 m/s ² per distance Trailing vehicle	100	m
		Accepted deceleration Own	-1	m/s ²
		Accepted deceleration Trailing vehicle	-1	m/s ²
		Waiting time before diffusion	60	s
		Min. headway (front/rear)	0.5	m
	Safety distance reduction factor		0.6	-
		Maximum deceleration for cooperative braking	-3	m/s ²
		Overtake reduced speed areas	no	
	Advance merging		yes	
		Consider subsequent static routing decisions	no	
		Cooperative lane change	Max. speed difference	-
	Max. collision time		-	s
	Max. speed		-	km/h
	Lateral correction of rear end position	From (after lane change start)	-	s
To (after lane change start)		-	s	
Lateral		Desired position at free-flow		Middle lane
	Collision time gain		2	s
	Consider next turning decision	Min. longitudinal speed	3.6	km/h
		Time between direction changes	0	s
	Default behaviour when overtaking vehicles on the same lane	Min. lateral distance standing (at 0 km/h)	1	m
		Min. lateral distance driving (at 50 km/h)	1	m
		Signal control	Reaction to amber signal	Decision model
Behaviour at amber signal	Go (same as green)			-
Reduction factor	0.6			-
Reduced safety distance close to a stop line	Start upstream of stop line		100	m
	End downstream of stop line		100	m

The Wiedemann 99 approach used to simulate freeway traffic takes into consideration ten main parameters. These are as follows:

- Standstill distance (CC0) that defines the distance between two vehicles.
- Following distance (CC1) that is the distance in seconds a driver wants to maintain at a certain speed. This variable has an important effect on road capacity.
- Following variation (CC2) restricts longitudinal oscillation and defines how much distance (from the desired safety distance) a driver allows before intentionally moving closer to the car in-front.
- Threshold for entering following (CC3) controls the start of the deceleration process when the driver recognises a slower preceding vehicle.
- Negative following threshold (CC4) defines the negative speed differences during the following process.
- Positive following threshold (CC5) defines the positive speed differences during the following process.
- Speed dependency of oscillation (CC6) is the influence of distance on the speed oscillation while in the following process.
- Oscillation acceleration (CC7) is the oscillation during the acceleration.
- Standstill acceleration (CC8) is the desired acceleration when starting from standstill and is limited by the acceleration curves.
- Acceleration with 80 km/h (CC9) is the desired acceleration at 80 km/h and is limited by the acceleration curves.

These parameters can be modified inside the driving behaviour data (Table 3.3).

Table 3.3. Default driving behaviour parameters for freeway traffic conditions.

Model parameters	Main variable	Specific variable	Value	Unit
Following	Look ahead	Min	0	m
		Max	250	m
	Look back	Observed vehicles	2	vehicles
		Min	0	m
	Car following model Wiedemann 99 parameters	Max	150	m
		CC0 (Standstill Distance)	1.5	m
		CC1 (Headway time)	0.9	-
		CC2 (Following variation)	4	m
		CC3 (Threshold for entering following)	-8	-
		CC4 (Negative following distance)	-0.35	-
		CC5 (Positive following threshold)	0.35	-
		CC6 (Speed dependency of oscillation)	11.44	-
		CC7 (Oscillation acceleration)	0.25	m/s ²
		CC8 (Standstill acceleration)	3.5	m/s ²
		CC9 (Acceleration with 80 km/h)	1.5	m/s ²
Lane change	General behaviour		Free lane selection	-
		Max. deceleration Own	-4	m/s ²
	Necessary lane change (route)	Max. deceleration Trailing vehicle	-3	m/s ²
		-1 m/s ² per distance Own	200	m
		-1 m/s ² per distance Trailing vehicle	200	m
		Accepted decelerat. Own	-1	m/s ²
		Accepted deceleration Trailing vehicle	-0.5	m/s ²
		Waiting time before diffusion	60	s
	Waiting time before diffusion	Min. headway (front/rear)	0.5	m
		Safety distance reduction factor	0.6	-
		Maximum deceleration for cooperative braking	-3	m/s ²
		Overtake reduced speed areas	no	
		Advance merging	yes	
		Consider subsequent static routing decisions	no	
	Cooperative lane change	Max. speed difference	-	km/h
		Max. collision time	-	s
Lateral correction of rear end position	Max. speed	-	km/h	
	From (after lane chg. start)	-	s	
	To (after lane change start)	-	s	
Lateral	Desired position at free-flow		Middle lane	-
		Collision time gain	2	s
	Consider next turning decision	Min. longitudinal speed	3.6	km/h
		Time between direction changes	0	s
	Default behaviour when overtaking vehicles on the same lane	Min. lateral distance standing (at 0 km/h)	1	m
		Min. lateral distance driving (at 50 km/h)	1	m
		Signal control	Reaction to amber signal	Decision model
Behaviour at amber signal	Go (same as green)			-
Reduced safety distance close to a stop line	Reduction factor		0.6	-
	Start upstream of stop line		100	m
	End downstream of stop line		100	m

3.2.1.3 Vehicle classification

In VISSIM a hierarchical classification that include three distinctions are made to classify vehicles:

- **Vehicle categories** incorporate vehicles with similar traffic interaction (driving behaviour and technical characteristics). Six fixed vehicle categories are predefined in VISSIM (Car, HGV, Bus, Tram, Pedestrian and Bike).
- **Vehicle class** allows to form groups of vehicle types for different analysis purposes. Usually to group vehicles with similar driving behaviour but different vehicle properties.
- Each **vehicle type** must be assigned to a category and is formed by a group of vehicles with the same technical driving characteristics. New vehicle types can be created (trailer truck, articulated truck, articulated bus, etc.) and also the given characteristics can be modified.

Their characteristics and default values included in VISSIM are shown in Figure 3.3.

CATEGORY		Car	HGV	Bus	Tram	Pedestrian		Bike
\$VEHICLECLASS:NO		10	20	30	40	50		60
\$VEHICLECLASS:NAME		Car	HGV	Bus	Tram	Pedestrian		Bike
\$VEHICLETYPE:NO		100	200	300	400	510	520	600
\$VEHICLETYPE:NAME		Car	HGV	Bus	Tram	Man	Woman	Bike
Vehicle characteristics	DESACCELFUNC\NAME	Car	HGV	Bus	Tram	Pedestrian	Pedestrian	Bike
	DESACCELFUNC\XMAX	250	250	250	250	250	250	250
	DESACCELFUNC\XMIN	0	0	0	0	0	0	0
	DESACCELFUNC\YMAX	3.5	2.5	1.49	1	3	3	3.5
	DESACCELFUNC\YMIN	0	0	0	0	0	0	0
	DESDECELFUNC\NAME	Car	HGV	Bus	Tram	Pedestrian	Pedestrian	Bike
	DESDECELFUNC\XMAX	240	240	240	240	240	240	240
	DESDECELFUNC\XMIN	0	0	0	0	0	0	0
	DESDECELFUNC\YMAX	-2.55	-1.05	-0.73	-0.73	-8.6	-8.6	-2.55
	DESDECELFUNC\YMIN	-3	-1.5	-1	-1	-9.5	-9.5	-3
	MAXACCELFUNC\NAME	Car	HGV	Bus	Tram	Pedestrian	Pedestrian	Bike
	MAXACCELFUNC\XMAX	250	250	250	250	250	250	250
	MAXACCELFUNC\XMIN	0	0	0	0	0	0	0
	MAXACCELFUNC\YMAX	3.5	9.3	1.49	1	3	3	3.5
	MAXACCELFUNC\YMIN	0	0	0	0	0	0	0
	MAXDECELFUNC\NAME	Car	HGV	Bus	Tram	Pedestrian	Pedestrian	Bike
	MAXDECELFUNC\XMAX	240	240	240	240	240	240	240
	MAXDECELFUNC\XMIN	0	0	0	0	0	0	0
	MAXDECELFUNC\YMAX	-4.1	-5	-4.1	-1.6	-8.5	-8.5	-4.1
	MAXDECELFUNC\YMIN	-8.5	-6	-8.5	-6	-9.5	-9.5	-8.5
Weight [kg]	WEIGHTDISTR	2						
	WEIGHTDISTR\NAME	HGV						
	WEIGHTDISTR\LOWERBOUND	2800						
	WEIGHTDISTR\UPPERBOUND	40000						
Power [kW]	POWERDISTR	2						
	POWERDISTR\NAME							
	POWERDISTR\LOWERBOUND	150						
	POWERDISTR\UPPERBOUND	400						

Figure 3.3. Default vehicle categories and characteristics (acceleration, weight and power) included in VISSIM.

Each vehicle type include default vehicle characteristics (representative for west European countries) regarding acceleration, weight and power distributions (Figure 3.3). These functions are defined by, at least, two values that are the minimum and maximum values for that distribution (lower and upper bound respectively). These values can be changed and the distributions can be adjusted accordingly if more precise data are available for a specific study.

3.2.1.4 Acceleration distribution

The acceleration distributions are divided into four main functions each one with individual functions assigned at vehicle category level. These functions are:

Desired acceleration functions: used in all situations in which maximum acceleration is not required. Default values included in VISSIM for vehicle categories car, heavy-duty vehicle (HGV), bus and bike are shown in Figure 3.4.

Figure 3.4. Default desired acceleration functions included in VISSIM for (a) Car, (b) HGV, (c) Bus and (d) Bike. X axis for speed (km/h), Y axis for acceleration (m/s^2).

Desired deceleration functions: is used as the upper bound of deceleration based on a desired speed decision, when approaching a red light, when closing up to a preceding vehicle (e.g. during stop & go traffic), when approaching an emergency stop on connectors of routes, for co-operative braking or in case of insufficient side clearance when overtaking on the same lane. Thereby maximum deceleration is not exceeded. Default values included in VISSIM for vehicle categories car, HGV, bus and bike are shown in Figure 3.5.

Figure 3.5. Default desired deceleration functions included in VISSIM for (a) Car, (b) HGV, (c) Bus and (d) Bike. X axis for speed (km/h), Y axis for acceleration (m/s^2).

Maximum acceleration functions: is the maximum acceleration technically possible. It is used to keep a certain speed on slopes (i.e. when stronger acceleration is required). The maximum acceleration is automatically adjusted for up and down gradients of links by $-0.1 m/s^2$ per gradient percent incline and by $0.1 m/s^2$ per gradient percent downgrade. Default values included in VISSIM for vehicle categories car, HGV, bus and bike are shown in Figure 3.6.

Figure 3.6. Default maximum acceleration functions included in VISSIM for (a) Car, (b) HGV, (c) Bus and (d) Bike. X axis for speed (km/h), Y axis for acceleration (m/s^2).

Maximum deceleration functions: is the maximum deceleration technically possible. As deceleration values have a negative algebraic sign, the maximum deceleration is the smallest acceleration value. Not even the desired deceleration can fall below it. The maximum deceleration is automatically adjusted for up and down gradients of links and connectors by $0.1 m/s^2$ per gradient percent incline and by $-0.1 m/s^2$ per gradient percent downgrade. Default values included in VISSIM for vehicle categories car, HGV, bus and bike are shown in Figure 3.7.

Figure 3.7. Default maximum deceleration functions included in VISSIM for (a) Car, (b) HGV, (c) Bus and (d) Bike. X axis for speed (km/h), Y axis for acceleration (m/s^2).

3.2.1.5 Weight and power distributions

Weight and power function distribution present a lineal distribution from the lower to the upper bound. These bounds are defined as the maximum and minimum weight and power that vehicles under this category can reach. From these distribution data, VISSIM randomly selects a value for each vehicle with a vehicle type under vehicle category HGV. The weight and power distribution values are independent from each other (could be assigned high power to low-weight vehicle). Using the weight and power data, the specific power is calculated in kW/t. The specific power is limited to a range between 7 and 30 kW/t. This has a direct effect on the speed-time profile of the vehicle of vehicles under HGV category.

3.2.1.6 Desired speed distribution

As for weight and power function distribution, desired speed present a lineal distribution from the lower to the upper bound. From these distribution data, VISSIM randomly selects a value for each vehicle within a vehicle type under any vehicle category. The desired speed distribution values are defined independently from each other and defines the speed that a vehicle reach at free-flow conditions. It is applied to all vehicle categories and it is reflected on the speed-time profile of the vehicle.

3.2.1.7 Add-on module for pedestrian simulation VISWALK

The PTV VISSIM 6.00-22 microscale traffic flow model includes an add-on module VISWALK for pedestrian simulation in order to generate realistic interactions between traffic and pedestrian flows. VISWALK module is able to simulate up to 2000 pedestrians simultaneously, provide user-defined priority rules for conflict areas and include the Social Force Model (Helbing & Molnár, 1995) that takes into account the shortest path to connect the beginning and the destination of each pedestrian.

3.2.2 Emission model VERSIT+_{micro}

VERSIT+_{micro} is an aggregated version developed on the basis of the VERSIT+ emission model to calculate the emissions for traffic streams simulated with a traffic microsimulation software.

3.2.2.1 VERSIT+

VERSIT+ is a multivariate regression cycle- and vehicle-variable model (emission model type A), which requires speed-time profiles to obtain various traffic flow variables that are used to predict representative emission factors (g/km) for different vehicle classes (Smit & Mcbroom, 2009). VERSIT+ consists on a set of 246 emission model classes (specific emission algorithms for each combination of vehicle category and air pollutant) (Smit et al., 2007) and provides representative emission factors based on speed-time profiles. Emission factors ($E_{j,k,l}$) are derived from a multiple linear regression analyses to find empirical relationships between emission rates, speed-time profiles and dynamic variables (Smit et al., 2007). References about model validation (Trachet et al., 2010; Smit et al., 2006 and references within), reported satisfactory correlation coefficients between measured and predicted emission factors (e.g. 0.91-0.97 for NO_x emission factors from diesel passenger cars), as well as reasonable biases (around $\pm 15\%$). Correlations for PM₁₀ emission factors were slightly poorer, with maximum values up to 0.93. Nevertheless, it should be noted that currently VERSIT+ exclusively considers exhaust emissions which can lead to important limitations in the computation of PM emissions. Nevertheless, the speed-time profile, is not the only factor determining the emission. Whether an engine of a vehicle is cold or the vehicle has been idling for a longer time may affect the emission significantly.

3.2.2.1.1 Emission computation

In VERSIT+ total traffic exhaust emissions (g/h) for a specific pollutant j (TE_j), are computed from the aggregation of individual emissions of vehicle class k , speed-time profile l , for a number of sections of road m as shown in Eq. 2. (Smit et al., 2006).

$$TE_j = \sum_{k,m} (E_{j,k,l}^F \cdot TV_{k,m} \cdot L_m) \quad (\text{Eq. 2})$$

Where:

$E_{j,k,l}^F$ mean emission factor for pollutant j , vehicle class k and speed-time profile l
 $TV_{k,m}$ traffic volume (vehicles/h) for a section of road m
 L_m length of the section (km).

The mean emission factor (g/km) is defined by Eq. 3.

$$E_{j,k,l}^F = \left(E_{j,k,l} + E_{j,k,l} (CF_{airco} - 1) P_{airco} + E_{j,k,l} (CF_{age,h} - 1) \right) + \frac{C_{j,k} \cdot n_{cold} \cdot CF_{age,cs}}{d} \quad (\text{Eq. 3})$$

Where:

$E_{j,k,l}$ predicted hot running emission factor
 CF_{airco} correction factor for the use of air conditioning
 P_{airco} proportion of vehicle-kilometre travelled (VKT) with air conditioning operating
 $CF_{age,h}$ correction factor for aging (hot running)
 $C_{j,k}$ cold start emission factor (g/start)
 n_{cold} number of cold starts
 $CF_{age,cs}$ cold start correction factor for in-use deterioration
 d average trip distance

3.2.2.1.2 Development of the Hot Running Emission Factors

VERSIT+ consists of a set of statistical models constructed using multiple linear regression models (MLR) analysis. The aim of the statistical approach is to find for each vehicle class and pollutant an empirical relationship between emission rates (g/km) and a limited number of speed-time profiles defined by vehicle related variables that capture the main features of these traffic situation. These model parameters include aspects such as number of stops, driving mode proportion, speed, acceleration, power demand, impulse variables and their derivatives and deviations that are used in a regression model to obtain the best match to the driving-cycle and so obtain the emission results. Detailed information about the 50 model parameters used for the development of VERSIT+ can be found in [Smit et al. \(2006\)](#).

Correction factors for hot running emissions are directly applied to the predicted hot running emission factor by multiplication (Eq. 3). The correction factors include the use of air conditioning and in-use deterioration. Air-conditioning use has a significant effect on the fuel consumption and emission estimation. The magnitude of the effect depends of the additional power demand required. Also, vehicle emissions increase with mileage and age due to deterioration of engine and emission control components.

3.2.2.1.3 Development of the Cold Start Emission Factors

Cold start emissions are influenced by several factors being the most important ones vehicle class (including type of fuel, engine type and emission standard), driving cycle or traffic situation and ambient temperature. The emission factors are based on measurements over the urban part of the CADC cycle subtracting the total hot running emissions for each vehicle class. Nevertheless correction factors for aging have been introduced. All these parameters are directly applied in the calculation of the hot running emission factor (Eq. 3). In VERSIT+ a cold start component for the calculation of the emission factors are included for vehicles under urban road type conditions. This is the case of urban hot-spots with more cold starts per travelled distance.

3.2.2.2 VERSIT+_{micro}

The main emission can be predicted on the basis of the speed-time profile. This is done in an aggregated version of the VERSIT+ model called VERSIT+_{micro}, which includes average vehicle types in the main categories and predict the emissions on basis of the speed profile. VERSIT+_{micro} predicts traffic emissions using VERSIT+ models. It is a statistical emission model able to calculate real-world CO₂, NO_x and PM₁₀ emissions based on the speed-time profiles of the individual vehicles for several categories. This aggregated version uses average vehicle types in the main categories and these are:

- Light-duty vehicles with vehicle mass up to 3500 kg. It includes passenger cars (M1) and commercial vehicles (N1 class 1 to 3).
- Buses such as public transport or coaches.
- Heavy-duty medium with 2 axes and more than 3500 kg. These are small trucks which behave dynamically.
- Heavy-duty vehicles with 3 axes and more than 20000 kg. These are trucks whose acceleration and speed are lower.

The combination of these 4 categories with different models for urban, rural and highway conditions provides a total of 21 models to estimate emissions. The models are updated once a year. Nevertheless, previous models remain available for comparison studies. These models use two parameters to compute the emissions: average speed from the speed profile and a measure for the acceleration with the dimensionless ln(TAD) parameter, which represents the dynamic driving behaviour of the drive cycle (Eq. 4):

$$\ln(TAD) = \ln\left(\frac{1}{x} \cdot \frac{\sum |v_{t+1} - v_t|}{f}\right) \quad (\text{Eq. 4})$$

Where:

- x covered distance (km) > 100 m
 v speed (m/s)
 f sample frequency (Hz) = 1

VERSIT+ data for different speed patterns have been used to fit VERSIT+_{micro} model as shown in Figure 3.8. In the left part of this figure points represent emissions from a driving cycle calculated with VERSIT+ plotted against the average speed and the $\ln(\text{TAD})$ of the cycle. The grey surface represents the fitted model included in VERSIT+_{micro}. On the right the trends of the emission factors computed by VERSIT+_{micro} are validated against the original ones of VERSIT+ to guarantee consistency.

Figure 3.8. Original emission factors from VERSIT+ plotted together to the adjusted model used in VERSIT+_{micro} (left) and emission factors validation between models for different driving situations (urban, rural and highway), pollutants (CO_2 , NO_x and PM) and vehicle class (Light Duty, Heavy-duty medium, Heavy-duty heavy and Bus) (right) (Ligterink et al., 2008).

3.2.3 High resolution post-processor interface ENVIVER

TNO ENVIVER v4.5.4.0 is a high resolution post-processor that combines the traffic model speed-time profiles with the VERSIT+_{micro} emission models to obtain high-resolution emissions. In this application, gridded NO_x and PM_{10} emissions were calculated using ENVIVER (Eijk et al., 2014), which provided emissions with up to 5 m x 5 m spatial resolution and aggregated to 1-hour. Nevertheless, one of the main limitations of the model are related to the computation of PM emissions for air quality assessment, since non-exhaust emissions are not included in the calculation and these can influence urban PM concentration level to a large extent (Abu-Allaban et al., 2003; Amato et al., 2009). Particularly, resuspension has been found a very relevant source of PM_{10} in Madrid, contributing to up to $9 \mu\text{g}/\text{m}^3$ to the mean annual concentration (de la Paz et al., 2015). However, this contribution focuses on the methodology to estimate exhaust emissions at microscale and the incorporation of non-exhaust PM emissions should be addressed in subsequent development stages.

3.3 System requirements

The necessary input data for the modelling system, including both the traffic and the emission models are synthetized in Table 3.4.

Table 3.4. Input data for VISSIM and VERSIT_{micro} through ENVIVER.

Data		VISSIM (f=1Hz)	ENVIVER (VERSIT _{micro}) (f=10Hz)
Files/Models		VISSIM output file “*.fzp”	x
		TNO emission models online	x
Road network configuration	Static	Network	x
		Lanes	x
		Direction	x
		Width	x
		Road curvature	x
		Direction change	x
		Road gradient	x
		Additional lanes	x
		Traffic withholdings length and duration	x
		Traffic lights	x
		Signals position	x
		Dynamic	Turning points
	Crossings		x
	Route		x
	Departure time		x
	Traffic characteristics		(*) Traffic volume (veh/t)
Travel time			x
Vehicle fleet			x
Vehicle and trip characteristics	Acceleration and deceleration functions	Max. accel. technically possible	x
		Instantaneous acceleration	x
		Max. decel. technically possible	x
		Instantaneous deceleration	x
	Speed distributions	(*) Desired speed	x
	Weight distribution	Heavy-duty vehicles weight	x
		Heavy-duty vehicle length	x
	Power distribution	Heavy-duty vehicles engine power	x
	Temperature distribution	Catalytic converter temperature	x
Vehicle types and categories (similar technical characteristics)	Passenger car, light-duty, heavy-duty, bus, bicycle, pedestrian.	x	x (**)
Public transport		Stops (retentions)	x
		Itinerary	x
		Schedule	x
		Vehicle	x
		Service stops	x

(**) Four vehicle classes:

LD passenger cars up to 3500 kg,
 HD medium from 15kW/ton or higher,
 HD heavy from 15 kW/ton or lower and
 HD bus.

(*) Input data for several functions

3.3.1 Traffic data information

As shown in Figure 3.1 on a first stage, detailed traffic data are compiled to feed the traffic model. These data are commonly subdivided into static and dynamic traffic data:

- **Static traffic data** are constant during the simulation and are related to the infrastructure. These data include detailed definitions of the road network with links (directional roadways), connectors (possible turns between links), public transport stops and lines, position of signal heads and stop lines.
- **Dynamic traffic data** comprise the necessary information to simulate the traffic. These data include vehicle types and composition, vehicle routes and traffic volume. This detailed information is not usually available for a specific urban area and should be gathered through specific field campaigns. In this sense, the collaboration with the Madrid City Council was essential to obtain very detailed and accurate information for the development of this Thesis. The accuracy and reliability of actual traffic records minimizes input data uncertainty and allows a more precise estimation of the intrinsic capabilities of the model.

This information about road network, traffic intensity, vehicle types, vehicle routes, public transport stops, lines and schedules and traffic signal position and phases has been obtained for the city of Madrid from different methods that are summarized in the following sections.

3.3.1.1 Traffic gauging stations

Traffic data counts were compiled from traffic gauging stations of the Madrid City Council. This is a commonly used method to measure traffic volumes for cities and is used by the Madrid City Council to obtain traffic information and calibrate regional demand traffic models. These detection systems are mostly electromagnetic loops that are embedded in the pavement and directly detect the metallic mass of the vehicles that pass over them. This systems are very reliable, although the main limitation is that the data collected are related to single points and they cannot provide information on any variable other than traffic volume and instantaneous speed at a particular road section. Madrid's traffic gauging infrastructure includes 3,613 measurement points. From these, 253 include speed control systems and vehicle characterization (through license plates reading devices and artificial vision systems) and 70 are the specific gauging stations that compile traffic data of the city ([Ayuntamiento de Madrid, 2016](#)).

3.3.1.2 CCTV cameras

Two types of cameras are used to capture traffic information. The first type (Figure 3.9 left) are used for the determination of the traffic intensity and fleet composition by vehicle counting and plate reading (continuous measurements representative of fleet composition on the surface and into the tunnel). Cameras such as the ones shown in Figure 3.9 (right) are used to define vehicle movements (entry and exit points and the trajectory followed between them) along the studied area (intersection, roundabout, etc.) as well as traffic intensities.

Figure 3.9. Traffic cameras for license plate read (left) and movements detection cameras (right).

3.3.1.3 Vehicle fleet composition

For the case of Madrid, this information was obtained from the study of the current vehicle park in Madrid ([Vehicle fleet characterization study, 2014](#)). In this study traffic cameras were distributed along the city and additional manual counts were performed in order to obtain the plate numbers of the vehicles traveling inside the city. This study contains a classification of the vehicles from Madrid in 2013. It includes information about vehicle type, fuel and emission standard that is essential information for the microscale study. Further details on the experimental campaign and data processing can be found in [Borge et al. \(2015\)](#). Traffic in Madrid municipality is dominated by passenger cars, responsible for more than 80 % of total mileage. Nevertheless, considering only vehicles that circulate inside the innermost ring-road (M-30) this percentage is reduced to 72.6 %. Also the mileage share of non-EMT buses, light commercial vehicles and heavy-duty trucks decrease significantly inside M-30 due to the greater number of mopeds, motorcycles, taxis and EMT buses circulating in the city centre (Figure 3.10). Passenger cars are mostly diesel cars, responsible for 68 % of total mileage. Petrol cars represent 31 % of passenger cars mileage and alternative propulsion types (electric, hybrid, CNG and LPG) the remaining 1 %. Nevertheless, this is rapidly changing with time due to the introduction of low-emission vehicles. In 2017 diesel has shrink to 55 % and ECO/CERO share has grown to 1.8 % ([Vehicle fleet characterization study, 2018](#) in preparation).

Figure 3.10. Composition of the standard vehicle at sector level (left) for the municipality and (right) inside M-30.

3.3.1.4 Network geometry

Detailed cartography has been used to obtain very fine resolution description of the road network. This information has been obtained from two sources. The street level cartography has been obtained from the Spanish National Centre for Geographic Information ([Centro Nacional de Información Geográfica, 2018](#)) in shapefile ("*.shp") format with the geographic reference system ETRS89 for Spain. This source provides detailed information about road widths and lengths, pedestrian's crossings and sidewalks, building areas and geometries, public gardens location, etc. From this source also satellite imagery has been obtained. The second source, the Madrid City Council open data portal ([Ayuntamiento de Madrid, 2018a](#)), was used to obtain information about network configuration and location of road infrastructure such as subway stations location, taxi stops, public bicycle parking's, location of the air quality monitoring stations, etc.

3.3.1.5 Traffic lights position and phases

The information required regarding traffic lights is divided in two parts. Firstly, the precise location of all of them is needed. This information is captured from a detailed GIS based map that incorporates the accurate position of each of the traffic lights in an area. Furthermore, the phases of all the traffic lights accounting for the green-yellow-red time of each individual traffic light and their combination to perform the signals interaction for a whole intersection are needed. This information was also provided by the Madrid City Council.

3.3.1.6 Bus line routes and frequencies

Additional information of regular bus line schedules and routes were obtained from the Municipal Transport Company (EMT) ([EMT, 2015](#)). The information includes detailed definite of bus stops and routes for each bus line so that it can be included in the traffic model. Figure 3.11 shows the example of bus line 60 crossing Fernández Ladreda roundabout.

Figure 3.11. Bus line 60, route across Fernández Ladreda square and all bus stops in the area.

Also, information about schedule and frequencies along the week and depending on the hour of the day are provided by the EMT. Running hours and frequencies interval for different days and hours are introduced to accurately represent buses traffic. An example of the information for one diurnal route is shown in Figure 3.12. For simulation purposes the average frequency for each time interval was used.

Horarios y frecuencias del servicio (Excepto puentes y temporadas de Semana Santa y Verano)				
Tipo de día	Horario de salida de cabecera Primer servicio - Último servicio		Frecuencias de paso programadas	
	Plaza Cebada	Orcasitas	Horas	Frecuencias
Lunes a Viernes Laborables	6:10 - 23:30	5:40 - 23:00	De 6 a 7 y 9 a 10 De 7 a 9 De 10 a 21 De 21 a 23	➤ Cada 7-12 min. ➤ Cada 6-9 min. ➤ Cada 8-11 min. ➤ Cada 9-15 min.
Sábados Laborables	6:10 - 23:30	5:40 - 23:00	De 6 a 8 y 22 a 23 De 8 a 10 y 21 a 22 De 10 a 21	➤ Cada 16-24 min. ➤ Cada 15-18 min. ➤ Cada 13-17 min.
Domingos y Festivos	7:30 - 23:30	7:00 - 23:00	De 7 a 9 y 21 a 23 De 9 a 10 y 16 a 21 De 10 a 16	➤ Cada 16-21 min. ➤ Cada 13-19 min. ➤ Cada 12-14 min.

Figure 3.12. Bus line 60 schedule and frequency information provided by EMT Madrid.

3.4 Traffic simulations set-up

As discussed in the previous section, all the static features for the network configuration are introduced in VISSIM traffic model to setup the traffic simulation: traffic lights position and phases, routes and stops for the bus lines, specific road network geometry, streets, number of lanes, direction, width, slope and the existing speeds signs for a specific area or selected emission calculation domain. To appropriately describe emissions under different vehicle flow conditions, the typical weekly and daily pattern in the area of interest is analysed using traffic profiles so that 1-h scenarios can be selected to perform detailed simulations of representative traffic conditions within the daily cycle. A perfectly normal, therefore representative, time period is selected to obtain traffic data where unusual circumstances do not happen (such as

bank holidays, sport or cultural events or heavy rain conditions) because they may alter the typical traffic flow in the area. This is explained in detail for each of the selected locations in Chapter 4.

Traffic volumes and routes are calculated and introduced in the modelling system for each road and scenario individually. This information is derived from the traffic cameras and traffic gauging stations measured data as previously explained. For each input street traffic volume per vehicle class are calculated and for each intersection vehicle routes are resolved by vehicle mass balance to adjust the observed data.

Traffic lights phases are integrated in VISSIM with add-on module for fixed signal control software VISSIG. To operate a traffic lights group with a specific cycle time, firstly the individual signal heads (each traffic light) that are included in the group must be placed on the correct locations and assigned the individual red-green-amber times. Signal heads for the same intersection are controlled only by one signal controller which is defined in a single “*vissig.config*” file. For each intersection in the network an individual signal controller is generated.

Public transport lines are defined in VISSIM manually. To define a bus line, firstly a bus route must be introduced and after that the schedule must be defined. For that the start time of the bus route, frequency or rate must be introduced. Also an average occupancy for the bus line must be specified. In the case of Madrid the average occupancy has been set to 48 passengers per bus which are the last available data from EMT bus occupancy statistics ([Ayuntamiento de Madrid, 2018b](#)).

As for the vehicle type definition in the traffic model, three main categories are generated to match the requirements of the emission model. These categories correspond to passenger cars, bus and heavy-duty trucks and the correspondent percentages of each type are obtained from the vehicle fleet study. Also scenario-specific traffic volumes and routes from camera observations are included in the simulations for each road and vehicle type. Conflict areas are defined as those areas where a link or connector overlap with another one in more than 0.5 m. On these areas vehicles intersect and priorities must be defined so that these conflict areas have been resolved individually for each intersection to adjust local traffic conditions. Modifications on the driving behaviour safety distance parameters (Eq. 1) are adjusted to the local traffic conditions but trying to follow closely those considered by the Wiedemann 74 model.

For performance and calibration purposes, several data collection points are introduced in the road network to get information of simulated traffic volumes for each road. Before calibrating the model is important to reach stable traffic conditions. For that purpose, simulations included

a 15-minute warming up period. Therefore, the first 15 min data are not included in the emission calculations or model evaluation tasks.

An example of the main steps for the set-up of the traffic simulations is shown in Figure 3.13.

Figure 3.13. Traffic modelling process for the static data: (above left) network generation (above right) routes introduction (below right) signal head cycles introduction and (below left) public transport stops and lines introduction.

3.5 Traffic speed-time profiles

For each simulation, second-by-second information of vehicle speed and position for every individual vehicle is generated by VISSIM is stored in a “*.fzp” file which contains the necessary information for the emission computation process. In order to import this file into the ENVIVER post-processor the preferred time resolution is 1 Hz (1 sample per second) and the minimum required fields to run the emission model are the number of the vehicle, number of the vehicle type, name of the vehicle type, simulation time (s) and speed at the end of the simulation step (m/s) for each vehicle in the modelling domain. Also, X and Y world coordinates (m) for each simulation step are highly recommended variables in order to locate emissions in space. Additionally, the road gradient of the specific links, world coordinate Z (m), road segment ID, available power and weight of the vehicle are also recommended. These profiles include information about congestion from the road network through the speed and acceleration profiles.

3.6 Fleet composition customization for emission computation

ENVIVER default values represent a valid fleet model and can therefore act as a starting point for simulations within Europe. Nevertheless these data are based on detailed information of the Dutch vehicle fleet and their exact representativeness for vehicle fleets from other countries cannot be granted.

Therefore, it is important to specify the actual vehicle fleet composition for each specific simulation. This is not only true due to the need to provide accurate outputs but also to understand local measures and policy options. For this reason, in this work, the vehicle fleet was determined according to the results provided by the Vehicle fleet characterisation study carried out by the UPM for the city of Madrid in 2014 ([Vehicle fleet characterization study, 2014](#)).

Other important source of variation for calculating vehicle emissions is the age distribution. ENVIVER includes a three-piece linear model to compute the exact profile distribution by setting three parameters: the percentage of the vehicles younger than 1 year, the average vehicle age and the average scrappage. The age distribution combined with the specified year will result in an Euro-class distribution that ENVIVER calculates.

However, the resulting Euro-class distribution also depends on the starting dates of the varying Euro legislations. In the European Union, the default values (Table 3.5) are valid in all countries and do not need to be changed. Nevertheless, ENVIVER allows the user to change these starting dates to best match the situation that is desired by the user.

Table 3.5. Default Euro Norms introduction years considered in the ENVIVER interface.

Euro Norm	Introduction year
Euro 1	1992
Euro 2	1996
Euro 3	2000
Euro 4	2005
Euro 5	2009
Euro 6	2014

3.7 Emission result description

For this research, traffic model outputs are used as input for a microscale emission simulation model to obtain a detailed estimation of vehicle-specific NO_x and PM_{10} exhaust emissions with 5 m x 5 m spatial resolution aggregated into 1-hour periods. Nevertheless, to obtain this information ENVIVER export the emission results in different files and formats useful for further analysis and diagnosis purposes.

Emission results are stored in a file which contains CO_2 , NO_x and PM_{10} total emissions in grams and in grams per kilometre for the whole data set and for each vehicle class. It also includes the total emissions per each individual trip (g and g/km) with details of the vehicle trip number, VISSIM vehicle type, VERSIT+ vehicle class, total travelled distance (km), trip duration (s).

The “*.ASC” files contains the emissions spatial information. This file includes a heading with the total number of columns, rows, X and Y coordinates and selected cell size (up to 5 m). The data are presented in a matrix where each number represents the value for one individual grid-cell. This kind of file can be generated for CO_2 , NO_x and PM_{10} total emissions, both (g) and (g/km).

CHAPTER 4

**CASE-STUDIES FOR DIFFERENT
TYPOLOGIES OF URBAN HOT-SPOTS**

The modelling system described in Chapter 3 has been applied for different typologies of urban hot-spots to demonstrate the implementation of the methodology proposed and to understand the applicability and extrapolation options of the modelling approach. Despite the simulation of two hot-spots of interests in Madrid (Chapter 5), the system is applied to other two case studies in very different urban environments in Brisbane (Australia) and Seoul (South Korea) for comparison and validation purposes (Chapter 6). These analysis were done in the frame of a research stay and ongoing collaboration studies during the Ph.D. period with the University of Queensland (Australia) and the Kangwon National University (South Korea), respectively.

4.1 Madrid's hot-spots analysis

Two different types of hot-spot areas with complex but different network configuration inside the city of Madrid are selected. The simulations of these hot-spots focused on the computation of NO_x emissions since the main problem in air quality issues in Madrid are related to exceedances of NO₂ Euro standards (Borge et al., 2014). However, PM₁₀ emission computation was also addressed due to their harmful effects to human health (Pietikäinen et al., 2009; Ristovski et al., 2012).

4.1.1 Signalized roundabout

4.1.1.1 *Modelling domain*

Fernández Ladreda (FL) square, where the highest NO₂ concentration values in Madrid are measured, is located in the district of Carabanchel-Usera in the southern part of the city (Figure 4.1). This area is a heavily trafficked roundabout that presents an enormous complexity in terms of interaction of sources and urban geometry with a motorway crossing the square through a tunnel, five additional access roads to the roundabout, high road transport volume, several specific services around (a public transport interchange hub, a petrol station, a park, 5 metro station exits, a taxi stop) and presence of pedestrians, including sensitive population such as schoolchild.

Figure 4.1. Location of Fernández Ladreda square, Madrid (Spain) and selected 300 m x 300 m modelling domain (black rectangle).

4.1.1.2 Data compilation

An experimental campaign was carried out in the study area from 22nd to 26th May 2013 to gather all the inputs required for the simulation. This was a perfectly normal, therefore representative, time period.

Detailed road network configuration is obtained from GIS shapefiles and information about traffic intensity, vehicle types and vehicle routes is collected in situ with 13 cameras installed throughout the roundabout to cover an area of 300 m x 300 m around the square (Figure 4.2).

Figure 4.2. Video cameras deployed in the FL roundabout to characterize traffic fluxes and detailed routes. Black rectangle for the selected 300 m x 300 m domain with black lines for GIS road network detailed information.

Signal head position and phases are obtained from detailed information by the Madrid City Council. A “*.pdf” file with the exact position of each signal head for FL square is provided (Annex 2) together with the corresponding phases (Annex 3) both provided by the Madrid City Council.

Regarding to the public transport lines, bus stops and routes have been obtained from EMT Madrid information (EMT, 2015) showed in Figure 4.3.

Figure 4.3. Public transport lines stops information around FL square from EMT Madrid.

4.1.1.3 Scenario selection

Being one of the main communication points between Madrid and the southern metropolitan area, the square presents large vehicle flows throughout the day. Although a commuting pattern can be observed, with two rush hours, one in the morning from 8:00 to 9:00 h (local time) and another in the evening from 19:00 to 20:00 h, traffic in FL differs the traditional two-humped urban commute pattern (Hallenbeck et al., 1997) since a third relative maximum can be observed (around 13:00 to 14:00 h) during working days.

To appropriately describe emissions under different vehicle flow conditions, the typical weekly and daily patterns in the area were analysed using the traffic profiles (Figure 4.4) generated from the continuous traffic intensity measured by cameras 1 (surface traffic) and 2 (tunnel traffic) (Figure 4.2). Twelve representative scenarios (1 h-length) were defined (Table 4.1 and black dots in Figure 4.4) to perform detailed simulations using observed data from the field campaign.

Figure 4.4. FL surface (a) and tunnel (b) daily traffic profiles for representative week days and selected traffic scenarios (black dots).

Table 4.1. Selected days and hours of simulations with correspondent scenarios and traffic intensity for surface and tunnel in FL.

Day	Hour	Scenario	Traffic intensity (veh/h)*	
			Surface	Tunnel
Wednesday, 22 nd May 2013	4:00 - 5:00	E1	487	176
	8:00 - 9:00	E2	4238	9134
	14:00 - 15:00	E3	4438	7963
	19:00 - 20:00	E4	4357	8069
Friday, 24 th May 2013	4:00 - 5:00	E5	402	315
	8:00 - 9:00	E6	4478	8870
	14:00 - 15:00	E7	4550	8976
	19:00 - 20:00	E8	4391	7842
Sunday, 26 th May 2013	4:00 - 5:00	E9	995	846
	8:00 - 9:00	E10	1122	984
	14:00 - 15:00	E11	3308	4259
	19:00 - 20:00	E12	3364	5090

* data refers to total number of vehicles inside the modelling domain for the selected hour

Wednesday (scenarios E1 to E4) is considered a regular workday, Friday (scenarios E5 to E8) is a transition day between weekdays and weekends and Sunday (scenarios E9 to E12) represents the typical non-working day conditions. The four 1-hour periods within each day (local time) were deemed representative of the daily variability according to the observed urban commuting pattern. The period between 4:00 and 5:00 h represents the non-rush hour. The period from 8:00 to 9:00 h corresponds to high northbound traffic flow on weekdays due to the beginning of the workday and the schools opening hour (morning rush hour). The period from 14:00 to 15:00 h, presents high traffic densities due to lunch time and leaving school hour. And finally, the period from 19:00 to 20:00 h presents high southbound traffic flow on weekdays due to the end of the workday, representative of the evening rush hour.

4.1.1.4 Traffic simulation specifications

The common features for all scenarios were introduced in VISSIM to setup the traffic simulation using data of the traffic lights position and phases, routes and stops for the nine bus lines in the

vicinity of FL, specific road network geometry, streets, number of lanes, direction, width, slope (for the highway throughout the tunnel) and the existing speeds signs Figure 4.5.

Figure 4.5. Real traffic network image from FL (left) and simulated network with VISSIM model (right).

Driving behaviour has been adjusted to match local urban traffic conditions from FL minimizing changes for the default data included in the model (Table 3.2). The main change included is the reduction of the safety distance by modifying the multiplicative part of the safety distance parameter.

Also the dynamic traffic data are adjusted to match the scenario requirements for each individual simulation.

Total traffic volumes obtained for surface and tunnel for each scenario are shown in Figure 4.6. Important differences between weekdays and weekend days were observed. Weekdays present higher vehicles intensities during the day, reaching the maximum intensity in scenario E7 (Friday, 14:00 h to 15:00 h) with more than 13,500 veh/h. The minimum flux was found to occur during weekday nocturnal time (E1 scenario) with less than 700 veh/h. At weekends, smaller differences were observed between peak and off-peak hours, corresponding to roughly 2,000 veh/h at morning hours (E9 and E10) and around 8,000 veh/h during afternoon hours (E11 and E12) (Figure 4.6).

Figure 4.6. Surface (a) and tunnel (b) vehicle volumes per hour and average speeds for each scenario.

As expected, a general inverse relationship between average speed and traffic intensity was obtained with high correlation factors for both surface and tunnel traffic (Figure 4.7).

Figure 4.7. Relationship between traffic intensity and average speed for surface (blue) and tunnel (orange) traffic.

Concerning fleet composition, the traffic flow in FL is dominated by light-duty vehicles, which represent more than 90 % of the vehicle volume of each scenario, so that motorcycles, buses and trucks represent less than 10 % of the vehicle volume of each scenario (Figure 4.8).

Figure 4.8. Vehicle composition for each scenario. The difference to 100 % corresponds to light-duty vehicles (passenger cars, taxis and vans).

4.1.1.5 Emission model specifications

The vehicle class distribution considered for the emission calculations is shown in Table 4.2. This classification was selected to adjust the three VERSIT+ vehicle type models that are included in the custom fleet composition tool from ENVIVER. The aggregated information has been elaborated from detailed fleet composition data (vehicle type, fuel used and Euro standard) according to camera observations in the study area (table included in Annex 4). In order to reflect differences on the fleet composition between surface (urban) and tunnel (freeway) traffic

each vehicle categories were separated in two classes. Motorcycles are excluded from the emission calculation because no emission model is included for this vehicle type. Although this is a limitation, it should be noted that motorcycles represent as average 3.5 % for the selected scenarios and account less than 7 % of the total traffic intensity in all cases (Figure 4.8). As indicated in Table 4.2, broadly 75 % of light-duty vehicles are propelled by diesel engines. Most of these vehicles are Euro-4 passenger cars that globally represent 23 % of total distance travelled.

Table 4.2. Vehicle classification for the different models, detailed fuel type and vehicle age distribution.

Area	Road type	VERSIT+ ^{micro} Vehicle type model	ENVIVER customized vehicle class name	VISSIM Classes	Petrol (%)	Diesel (%)	LPG ³ (%)	CNG ⁴ (%)	Electric (%)	Average vehicle age (year)
Surface	Urban ¹	Light-duty	Urban_Car_2013_FL	Car	24.7	74.7	0.2	0.0	0.4	8.6
		Heavy-duty	Urban_HGV_2013_FL	Taxi	0.6	99.4	0.0	0.0	0.0	8.2
		Bus	Urban_Bus_2013_FL	Truck	0.0	99.7	0.0	0.0	0.3	7.4
		Not assigned	Not assigned	Bus	-	-	-	-	-	-
Tunnel	Highway ²	Light-duty	Highway_Car_2013_FL	Motorcycle	23.9	75.1	0.7	0.3	0.0	7.7
		Heavy-duty	Highway_HGV_2013_FL	Car_tunnel	0.5	99.5	0.0	0.0	0.0	8.1
		Bus	Highway_Bus_2013_FL	Taxi_tunnel	0.0	95.5	0.0	1.8	2.7	7.0
		Not assigned	Not assigned	Truck_tunnel	-	-	-	-	-	-
				Bus_tunnel	-	-	-	-	-	-
				Moto_tunnel	-	-	-	-	-	-

1 Takes into account cold start component. 2 Does not take into account cold start emission component. 3 Liquefied petroleum gas. 4 Compressed natural gas.

4.1.2 Signalized interconnected junctions

4.1.2.1 Modelling domain

Escuelas Aguirre (EA) interconnected junctions, are located in the district of Salamanca-Retiro in the centre of Madrid (Figure 4.9). This area includes a major intersection with several lanes, two tunnels (Alcala Street and one in O'Donnell Street) and other crossings under a grid plan street configuration. The 1000 m x 600 m area of study includes complex urban geometries combination with several intersections but also part of the Retiro Park (the biggest one in Madrid city) on the southern area of the domain.

Figure 4.9. Location of Escuelas Aguirre intersections, Madrid (Spain) and selected 1000 m x 600 m modelling domain (black rectangle).

4.1.2.2 Data compilation

As in the case of FL, detailed road network configuration for Escuelas Aguirre (EA) is obtained from GIS shapefiles and signal head position (red arrows in Figure 4.10) and phases are provided by the Madrid City Council. Information about vehicle types and vehicle routes is collected from previous studies carried out by the Madrid City Council with cameras (Figure 3.9) installed throughout the main intersections of the domain (Figure 4.10). Traffic volumes are obtained from traffic gauging stations inside the study area (blue arrows in Figure 4.10). These instruments provide hourly records of total number of vehicles crossing the measured section. The information is included in a weekly report file that contains hourly traffic volumes (local time) for a specified station number, street location, coordinates and measured timespan (weekly).

Figure 4.10. Escuelas Aguirre intersections covered with traffic cameras (green, yellow and blue rectangles, white arrows referring lane direction) to characterize traffic fluxes and detailed routes. Black rectangle for the selected 1000 m x 600 m domain with black lines for GIS network detailed information, red arrows for traffic signal position and blue arrows for traffic measurement points.

EMT Madrid information ([EMT, 2015](#)) is used to obtain the public transport lines that cross the domain and the location of the bus stops showed in Figure 4.11 to generate the public transport routes for EA simulations.

Figure 4.11. Public transport lines stops information in EA intersections domain from EMT Madrid.

4.1.2.3 Scenario selection

These intersections present large vehicle flows throughout the day. As in FL, a commuting pattern can be observed, with two rush hours, one in the morning (from 8:00 to 9:00 h) and another in the evening (from 18:00 to 19:00 h), traffic follows the traditional two-humped urban commute pattern (Hallenbeck et al., 1997). Nevertheless, on Fridays the second relative maximum can be observed around 14:00 to 15:00 h.

As for FL, traffic profiles (Figure 4.12) generated from the weekly traffic intensity reports of hourly traffic volumes and crossing these data with the camera measurements (Figure 4.10). Eleven representative scenarios (1 h-length) were defined (Table 4.3 and black dots in Figure 4.12) to perform detailed simulations in this location. Similarly to the FL case, they cover both weekday (including simulations representative from Monday to Friday) and weekend (for Saturday and Sunday average traffic per hour) with one exception for Friday second relative maximum (14:00 to 15:00 h) (Figure 4.12).

Figure 4.12. Daily traffic profiles for representative week days and selected traffic scenarios (black dots) in EA.

As for FL weekday scenarios (S1 to S6) are representative for regular working days, Friday (scenario S7) shows a second relative maximum between 14:00 to 15:00 h due to people leaving work earlier on Fridays and weekend scenarios (S8 to S11) represent the typical conditions for non-working day. The selected hours within each day (local time) were deemed representative of the daily variability according to the observed urban commuting pattern.

Table 4.3. Selected days and hours of simulations with correspondent scenarios and traffic intensity in EA.

Day	Hour	Scenario	Traffic intensity (veh/h)
Weekday	4:00 - 5:00	S1	783
	6:00 - 7:00	S2	2714
	8:00 - 9:00	S3	9388
	10:00 - 11:00	S4	8789
	15:00 - 16:00	S5	7805
	18:00 - 19:00	S6	9369
Friday	14:00 - 15:00	S7	10347
Weekend	4:00 - 5:00	S8	2037
	13:00 - 14:00	S9	7089
	15:00 - 16:00	S10	4734
	18:00 - 19:00	S11	6812

4.1.2.4 Traffic simulation specifications

The comparison of the real and simulated network for EA (static features) is shown in Figure 4.13.

Figure 4.13. Real traffic network image from EA (left) and simulated network with VISSIM model (right).

Driving behaviour has been adjusted to match local urban traffic conditions from EA (Table 3.2). Similarly to FL the main change included is the reduction of the safety distance by modifying the safety distance parameters reducing the gap between vehicles. Nevertheless, in this case also the number of observed vehicles has been increased for a more realistic reproduction of vehicles movements since this parameter affects how well vehicles in a link can predict other vehicles movements and react accordingly.

As shown in Table 4.3, total traffic volumes obtained for each scenario present important differences between weekdays and weekend days. Similarly to FL weekdays present higher vehicles intensities during the day, reaching the maximum intensity in scenario S3 (Weekday, 8:00 h to 9:00 h) with more than 9,300 veh/h. The minimum flux was found to occur during weekday nocturnal time (S1 scenario) with less than 800 veh/h. At weekends, smaller differences were observed between peak and off-peak hours, corresponding to roughly 2,000 veh/h at morning free-flow hour (S8) and around 7,000 veh/h for peak hours (S9 and S11).

Concerning fleet composition, the traffic flow in EA is dominated by light-duty vehicles, which represent more than 92 % of the vehicle volume of each scenario, so that motorcycles, buses and trucks represent less than 8 % of the vehicle volume of each scenario (Figure 4.14). However, the main difference to FL scenarios is that despite the low contribution of motorcycles in both domains, in EA there are even less representative (up to 2 % of the vehicle fleet in all scenarios).

Figure 4.14. Vehicle composition for each scenario in EA. The difference to 100 % corresponds to light-duty vehicles (passenger cars, taxis and vans).

4.1.2.5 Emission model specifications

The vehicle class distribution considered for the emission calculations is shown in Table 4.4. As for FL the aggregated information has been elaborated from detailed fleet composition data (vehicle type, fuel used and Euro standard) according to vehicle characterization study ([Vehicle fleet characterization study, 2014](#)). As indicated in Table 4.4, broadly 65 % of light-duty vehicles (75 % in FL) are propelled by diesel engines and 35 % by petrol engines (25 % in FL). This represent an increase of petrol propelled vehicles in the inner part of Madrid city.

Table 4.4. Vehicle classification for the different models, detailed fuel type and vehicle age distribution.

Road type	VERSIT+ _{micro} Vehicle type model	ENVIVER customized vehicle class name	VISSIM Classes	Petrol (%)	Diesel (%)	LPG (%)	CNG (%)	Electric (%)	Average vehicle age (year)
Urban	Light-duty	Urban_Car_2013_EA	Car	34.8	65.1	0.0	0.0	0.1	7.0
		Urban_Taxi_2013_EA	Taxi	5.8	78.0	6.2	0.0	10.0	7.0
		Urban_LCV_2013_EA	LCV	3.1	96.9	0.0	0.0	0.0	7.0
	Heavy-duty	Urban_HGV_2013_EA	Truck	0.8	99.2	0.0	0.0	0.0	7.3
		Urban_HGV-A_2013_EA	Art.Truck	0.0	100	0.0	0.0	0.0	7.3
	Bus	Urban_Bus_2013_EA	Bus	0.0	75.5	0.0	24.5	0.0	6.9
	Not assigned	Not assigned	Motorcycle	-	-	-	-	-	-

4.2 Additional hot-spots simulation for comparison and validation purposes

4.2.1 Urban roads combination - Arterial-collector-local roads

This part of the work was done in collaboration with the University of Queensland – UQ – (Brisbane, Australia) in the frame of an international research stay. UQ provide traffic data from the different sources, software licenses and contributes significantly to the road network generation.

4.2.1.1 Modelling domain

Brisbane is the third biggest city in Australia with a population of roughly 2.3 million in the metropolitan zone. The study area of 1250 m x 600 m in Woolloongabba (Gabba) around the South Brisbane Air Quality monitoring is shown in Figure 4.15. Located adjacent to the South East Freeway, this area present a typical configuration of boundary of major traffic corridor. The domain includes part of the Pacific Motorway with the access to the Woolloongabba bus station and The Gabba Brisbane Cricket Ground presenting a complex interaction of different traffic conditions.

Figure 4.15. Location of Woolloongabba, Brisbane (Australia) and selected 1250 m x 600 m modelling domain (black rectangle).

4.2.1.2 Data compilation

Brisbane City Council provided traffic volume counts for signalized intersections that include an associated automatic traffic counting facility. Traffic data are obtained through electronic traffic counts operated under SCATS system. This system is an adaptive urban traffic management system that synchronises traffic signals to optimise traffic flow across a whole city. SCATS is installed in Brisbane's intersections to get monthly traffic information with 5 minutes resolution. The information used was obtained from the SCATS-TSC detectors inside the analysed area (orange dots in Figure 4.16).

Figure 4.16. TSC-SCATS detectors (orange dots), VISSIM road network (light grey roads), bus stops (blue rectangles) and traffic lights (red lines) located inside the 1250 m x 600 m domain in Woolloongabba.

Regarding traffic signals, these were obtained from the public traffic data interface specification – TRANSMAX – which contains the information of the current controlled intersections for the public traffic data system for each intersection in the domain. Also bus lines that crosses the domain and their stops (blue rectangles in Figure 4.16) were identified. There are 7 bus lines arriving/departing at Gabba bus station. Road gradient is a very important factor in this network (23 % of the roads with gradient) due to the number of roads overcrossing the surface streets by bridges (freeway and secondary streets), so that a detailed calculation per road link has been performed with maximum road gradient of -13 % (downhill) to 13 % (uphill).

4.2.1.3 Scenario selection

Daily traffic patterns were analysed taking the average from all measurement stations in order to select two 1-h scenarios representative of weekday peak and off-peak conditions (Figure 4.17). Peak hour traffic conditions (saturated) are represented by the 16:30 to 17:30 h period (more than 19400 veh/h in the whole domain) and low intensity traffic typical of non-peak hours (free-flow) are studied through the 4:30 to 5:30 h (less than 3600 veh/h in the whole domain).

Figure 4.17. Daily traffic profiles for representative week days and selected traffic scenarios (black dots) in Gabba.

4.2.1.4 Traffic simulation specifications

In this case and due to the importance of the interaction between different road segments (long freeway link that interact with urban roads), the inclusion of two driving behaviours was needed. One for urban motorized roads and collectors (Urban driving behaviour shown in Table 3.2) and the other one for freeway traffic links (Freeway driving behaviour shown in Table 3.3).

The corresponding vehicle fleet composition related to each of the selected scenarios correspond to a representative vehicle fleet from Queensland (Australia) in 2010. Australian fleet is slightly different to the European one, with bigger vehicles that present higher engine capacities. In this sense, the vehicle classification used corresponds to the one included in the PΔP Australian emission model (Table 4.5 and Figure 3.3).

Table 4.5. Vehicle classification in the PΔP emission model and VISSIM vehicle category correspondence.

Main vehicle category	VISSIM category	PΔP	
		Vehicle class	Description
Light-duty	Car	PC-L-petrol	Large passenger car Engine capacity >3 L
		PC-ML-diesel	Large and medium passenger car Engine capacity >2 L
		PC-S-petrol	Small passenger car Engine capacity <2 L
		PC-M-petrol	Medium passenger car Engine capacity 2-3 L
		LCV-petrol	Light commercial vehicles GVM ≤3.5 T
		LCV-diesel	Light commercial vehicles GVM ≤3.5 T
		SUV-diesel	Sport utility vehicle 4-wheel drives
		SUV-C-petrol	Compact sport utility vehicle 4-wheel drives, Engine cap. ≤2.5 L
		SUV-L-petrol	Large sport utility vehicle 4-wheel drives, Engine cap. >2.5 L
Heavy-duty	HGV	MCV-diesel	Rigid medium commercial vehicle GVM 3.5-12.0 T
		HCV-diesel	Rigid heavy commercial vehicle GVM 12.0-25.0 T
		AT-diesel	Articulated truck GVM >25 T
	Bus	BUS-H-diesel	Heavy bus GVM >8.5T
		BUS-L-diesel	Light bus GVM ≤8.5T

* GVM for Gross Vehicle Mass (maximum weight, vehicle fully loaded)

The main difference between vehicle fleets (Spain and Australia) is related to the prevalence of petrol-fuelled vehicles in the Australian context (Figure 4.18).

Figure 4.18. Vehicle fleet composition in Gabba for free-flow (left) and saturated (right) scenarios.

4.2.1.5 Emission model specifications

The vehicle class distribution considered for the emission calculations is shown in Table 4.6. As mentioned before, petrol-fuelled vehicles dominate the vehicle fleet in this case. Broadly 93 % of light-duty vehicles are propelled by petrol engines.

Table 4.6. Vehicle classification for the different models, detailed fuel type and vehicle age distribution for Gabba.

Road type	VERSIT ⁺ micro Vehicle type model	ENVIVER customized vehicle class name	VISSIM Classes	Petrol (%)	Diesel (%)	LPG (%)	CNG (%)	Electric (%)	Average vehicle age (year)
Urban	Light-duty	Urban_Car_2010_Gabba	Car	93.0	7.0	0.0	0.0	0.0	9.0
	Heavy-duty	Urban_HGV_2010_Gabba	Truck	4.0	96.0	0.0	0.0	0.0	9.0
	Bus	Urban_Bus_2010_Gabba	Bus	0.0	100.0	0.0	0.0	0.0	8.0

4.2.2 Signalized intersection

The work was done in collaboration with the Kangwon National University – KNU – for the data collection and emission results comparison.

4.2.2.1 Modelling domain

Posco intersection is the crossing of two main roads, Samseong-ro (South-North) and Teheran-ro (East-West). It is located in the district of Gangnam-gu in the south-east part of Seoul, South Korea (Figure 4.19). This is a key intersection for commuters at peak hours to arrive at the city centre. The selected modelling domain covers an area of 300 m x 300 m.

Figure 4.19. Location of Posco intersection in Seoul, South Korea and the selected modelling domain of 300m x 300m.

This location was selected for modelling system validation purposes in order to compare emission results to high-resolution mobile laboratory measured data (Quaassdorff et al. 2017a).

4.2.2.2 Data compilation

Traffic data were obtained from an experimental measurement campaign. The campaign was carried out from 28th July to 10th August 2015, a representative period for summer traffic conditions. In this period traffic volumes and vehicle routes were recorded with CCTV cameras. Traffic compositions for the two scenarios were obtained from a previous study carried out in 2013 (Kwak et al., 2016a, 2016b) (Table 4.7). Network configuration, traffic signs location and bus stops were obtained from satellite images from Google maps.

Table 4.7. Traffic composition for the two selected scenarios in Posco.

Vehicle type	Peak (9:00 - 10:00 h)	Off-peak (15:00 - 16:00 h)
Car	51.4 %	51.1 %
Taxi	21.9 %	22.6 %
SUV	12.0 %	11.8 %
HGV	5.5 %	5.4 %
Van	2.7 %	2.2 %
Bus	2.7 %	2.7 %
Bike	3.8 %	4.3 %

4.2.2.3 Scenario selection

Two scenarios were selected for modelling purposes. The first one is a peak hour (9:00 to 10:00 h) from a typical weekday and a second one, an off-peak hour (15:00 to 16:00 h) with similar traffic intensity (Figure 4.20). The fundamental difference between both scenarios is that for the peak scenario there are substantial commuter's movements from south to west (into the city centre) and in the off-peak scenario they return from north to south. Nevertheless in both scenarios the most used route is the one from east to west.

Figure 4.20. Daily traffic profiles for representative week days and selected traffic scenarios (black dots) in Posco.

4.2.2.4 Traffic simulation specifications

The baseline traffic network configuration (Figure 4.19 right) consists of 20 links, 27 connectors, 4 signal heads (red lines), 9 bus stops (blue rectangles) and 24 bus lines. Traffic volume, traffic compositions and vehicle movements for each scenario were added to the baseline simulation to obtain peak and off-peak simulations (Quaassdorff et al. 2017a).

Driving behaviour for urban roads was included for the simulations of Posco intersection (Table 3.2).

4.2.2.5 Emission model specifications

Fuel distribution data were obtained from official statistics for motor vehicles registered in Seoul in 2015 (KOSIS, 2017). This classification is subdivided as commercial and non-commercial passenger's car (Car), Van and Bus (Bus), HGV and by fuel type as petrol, diesel, LPG, CNG and electric vehicles. This classification was used in the emission model to generate the emission classes (Figure 4.21) and were assigned to the vehicle types from the traffic model.

Figure 4.21. Fuel distribution data for the vehicle classes introduced in the emission model.

The vehicle class distribution considered for the emission calculations is shown in Table 4.8. Similarly to the Australian case, petrol-fuelled vehicles dominate the vehicle fleet (64 % of light-duty vehicles).

Table 4.8. Vehicle classification for the different models, detailed fuel type and vehicle age distribution for Posco.

Road type	VERSIT ⁺ micro Vehicle type model	ENVIVER customized vehicle class name	VISSIM Classes	Petrol (%)	Diesel (%)	LPG (%)	CNG (%)	Electric (%)	Average vehicle age (year)
Urban	Light-duty	Urban_Car_2015_Posco	Car	64.0	24.0	11.0	0.1	0.1	7.3
	Heavy-duty	Urban_HGV_2015_Posco	Truck	0.5	87.8	11.6	0.1	0.0	8.3
	Bus	Urban_Bus_2015_Posco	Bus	0.9	71.9	21.2	6.0	0.0	8.8

CHAPTER 5

**APPLICATIONS OF THE SIMULATION
SYSTEM**

In this chapter possibilities and applications of the modelling system and their main results and their utility policy-wise are presented. A detailed analysis of the emission results from FL square is presented to show the modelling system capabilities along with a pedestrian exposure analysis. After that, emission reduction measures have been examined for two hot-spots in Madrid. Finally, also the linkage to high resolution air quality models is presented.

5.1 Detailed analysis of traffic emissions

To analyse different measures and policy options in hot-spots, a detailed analysis of the emissions results obtained with the simulation system for a very complex and highly polluted microenvironment are presented, in this case, FL square (Quaassdorff et al., 2016a, 2016b).

The microscale model clearly reflects the influence of congestion (low average speed) on exhaust emissions. Speed-time profiles for individual trips can vary substantially depending on traffic conditions as shown in Figure 5.1. This examples correspond to FL E1 and E2 scenarios and the emission for the same trip are 0.599 g NO_x and 0.043 g PM₁₀ under free-flow conditions and 0.854 g NO_x and 0.055 g PM₁₀ under stop & go conditions; i.e. emissions for the same trip increase in 42.6 % and 27.9 % for NO_x and PM₁₀ respectively.

Figure 5.1. Speed-time profile for the same route across FL for a passenger car in E1 free-flow (left) and E2 congested (right) conditions.

Figure 5.2 show the corresponding results for the whole modelling domain. It can be seen that not only emissions change remarkably (increase of 96.3 % for NO_x and 95.7 % for PM₁₀), but also spatial patterns are affected by the traffic changes throughout the day. Figure 5.2 above (E1 scenario) clearly shows that the position of the traffic lights has an important impact on emissions. In these areas, vehicles slow down to a complete stop, generating lower speed areas, and then accelerate, increasing emissions. In the case of congested traffic conditions such as in E2 scenario (Figure 5.2), saturation and therefore lower average speed are propagated by surrounding streets due to the generation of queues, and in turn, increase breaking-acceleration

patterns and emissions. As shown in Annex 5 maps, this pattern is reproduced along the week with low speed areas after traffic lights, increasing the emissions per grid cell. These results are in agreement with previous microscale emission simulations (Abou-Senna et al., 2013; Smit et al., 2008) that highlight the pronounced sensitivity of emissions to stop & go situations and to the associated driving cycles (braking-acceleration) that occurs in congested traffic situations with lower average speeds.

Figure 5.2. Average speed (left), NO_x (centre) and PM (right) emissions for free-flow traffic conditions (E1 scenario) (upper row) and saturated traffic conditions (E2 scenario) (lower row).

It is observed that fluid traffic scenarios such as E1 (Figure 5.2) have lower emissions than saturated traffic scenarios as E2 (Figure 5.2). On the one hand this is due to a smaller total number of vehicles in E1 but also related to a constant speed without braking-acceleration patterns that occur in stop & go conditions, which is the case of high vehicle density conditions. The same result was obtained by Csikós & Varga (2012), which showed that the total emission rate in a given space and time is minimal if traffic density is minimal too.

Stop & go traffic conditions become important on weekdays in general, which present the highest emissions. Along the week, NO_x and exhaust PM₁₀ emissions follow similar trends (Figure 5.3). On weekdays the daily trend remains similar with low emissions at non-rush traffic hours (E1 and E5 scenarios) and higher constant emissions for the rest of the scenarios. Emissions from these non-rush hours are, approximately, 95 % lower than those of the morning rush hours (E2 and E6) for both pollutants. However, there are minimal differences for NO_x and

PM₁₀ emissions between weekdays for morning and evening rush hours. For instance, E6 and E8 scenarios (Friday morning and evening rush hours) present only a 3 % difference compared to the emissions from their counterpart E2 and E4 scenarios (Wednesday morning and evening rush hours) as shown in Figure 5.3. This is not reproduced in the case of weekday midday hours (14:00 to 15:00 h) where NO_x emissions from E3 scenario (Wednesday) are 15 % higher than those obtained for E7 scenario (Friday). In this case, even though total traffic volume is lower (12400 veh/h and 13526 veh/h for E3 and E7 scenarios, respectively) the corresponding NO_x emission factor (Figure 5.4) is higher. This is due to a lower average speed (Figure 4.6) and a larger proportion of trucks in E3 (1.94 % Vs. 1.55 % in E7). Comparing morning rush hour (E2 scenario) with midday hour (E3 scenario), although E2 has the highest emission factor for the surface traffic (3.6 g/km NO_x and 0.176 g/km PM₁₀, compared to 3.5 g/km NO_x and 0.166 g/km PM₁₀) it presents 5 % lower total emissions than E3. This is because the total travelled distance in E2 is 1728 km compared to 1856 km in E3, due to more intense congestion. Larger differences were observed at the weekend morning rush hour (E10 scenario), where emissions are 75 % lower than at its weekday counterpart (E2 and E6 scenario). It is also remarkable that surface emissions (with lower average speeds) are higher than tunnel emissions despite higher traffic volumes in the tunnel. This is related to the stop & go patterns that are related to congestion at lower speeds. So that trying to regulate speed on highways could not be so effective pollution-wise due to congestion generation on these roads.

Figure 5.3. Total NO_x and PM₁₀ emissions results for the 12 FL scenarios.

Figure 5.4. Emission factors for NO_x and PM₁₀ for each FL scenario for the tunnel and the surface.

Concerning emissions by vehicle type, they are dominated by cars, especially in scenarios with low traffic volume (E1, E5 and E9) as represented in Figure 5.5. Overall, 76 % of NO_x emissions are related to cars, although trucks also have a significant contribution (15 % as average) reaching the maximum share in E3 scenario (28 % of NO_x emissions and 10 % of PM₁₀) as shown in Figure 5.5. As for PM₁₀ emissions, they are clearly dominated by cars, which are responsible for more than 85 % of the emissions in all scenarios due to the strong dieselization of the fleet in FL (75 % diesel and 25 % petrol) as shown in Annex 4. From the perspective of local measures, this kind of analysis show the potential effect of the restriction by vehicle type. Nevertheless, specific measures deserve detailed analysis in order to take into consideration also related effects on congestion.

Figure 5.5. NO_x and exhaust PM₁₀ emissions percentage by vehicle type in each scenario.

5.2 Evaluation of pedestrian exposure to air pollution

The European limit values for NO₂ are targeted to the protection of human health. However, legal compliance is assessed from the data collected in air quality monitoring networks and it is not clear to what extent the information captured in these particular points may be representative of population exposure to air pollution for the area it covers and thus, the real implications of such exceedances. This is crucial at many urban intersections where pedestrians and vehicles share the same space being exposed to high pollution levels, mainly in hot-spots. Moreover, pedestrian and traffic fluxes are closely related and present mutual dependencies. Therefore a consistent simultaneous simulation of both pedestrian and vehicles is necessary to understand population exposure at microscale level. These interactions have been resolved with the VISSIM add-one module VISWALK.

It is suspected that limit values for traffic-related pollutants may be exceeded near busy streets, and the combination of monitoring and modelling techniques can be seen as a reliable and cost-effective method for assessing air quality in urban microenvironments (Vardoulakis et al., 2003). To investigate the exposure of people to ambient air pollution the directions taken in the last years affront the issue of population exposure bettering models (Ragetti et al., 2014; Schlink et al., 2010; Soares et al., 2014) but also many efforts have been made using microsimulation models for pedestrian movement (Ishaque & Noland, 2008; Ishaque & Noland, 2007; Schlink et al., 2010). In order to gain some understanding of pedestrian exposure in Madrid, a microscale assessment of NO₂ concentration measurements was performed in a domain 600 m x 700 m around FL. The crowded and trafficked 300 m x 300 m sub-domain (section 4.1.1) was selected for the pedestrian microsimulation. The basic flowchart of the process is explained in Figure 5.6.

Figure 5.6. Flowchart of the modeling system to characterize population exposure at FL.

In order to feed the different models and to obtain the required data, a set of experimental campaigns took place in the square in order to measure different data.

5.2.1 NO₂ concentration

To assess the spatial and temporal variations of NO₂ along the square, passive samplers concentration and hourly measurements from the air quality monitoring station was obtained.

5.2.1.1 Passive samplers

NO₂ spatial distribution was recorded on a measurement campaign that took place from February 9th to 27th, 2015 (Borge et al., 2016a). NO₂ average concentration levels were assessed through Palmes-type passive diffusion tubes (PDT) (Figure 5.7), a device that absorbs gaseous pollutants directly from the surrounding ambient air by diffusion without power supply. The samplers consist in a hollow acrylic tube (71.0 mm long and 11.0 mm of internal diameter) equipped with a plastic cap fixed at the end of the device which holds inside two stainless steel mesh grids coated with an absorbent solution of 20 % triethanolamine (TEA)/water (Palmes et al., 1976; Vardoulakis et al., 2009).

Figure 5.7. NO₂ Palmes passive samplers used in FL.

A dense network of 205 PDT were homogeneously distributed throughout the area of study (Figure 5.8) in lampposts, traffic signs, etc., approximately 3 m above the surface level. Four additional PDT were co-located in the air quality monitoring station to calculate relative error (10.1 %) and the correction factor (0.91) needed to match the observations made through the reference quimioluminescence method. Airborne pollutants as NO₂ are diffused into the tube and captured by an absorbent (TEA). After the 3-week period exposure all tubes were collected. The resultant specie is chemically analyzed using colorimetric techniques by UV-spectrophotometry and then related to know-concentration patterns to derive concentration results. These methodology for the calculation of NO₂ concentration is described in AEA, 2008 and was selected because it is an inexpensive method useful to understand spatial (not temporal) gradients in urban areas with high resolution. The obtained concentrations (µg/m³) were referred to a temperature of 20 °C. No corrections on the atmospheric pressure were carried out whatsoever, assuming it equivalent to 1 atm.

Figure 5.8. Spatial distribution of the 205 passive samplers along FL.

This information was used to create a concentration map by interpolating individual PDT results through a spline with barriers algorithm (minimum curvature method) with the ArcGIS software through the 600 m x 700 m domain (Figure 5.9).

Figure 5.9. NO₂ concentration distribution in the 600 m x 700 m domain from the interpolation of the laboratory results of PDT measurements (Borge et al., 2016).

5.2.1.2 Air Quality Monitoring Station

Temporal resolution of NO₂ concentration in the square along the three weeks was obtained from hourly measured data from the FL air quality monitoring station and an average daily variation pattern was computed (Figure 5.10).

Figure 5.10. Temporal weighted pattern from the measurements of FL air quality monitoring station.

5.2.2 Traffic and Pedestrian data

An intensive field campaign was made to compile all the information needed to feed the microscale traffic simulation model VISSIM for FL square. The fundamental data consists on traffic volume, composition and routes along with data of the traffic network for the traffic microsimulation model (Quaassdorff et al., 2016a). For the additional data required for the pedestrian simulation, a field campaign was carried out to count the number of pedestrian within the vicinity of FL.

5.2.2.1 Scenarios

To appropriately describe interaction patterns of pedestrian flows along with different traffic conditions, a 4-day field campaign (February 16th, 25th, 27th and March 8th, 2015) to cover 15 1-hour length scenarios (local time) representative of typical activity patterns for different hours of working days and weekends (Table 5.1).

Table 5.1. Selected days and hours for pedestrian simulations with the correspondent scenarios.

Day	Hour	Scenario
Monday 16/February/2015	4:00 - 5:00	S1
	8:00 - 9:00	S2
	14:00 - 15:00	S3
	19:00 - 20:00	S4
	23:00 - 24:00	S5
Wednesday 25/February/2015	14:00 - 15:00	S6
Friday 27/February/2015	8:00 - 9:00	S7
	14:00 - 15:00	S8
	19:00 - 20:00	S9
	23:00 - 24:00	S10
Sunday 8/March/2015	4:00 - 5:00	S11
	8:00 - 9:00	S12
	14:00 - 15:00	S13
	19:00 - 20:00	S14
	23:00 - 24:00	S15

Similarly to the FL traffic scenarios, in the case of pedestrian dynamics, Monday (scenarios S1 to S5) and Wednesday (scenario S6) are considered as regular work days, Friday (scenarios S7 to S10) is a transition day between weekdays and weekends and Sunday (scenarios S11 to S15) represents the typical non-working day. The four 1-hour periods between 8:00 and 24:00 h within each day (local time) were deemed representative of the daily variability according to the observed two-humped urban commuting pattern. The period between 4:00 and 5:00 h represents the slack hour and the data was assumed from the counts done for 23:00 to 24:00 h without public transport. The period from 8:00 to 9:00 a.m. corresponds to high pedestrian activity on weekdays due to the beginning of the workday and the schools opening hour (morning rush hour). The period from 14:00 to 15:00 h, usually presents high pedestrian densities, mainly in the vicinity of the school, due to lunch time and leaving school hour. The period from 19:00 to 20:00 h presents high pedestrian flow on weekdays due to the end of the workday, representative of the evening rush hour. And finally, the period from 23:00 to 24:00 h normally presents low pedestrian activity due to the evening slack hour period.

5.2.2.2 Data measurement campaign

The goal of the pedestrian experimental campaign was to obtain data about pedestrian routes and intensities (ped/h) along the square in representative points. 15 pedestrian crossings, 15 sidewalks, 5 metro stations, 12 bus stops, 1 taxi parking station and 2 pedestrian stop spaces (1 playground and 1 transfer waiting area) were identified in the sub-domain. 50 significant places with a total of 98 measurements points (Figure 5.11) to cover the pedestrian flows along the domain due to the measurement of the in and out flow for each place and the quantification of

bus passengers getting on and off the buses. For the measurement campaign the square was divided in 6 sampling areas which include between 15 and 17 measurement points. For each area, 15-min pedestrian counts were carried out for selected hours and days. A total of 12 15-min counts to cover the 98 sampling points for each scenario were made (total of 96 15-min counts) within the experimental campaign. This observations were combined with the information regarding bus routes, stops and frequencies provided by the Municipal Transport Company (EMT). Counts of in and out fluxes of pedestrians for each area and scenario were post processed to assure consistency and flux continuity (Borge et al., 2016a).

Figure 5.11. Distribution of the 98 sampling points along FL square.

5.2.3 Pedestrian simulation setup

Both traffic and pedestrian fluxes were simulated with a microscale modelling system VISSIM-VISWALK (v.6-00.22).

In order to simulate pedestrian fluxes in the square, pedestrian areas (sidewalks), conflict areas (crosswalks) and obstacles were previously defined along with bus stops and metro stations (Figure 5.12) that were included in the simulation as input/output areas. Every possible route along the square was defined as a Pedestrian Static Route Decision using the collected data as input or output of the areas from the simulation. These data were introduced in the simulation as percentage of usage of the pedestrian static routes defined in the domain. In this case, the social force approach resolves the shortest path for the pedestrians to connect the defined beginning and end of each route through the pedestrian areas with a user-defined speed distribution in the range of 2.6 – 5.8 km/h.

Figure 5.12. Pedestrian simulation domain (300 m x 300 m) and caption of a specific sampling area with defined pedestrian static routes.

The location of each individual pedestrian was computed with 2 second resolution. Pedestrian locations were interpolated to a 5 meter resolution grid and integrated throughout 1 hour time for each scenario. From the result of the 15 representative scenarios an average day of pedestrian fluxes were derived (Figure 5.13).

Figure 5.13. Average daily pattern for pedestrian fluxes from weekly weighted data.

5.2.4 Exposure assessment results

To assess exposure to NO₂, two variables were calculated, Total Exposure (TE) and Total Theoretical Exposure (TTE) (Borge et al., 2015, 2016a). Total exposure in the area can be computed by aggregating individual grid cell results for every hour or for the whole representative day from aggregated weekly data. First, to compute TE for every hour of the day, NO₂ concentration values from PDT and pedestrians figures were multiplied for every grid cell (5 m x 5 m) within the pedestrian simulation sub-domain (300 m x 300 m).

To generate a complete representative day, data from the pedestrian simulated scenarios were combined. For that, a whole week pattern was generated by extrapolating the simulated hours for similar days and hours. Finally, from these matrix, the weight of each scenario to each hour was calculated to obtain the contribution of each simulation to an average representative day.

In addition, TTE was computed as the product of the total number of pedestrians (persons·s) and the hourly concentration recorded in the air quality monitoring station. The use of the ratio obtained by this two values - TTE/TE ratio - is proposed as an index to assess the representativeness of the air quality monitoring station in terms of population exposure.

5.2.5 TTE/TE index

Spatial information from the passive tubes was combined with the temporal information from the air quality monitoring station to produce 24 hourly concentration maps. Results were interpolated to a 5 meter resolution grid and the spatial-temporal data of the pedestrians are then integrated into these concentration maps to calculate pedestrian exposure to vehicle pollutants for a representative day (Figure 5.14).

Figure 5.14. Daily total exposure interpolated to 5 m x 5 m grid resolution and crossed with averaged daily pedestrian data (Borge et al., 2016a).

From the hourly maps it can be observed that the maximum exposure is in the roundabout area, especially in the crosswalks of the main streets. But also, high exposure figures are presented in bus stops and gathering areas. The maximum exposure is observed during the morning peak hour (8:00 to 9:00 h) as shown in Figure 5.15 even though strong variations throughout the day appear due to traffic emissions (and therefore pollutant concentration values) and pedestrian temporal patterns.

Figure 5.15. Hourly total exposure for an averaged representative day. Data crossed from pedestrian fluxes, air quality monitoring station registers and PDT interpolated measurements.

Although general spatial patterns are similar throughout the day, changes on traffic fluxes, pedestrian routes and public transportation schedules also have an effect on exposure distribution (Figure 5.16).

Figure 5.16. Total exposure (person·s· $\mu\text{g}/\text{m}^3$) for off-peak 4:00 - 5:00 h (left) and peak 8:00 - 9:00 h (right) of the average day (Borge et al., 2015).

This implies that it is difficult to extract exposure-representative information from a single air quality monitoring station. In this particular case, the TTE/TE ratio was below 1 (0.78 as an average), indicating that recorded NO_2 levels in FL monitoring station would underestimate population exposure in that particular 300 m x 300 m sub-domain.

The TTE/TE ratio could be used to compute the concentration that the monitoring station should measure for a value of 1, i.e. to be representative in terms of actual exposure. If the spatial concentration pattern is known, this allows the definition of an exposure-representative location for the air quality monitoring station (area in blue in the examples in Figure 5.17).

Figure 5.17. Exposure-representative areas for the air quality monitoring station for off-peak hour (left) and peak hour (right) of the average day (Borge et al., 2015).

5.3 Assessment of emission abatement measures on urban hot-spots

Since pollution levels exceed the legal limits in specific traffic-related urban locations in Madrid it is necessary to develop additional emission reduction measures on hot-spots and highly polluted micro-environments as a complement to city-wide policies and measures (Borge et al., 2014). However, local characteristics (urban typology, traffic conditions, street geometry, etc.) play a very important role to accurately predict the effect of any particular measure at this scale. Therefore, there is a need to test microsimulation models that may reproduce with great detail traffic activity in small areas and may provide reliable emissions (Quaassdorff et al., 2016a) and support the definition of effective pollution abatement options.

The high spatial and temporal resolution (seconds and meters) from the proposed modelling system allows assessing possible effects of different local scale interventions such as vehicle volume reduction, fleet composition and vehicle technology changes, both on the total emission amount and their spatial distribution.

In the scope of this Ph.D. Thesis, a series of abatement measures were assessed (Quaassdorff & Borge, 2017) for the two hot-spots described in section 4.1 (FL square and EA area). The selection of the measures to be evaluated in each location was made through the Multiple Criteria Decision Analysis (MCDA) system. In this system, values are assigned to each measure to classify the alternatives according to their relevance. To do this, a minimum of eight possible measures and those with higher priority were selected to be analysed. The potential measures selected were:

- 1) Access restriction to heavy vehicles, which consists in the exclusion of Heavy Goods Vehicles (HGV) during peak hours.
- 2) Change in the propulsion technology of Public Transport buses, from diesel to Compressed Natural Gas (CNG).
- 3) EMT bus stops relocation, which consists in the reconfiguration of the bus stops sites so that they are relocated on places with lower emissions. This measure is specific for FL due to its particular configuration as a transport interchange station with 11 bus stops (at the surface close to the roundabout) in the 300 m x 300 m area.

The comparison was made using the base simulation (simulated traffic from measured traffic conditions) compared to the same simulation including the measure to be analyse for the selected scenarios (Figure 5.18 for FL and Figure 5.19 for EA morning rush hour).

Figure 5.18. Base emission for weekday peak hour scenario in FL (left) and after application of measures 1 (right above) and measure 2 (right below).

Figure 5.19. Base emission for weekday peak hour scenario in EA (above) and after application of measures 1 (below left) and measure 2 (below right).

5.3.1 HGV access restriction

To evaluate this measure, scenarios where HGV plays an important role on emissions have been selected. These are scenarios with high traffic volume and saturated traffic conditions (more acceleration-deceleration patterns) which lead to a significant apportionment of heavy-duty trucks to total emissions (Figure 5.5).

To compare scenarios with measurement implementation to the base simulation, HGV's that circulate during rush-hour scenarios have been excluded from the traffic simulations, keeping traffic intensity constant for the remaining vehicle categories. From these measure scenarios, the new vehicle speed-time profiles were extracted through “*.fzp” files and emissions were calculated with the same vehicle fuel proportions used in the base scenario.

The access restriction for HGV to FL roundabout has a maximum reduction effect of up to 28 % for NO_x and up to 11 % for PM_{10} total traffic emissions at scenario level (Figure 5.20).

Figure 5.20. FL emission reduction rates (left) and effect on emission factors (right) for NO_x (above) and PM_{10} (below).

The analogous exercise was made in EA for the morning rush hour, when there is greater congestion and, therefore, higher emission rates. In this case, the effect is also very high but slightly lower than in FL, with reductions of 22 % of NO_x and 6 % in PM_{10} regarding the same scenario (weekday 8:00 to 9:00 h).

In both cases, these reductions are mainly due to the elimination of emissions that comes from heavy-duty vehicles due their high emission factors, although there is also a slight reduction (up to 16 %) in the vehicle-specific emission factors of other types of vehicles due to the fluidization of traffic.

5.3.2 Change in the propulsion technology of Public Transport buses

The effect of a change in technology on buses from the EMT from diesel to CNG (Compressed Natural Gas) has been analysed. This is interesting since EMT is increasing the number of CNG units and these can be relatively simple allocate to more vulnerable or sensitive routes air quality-wise.

To simulate this strategy, a new vehicle class was generated in the emission model that accounts for the diesel buses that switch to CNG. These represents 99.7 % of the urban bus fleet in the analysed scenarios. After the generation of the new vehicle class, the same “*.fzp” files used for the base simulations were run with the new vehicle class to obtain total emissions (g/h) and emission factors for buses (g/km) so that changes in emission factors and total emissions are only related to changes on the bus class.

This measure has led to a reduction in total emissions in FL area of up to 3 % in NO_x and 2 % in PM₁₀ in the FL domain at scenario level (Figure 5.21). The result obtained for EA domain is very similar, with reductions of 2 % and 3 % respectively with the same reduction percentages on the emission factors (reductions are only related to bus class). This is related to the fact that EMT buses are relatively new and Euro 6 diesel buses have rather low emission factors, so that, replacing older buses should have a stronger effect.

Figure 5.21. FL emission reduction rates (left) and effect on emission factors (right) for NO_x (above) and PM₁₀ (below).

5.3.3 Public Transport bus stops relocation

This measure is specific for FL, due to its particular configuration. The effect of relocating EMT bus stops located on the surface to be further away from the square but maintaining those of the underground interchange station (Plaza Elíptica) has been analysed. This implies that there would not be any stops in the area near the roundabout where emission peaks appear. This measure must be applied at traffic model level to include the effect of non-stopping vehicles in the simulations. The resulting effect on emissions is a maximum reduction of up to 8 % for NO_x and 6 % for PM_{10} and on emission factors of up to 13 % and 12 % respectively (Figure 5.22). It may be considered a possible increase outside the modelling domain on the new locations of the bus stops. Nevertheless, the purpose of this analysis is the possible effect of specific measures to reduce emissions on very sensitive crowded points where high pollution concentrations appear.

Figure 5.22. FL emission reduction rates (left) and effect on emission factors (right) for NO_x (above) and PM_{10} (below).

According to this analysis, some local measures may bring about important emission reductions in both locations and can be considered at least for high pollution episodes. NO_x emissions reduction is up to 27 % in the case of HGV restrictions which is most effective measure. Such measures may therefore constitute a valuable complement for city-scale policies actions.

5.4 Linkage to CFD air quality model

Atmospheric processes within the urban canopy are complex due to the heterogeneities induced by urban morphology. This fact is linked with the irregular distribution of traffic emissions and complex atmospheric circulation patterns imposed by buildings and other manmade obstacles in the city. This produces strong pollutant concentrations gradients at meters resolution that can only be captured by very high resolution models. Computational Fluid Dynamics (CFD) models are used to resolve complex air flow movements and pollution dispersion over small areas (up to few kilometres) (Santiago and Martilli, 2010; Santiago et al., 2013).

Nevertheless, one of the most important limitations is the accuracy of the inputs, in particular the level of detail from traffic emissions. In this sense, several approaches can be used to estimate the emissions to feed this models (Sanchez et al., 2017a). Usually, these estimations are based on mean daily or hourly traffic intensity data for streets. However, these approximations reduce the accuracy of the emission input since the same emission input is assumed for a whole street. For detailed analysis, high temporal and spatial resolution emission inputs (seconds and meters) are needed. Therefore, the methodology presented in this Ph.D. Thesis may significantly contribute to improve the applicability of microscale air quality models in urban areas. In order to demonstrate the capabilities of the modelling system presented for this kind of assessment, a CFD simulation was performed for the FL area (and for Posco domain for validation purposes in section 6.2.3). The first coupling test consisted on a series of steady-state simulations with no reactive pollutants for this particular urban hot-spot (Sanchez et al., 2017b). The coupling to the CFD model STARCCM+ from CD-Adapco was tested in collaboration with the Atmospheric Pollution Modelling Group (GMCA initials in Spanish) from CIEMAT. In order to obtain detailed concentration results this CFD model needs the detailed traffic emission estimations in addition to meteorological data of wind speed and direction to solve the flow field by employing the $k-\epsilon$ turbulence model.

5.4.1 CFD model set-up

To couple the highly detailed traffic emissions obtained from the emission estimation methodology to include it in the CFD model, traffic emissions rates for each scenario (to obtain a complete weekly pattern) were generated. Total emissions per scenario and emissions per grid cell have been provided. These emissions are placed on 5 m x 5 m grid cell resolution mesh over the analysed domain and coordinates of the centre of each of the grid cells is specified.

Traffic emission information is included in a bigger simulation domain which contains highly detailed buildings geometry and vegetation (Figure 5.23) to calculate wind flow camps.

Figure 5.23. CFD modelling domain with detailed building geometry (grey), vegetation (green) and traffic emissions (red) (Sanchez et al., 2017b).

To characterise the local meteorological conditions and provide a more comprehensive view of pollution-relevant atmospheric processes several atmospheric parameters must be recorded in addition to the air quality station measurements. This was done in the frame of the TECNAIRE project (S2013-MAE2972) by the MICROMET group (Complutense University of Madrid - UCM) with long-lasting experience measuring micro-meteorological and climatic data (Yagüe et al., 2017, 2018; Sastre et al., 2017). In this case, micro-meteorological parameters were measured with two sonic anemometers (METEK USA-1 and Young 81,000) deployed at around 6 m and 8 m above ground level. Data of wind flow, air temperature, relative humidity, atmospheric pressure, precipitation and global (incoming) solar radiation were daily recorded with a high sampling frequency of 20 Hz, producing 10-min averages from instantaneous measurements. Also, the three wind speed components (u , v , w) and the air temperature were measured. This information is used to calculate micro-meteorological parameters of sensible heat flux, friction velocity and turbulent kinetic energy. These parameters are useful to assess atmospheric stability and diffusion processes that are important for local pollution dispersion (Borge et al., 2016a).

From these data, 16 wind directions are simulated and the NO_x emissions for each scenario are implemented for each wind direction distributing them into the CFD simulation with a spatial resolution up to 1m. A meteorological mesoscale model provides additional detailed information about vertical profiles and boundary conditions for every hour to initialize the microscale CFD simulation.

5.4.2 NO_x concentrations at microscale

NO_x dispersion is calculated as non-reactive and traffic induced turbulence is not considered at this first stage. Although this could induce biases in the results since these are important parameters for pollutant concentrations description, some tests have been performed to analyse the accuracy of the modelling system. In this sense, modelled NO_x concentrations have been compared to passive sampler's measurements across the domain showing good agreement ($R = 0.72$) (Figure 5.24) (Sanchez et al., 2017b).

Figure 5.24. Passive sample's measurements vs. CFD modelled NO_x concentrations (Sanchez et al., 2017b).

So that cycle-variable emissions have been found to perform well for stationary-state CFD simulations based on a Reynolds-Averaged Navier-Stokes (RANS) approach (Sanchez et al., 2017a, 2017b; Santiago et al., 2017a). Nonetheless, suitable emissions for non-stationary simulations with very high temporal resolution (seconds) require the integration of modal emission models.

5.4.3 PM concentrations at microscale

In the case of particulate matter in addition to exhaust emissions, also resuspension, pavement abrasion and brake and tire wear must be included in the emissions results to accurately describe PM concentrations at microscale with the CFD model.

Since the emissions estimation methodology only calculates PM₁₀ exhaust emissions, additional information for non-exhaust emissions including resuspension and PM_{2.5} must be obtained from other sources (de la Paz et al., 2015). In this case, the emission factor calculations from the COPERT (average speed based) model were used. Non-exhaust emission factors for PM₁₀ and PM₁₀/PM_{2.5} ratio were obtained. These information was combined with that provided by the

microscale modelling system, so that total PM_{10} non-exhaust emissions could be obtained for the whole domain.

To obtain the required spatial resolution of 5 m x 5 m, total non-exhaust emissions were disaggregated as a directly proportional function to the location of the exhaust emissions. This is reasonable since the spatial distribution will remain the same (related to the position of the vehicles). Nevertheless, it would be worthy an expansion of the emission model that include a complete calculation of PM emissions with high resolution.

To evaluate the particulate matter concentrations obtained through the CFD simulations, the simulated results are compared to measured data for one representative hour. In this case 10:00 h (local time) from the 6th of July was selected for this purpose due to the PM airborne concentration and meteorological data availability. Also, inside the simulated domain, 10 points are selected (Figure 5.25) and measurements are taken during several minutes with a portable TSI DustTrakTM instrument which provides very high spatial and temporal resolution of PM concentrations (used for personal exposure). Also a GRIMM instrument was used to provide PM measurements for one hour. This instrument provides spatial and temporal gradients of aerosols, PM size distribution and is useful to evaluate source contributions (Borge et al., 2016a). In general, results point out that modelled concentrations by CFD underestimate PM concentrations in some points near roadside. Nevertheless, these emissions lead to reasonable results (Figure 5.26) reproducing the variability in the measured points with. Further analysis on CFD parameters and through the modelling system are been done to analyse improvement possibilities.

Figure 5.25. PM_{10} concentration maps from CFD at 10:00 h at 1.5 m (Santiago et al., 2017b).

Figure 5.26. PM₁₀ concentration at 10:00 h in the measured points in Figure 5.27. Vertical bars in experimental data indicates the maximum and minimum measured (Santiago et al., 2017b).

CHAPTER 6

MODEL PERFORMANCE STUDIES

This chapter presents the performance analysis and comparison studies between models and real-world measurements carried out to assess the modelling system presented. These performance studies are important in order to state the accuracy of the predictions obtained with the modelling system. In this particular case the complexity of the processes that are involved in traffic emission formation and the number of models involved require detailed assessment of the whole system performance.

6.1 Assessment of the traffic model VISSIM

6.1.1 Traffic volume model estimations vs. field counts

The main goal of this comparison is to analyse the performance of VISSIM model estimates using field measurements. The best statistic to compare field data and simulation outputs regarding traffic flow is the GEH (Geoffrey E. Havers) statistic (Eq. 5) with a calibration acceptance target of $GEH < 5$ for the sum of all links from a simulation (Dowling et al., 2004; FDOT, 2014; Morgan & Veysey, 2013; WSDOT, 2014).

$$GEH = \sqrt{\frac{2 \cdot (m - c)^2}{m + c}} \quad (\text{Eq. 5})$$

Where:

m model estimated traffic volume (veh/h)
 c measured field count (veh/h)

Model performance for all simulations according to this index are presented in Table 6.1. Measured traffic intensity is an input variable to the traffic model. The maximum possible traffic volume depends on the speed and the driving behaviour parameters which have been set. However, due to the model stochasticity in vehicle inputs generation and congestion formation in some access roads differences between modelled and measured traffic intensity arise. Nevertheless, in all the cases GEH statistic falls well below the acceptable calibration target of 5.00.

Table 6.1. Modelled and measured traffic volume data in FL, EA, Gabba and Posco and GEH statistic results per scenario.

Area	Scenario	Total traffic intensity (veh/h)		GEH statistic
		Modelled	Measured	
FL	E1	663	631	1.26
	E2	13372	13833	3.95
	E3	12401	12522	1.09
	E4	12426	12548	1.09
	E5	717	687	1.14
	E6	13348	13663	2.71
	E7	13526	13634	0.93
	E8	12233	12394	1.45
	E9	1841	1820	0.48
	E10	2106	2064	0.93
	E11	7567	7467	1.15
	E12	8454	8340	1.24
EA	S1	783	756	0.97
	S2	2714	2484	4.51
	S3	9388	9372	0.17
	S4	8789	8372	4.50
	S5	7805	7377	4.91
	S6	9369	8942	4.46
	S7	10347	9938	4.06
	S8	2037	1940	2.18
	S9	7089	6711	4.55
	S10	4734	4460	4.04
	S11	6812	6420	4.82
Gabba	Off-peak	3330	3332	0.03
	Peak	18534	18606	0.53
Posco	Off-peak	6598	6591	0.09
	Peak	8354	8667	3.39

6.1.2 Comparison to AIMSUN results

In order to get a complementary view of VISSIM performance, three representative simulations from FL square were selected to be simulated also with the AIMSUN traffic modelling software (Barceló & Casas, 2005) used by the Madrid City Council. The selected scenarios to compare were E3 (Weekday, 14:00 to 15:00 h – afternoon peak hour), E6 (Friday, 8:00 to 9:00 h – morning rush hour) and E12 (Weekend, 19:00 to 20:00 h – no congestion). For this purpose a smaller domain of 250 m x 250 m and only including surface traffic (not the tunnel) was selected. To be consistent on the calculations between models, only streets directly measured with cameras (main accesses and exits of the roundabout) were used to provide traffic inputs volumes to the traffic models (Figure 6.1). Average differences between models are less than 5 % regarding traffic volume simulation and compared to the measured field data differences of less than 7 % appear.

Figure 6.1. Traffic volume (veh/h): measurements Vs VISSIM and AIMSUN simulations for selected FL scenarios.

The comparison was extended to other relevant averaged variables such as those presented in Table 6.2. Although there are no experimental data to contrast the results, the model intercomparison provides an idea of the robustness of the traffic simulation performed for FL area where satisfactory results have been obtained.

These parameters have been selected because they are important to define road capacity, essential to account for congestion. Density values are similar in both models, showing a clear decrease (roughly to the half) for E12 scenario (no congestion). Also average speeds are very similar with lower speeds for higher densities and traffic volumes (E3 and E6 scenario). This has also an effect on travel times and standstill times that are higher for the more congested scenarios (maximums at E3 scenario where differences of up to 28 % appear) and decreasing also average speed.

Table 6.2. Results from Aimsun and VISSIM for representative traffic parameters.

Parameters	Units	AIMSUN			VISSIM		
		E3	E6	E12	E3	E6	E12
Density	veh/km/lane	20.33	21.06	13.56	19.12	18.38	9.47
Average speed	km/h	18.98	18.76	20.59	18.58	17.98	21.70
Average standstill time	seg/veh/km	143.65	164.35	-	103.40	124.45	48.27
Average travel time	seg/veh/km	111.98	116.24	-	122.70	137.48	62.20

6.2 Assessment of the emission model VERSIT⁺micro

Once the traffic simulation performance has been addressed, it is necessary to try to assess the skills of the emission estimation model. This is particularly challenging since a formal evaluation would require measured emissions from each of the vehicles involved in the simulation. Being this unfeasible, the evaluation is mostly based on a comparison with other emission models based on alternative conceptual approaches. Nonetheless, a novel methodology to try to contrast aggregated traffic emissions in a real modelling domain was developed and tested. Although no conclusive results were obtained, a brief summary of the results are also included.

6.2.1 Comparison to average speed model COPERT 4

The emission results computed with this system were compared with those obtained from the implementation of the Computer Programme to calculate Emissions from Road Transport (COPERT 4). This is an average-speed model (Ntziachristos et al., 2009) used to estimate distance-based emission factors (section 2.1.3.2) and currently integrated in the EMEP/EEA methodology for emission computation (Ntziachristos & Samaras, 2017). It is a reference model widely used in the compilation of regional and national emission inventories and it has been implemented and evaluated in the metropolitan area of Madrid with a resolution of 1 km² and 1 h (Borge et al., 2012). Therefore it can be used as a plausible reference for the comparison of the results from microscale models in particular areas of the city of Madrid. So that a comparison of the results was performed as a first step of the validation of the microscale approach presented.

In this case, measured traffic data were crossed with the National Traffic Authority data to get the information needed to classify every single vehicle into COPERT 4 categories (technology and fuel type). Also, COPERT 4 uses average speed to predict hot running emission factors. For this analysis, the average speed was calculated from the instantaneous speed results from VISSIM for FL square and the comparison is done by means of resulting emission factors (g/km) for cars due to the important contribution of passenger cars to the total emissions, as discussed in previous sections. So that, secondary emission factors as function of average speed have been computed for each FL scenario and pollutant (NO_x and PM₁₀ exhaust) and compared with those calculated with COPERT 4 for the same fleet composition.

Figure 6.2. COPERT 4 and VERSIT+_{micro} NO_x emissions factors (g/km) for the “Car” class.

Figure 6.2 shows that NO_x emissions factors calculated by VERSIT+_{micro} and COPERT 4 are in reasonable agreement. VERSIT+_{micro} emissions range between a -6 % and 31 % compared to those of COPERT, and present a mean normalized bias error of 14 % (taking COPERT as a reference). As explained in [Smit et al. \(2007\)](#), the main difference between the two models is that VERSIT+ calculates different emission factors for various traffic situations that present similar average speeds but different dynamics. VERSIT+ uses driving patterns for specific local situations (calculated by VISSIM) while COPERT 4 calculates equivalent average driving patterns. This is the reason why the results from VERSIT+ should reproduce better emissions at microscale ([Csikós & Varga, 2012](#)).

However, both modelling approaches are supposed to provide similar magnitude order since congestion is implicitly considered in speed-average models ([Smit et al., 2008](#)). It is interesting to note that the largest deviations correspond to those scenarios with more congestion and higher emissions. This highlights the limitations of average-speed models describe congestion for a specific traffic situation and the importance of detailed and precise microscale hot-spot simulations to identify potential measures to reduce emissions from road traffic in urban areas, specifically at hot-spots.

6.2.2 Comparison to modal models PHEM-light and PΔP

The aim of this section is to compare detailed traffic emission predictions from two microscale modal emission models, the Australian PΔP (Power-delta-Power) ([Smit, 2013](#)) and the simplified version of the European PHEM (Passenger Car and Heavy Duty Emission Model), PHEM-light model ([Hausberger & Krajzewicz, 2014](#)) for different urban network configurations (in Australia and Spain) and compare their results to the estimations from the cycle-variable model used in this thesis (VERSIT_{micro}) ([Quaassdorff et al., 2017b](#)).

For the comparison of the emission models, driving patterns for individual vehicles were generated with the traffic micro-simulation model VISSIM providing speed-time profiles with 1 second resolution under different traffic congestion conditions ([Quaassdorff et al., 2016](#)) for two hot-spot areas: Gabba in Brisbane (Australia) and FL in Madrid (Spain).

The Australian modal emission model PΔP ([Smit, 2013](#); section 2.1.3.6) is feed with relevant information on vehicle type (PC, SUV, LCV, MCV, AT, BUS-L and BUS-H), cycle (user defined name), time (s), speed (1 Hz in km/h), vehicle loading (% of full load), road gradient (%) and other relevant parameters for the emission and fuel consumption computation.

For the PHEM-light model ([Hausberger & Krajzewicz, 2014](#); section 2.1.3.6) implementation, is feed with information of vehicle speeds (1 Hz in km/h) and road gradient (%) for each driving cycle. Vehicle parameters such as vehicle mass, loading or engine rated power among others are stored in 131 files which combine vehicle type (PC, LCV, HDV), vehicle size class (LCV I, II, III and HDV I and II), vehicle category (Rigid truck, Trailor Truck, Coach, City Bus), fuel (Diesel, Petrol, BEV, CNG) and Euro standard (Euro 0 to Euro 6c). These information is then coupled for engine power computation of each individual vehicle over one driving cycle.

The general flowchart for the modal emission modelling and comparison to VERSIT_{micro} is presented in Figure 6.3.

Figure 6.3. General flowchart of the modelling system and comparison approach of microscale emission models (Quaassdorff et al., 2018 in preparation).

Firstly, to understand the response of the modal emission models, vehicle classes considered in both models were mapped to a common classification using engine power and vehicle mass (power-to-mass ratio) to ensure a consistent comparison. Power is one of the fundamental parameters in emission calculations in these models, and this variable is significantly affected by acceleration-deceleration patterns. An example trip for free-flow (weekday 4:00 to 5:00 h) scenario (E1) in FL (Madrid, Spain) is shown in Figure 6.4a. These cycles are the main input for the engine power calculation in both models (Figure 6.4b). Detailed estimations of NO_x emissions and fuel consumption (FC) were compared (Figure 6.4c) in order to assess differences and to identify the most important variables involved in the emission calculation. The same analysis was performed for saturated scenario in Gabba (Brisbane, Australia) (Figure 6.5).

Figure 6.4. a) Speed-acceleration-time profile for a car in E1 scenario, b) Engine power (kW) and road gradient (%) and c) NO_x and FC emission (g/s) comparison.

Figure 6.5. a) Speed-acceleration-time profile for a car in Gabba saturated scenario, b) Engine power (kW) and road gradient (%) and c) NO_x and FC emission (g/s) comparison.

The results point out once more the importance of congestion (included in the speed-time profile through the acceleration), road gradient, vehicle load and power for the emission calculation. Maximum NO_x emission rates for the saturated traffic scenario (Gabba) with variable gradient, reach up to 134.5 mg/s and 76.8 mg/s calculated with PΔP and PHEM-light

respectively. Whereas, in the free-flow scenario (E1-FL) with constant gradient, NO_x emission maximums are 71.3 mg/s and 48.8 mg/s correspondently. These differences are due to the power calculation variation between models. PHEM-light tends to predict lower power values than PΔP and this is reflected in emission results. The analysis of emission estimations for driving patterns under different traffic conditions points out the importance of an accurate definition of the model parameters for a specific vehicle fleet. In particular, large differences in the results are observed due to differences in Power-to-Mass ratios considered for each vehicle category. For the same Power-to-Mass ratio, Australian vehicles are larger and present higher engine power than European ones. Nevertheless, satisfactory results can be achieved with any of the models, if reliable information on the vehicle fleet composition and vehicle characteristics is provided. In this sense, a larger number of vehicle classes included in a particular model (in addition to realistic driving patterns) implies a better chance to provide representative emissions estimates.

The second-by-second emission results provided by both emission models coupled to the instantaneous position provided by the traffic simulation model can be used to produce emission maps for individual trips with meters and seconds resolution (Figure 6.6).

Figure 6.6. Second-by-second NO_x emission distribution for scenario E1 and driving profile from Figure 6.4.

Furthermore, aggregated emissions maps for the whole domain can also be generated and compared to the cycle-variable model (Figure 6.7) used in this Ph.D. Thesis. This methodology has been successfully applied to different scenarios with different levels of congestion and compared to VERSIT+_{micro} emission results. An example is provided for FL free-flow scenario and saturated (weekday 8:00 to 9:00 h) scenario E2 (Table 6.3 and Figure 6.7).

Table 6.3. Total NO_x emissions (g/h) for the four scenarios and the three emission models.

Scenario	PHEM-light (g/h)	PΔP (g/h)	VERSIT+ _{micro} (g/h)
Free-flow (E1)	197	322	293
Saturated (E2)	4148	5702	7818

Figure 6.7. NO_x emission results for Madrid free-flow (above) and saturated (below) scenarios computed to a spatial resolution of $5 \text{ m} \times 5 \text{ m}$ with PHEM-light (left), $\text{P}\Delta\text{P}$ (centre) and $\text{VERSIT}^+_{\text{micro}}$ (right).

Taking the example of Madrid saturated scenario and analysing emission factors per vehicle category the main differences between emission computation of modal models and the cycle-variable model are related to heavy-duty vehicles emissions factors. Mean emission factors from $\text{VERSIT}^+_{\text{micro}}$ are 70 % higher than those from $\text{P}\Delta\text{P}$ and PHEM-light. Since there are no heavy-duty vehicles (HDV) in the E1 scenario, differences between $\text{P}\Delta\text{P}$ and $\text{VERSIT}^+_{\text{micro}}$ are the lowest, around 9 %. Nevertheless, NO_x emissions from heavy-duty vehicles differ up to 49 % between modal models, so that PHEM-light predicts roughly half of the emissions for this vehicle class. This is directly reflected on the total emissions per scenario (Table 6.3). On the other hand, there is a good agreement between $\text{VERSIT}^+_{\text{micro}}$ and $\text{P}\Delta\text{P}$ for the passenger car category (more than 90 % of the vehicle fleet in all scenarios) with differences below 6 % and a goodness of fit that reaches an R^2 value of 0.79. Also the spatial distribution shows general good agreement among models with higher emissions after traffic lights (access roads to the roundabout) and inside the roundabout links.

So that the proposed modelling system based on $\text{VERSIT}^+_{\text{micro}}$ reproduce the spatial distributions obtained with more detailed modal models. Also, emission results for passenger cars are in agreement with those from $\text{P}\Delta\text{P}$. And the main differences among models are related to the emission factors estimation of HDV.

6.2.3 Comparison with on-road measured data

This is done through the comparison of NO_x traffic computed emissions and measured on-road data from a mobile laboratory in collaboration of the Kangwon National University (refs). This constitutes a novel approach to model validation that may help in the harmonization of the application and assessment of microscale modelling tools. To test the approach, the Posco intersection in South Korea (section 4.2.2) was selected and two scenarios were analysed peak (9:00 – 10:00 h) and off-peak (15:00 – 16:00 h).

The Mobile Laboratory (ML) of the Korean Institute of Science and Technology (Figure 6.8) has been used in the past to produce very high spatial and temporal resolution NO_x concentration maps on urban roads (Woo et al., 2016). The sampling inlets of the ML consisted of a Teflon tubing for gaseous pollutants. The sampling height was approximately 2 m above ground level. Nitrogen oxides were measured using a NO_x analyser (CLD 700 EL, ECO PHYSICS INC., USA) and it was calibrated before and after measurements to check standard concentrations. Global position system (GPS) information was collected every second in order to locate the measured concentrations in space (Kim et al., 2014; Woo et al., 2016). To take the measurements, the mobile laboratory travels defined trips through the domain so that a total of 4 trips for off-peak interval 6 trips for peak interval were done.

Figure 6.8. Instrumented Mobile Laboratory used by KIST (Korean Institute of Science and Technology) to measure on road NO_x concentrations.

The initial hypothesis was that such near-ground, highly resolved concentration fields may be used as a proxy of emissions. Nonetheless, after different analysis, it was concluded that the effect of advection and diffusion could not be neglected, even for such small temporal and spatial scales. Therefore, these processes were incorporated in the comparison by performing a detailed CFD simulation for the intersection. This approach is similar to those previously used

for the validation of CFD codes (Santiago et al., 2017a). The methodology followed in this study consists in the combination of the traffic emission microsimulation modelling system (section 4.2.2) with a CFD air quality model (Kwak et al. 2015) to solve the continuity, momentum, energy, and diffusion equations for the vehicle exhaust-gas dispersion and flow characteristics considering the emission and weather conditions.

6.2.3.1 Traffic emission results

Emission result for this test are shown in Figure 6.9 (5 m x 5 m grid resolution). These maps clearly reflect the influence of congestion (low average speed) on exhaust emissions. Total emissions for each scenario vary from 7780.4 g/h (mean emission factor of 2.34 g/km) at peak hour (Figure 6.9a) to 5074.6 g/h (mean emission factor of 1.86 g/km) at off-peak hour (Figure 6.9b) which is influenced by the stop & go patterns generated by queuing after a traffic lights. More fluent traffic conditions in the off-peak hour generate less acceleration-deceleration cycles which have a clear effect on the emission factor showing a reduction of 20 %. These results are in agreement with emissions estimations from the Madrid's networks where also significant emission reductions have been observed from saturated to free-flow scenarios due to fewer vehicles but also to the more fluent traffic conditions. The main differences between both scenarios are the length of the vehicle queue in Samseong-ro (from South to North) and also the vehicle movements from South to West direction in the peak hour that in the off-peak hour are clearly reduced. The length of the queue generated on Teheran-ro (east) remains similar for both scenarios.

Figure 6.9. NO_x emission results with 5 m x 5 m grid resolution for (a) peak and (b) off-peak hour.

6.2.3.2 CFD simulation

Taking the simulated traffic emissions as input and the meteorological data of wind speed and direction, flow field was solved by employing the renormalization group (RNG) $k-\varepsilon$ turbulence model, which has been extensively used to solve atmospheric flow field and pollutant dispersion in urban areas (Kwak et al., 2015). Also, a wall function was used to model the near-wall velocity profile with a number of grid-cells of approximately 4,300,000.

NO_x concentration distribution in the domain was simulated using the same 5 m x 5 m resolution grid (Figure 6.10) by the Seoul National University. The concentration maps are based on two different wind speeds (2 and 3 m/s) and two wind directions (different angles both from North-West to South-East). In general terms the CFD model is predicting higher concentrations after traffic lights where vehicles are queuing and present the highest values near to the intersection. Nevertheless, future work must be done in order to compare the results values directly to the on-road measured data.

Figure 6.10. NO_x concentration results from simulated traffic emissions with 10 m x 10 m grid resolution for (a) peak and (b) off-peak scenario.

6.2.3.3 Observations

The ML information was used to generate pollution concentration maps with 10 m x 10 m grid resolution (maximum resolution allowed by current on board GPS instrument) for both, peak hour (based on 6 trips) and off-peak hour (based on 4 trips). This information was adjusted to the emissions and CFD modelling domain for comparison purposes (Figure 6.11). On this maps vehicle queues after traffic lights can be observed on Teheran-ro (East-West) with maximums of up to 700 ppb near to the intersection. In general, the concentration distribution present slight similarities to the observations with higher concentrations after traffic lights and near to the intersection. Nevertheless, this comparison is limited due to the representativeness of full hour estimated emission and concentration data (for individual grid cells) to be compared to the trip measured data with second resolution. In this sense, the relationship between measured data from the ML per 5 m x 5 m grid cells are compared to the corresponding CFD calculated values with low correlation value which is extremely influenced by the position of the GPS measurements with a position accuracy of up to 10 m.

Figure 6.11. NO_x concentration distribution from ML measured data geolocated using GPS adjusted to the 5 m x 5 m grid resolution mesh for (a) peak and (b) off-peak hour.

Despite the need for further research, this is a first approach to the validation of the high resolution emission estimation modelling system VISSIM-VERSIT_{micro}/ENVIVER on a real hot-spot using ML data. These simulated concentration results are hard to compare with measured trips data from the Mobile Laboratory due to difficulties to obtain individual trip data that covers the whole domain for a complete hour. Also, ML data comparison to CFD concentrations are extremely dependant of a correct location of measurements for this high spatial resolution of 5 m x 5 m. Nevertheless, concentration distribution maps obtained from the modelling system and from the ML measured data present, in general terms, similar concentration patterns. Both techniques present higher concentrations near to the intersection and for queuing vehicles after traffic lights in main roads.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH NEEDS
CONCLUSIONES Y FUTURAS LÍNEAS DE INVESTIGACIÓN

7.1 CONCLUSIONS AND FUTURE RESEARCH NEEDS

7.1.1 Conclusions

The methodological approach and the level of detail used to calculate emissions from road traffic (macroscopic or microscopic) have a clear influence on emission estimates. Moreover, the input data also play a key role and have important implications regarding the assessment of potential emission abatement measures. Microscale models can provide a very detailed view of traffic flows and offer a suitable basis for emission computation under alternative scenarios, such as those considered in this study for the Fernández Ladreda square and Escuelas Aguirre area in Madrid.

To provide such high spatial and temporal resolution reliable emissions in traffic hot-spots, a suitable combination of traffic and emission micro-simulation models is needed. The simulation system needs to capture the effects that influence the emission generation processes at street level. In this Ph.D. Thesis a traffic emission micro-simulation system (with meters resolution) has been implemented and tested with good results for 1-hour aggregated emission computation.

The simulation system VISSIM-VERSIT_{micro}/ENVIVER has been demonstrated to be useful to provide highly detailed emissions for complex urban hot-spot locations. A successful application to FL (signalized roundabout) and EA (signalized intersections) areas inside the city of Madrid and to a combination of urban roads connected to a highway (Gabba) and a single intersection (Posco) demonstrates the flexibility of the system and its applicability to a wide extent of urban configurations (road network configuration, fleet composition, etc.).

According to the methods used and the detailed emission analysis performed in FL, total hourly emissions in the modelling area vary remarkably throughout the day, being total NO_x and exhaust PM₁₀ emissions up to 27 and 23 times larger respectively during peak hours than those of non-rush hours. This is obviously influenced by the typical variation in traffic volumes but there is a strong influence on traffic conditions as well. It was observed that simulations under free-flow traffic conditions generate the lowest average emission factors. Vehicle-specific emission factors may increase during the peak hours up to 43 % and 28 % for NO_x and PM₁₀ respectively. These results evidence the potential that local measures aimed at alleviating congestion may have in urban areas to reduce emissions. The importance that congestion plays on emissions was depicted since for the same vehicle type and same trip, emission increases up to 30 % only due to the stop & go patterns that are generated in traffic saturated scenarios. So

that, the differences in emission factors (g/km) from situations of free-flow to saturated scenarios highlight the potential of local emission abatement measures.

It was found that trucks and buses also play an important role because of their high emission factors, especially in the case of trucks (with an average contribution to emissions of 15 % in the case of NO_x). This indicates that optimized goods transport and road network planning at the local scale may significantly contribute to reduce travel time and emissions, as complement to general urban-scale strategies. The assessment of some of those measures (e.g. HGV access restriction) points out that significant reductions (of up to 28 % of NO_x and 11 % of PM₁₀) can be achieved. Nevertheless, this methodology can be used to analyse specific measures that affect traffic flow, traffic composition and also changes on vehicles technology and emission standards.

In addition to the implementation and application of the microscale emission modelling methodology, this Ph.D. Thesis includes an assessment of the system. As a first step for this assessment, a comparison of aggregated microscale emission estimates with a well-known reference mesoscale model (COPERT) was carried out. The comparison of the resulting NO_x emission factors for cars with the corresponding ones computed through COPERT showed relative differences from –6 % to 31 % depending on the traffic conditions. This points out that the magnitude order is correct but also highlights the limitations of average-speed emission models to support microscale analysis.

Also, even more detailed modal emission models (PΔP and PHEM-light) have been successfully applied, analysed and compared to VERSIT_{micro} for two case studies. These results indicate that precise engine power calculation is a very important parameter for an accurate emission computation. In turn, this variable depends on a reliable estimation of the speed-acceleration pattern, road gradient and vehicle loading. Also, it is essential to define power and load parameters as accurately as possible for each vehicle class to obtain accurate emissions, regardless of the specific model being used. Furthermore, a larger number of vehicle classes included in a particular model (e.g. motorcycles or alternative technologies) implies a better chance to provide representative emissions estimates. However, larger spread on emission factors for low average speeds reveals the difficulty of accurately predicting emissions for stop & go conditions, which are usually the main cause for traffic hot-spots and air quality non-compliance situations in urban areas. The proposed modelling system shows good performance for the main vehicle category (car) compared to more detailed modal models.

Despite providing reasonable estimate of emission rates and spatial distribution, the modelling system has been proved useful to support further analysis that are interesting for other scientific fields as well as relevant policy-wise.

The methodology has also been useful to perform a preliminary study case for population exposure and to assess the representativeness of air quality monitoring stations. The methods used to simulate pedestrians and to obtain concentration maps can only be applied at microscale and may be used to support studies of monitoring station micro-siting. However, if pedestrians location and concentration values are provided by other means, the methodology based on the TTE/TE index assessment may be applied to larger areas and contribute to the definition of monitoring points that may be representative of population exposure and thus, assessment of the compliance of health-related ambient air quality legal standards.

Detailed emissions results from VERSIT+_{micro} have been successfully coupled to stationary simulations from highly detailed air quality models based on CFD-RANS. The modelling system is suitable for state-of-the-art CFD modelling in urban areas since they have been successfully used in this Ph.D. Thesis in two cases: for a complex urban roundabout and a signalized intersection (FL and Posco, respectively).

In this sense, a first approach to the validation of the high resolution emission estimation modelling system VISSIM-VERSIT+_{micro}/ENVIVER on a real hot-spot using ML data has been performed. This emission modelling system was coupled to the CFD based air quality model from Seoul National University to obtain concentration results with 5 m x 5 m resolution. ML data comparison to CFD concentrations are extremely dependant of a correct location of measurements for this high spatial resolution. Nevertheless, concentration distribution maps obtained from the modelling system and from the ML measured data present, in general terms, similar concentration patterns.

7.1.2 Future research needs

The simulation system VISSIM-VERSIT+_{micro}/ENVIVER methodology could be improved by testing the modelling system in hot-spot areas that include traffic collectors, arterial roads and combinations of different road types to test its applicability to these specific configurations. Also, trying to increase the modelling domains to up to 1km² to study a bigger influence area around the analysed point. The main limitation for that is the number of necessary input data, the accuracy of these data and their consistency.

Although the modelling system is deemed satisfactory to analyse microscale emission dynamics, future research efforts should be aimed at reviewing and improving emission algorithms, including more specific emissions depending on vehicle type and non-exhaust emissions (including resuspension for PM). This would allow using the specific data available, and should increase the accuracy and usefulness of the results. This, however, does not prevent from using

the modelling system presented as a platform to design and test measures for emission abatement options and exposure assessment for specific hot-spots in Madrid.

Despite good agreement between modal models and cycle-variable model for the vehicle category Car, differences in HGV category deserve further analysis. Nevertheless, real-world emission measurements are essential towards the validation of emission factors and total emissions computed by these modelling techniques.

Ongoing research on the improvement and development of methods needed to couple microscale emissions to CFD in a dynamic way needs second-by-second (5 to 10 second) resolved emissions that can be provided by modal emission models. The instantaneous emission information generated by modal models is suitable to generate emission maps with high spatial and temporal resolution. They are a good option to provide emission estimates for different traffic scenarios for non-stationary CFD air quality modelling in urban areas. So that abatement options and local measures can also be assessed in terms of their accurate impact on air quality.

Nevertheless, future work in order to compare the CFD results values directly to the on-road measured data must be done for validation purposes. Also, to compare simulated emission data using inverse emission estimation from the on-road measured concentrations.

Regarding population exposure analysis, determining the inhaled volume of polluted air by means of physiological parameters and/or the pedestrian's instant speed should be also considered in future studies to obtain more accurate results.

7.2 CONCLUSIONES Y FUTURAS LÍNEAS DE INVESTIGACIÓN

7.2.1 Conclusiones

El enfoque metodológico y el nivel de detalle utilizado para calcular las emisiones del tráfico rodado (macroscópico o microscópico) tienen una clara influencia en la estimación de las emisiones. Además, los datos de entrada también desempeñan un papel clave y tienen implicaciones importantes con respecto a la evaluación de posibles medidas de reducción de emisiones. Los modelos de microescala pueden proporcionar una visión muy detallada de los flujos de tráfico y ofrecen una base adecuada para el cálculo de emisiones de escenarios alternativos, como los considerados en este estudio para la plaza Fernández Ladreda y el área de Escuelas Aguirre en Madrid.

Para proporcionar emisiones precisas con una resolución espacial y temporal tan alta en hot-spots de tráfico, se necesita una combinación adecuada de modelos de microsimulación de tráfico y emisiones. El sistema de simulación debe capturar los efectos que influyen en los procesos de generación de emisiones a nivel de la calle. En esta Tesis se ha implementado y probado un sistema de microsimulación de emisiones del tráfico (con resolución de metros) con buenos resultados para el cómputo de emisiones agregadas de 1 hora.

Se ha demostrado que el sistema de simulación VISSIM-VERSIT_{micro}/ENVIVER es útil para proporcionar emisiones altamente detalladas para ubicaciones urbanas complejas. Se ha aplicado con éxito a las áreas de FL (rotonda señalizada) y EA (intersecciones señalizadas) dentro de la ciudad de Madrid y además a una combinación de vías urbanas conectadas a una autovía (Gabba) y una sola intersección (Posco) lo que demuestra la flexibilidad del sistema y su aplicabilidad en una amplia gama de configuraciones urbanas (configuración de la red vial, composición de la flota, etc.).

Según los métodos utilizados y el análisis detallado de emisiones realizado en FL, las emisiones totales por hora en el área simulada varían notablemente a lo largo del día, siendo las emisiones totales de NO_x y PM₁₀ (solo tubo de escape) hasta 27 y 23 veces mayores durante las horas punta que las de las horas valle. Obviamente, esto está influenciado por la variación típica en los volúmenes de tráfico, pero también existe una gran influencia en las condiciones del tráfico. Se ha observado que las simulaciones en condiciones de tráfico de flujo libre generan factores de emisión promedio más bajos. Los factores de emisión específicos del vehículo pueden aumentar durante las horas punta hasta 43 % y 28 % para NO_x y PM₁₀ respectivamente. Estos resultados evidencian el potencial que las medidas locales destinadas a aliviar la congestión pueden tener en las áreas urbanas a la hora de reducir las emisiones. La importancia que tiene la congestión

en las emisiones es evidente ya que para el mismo tipo de vehículo que sigue exactamente la misma ruta, las emisiones aumentan hasta un 30 % solo debido a los patrones intermitentes de frenado y aceleración que se generan en escenarios de tráfico saturado. De modo que, las diferencias que se observan en los factores de emisión (g/km) de situaciones de flujo libre a escenarios saturados resaltan el potencial de las medidas reducción de emisiones a nivel local.

Por otro lado, los camiones y autobuses también juegan un papel importante debido a los altos factores de emisión, especialmente en el caso de los camiones (con una contribución promedio a las emisiones del 15 % en el caso de los NO_x). Esto indica que la optimización del transporte mercancías y la planificación de la red de carreteras a escala local pueden contribuir significativamente a reducir el tiempo de viaje y las emisiones, como complemento a las estrategias generales a escala urbana. La evaluación de algunas de estas medidas (por ejemplo, la restricción de acceso de HGV) señala que se pueden lograr reducciones significativas (de hasta 28 % de NO_x y 11 % de PM_{10}). Sin embargo, esta metodología se puede utilizar para analizar también más tipos de medidas específicas que afecten al flujo de tráfico, a la composición de la flota y también a cambios en la tecnología de los vehículos y las normativas de emisión.

Además de la implementación y aplicación de la metodología de modelado de emisiones a microescala, este Tesis incluye una evaluación del sistema. Como primer paso para esta evaluación, se llevó a cabo una comparación de estimaciones de emisiones de microescala agregadas con un modelo de mesoescala de referencia bien conocido (COPERT). La comparación de los factores de emisión de NO_x resultantes para automóviles comparados con los computados con COPERT muestran diferencias relativas de -6 % a 31 % dependiendo de las condiciones del tráfico. Esto indica que el orden de magnitud es correcto, pero también resalta las limitaciones de los modelos de emisión de velocidad media para análisis a microescala.

Además, se han aplicado con éxito modelos de emisiones modales más detallados (PΔP y PHEM-light) los cuales se han analizado y comparado con $\text{VERSIT}_{\text{micro}}$ para dos estudios de casos. Los resultados indican que el cálculo preciso de la potencia del motor es un parámetro muy importante para un cálculo de emisiones preciso. A su vez, esta variable depende de una estimación fiable del patrón de velocidad-aceleración, la pendiente de la carretera y la carga del vehículo. Asimismo, es esencial definir los parámetros de potencia y carga con la mayor precisión posible para cada clase de vehículo para obtener emisiones precisas, independientemente del modelo específico que se utilice. Por ello, un mayor número de clases de vehículos incluidas en un modelo particular (por ejemplo, motocicletas o tecnologías alternativas) implica una mejor oportunidad de proporcionar estimaciones de emisiones representativas. Sin embargo, una mayor dispersión de los factores de emisión para velocidades medias bajas revela la dificultad de predecir con precisión las emisiones para las condiciones stop & go, que suelen ser la causa

principal de los hot-spots de tráfico y las situaciones de incumplimiento de la calidad del aire en las zonas urbanas. En general, el sistema de simulación propuesto muestra un buen rendimiento para la principal categoría de vehículos (automóvil) en comparación con los modelos modales más detallados.

A pesar de proporcionar una distribución espacial y estimación de las tasas de emisión razonables, el sistema de modelado puede ser útil para respaldar futuros análisis que sean de interés en otros campos científicos, así como para las políticas pertinentes.

La metodología también ha sido útil para llevar a cabo un caso de estudio preliminar sobre la exposición de la población y para evaluar la representatividad de las estaciones de calidad del aire. Los métodos utilizados para simular peatones y obtener mapas de concentración solo se pueden aplicar a microescala y se pueden usar para respaldar los estudios sobre la micro-ubicación de las estaciones. Sin embargo, si los valores de ubicación de peatones y concentración de contaminantes se proporcionan por otros medios, la metodología basada en la evaluación del índice TTE/TE puede aplicarse a áreas más grandes y contribuir a la definición de puntos de medida que pueden ser representativos de la exposición poblacional teniendo en cuenta el cumplimiento de los estándares legales de calidad del aire ambiente relacionados con la salud.

Los resultados de emisiones detallados que proporciona VERSIT+_{micro} se han acoplado con éxito a simulaciones estacionarias de modelos de calidad de aire altamente detallados basados en CFD-RANS. El sistema de simulación es adecuado para utilizarse en CFD aplicados en áreas urbanas ya que se han utilizado con éxito en esta Tesis en dos casos: una rotonda urbana compleja y una intersección señalizada (FL y Posco respectivamente).

En este sentido, se ha realizado un primer acercamiento a la validación del sistema de simulación de emisiones con alta resolución (VISSIM-VERSIT+_{micro}/ENVIVER) en un hot-spot real utilizando datos de un laboratorio móvil (ML). Este sistema de simulación de emisiones se acopló al modelo de calidad del aire basado en CFD de la Universidad Nacional de Seúl para obtener resultados de concentración con una resolución de 5 m x 5 m. La comparación de los datos del ML con las concentraciones de CFD es extremadamente dependiente de una ubicación correcta de las mediciones para esta alta resolución espacial. Sin embargo, los mapas de distribución de concentraciones obtenidos del sistema de simulación y de los datos medidos del ML presentan, en términos generales, patrones de concentración similares.

7.2.2 Futuras líneas de investigación

La metodología basada en el sistema de simulación VISSIM-VERSIT+_{micro}/ENVIVER podría perfeccionarse probando el sistema de simulación en hot-spots que incluyen colectores de

tráfico, carreteras principales y combinaciones de diferentes tipos de carreteras para probar su aplicabilidad a estas configuraciones específicas. Además de tratar de aumentar los dominios de modelado hasta 1 km² para estudiar un área de influencia más grande alrededor del punto analizado. La principal limitación es la cantidad de datos de entrada necesarios, la precisión de los mismos y su consistencia.

Aunque el sistema de modelado se considera satisfactorio para analizar las dinámicas de emisión a microescala, futuros esfuerzos de investigación deben estar dirigidos a revisar y mejorar los algoritmos de emisión, incluyendo emisiones más específicas dependiendo del tipo de vehículo y emisiones de no tubo de escape (incluyendo resuspensión para PM). Esto permitiría usar datos específicos disponibles y debería aumentar la precisión y la utilidad de los resultados. Sin embargo, esto no impide utilizar el sistema de modelado presentado como una plataforma para diseñar y probar medidas para las opciones de reducción de emisiones y la evaluación de la exposición para puntos críticos específicos en Madrid.

A pesar de la buena concordancia entre los modelos modales y el modelo de variable de ciclo para la categoría de vehículo Automóvil, las diferencias en la categoría de vehículos pesados merecen un análisis adicional. Sin embargo, para ello mediciones de emisiones en el mundo real son esenciales para la validación de los factores de emisión y las emisiones totales calculadas mediante estas técnicas de modelado.

Investigaciones en curso sobre la mejora y el desarrollo de los métodos necesarios para acoplar las emisiones a microescala a CFD de una manera dinámica requiere de emisiones resueltas segundo a segundo (5 a 10 segundos) que pueden proporcionar los modelos modales. La información de emisiones instantáneas proporcionada por los modelos modales es adecuada para generar mapas de emisión con alta resolución espacial y temporal. Estos son una buena opción para proporcionar estimaciones de emisiones para diferentes escenarios de tráfico para modelos de calidad de aire CFD no estacionarios en áreas urbanas. De modo que las opciones de reducción y las medidas locales también pueden evaluarse en términos de su impacto preciso en la calidad del aire.

En cuanto a la validación del sistema, con datos medidos con ML se debe seguir investigando para poder llegar a comparar resultados de CFD directamente con los datos medidos. Además de comparar los datos de emisiones simulados utilizando la estimación de emisiones inversas a partir de las concentraciones medidas en la carretera.

Con respecto al análisis de la exposición de la población, la determinación del volumen inhalado de aire contaminado mediante parámetros fisiológicos y/o la velocidad instantánea del peatón también debe considerarse en futuros estudios para obtener resultados más precisos.

CHAPTER 8

DISSEMINATION OF RESULTS

8.1 Journal papers

Here are listed the published JCR indexed journal papers related to this Ph.D. Thesis, including the impact factor (JIF) and the ranking within the corresponding journal category:

<p>JIF 4.900</p>	<p>Quaassdorff, C., Borge, R., de la Paz, D., Pérez, J., de Andrés, J. M., and Lumbreras, J. 2016. Microscale traffic simulation and emission estimation in a heavily trafficked roundabout in Madrid (Spain). <i>Science of The Total Environment</i> 566-567:416-427. DOI: http://dx.doi.org/10.1016/j.scitotenv.2016.05.051.</p> <p>Year 2016, Category Environmental sciences: Rank 22/229, Quartile Q1, JIF percentile 90.611</p>
<p>JIF 3.629</p>	<p>Borge, R., Narros, A., Artiñano, B., Yagüe, C., Gómez-Moreno, F.J., de la Paz, D., Román-Cascón, C., Díaz, E., Maqueda, G., Sastre, M., Quaassdorff, C., Dimitroulopoulou, C. & Vardoulakis, S. 2016. Assessment of microscale spatio-temporal variation of air pollution at an urban hotspot in Madrid (Spain) through an extensive field campaign. <i>Atmospheric Environment</i>. 140:432-445. DOI: 10.1016/j.atmosenv.2016.06.020</p> <p>Year 2016, Category Environmental sciences: Rank 49/229, Quartile Q1, JIF percentile 78.821. Meteorology and Atmospheric sciences: Rank 16/85, Quartile Q1, JIF percentile 81.765</p>
		<p>Sanchez, B., Santiago, J.L., Martilli, A., Martin, F., Borge, R., Quaassdorff, C., de la Paz, D. 2017. Modelling NO_x concentrations through CFD-RANS in an urban hot-spot using high resolution traffic emissions and meteorology from a mesoscale model. <i>Atmospheric Environment</i>. 163:155-165. DOI: 10.1016/j.atmosenv.2017.05.022</p> <p>Year 2016, Category Environmental sciences: Rank 49/229, Quartile Q1, JIF percentile 78.821. Meteorology and Atmospheric sciences: Rank 16/85, Quartile Q1, JIF percentile 81.765</p>

In preparation: Quaassdorff, C., Smit, R., Borge, R., et al., 2018. *Comparison of microscale traffic emission models for urban networks*.

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Microscale traffic simulation and emission estimation in a heavily trafficked roundabout in Madrid (Spain)

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HIGHLIGHTS

- Microscale traffic and related NO_x and PM₁₀ emissions were simulated in a hot-spot.
- 12 representative traffic situations throughout the week were analysed.
- Peak-hour emission factors up to 43% higher than those for free-flow conditions.
- Non-proportional dependency of total emissions with intensity in saturated conditions
- Emission results from ENVIVER fit well with the widely validated model COPERT 4.

GRAPHICAL ABSTRACT

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Microsimulation

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VERSIT+_{micro} - ENVIVER

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ABSTRACT

This paper presents the evaluation of emissions from vehicle operations in a domain of 300 m × 300 m covering a complex urban roundabout with high traffic density in Madrid. Micro-level simulation was successfully applied to estimate the emissions on a scale of meters. Two programs were used: i) VISSIM to simulate the traffic on the square and to compute velocity-time profiles; and ii) VERSIT+_{micro} through ENVIVER that uses VISSIM outputs to compute the related emissions at vehicle level. Data collection was achieved by a measurement campaign obtaining empirical data of vehicle flows and traffic intensities. Twelve simulations of different traffic situations (scenarios) were conducted, representing different hours from several days in a week and the corresponding NO_x and PM₁₀ emissions were estimated. The results show a general reduction on average speeds for higher intensities due to braking-acceleration patterns that contribute to increase the average emission factor and, therefore, the total emissions in the domain, especially on weekdays. The emissions are clearly related to traffic volume, although maximum emission scenario does not correspond to the highest traffic intensity due to congestion and variations in fleet composition throughout the day. These results evidence the potential that local measures aimed at alleviating congestion may have in urban areas to reduce emissions. In general, scenario-averaged emission factors estimated with the VISSIM-VERSIT+_{micro} modelling system fitted well those from the average-speed model COPERT, used as a preliminary validation of the results. The largest deviations between these two models occur in those scenarios with more congestion. The design and resolution of the microscale modelling system

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Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Assessment of microscale spatio-temporal variation of air pollution at an urban hotspot in Madrid (Spain) through an extensive field campaign

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HIGHLIGHTS

- An intensive field campaign was carried out in an air pollution hotspot in Madrid.
- Several techniques were combined to assess NO₂, PM and meteorology at microscale.
- Pedestrian counts were made and fluxes simulated for exposure assessment.
- NO₂ spatial and PM₁₀ temporal gradients up to 2 μg m⁻³ m⁻¹ and 55 μg m⁻³ min⁻¹.
- Local measures are important to improve air quality and reduce pedestrian exposure.

GRAPHICAL ABSTRACT

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Air quality
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Experimental campaign
Microscale
Exposure

ABSTRACT

Poor urban air quality is one of the main environmental concerns worldwide due to its implications for population exposure and health-related issues. However, the development of effective abatement strategies in cities requires a consistent and holistic assessment of air pollution processes, taking into account all the relevant scales within a city. This contribution presents the methodology and main results of an intensive experimental campaign carried out in a complex pollution hotspot in Madrid (Spain) under the TECNARE-CM research project, which aimed at understanding the microscale spatio-temporal variation of ambient concentration levels in areas where high pollution values are recorded. A variety of instruments were deployed during a three-week field campaign to provide detailed information on meteorological and micrometeorological parameters and spatio-temporal variations of the most relevant pollutants (NO₂ and PM) along with relevant information needed to simulate pedestrian fluxes. The results show the strong dependence of ambient concentrations on local emissions and meteorology that turns out in strong spatial and temporal variations, with gradients up to 2 μg m⁻³ m⁻¹ for NO₂ and 55 μg m⁻³ min⁻¹ for PM₁₀. Pedestrian exposure to these pollutants also presents strong variations

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Atmospheric Environment

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Modelling NO_x concentrations through CFD-RANS in an urban hot-spot using high resolution traffic emissions and meteorology from a mesoscale model

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HIGHLIGHTS

- High resolution NO_x concentration map computed for an urban heavily trafficked area.
- Results from a detailed traffic emission model are implemented in the CFD simulations.
- Long-period average NO_x estimated through weighted-average of CFD simulations.
- Meteorological information used in the methodology is derived from a mesoscale model.
- Modelled results are validated with data from an intensive passive sampling campaign.

GRAPHICAL ABSTRACT

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CFD Model

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Mesoscale model

Passive samplers

ABSTRACT

Air quality management requires more detailed studies about air pollution at urban and local scale over long periods of time. This work focuses on obtaining the spatial distribution of NO_x concentration averaged over several days in a heavily trafficked urban area in Madrid (Spain) using a computational fluid dynamics (CFD) model. A methodology based on weighted average of CFD simulations is applied computing the time evolution of NO_x dispersion as a sequence of steady-state scenarios taking into account the actual atmospheric conditions. The inputs of emissions are estimated from the traffic emission model and the meteorological information used is derived from a mesoscale model. Finally, the computed concentration map correlates well with 72 passive samplers deployed in the research area. This work reveals the potential of using urban mesoscale simulations together with detailed traffic emissions so as to provide accurate maps of pollutant concentration at microscale using CFD simulations.

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1. Introduction

Air pollution is nowadays the largest environmental health risk in Europe (EEA, 2015a) and so, air quality management in cities has become an important challenge. Broadly half of the global

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8.2 Congress communications

8.2.1 Oral communications

II Symposium "Cuéntanos tu tesis". Madrid, Spain	C. Quaassdorff . March 2018. Estimating emissions for traffic hot-spots in Madrid. Category Sustainability and Environment & Energy. Best speech award .
III Congreso Internacional aplicación, transporte y almacenamiento de fluidos en procesos industriales, hidrocarbúricos y ambientales. Riobamba, Ecuador	Invited talk: C. Quaassdorff . November 2017. TECNAIRE, Técnicas para la mejora de la calidad del aire urbano.
23 rd Biennial International Clean Air and Environment Conference – The critical Atmosphere. Brisbane, Australia	C. Quaassdorff , R. Smit, R. Borge, M. Hickman. October 2017. Comparison of microscale traffic emission models for urban networks.
18 th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes. Bologna, Italy	C. Quaassdorff , K-H Kwak, R. Borge, S-B Lee. October 2017. Traffic emission simulation and validation with measured data in South Korea. R. Borge, D. de la Paz, J. Domingo, C. Valdés, M.T. Rozas, S. Lázaro, J. Pérez, C. Quaassdorff , A. Fernández, J.M. de Andrés, J. Lumbreras. October 2017. Modelling the impact of recent traffic measures taken in Madrid (Spain) during a high pollution episode. B. Sanchez, J.L. Santiago, F. Martín, A. Martilli, C. Quaassdorff , D. de la Paz, R. Borge. October 2017. Modelling reactive pollutants dispersion in an urban hot-spot in summer conditions using a CFD model coupled with meteorological mesoscale and chemistry-transport models. J.L. Santiago, B. Sanchez, F. Martin, A. Martilli, C. Quaassdorff , D. de la Paz, R. Borge, F.J. Gómez-Moreno, E. Díaz, B. Artíñano, C. Yagüe, C. Blanco, S. Vardoulakis. October 2017. CFD modelling of particle matter dispersion in a real hot-spot.
17 th IUAPPA World Clean Air Congress and 9th CAA Better Air Quality Conference. Busan, South Korea	R. Borge, A. Narros, J.L. Santiago, B. Sánchez, F. Martín, C. Quaassdorff , D. de la Paz, A. Martilli, E. Rivas, J. Pérez. Aug-Sept 2016. Assessment of NO ₂ concentration levels in a traffic urban hotspot in Madrid (Spain) through an experimental field campaign and high resolution modelling.
ICCS 2016 – 2 nd International Conference on City Sciences – New architectures, infrastructures and services for future cities. Santiago, Chile	R. Borge, C. Quaassdorff , J. Lumbreras, M. Picornell, P. García-Albertos, D. de la Paz. June 2016. Recent developments for the assessment of air pollution exposure of urban population under the TECNAIRE-CM research project.
XII Congreso de Ingeniería del Transporte. PTV Workshop. Valencia, Spain	C. Quaassdorff , June 2016. Aplicación del modelo de microsimulación PTV VISSIM para el cálculo de emisiones del tráfico.
17 th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes. Budapest, Hungary	B. Sánchez, C. Quaassdorff , J.L. Santiago, R. Borge, F. Martín, D. de la Paz, A. Martilli, E. Rivas. May 2016. Effects of Traffic Emission Resolution on NO _x Concentration Obtained by CFD-RANS Modelling Over a Real Urban Area in Madrid (Spain).

Air Quality 2016 – 10th
International Conference on Air
Quality – Science and Application.
Milan, Italy

C. Quaassdorff, R. Borge, D. de la Paz, J. Pérez, J.M. de Andrés, J. Lumbreras. March 2016. High resolution emission estimation in a heavily trafficked urban area in Madrid (Spain).

B. Sánchez, J.L. Santiago, A. Martilli, F. Martin, R. Borge, **C. Quaassdorff** & D. de la Paz. March 2016. Modelling NO_x concentration using CFD-RANS model with high resolution traffic emissions.

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Conference on City Sciences -
New architectures,
infrastructures and services for
future cities. Shanghai, China

R. Borge, J. Lumbreras, D. de la Paz, J. Pérez, J.M. de Andrés, **C. Quaassdorff**. June 2015. Development of urban air quality plans and measures in Madrid (Spain) under a multi-scale air quality modeling approach.

2nd Healthy Polis Workshop on
Climate Change and Urban Health
– II during Kunshan Forum.
Kunshan, China.

R. Borge, **C. Quaassdorff**, D. de la Paz, A. Narros, J. Pérez, J.M. de Andrés, R. Viteri, M. Paredes. May 2015. Experimental campaign in a heavily trafficked roundabout in Madrid for the assessment of air quality monitoring station representativeness in terms of population exposure to NO₂.

21st USEPA International Emission
Inventory Conference. San Diego,
USA

R. Borge, **C. Quaassdorff**, J. Pérez, D. de la Paz, J. Lumbreras, J.M. de Andrés, A. Narros, E. Rodríguez. April 2015. Development of road traffic emission inventories for urban air quality modeling in Madrid (Spain).

8.2.2 Poster communications

European Geosciences Union General Assembly 2018 (Vienna, Austria, 8th-13th April 2018). C. Yagüe, C. Román-Cascón, M. Sastre, G. Maqueda, J.A. Arrillaga, B. Artíñano, E. Díaz-Ramiro, F.J. Gómez-Moreno, R. Borge, A. Narros, J. Pérez, **C. Quaassdorff**. Key turbulence parameters influencing pollutant concentrations during summer and winter field campaigns in a hot spot in Madrid.

European Geosciences Union General Assembly 2017 (Vienna, Austria, 23th-28th April 2017). C. Yagüe, C. Román-Cascón, M. Sastre, G. Maqueda, J.A. Arrillaga, B. Artíñano, E. Díaz-Ramiro, F.J. Gómez-Moreno, R. Borge, A. Narros, J. Pérez, **C. Quaassdorff**. Turbulence influence on urban air pollution in a hot spot in Madrid: comparison of winter and summer field campaigns.

European Geosciences Union General Assembly 2017 (Vienna, Austria, 23th-28th April 2017). M. Sastre, C. Yagüe, C. Román-Cascón, G. Maqueda, J.A. Arrillaga, B. Artíñano, E. Díaz-Ramiro, F.J. Gómez-Moreno, M. Barreiro, R. Borge, A. Narros, J. Pérez, **C. Quaassdorff**. Study of the air quality in the surroundings of an urban park: A micrometeorological approach.

Industriales Research Meeting 2017 (Madrid, Spain, 4th-5th April, 2017). **Quaassdorff C.** & Borge, R. 2017. Modelling the effects of local emission abatement measures in hot-spots of Madrid.

17th IUAPPA World Clean Air Congress and 9th CAA Better Air Quality Conference (Busan, South Korea, 29th August-2nd September 2016). R. Borge, J. Lumberas, M. Picornell, P. García-Albertos, **C. Quaassdorff**, D. de la Paz, M. Álvarez. Multi-scale assessment of urban population exposure to air pollution in Madrid (Spain). (*Excellent Poster Award*)

Industriales Research Meeting 2016 (Madrid, Spain, 20th April, 2016). Borge, R., Narros, A., Martín, F., Artíñano, B., Yagüe, C., Saiz-López, A., Gómez-Moreno, F. J., de la Paz, D., **Quaassdorff C.**, Lumberas, J., Pérez, J., de Andrés, J. M., Gatóo, B. & Rodríguez, E. 2016. Innovative technologies for the assessment and improvement of urban air quality (TECNAIRE-CM).

Industriales Research Meeting 2016 (Madrid, Spain, 20th April, 2016). **Quaassdorff C.**, Borge, R., de la Paz, D., Pérez, J., de Andrés, J. M. & Lumberas, J. 2016. High resolution emission estimation in hot-spots of Madrid (Spain).

10th International Conference on Air Quality – Science and Application (Milan, Italy, 14th – 18th March, 2016). Artíñano, B., Díaz Ramiro, E., Gómez-Moreno, F. J., Vardoulakis, S., Dimitroulopoulou, C., Yagüe, C., Maqueda, G., Román-Cascón, C., Sastre, M., **Quaassdorff, C.**, Lumberas, J., Latorre, E. & Borge, R. 2016. Distribution of particulate mass concentrations in a complex traffic hot spot.

Excellent Poster Award

8.3 News and Press

8.3.1 Informative article

Searching for effective measures to improve the air quality that citizens breathe

This article how researchers from the UPM are carrying out measurement campaigns and simulations of air quality to improve knowledge of air pollution in Madrid. The research group in Environmental Technologies and Industrial Resources (TARIndustrial) from the UPM is working to develop new techniques capable of diagnosing air quality problems in an integrated way in urban environments for their evaluation and resolution. The work is part of the TECNAIRE-CM Program (Innovative techniques for the evaluation and improvement of urban air quality) in which researchers from the Complutense University of Madrid (UCM), from the Center for Energy, Environmental and Technological Research (CIEMAT) and the Higher Scientific Research Council (CSIC), together with associated companies and air quality technicians from the Madrid City Council and the Community of Madrid.

Full article (*En busca de medidas eficaces para mejorar la calidad del aire que respiran los ciudadanos*) in Spanish (April 19th, 2018): <https://bit.ly/2HvzOLs>

8.3.2 Telemadrid reportage

The air we breath

On February 15th, 2017 Telemadrid (Spanish TV network) issued a report on the research work carried out by one of the Project TECNAIRE groups. In the reportage, the TARINDUSTRIAL group from the UPM explains what the research work consists of. It begins with an explanation of the basis of the pollution problem in Madrid, through field campaigns to measurements in the laboratory and the analysis with modelling techniques.

Full reportage (*El aire que respiramos*) in Spanish (3min (April 19th, 2018)): <https://bit.ly/2HeLsam>

8.3.3 PTV Blog Post

How to clarify pedestrian's exposure

Published September 1st, 2015, on the PTV GROUP web page which is partner in the TECNIRE-CM Project. In the article the most relevant aspects for the application of the software to pedestrian's exposure to air pollutants are explained.

Full article (April 19th, 2018): <https://bit.ly/2HC59fB>

ANNEXES

Annex 1. Software requirements

Software	Software version	Description
the mind of movement	PTV VISSIM 6	PTV Vissim is a microscopic multi-modal traffic flow simulation software developed by PTV Planung Transport Verkehr AG in Karlsruhe, Germany. The name is derived from "Verkehr In Städten - SIMulationsmodell" (German for "Traffic in cities - simulation model"). PTV Vissim was first developed in 1992 and is today a global market leader.
ENVIVER Enterprise 4.0	ENVIVER Enterprise is a tool used to calculate emissions based on 1Hz vehicle record data. It is based on the microscopic exhaust gas/emission model VERSIT+ by TNO. This model is based on data collected from around 2800 vehicles, whose emissions were measured under several driving conditions. ENVIVER calculates the CO ₂ , NO _x and PM ₁₀ emissions for an area with high spatial detail.
PΔP vehicle emission software	PΔP v1	Power-delta-power (PΔP) model predicts second-by-second emissions (CO ₂ , NO _x), energy use and fuel consumption for 73 Australian vehicle classes. The input to the model is speed-time data (1 Hz) and information on air speed, road gradient, vehicle loading and use of air conditioning. The model is designed to simulate the impacts of changing traffic and operational conditions, as well as a wide range or traffic measures.
PHEM-light 1.0.0	PHEM-light model is a simplification of the PHEM model (Passenger Car and Heavy Duty Emission Model) that is an instantaneous vehicle emission model based on a European set of vehicle measurements that covers 131 vehicle classes including passenger cars, light-duty vehicles and heavy-duty vehicles. The model provides a simulation technique to derive modal emission (NO _x , CO ₂ , CO, HC and PM) and fuel consumption quantities for given speed and acceleration demands taking into account vehicle parameters (road load coefficients, mass, loading...), speed in (m/s), acceleration in (m ² /s) and slope (°).
R 3.3.2	R is a free programming language and software environment for statistical computing and graphics that is supported by the R Foundation for Statistical Computing
ArcGIS 10.3	ArcGIS is a geographic information system (GIS) for working with maps and geographic information. The main component of the geospatial processing programs is ArcMap that is used to view, edit, create and analyze geospatial data.

Annex 2. Traffic light position information

Annex 3. Traffic light phases information

Annex 4. Vehicle fleet mileage distribution by EURO standard for FL square

Sector	Propulsion	Technology	Subsector	Mileage (%)
Passenger Cars	Petrol	ECE 15/00-01	Petrol <0,8 l	0.03
			Petrol >2,0 l	0.01
			Petrol 0,8 - 1,4 l	0.36
			Petrol 1,4 - 2,0 l	0.07
			Petrol <0,8 l	0.00
			Petrol 0,8 - 1,4 l	0.01
			Petrol 1,4 - 2,0 l	0.00
			Petrol >2,0 l	0.00
			Petrol 0,8 - 1,4 l	0.01
			Petrol 1,4 - 2,0 l	0.01
			Petrol >2,0 l	0.01
			Petrol 0,8 - 1,4 l	0.17
			Petrol 1,4 - 2,0 l	0.37
			Petrol <0,8 l	0.00
			Petrol >2,0 l	0.18
			Petrol 0,8 - 1,4 l	0.40
			Petrol 1,4 - 2,0 l	0.77
		PC Euro 2 - 94/12/EEC	Petrol <0,8 l	0.03
			Petrol >2,0 l	0.31
			Petrol 0,8 - 1,4 l	0.91
			Petrol 1,4 - 2,0 l	1.81
		PC Euro 3 - 98/69/EC Stage2000	Petrol <0,8 l	0.09
			Petrol >2,0 l	0.69
			Petrol 0,8 - 1,4 l	2.58
			Petrol 1,4 - 2,0 l	4.27
		PC Euro 4 - 98/69/EC Stage2005	Petrol <0,8 l	0.06
			Petrol >2,0 l	0.58
			Petrol 0,8 - 1,4 l	3.33
			Petrol 1,4 - 2,0 l	3.64
			Hybrid Petrol <1,4 l	0.01
			Hybrid Petrol 1,4 - 2,0 l	0.02
		PC Euro 5 - EC 715/2007	Petrol <0,8 l	0.00
			Petrol >2,0 l	0.05
			Petrol 0,8 - 1,4 l	1.35
			Petrol 1,4 - 2,0 l	0.81
		PRE ECE	Petrol <0,8 l	0.00
			Petrol >2,0 l	0.00
			Petrol 0,8 - 1,4 l	0.01
			Petrol 1,4 - 2,0 l	0.00

Sector	Propulsion	Technology	Subsector	Mileage (%)
	Diesel	Conventional	Diesel <1,4 l	0.00
			Diesel >2,0 l	0.05
			Diesel 1,4 - 2,0 l	0.05
		PC Euro 1 - 91/441/EEC	Diesel <1,4 l	0.00
			Diesel >2,0 l	0.14
			Diesel 1,4 - 2,0 l	0.58
		PC Euro 2 - 94/12/EEC	Diesel <1,4 l	0.01
			Diesel >2,0 l	0.45
			Diesel 1,4 - 2,0 l	3.25
		PC Euro 3 - 98/69/EC Stage2000	Diesel <1,4 l	0.94
			Diesel >2,0 l	1.91
			Diesel 1,4 - 2,0 l	14.07
		PC Euro 4 - 98/69/EC Stage2005	Diesel <1,4 l	2.59
			Diesel >2,0 l	3.44
			Diesel 1,4 - 2,0 l	23.02
		PC Euro 5 - EC 715/2007	Diesel <1,4 l	0.84
			Diesel >2,0 l	0.77
			Diesel 1,4 - 2,0 l	7.03
	Liquefied Petroleum Gas	PC Euro 3 - 98/69/EC Stage2000	LPG	0.00
		PC Euro 4 - 98/69/EC Stage2005	LPG	0.00
		PC Euro 5 - EC 715/2007	LPG	0.00
	Compressed Natural Gas	PC Euro 4 - 98/69/EC Stage2005	CNG	0.00
	Electric	Electric	Electric	0.00
Light Commercial Vehicles	Petrol	Conventional	Petrol <3,5t	0.05
		LD Euro 1 - 93/59/EEC	Petrol <3,5t	0.01
		LD Euro 2 - 96/69/EEC	Petrol <3,5t	0.02
		LD Euro 3 - 98/69/EC Stage2000	Petrol <3,5t	0.07
		LD Euro 4 - 98/69/EC Stage2005	Petrol <3,5t	0.07
		LD Euro 5 - 2008 Standards	Petrol <3,5t	0.00
	Diesel	Conventional	Diesel <3,5t	0.08
		LD Euro 1 - 93/59/EEC	Diesel <3,5t	0.16
		LD Euro 2 - 96/69/EEC	Diesel <3,5t	0.53
		LD Euro 3 - 98/69/EC Stage2000	Diesel <3,5t	2.72
		LD Euro 4 - 98/69/EC Stage2005	Diesel <3,5t	5.10
		LD Euro 5 - 2008 Standards	Diesel <3,5t	1.36
	Electric	Electric	Electric	0.00
Taxis	Diesel	PC Euro 3 - 98/69/EC Stage2000	Diesel >2,0 l	0.00
			Diesel 1,4 - 2,0 l	0.26
		PC Euro 4 - 98/69/EC Stage2005	Diesel <1,4 l	0.00
			Diesel >2,0 l	0.03
			Diesel 1,4 - 2,0 l	2.03
		PC Euro 5 - EC 715/2007	Diesel >2,0 l	0.00
			Diesel 1,4 - 2,0 l	0.54

Sector	Propulsion	Technology	Subsector	Mileage (%)
Heavy-duty Trucks	Liquefied Petroleum Gas	PC Euro 4 - 98/69/EC Stage2005	LPG	0.11
		PC Euro 5 - EC 715/2007	LPG	0.11
	Compressed Natural Gas	PC Euro 4 - 98/69/EC Stage2005	CNG	0.00
		PC Euro 4 - 98/69/EC Stage2005	Hybrid Petrol 1,4 -2,0 l	0.58
	Petrol	Conventional	Petrol >3,5 t	0.01
			Rigid <=7,5 t	0.02
			Rigid >32 t	0.00
			Rigid 12 - 14 t	0.00
		Conventional	Rigid 14 - 20 t	0.01
			Rigid 20 - 26 t	0.00
			Rigid 28 - 32 t	0.00
			Rigid 7,5 - 12 t	0.01
		HD Euro I - 91/542/EEC Stage I	Rigid <=7,5 t	0.01
			Rigid 12 - 14 t	0.00
			Rigid 7,5 - 12 t	0.00
		HD Euro II - 91/542/EEC Stage II	Rigid <=7,5 t	0.10
			Rigid 14 - 20 t	0.01
			Rigid 20 - 26 t	0.00
			Rigid 7,5 - 12 t	0.01
		HD Euro III - 2000 Standards	Rigid <=7,5 t	0.48
			Rigid >32 t	0.00
			Rigid 12 - 14 t	0.00
			Rigid 14 - 20 t	0.04
			Rigid 20 - 26 t	0.01
			Rigid 28 - 32 t	0.00
			Rigid 7,5 - 12 t	0.04
		HD Euro IV - 2005 Standards	Rigid <=7,5 t	0.53
			Rigid >32 t	0.00
			Rigid 12 - 14 t	0.00
			Rigid 14 - 20 t	0.02
			Rigid 20 - 26 t	0.01
			Rigid 28 - 32 t	0.00
			Rigid 7,5 - 12 t	0.03
	Diesel	HD Euro V - 2008 Standards	Rigid <=7,5 t	0.55
			Rigid 12 - 14 t	0.00
			Rigid 14 - 20 t	0.03
			Rigid 20 - 26 t	0.01
			Rigid 7,5 - 12 t	0.04

Sector	Propulsion	Technology	Subsector	Mileage (%)
Heavy-duty Trucks Articulated	Diesel	Conventional	Articulated 14 - 20 t	0.00
			Articulated 20 - 28 t	0.00
		HD Euro II - 91/542/EEC Stage II	Articulated 14 - 20 t	0.00
		HD Euro III - 2000 Standards	Articulated 14 - 20 t	0.00
		HD Euro IV - 2005 Standards	Articulated 14 - 20 t	0.00
			Articulated 28 - 34 t	0.00
		HD Euro V - 2008 Standards	Articulated 14 - 20 t	0.00
			Articulated 20 - 28 t	0.00
Buses	Diesel	Conventional	Urban Buses Articulated >18 t	0.00
			Urban Buses Midi <=15 t	0.00
			Urban Buses Standard 15 - 18 t	0.00
		HD Euro I - 91/542/EEC Stage I	Urban Buses Articulated >18 t	0.00
		HD Euro II - 91/542/EEC Stage II	Urban Buses Midi <=15 t	0.01
			Urban Buses Standard 15 - 18 t	0.02
		HD Euro III - 2000 Standards	Urban Buses Articulated >18 t	0.01
			Urban Buses Midi <=15 t	0.03
			Urban Buses Standard 15 - 18 t	0.07
		HD Euro IV - 2005 Standards	Urban Buses Articulated >18 t	0.01
			Urban Buses Midi <=15 t	0.04
			Urban Buses Standard 15 - 18 t	0.08
		HD Euro V - 2008 Standards	Urban Buses Articulated >18 t	0.08
			Urban Buses Midi <=15 t	0.07
			Urban Buses Standard 15 - 18 t	0.03
	Compressed Natural Gas	EEV	Urban CNG Buses	0.01
	Electric	Electric	Electric	0.01
Buses Coaches	Diesel	HD Euro V - 2008 Standards	Coaches Standard <=18 t	0.00
Motorcycles	Petrol	Conventional	4-stroke <250 cm ³	0.02
			4-stroke >750 cm ³	0.01
			4-stroke 250 - 750 cm ³	0.02
		Mot - Euro I	4-stroke <250 cm ³	0.03
			4-stroke >750 cm ³	0.02
			4-stroke 250 - 750 cm ³	0.03
		Mot - Euro II	4-stroke <250 cm ³	0.12
			4-stroke >750 cm ³	0.02
			4-stroke 250 - 750 cm ³	0.07
		Mot - Euro III	4-stroke <250 cm ³	0.56
			4-stroke >750 cm ³	0.20
			4-stroke 250 - 750 cm ³	0.46
	Electric	Electric	Electric	0.00

Annex 5. Average speed, NO_x and PM emission maps for FL**E1 scenario**

Average speed surface: 5.58 m/s
Average speed tunnel: 27.01 m/s

NO_x: 248.50 g/h surface
84.45 g/h tunnel
1.20 g/km surface
0.87 g/km tunnel

PM₁₀: 18.47 g/h surface
5.47 g/h tunnel
0.09 g/km surface
0.06 g/km tunnel

E2 scenario

Average speed surface: 6.17 m/s
Average speed tunnel: 26.08 m/s

NO_x: 6210.14 g/h surface
2783.03 g/h tunnel
3.59 g/km surface
0.54 g/km tunnel

PM₁₀: 304.01 g/h surface
253.12 g/h tunnel
0.18 g/km surface
0.05 g/km tunnel

E3 scenario

Average speed surface: 5.02 m/s
Average speed tunnel: 26.17 m/s

NO_x: 6444.00 g/h surface
3015.00 g/h tunnel
3.47 g/km surface
0.66 g/km tunnel

PM₁₀: 309.60 g/h surface
232.50 g/h tunnel
0.17 g/km surface
0.05 g/km tunnel

E4 scenario

Average speed surface: 6.38 m/s
Average speed tunnel: 26.16 m/s

NO_x: 4632.00 g/h surface
2453.00 g/h tunnel
2.55 g/km surface
0.53 g/km tunnel

PM₁₀: 246.20 g/h surface
225.30 g/h tunnel
0.14 g/km surface
0.05 g/km tunnel

E5 scenario

Average speed surface: 5.72 m/s
Average speed tunnel: 27.06 m/s

NO_x : 214.00 g/h surface
92.10 g/h tunnel
1.24 g/km surface
0.52 g/km tunnel

PM_{10} : 15.60 g/h surface
8.70 g/h tunnel
0.09 g/km surface
0.05 g/km tunnel

E6 scenario

Average speed surface: 5.97 m/s
Average speed tunnel: 26.11 m/s

NO_x : 6053.89 g/h surface
2718.00 g/h tunnel
3.36 g/km surface
0.54 g/km tunnel

PM_{10} : 294.74 g/h surface
246.30 g/h tunnel
0.16 g/km surface
0.05 g/km tunnel

E7 scenario

Average speed surface: 6.48 m/s
Average speed tunnel: 26.11 m/s

NO_x : 5095.00 g/h surface
3103.00 g/h tunnel
2.77 g/km surface
0.61 g/km tunnel

PM_{10} : 260.10 g/h surface
255.00 g/h tunnel
0.14 g/km surface
0.05 g/km tunnel

E8 scenario

Average speed surface: 6.73 m/s
Average speed tunnel: 26.16 m/s

NO_x : 4335.00 g/h surface
2713.00 g/h tunnel
2.40 g/km surface
0.61 g/km tunnel

PM_{10} : 235.00 g/h surface
223.70 g/h tunnel
0.13 g/km surface
0.05 g/km tunnel

E9 scenario

Average speed surface: 5.98 m/s
Average speed tunnel: 26.82 m/s

NO_x: 531.80 g/h surface
243.50 g/h tunnel
1.21 g/km surface
0.51 g/km tunnel

PM₁₀: 40.11 g/h surface
23.31 g/h tunnel
0.09 g/km surface
0.05 g/km tunnel

E10 scenario

Average speed surface: 5.97 m/s
Average speed tunnel: 26.78 m/s

NO_x: 829.00 g/h surface
313.80 g/h tunnel
1.67 g/km surface
0.57 g/km tunnel

PM₁₀: 48.57 g/h surface
27.62 g/h tunnel
0.10 g/km surface
0.05 g/km tunnel

E11 scenario

Average speed surface: 6.52 m/s
Average speed tunnel: 26.16 m/s

NO_x: 2657.00 g/h surface
1335.87 g/h tunnel
1.77 g/km surface
0.56 g/km tunnel

PM₁₀: 166.30 g/h surface
117.70 g/h tunnel
0.11 g/km surface
0.05 g/km tunnel

E12 scenario

Average speed surface: 6.53 m/s
Average speed tunnel: 25.98 m/s

NO_x: 2369.17 g/h surface
1656.71 g/h tunnel
1.54 g/km surface
0.58 g/km tunnel

PM₁₀: 161.31 g/h surface
141.93 g/h tunnel
0.11 g/km surface
0.05 g/km tunnel

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