



Estimation of future emission scenarios for analysing the impact of traffic mobility on a large Mediterranean conurbation in the Barcelona Metropolitan Area (Spain)

Albert Soret¹, Pedro Jimenez–Guerrero², David Andres³, Francisco Cardenas³, Salvador Rueda³, Jose M. Baldasano^{1,4}

¹ Barcelona Supercomputing Center–Centro Nacional de Supercomputación (BSC–CNS). Earth Sciences Department, Jordi Girona 29, Edificio Nexus II, 08034 Barcelona, Spain

² Physics of the Earth, University of Murcia, Ed. CIOyN, Campus de Espinardo, 30100 Murcia, Spain

³ BCN Ecologia. Agència d'Ecologia Urbana de Barcelona, Escar 1, 3^a, 08039 Barcelona, Spain

⁴ Environmental Modelling Laboratory, Technical University of Catalonia, Avda. Diagonal 647, Edificio H, Oficina 10.23, 08028 Barcelona, Spain

ABSTRACT

Emission modelling permits us to quantitatively assess the effects of emission abatement strategies. In urban areas, such strategies are designed mainly to reduce the emissions from the on–road traffic sector. This work analyses the impact of several mobility strategies on urban emissions in the coastal city of Barcelona, Spain, when the High Elective Resolution Modelling Emission System (HERMES) is applied at a very high resolution (1 km × 1 km and 1 h). The analysis was conducted by projecting the emissions data obtained from a base case scenario in 2004 onto three future scenarios set in 2015, where each future scenario represented a set of traffic mobility management measures. Specific developments were considered per emission sector, including power generation, industrial activities, domestic–commercial, solvents, on–road traffic, biogenic emissions, ports and airports, to best compare the present base case scenario with the future mobility scenarios generated for 2015. These emission scenarios for 2015 take into account the population projections and the variations in port and airport activities among other factors, while the main focus is on the on–road traffic sector, the types of vehicles used, such as technologically improved buses and hybrid vehicles, as well as the types of fuels used, including natural gas and biofuels. The results of the emission model indicate that the mobility management strategies, the technological improvements and the use of alternative fuels reduce the emissions from on–road traffic by approximately 75% (in terms of nitrogen oxides emission reductions in the city centre of Barcelona). This decrease leads to a 35% reduction in overall nitrogen oxides emissions, even if some sectors individually experience increases based on their specific projections.

Keywords: Emissions management, urban pollution, air quality management, traffic mobility

doi: 10.5094/APR.2013.003



Corresponding Author:

Albert Soret

☎ : +34-9341-34076

☎ : +34-9341-37721

✉ : albert.soret@bsc.es

Article History:

Received: 17 June 2012

Revised: 28 August 2012

Accepted: 29 August 2012

1. Introduction

According to the European Environment Agency (EEA, 2005), air pollution is the environmental factor with the greatest health impacts in Europe. The city of Barcelona and its metropolitan area present several air quality problems that are particularly related to PM₁₀ (particulate matter with a diameter up to 10 μm) and nitrogen dioxide (NO₂) in particular (Generalitat de Catalunya, 2011). In the Barcelona Metropolitan Area, 9 out of 15 stations exceeded the annual air quality limit of NO₂ (40 μg m⁻³) during 2010. Only 1 station out of 6 in the city of Barcelona had an annual ambient air concentration of less than 40 μg m⁻³, and that location was the urban background station of the Vall d'Hebron Park (Generalitat de Catalunya, 2011).

The largest contribution to the emission of atmospheric pollutants in urban areas today comes from the transport sector, especially from on–road transport (Chin, 1996; Cirillo et al., 1996; Palmgren et al., 1996; Oduyemi and Davison, 1998; Crabbe et al., 1999; Palmgren et al., 1999; Colvile et al., 2001; Ghose et al., 2004; Guo et al., 2007). In recent years, there have been significant efforts made to study the effects of strategies that are used to reduce on–road traffic emissions and the subsequent impacts of these emissions on air quality. Currently, the main objective of

these strategies is targeted at reducing the emissions from each vehicle either by adopting less polluting fuels and technologies (Wang et al., 2008; Goncalves et al., 2009; Stephens–Romero et al., 2009; Brady and O'Mahony, 2011) or by reducing the speed limit (Baldasano et al., 2010). Nevertheless, despite the reduction in the emissions from each vehicle, the constant increase in traffic intensity prevents an overall reduction in total on–road traffic emissions (Moriarty and Honnery, 2008a; Moriarty and Honnery, 2008b). Therefore, there is a need for a suitable transport system that features mobility management strategies (Caserini et al., 2008; Lumbreras et al., 2008; Bandeira et al., 2011; Ozan et al., 2011).

Therefore, this study analyses the impact of the introduction of traffic mobility management strategies on on–road traffic emissions in the city of Barcelona (Figures 1a, 1b), where approximately 70% of the NO_x emissions come from the on–road transport sector.

The mobility strategies are planned for implementation in the city centre of Barcelona by 2015; red domain in Figure 1c. Each strategy is applied to three future scenarios: (1) the business–as–usual scenario, which represents what would happen if the traffic intensity were to grow without any mitigating measures taken to

reduce the emissions from each vehicle; (2) the super-blocks scenario, where the road network is remodelled; and (3) the super-blocks reversal scenario, which adds some directional reversals to Scenario 2. These future scenarios were compared to a base case scenario obtained from 2004. Super-blocks are a mobility management measure that consists of transforming inner streets with light traffic into pedestrian areas to achieve a better traffic flow on the streets, delimiting the super-block (MMA, 2006). The study was made more consistent by considering specific city developments per emissions sector.

This paper starts by describing the HERMES emission modelling system in Section 2. The future mobility management measures are defined for Barcelona (Section 3), followed by the results in Section 4. Finally, Section 5 summarises the main conclusions.

2. Methods

This study is focused on the city of Barcelona and its metropolitan area, as shown in Figures 1b and 1c. Two nested domains have been defined to better analyse atmospheric emissions:

- (i) Barcelona Ring Roads (BRR), an inner domain 110 km² in size that comprises the most populated area of Barcelona where the mobility management measures are applied.
- (ii) Barcelona Metropolitan Area (BMA), an area that is 692 km² in size.

The emissions for these two domains are estimated at high spatial resolution (1 km × 1 km) with the HERMES emission model.

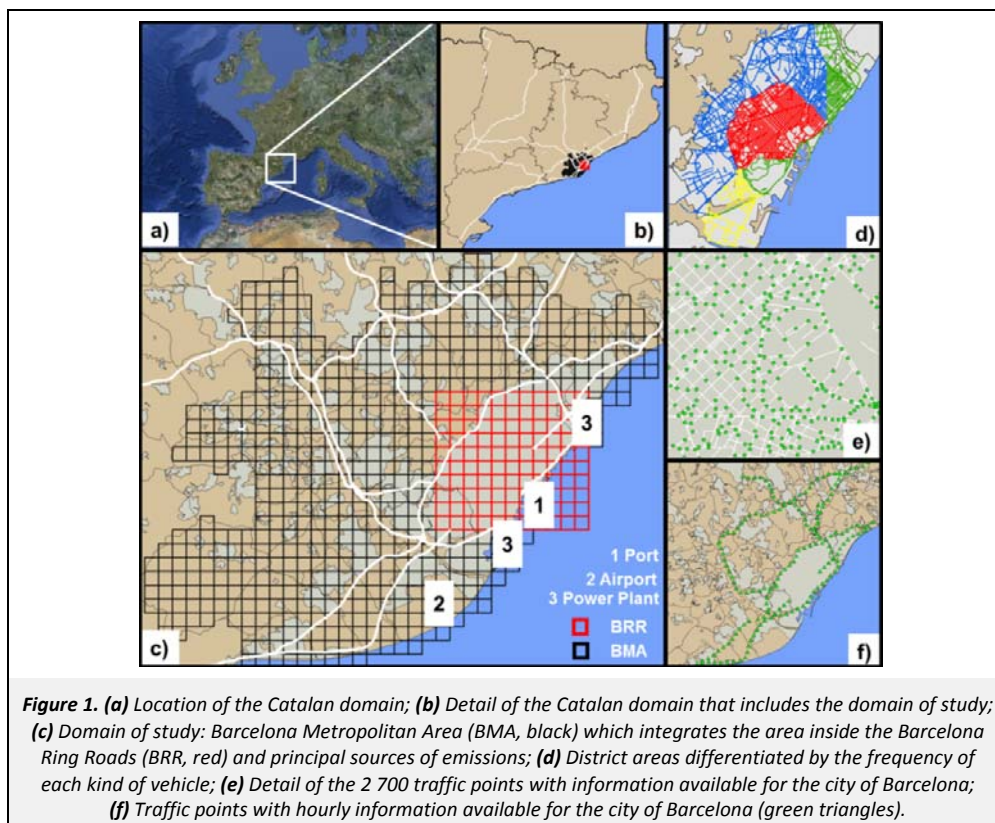
2.1. HERMES emission model

In this paper, the emission estimation comes from the application of the High Elective Resolution Modelling Emission

System (HERMES) (Baldasano et al., 2008). The HERMES model estimates the emissions either for the whole country of Spain or for configurable inner domains within Spain. It runs with a temporal resolution of 1 h and a spatial resolution of 1 km × 1 km. The current version of the HERMES model refers to the year 2004. The HERMES model takes into account anthropogenic emission sources such as power generation, industrial activities, on-road traffic, ports, airports, solvent use, domestic and commercial fossil fuel use, and biogenic sources such as vegetation and uses a bottom-up approach, up-to-date information and state-of-the-art methodologies for estimating future emissions. The HERMES model is capable of calculating emissions from sector-specific sources or from individual installations and stacks. The Supporting Material (SM) provides a comparison between the HERMES inventory and the Spanish National Inventory (SNIE) for a validation of the HERMES model.

2.2. Traffic module in HERMES

A relevant module in the HERMES model was used in this study to estimate the on-road traffic emissions that will be affected by the mobility strategies. The module is designed based on a bottom-up approach and takes into account 72 types of diesel and petrol vehicles categorised according to the COPERT-EEA-E MEP/CORINAIR methodology (EEA, 2009). These vehicles are divided into various categories including the fuel type, the vehicle weight, the vehicle age and the volumetric engine capacity. Each of these categories has specific emission factors defined as functions of traffic speed, and a detailed methodology for developing these functions is provided by Baldasano et al. (2008). A detailed characterization of the uncertainty for each vehicle category, pollutant and speed is described in Kouridis et al. (2010). Traffic emission estimation considers hot and cold exhaust, evaporative emissions, particulate matter produced by brake abrasion, tire wear and pavement erosion.



The vehicular fleet distribution for Spain distinguishing between six categories (i.e., heavy duty vehicles, buses, passenger cars, motorcycles and others) was obtained from the Spanish traffic department for the year 2004 (DGT, 2008). These data were organised in the 72 aforementioned categories specifically for Barcelona. The base vector database with traffic speed information has been provided by Tele Atlas Multinet™ 2005. The model includes the definition of the road network, dividing it into stretches within the 1 km² cells and specifying the day and the month to distinguish between working days and holidays, the specific average speed, the daily average traffic intensity on the road, the stretch length and the route type (highway, road or urban streets). The available information for Barcelona covers the total urban road network and identifies five district areas as shown in Figure 1d. These areas are differentiated by the frequency of each kind of vehicle that uses them, including mopeds, private cars, taxis, buses and heavy duty vehicles, and is detailed by Goncalves et al. (2009). The on-road transport emissions were based on the daily average traffic intensity, and the traffic speed measured at more than 2 700 observation points throughout Barcelona, as shown in Figure 1e. These data points were used to generate an attributed digital vector map with all the roads that were used by more than 200 vehicles per day, including highways, freeways and urban streets.

Alternative on-road traffic emission models such as MOBILE or COPERT apply average speeds per road to estimate the emission factors of their vehicles. The real circulation conditions, such as traffic congestion, involve variations of this ideally represented speed. Following this advice, for the estimation of the emissions coming from on-road traffic, an hourly-variable speed has been established according to the methodology of Baldasano et al. (2010) instead of using a specific constant speed for each stretch. Data coming from 125 measurement points for the main access roads to the city of Barcelona have been passed to the emission model in such roads (Figure 1f). These points contain hourly detailed information of average circulation speed. This hourly variable speed is common to the base case scenario and future scenarios.

3. Implementation of the Future Scenarios for 2015 in HERMES

In this section, the three future mobility management scenarios are discussed in terms of the mobility management strategies in Section 3.1 and a comprehensive projection of emissions from each sector in Section 3.2.

3.1. Mobility management scenarios

To compare the emissions between 2004 and 2015, a base case (BC) scenario for 2004 and three future scenarios for 2015 were defined in the HERMES model, as shown in Table 1. Each of these future scenarios presents an emission projection from 2004 to 2015 by applying a different set of traffic mobility management measures in the BRR domain:

- (i) The business-as-usual (BAU) scenario, which represents what would happen if no measures were adopted, taking into account the tendency of the last years, such as an increase in the number of total vehicle kilometres travelled (VKT) by 37% with respect to the BC scenario (Mobility Service of Barcelona Town Hall, personal communication). An increase of VKT implies a reduction in traffic mobility, which is represented by the average speed in the BRR domain and is shown to be reduced from 19.5 km h⁻¹ in the BC scenario to 10.8 km h⁻¹ in the BAU scenario.
- (ii) The super-blocks (SB) scenario, which considers the remodeling of the road networks in the super-blocks, reducing the VKT by 32% with respect to the BC scenario and 50% with respect to the BAU scenario. This scenario allows for the traffic mobility to be maintained at 18.4 km h⁻¹, which is similar to that of the BC scenario.
- (iii) The super-blocks reversal (SBR) scenario, which applies the super-blocks scenario in conjunction with the introduction of some strategic direction reversals, reducing the number of VKT by 24% with respect to the BC scenario and 44% with respect to the BAU scenario. The traffic mobility was maintained at 20.2 km h⁻¹, which is similar to that of the BC scenario.

3.2. City developments

To compare the emissions between a BC scenario defined for 2004 and the three mobility scenarios projected for 2015, we also need to consider specific projections for each emission sector. A set of envisaged city developments were defined in the HERMES model for each emission sector according to specific estimations based on the population forecast by IDESCAT (2008), the Energy Plan for Catalonia (Generalitat de Catalunya, 2006) and other estimates shown in Table 2. Note that such projected city developments were applied on the two nested domains (BRR and BMA), while the mobility measures were only applied within the BRR.

Several factors have been taken into account in the particular case of on-road traffic emissions to better estimate the vehicular fleet for 2015: firstly, technological changes such as the improvements made to existing engines and the introduction of hybrid cars were considered; secondly, the use of alternative fuels such as an increase in the use of natural gas and biofuels were also considered (Larive, 2007). All of these changes are summarised in Table 2. As a working hypothesis, the profile of the vehicular fleet, based on the ratio of private cars to mopeds and heavy duty vehicles, was assumed to be invariant with time. The oldest vehicles were replaced by new vehicles. These new vehicles are placed in categories from Euro 4 to Euro 6 and in other specific categories that consider the use of alternative fuels and new technologies. The ratio of annual renewal was 9% for heavy duty and private vehicles, 8% for buses and 10% for mopeds and motorbikes as obtained from DGT (2008), and was assumed to remain constant from 2004 to 2015.

Table 1. Scenarios defined for the year 2015 together with the base case applied inside the ring roads in the city of Barcelona (BRR) (Source: Mobility Service of Barcelona Town Hall, personal communication)

Scenario	Description	Total vehicle km travelled (VKT)	ΔVKT respect to Base Case	Avg speed (km h ⁻¹)
Base Case (BC), 2004	Situation in 2004	15 285 286		19.5
Business as usual, road network on 2015 (BAU)	Represents what would happen if no measures were adopted, taking into account the tendency of the last years	20 940 842	+37%	10.8
Road network with super-blocks in year 2015 (SB)	Application of super-blocks in year 2015	10 393 994	-32%	18.4
Road network with super-blocks and reversal of direction 2015 (SBR)	Application of super-blocks and reversal of direction in year 2015	11 616 817	-24%	20.2

Table 2. Criteria taken into account for the projection of the different sectors for the year 2015, including modifications in the vehicular fleet for the year 2015

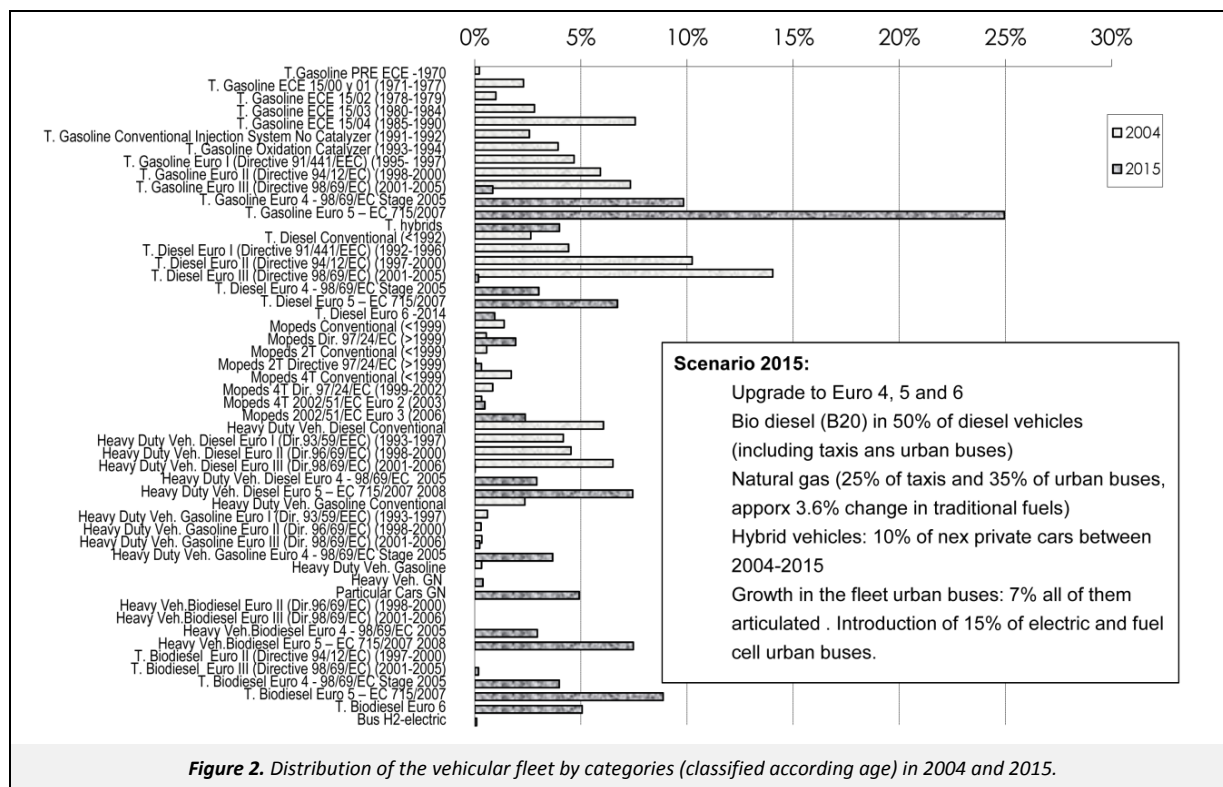
Sector	Projection criteria	
Power generation	The perspective in the evolution of power generation has been implemented according to the Energy Plan for Catalonia (2015) bearing in mind the planned opening of new combined-cycle power plants and the closure of some of the existing plants (Generalitat de Catalunya, 2006).	
Industry	The industrial sector does not plan substantial changes and therefore it is kept constant in the different scenarios.	
Domestic-Commercial, Solvents	These two sectors are directly related with demography, so their projection is proportional to the evolution of the population for 2015 (IDESCAT, 2008)	
On-road traffic	<ul style="list-style-type: none"> • Consideration of the points of traffic density with hourly speed data for the base-case scenario and future scenarios (Baldasano et al., 2010). • Upgrade of the vehicular fleet (DGT, 2008) to 2015 considering technological improvements (engines, hybrid vehicles, etc.) and new fuels (natural gas, biofuels): 	
	General vehicles	Gradual introduction of new European emission standards Euro 4, Euro 5 and Euro 6 standard in the temporal scenarios for 2015.
	Mopeds and motorbikes	Renewal of 10% per year in the number of mopeds and motorbikes, taking into account the data from the composition of the vehicle fleet (DGT, 2008).
	Natural gas	Increase in the use of this fuel (5% for 2015), based on EU documents (COM-2001-547).
	Biodiesel	For biofuels, its use has been estimated as 7% for 2015, as biodiesel (B20).
	Hybrids	Hybrids are considered as 10% of the new private cars in the period 2010-2015.
	Private cars/ commercial vehicles	Renewal of 9% per year in the number of heavy duty vehicles and private cars, taking into account the data from the composition of the vehicle fleet (DGT, 2008).
	Taxis	Constant number, a proportional distribution is established for the different fuels (gasoil, natural gas, hybrids and biodiesel).
Buses, public transportation	Renewal of 8% per year (DGT, 2008).	
Biogenic	No changes have been implemented in biogenic emissions with respect to the base-case scenario.	
Airports, Ports	The growth in their activity is a function of the projection made by the Relevant Authorities (AENA, 2008; Barcelona Port Authority).	

The changes introduced to the HERMES emission model that are related to on-road traffic emissions estimations for the future scenarios with respect to the BC scenario (see Table 2) are listed below:

- (i) The updating of the Euro standards: 90% of the new vehicles are introduced in the Euro 4 (2005), the Euro 5 (2008–2010) and the Euro 6 (2014–2015) categories (EC, 2007).
- (ii) The introduction of hybrid cars: 10% of the new private cars are considered to contain hybrid engines running on a mixture of petrol and electricity.
- (iii) The introduction of biofuels: B20 diesel blends containing 20% biodiesel mixed with 80% fossil fuel are used by 50% of the diesel vehicles, including the urban bus fleet, where there is an approximate replacement of 0.3% of the total diesel consumed, and the taxi fleet, where there is an approximate replacement of 1% of the total diesel consumed. The objective is to replace 7% of the total diesel that is currently consumed with biofuels. The B20 blend is the most used biofuel today and does not require modifications to the engines of the current diesel vehicles for use (EPA, 2002; EC, 2009).
- (iv) The introduction of natural gas: 35% of the public transport buses will use natural gas, where there is an approximate replacement of 1.05% of the total diesel consumed, as well as 25% of taxis, where there is an approximate replacement of 2.5% of the total diesel consumed. The substitution of traditional fuels such as diesel and petrol by natural gas was proposed by the European Union (COM(2001)547 and COM(2001)370) (EC, 2001a; EC, 2001b) to be 5% for the year 2015. This scenario requires a slightly lower introduction of natural gas of approximately 3.6%.
- (v) The urban bus fleets: a growth of 7% is estimated for the bus fleet with respect to 2004. All standard buses are replaced by articulated buses that fall within a weight of 16 to 32 tons. The distribution of the buses according to the fuel that they consumed is as follows: 15% run on a mix of hydrogen and electricity, 35% run on natural gas, 30% run on biodiesel, and 20% run on fossil fuel diesel (Cohen et al., 2003; Ntziachristos and Samaras, 2005).

The final distribution of the vehicular fleet in Barcelona in 2004 and 2015 is shown in Figure 2. The vehicular fleet has an average age of 15 years; hence, in the forecast of the 2015 scenarios, the oldest vehicles in 2015 will be those vehicles that were made between 1999 and 2001 (Euro I).

The emission factors that allow estimating emissions for those 72 vehicle categories that compose the vehicular fleet in 2004 and 2015 for this work have two requirements: (1) speed-dependent emission factors, and (2) emission factors for Euro standards due to the area of study. According to these requirements, tier 3 method (EEA, 2009) has been implemented in the HERMES emission model. Figure 3 shows hot emission factors for NO_x, PM and CO for the main passenger cars (PC) and light-duty vehicles (LDV). The emission factors (g km⁻¹) are referred to 20 km h⁻¹, similar to the average speed in Barcelona (Table 1). For new technologies and alternative fuels, some considerations have been assumed due to a lack of available emission factors:



- Regarding to Euro V and Euro VI passenger cars, there are no emission factors in EEA (2009). For those categories, authors have assumed the same emission factors that for Euro IV.
- The emission factors for biodiesel are obtained from EEA (2009) methodology. This methodology presents emission differences of a Euro III diesel vehicle fuelled by B20 with respect to that same technology using regular diesel. However following this methodology, two assumptions were done: (1) the emission variation is constant in all the speed range, and (2) the emission variation is constant for other vehicle technologies.
- Natural gas can be used as a fuel for different vehicle technologies, and therefore, a wide range of emission factors can be found. The European Natural Gas Vehicles Association (ENGVA) reduction factors have been implemented in the HERMES emission model, based on Goncalves et al. (2009), that provides a review of the most suitable emission factors for natural gas vehicles. Again, such factors are assumed constants for all the speed range.

4. Results: Comparison between Base Case and Future Scenarios

This section presents the detailed emission results of the traffic mobility measures and city developments for the BRR and the BMA regions by 2015. Two days of study have been selected, related to two different typical meteorological patterns observed in the Barcelona region. The emissions data obtained for these two days will later provide the input information for a chemical transport model, as described in a previous work by Soret et al. (2011).

The selected days were June 18th 2004, for a typical summertime pattern representing stagnant meteorological conditions and a low pressure gradient, and February 11th 2004, representing a wintertime pattern with re-circulation from an anticyclone situation. The selection of these days was based on the methodology of Jorba et al. (2004) and two other criteria: those days (1) exhibited poor air quality and (2) had usual traffic

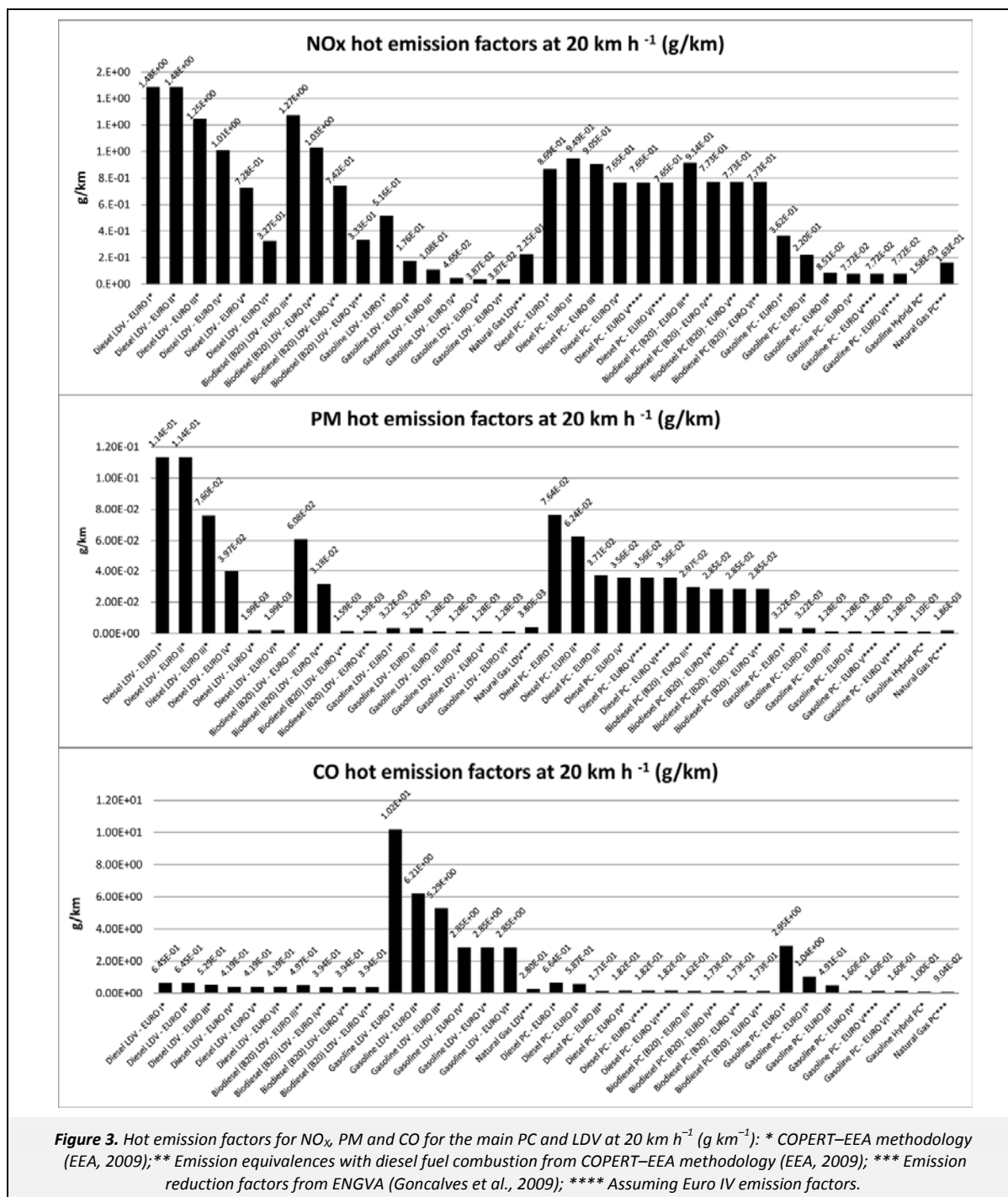
circulation patterns, i.e., they were working days, to ensure that the results were well-represented. The analysis focuses on the winter day, which was chosen to minimise the biogenic emissions from non-methane volatile organic compounds for better focusing on the anthropogenic emissions.

4.1. The estimation of emissions from each activity sector

On-road traffic. Two implementations for future scenarios are considered with regard to on-road traffic emissions: (1) mobility management measures and (2) city developments, which involve technological changes and the use of alternative fuels. Such city developments lead to a reduction in traffic emissions, especially for sulphur dioxide (SO₂) (EC, 2003).

The measures defined for the three scenarios of mobility produce an important reduction in emissions within the BRR. This section focuses on NO_x emissions as a representative because other emissions follow the exact same pattern. The emissions of NO_x were selected for the analysis because they were typical pollutants associated with on-road traffic and, together with particulate matter, were the main pollutants associated with the poor air quality of the city of Barcelona (Jimenez-Guerrero et al., 2008).

Within the BRR domain, the present-day emissions based on the 2004 BC scenario for February 11, 2004 was estimated to be 16.05 t day⁻¹, as shown in Table 3 and Figure 4a. Despite the fact that the VKT increases by 37%, and consequently, the average speed is reduced from 19.5 to 10.8 km h⁻¹, the BAU scenario provides a 36% decrease in the total emissions compared to BC. Such decrease is caused by the introduction of technological improvements and the use of cleaner fuels. In the SB and SBR scenarios, the modification of the road networks into super-blocks coupled with a reduction in the VKT leads to a 73% and a 78% decrease in the total emissions, respectively, as shown in Figure 4b. Hence, a comparison between the SB and SBR scenarios shows that there is a greater reduction in emissions when the mobility measures are more ambitious.

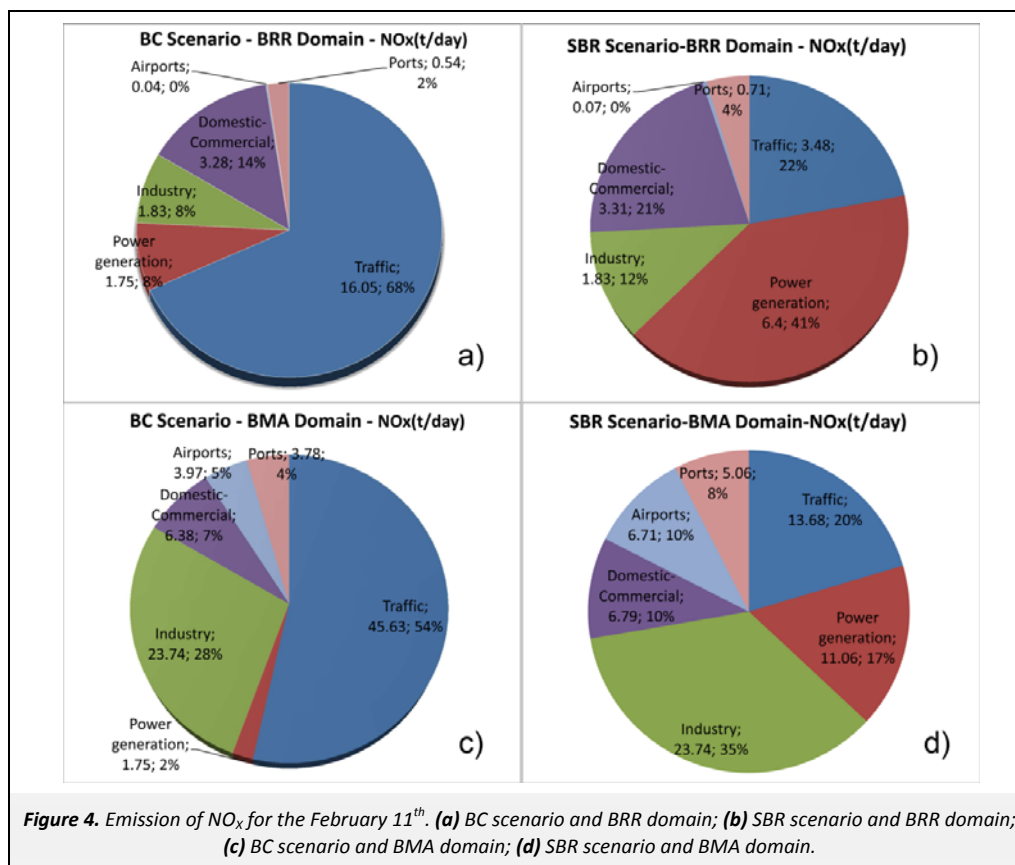


The same conclusions were reached when the results for the summer day on June 18, 2004 were analysed. In the traffic sector, there were no significant differences observed between the summertime and wintertime emissions. The considered days only differed in the emissions of non-methane volatile organic compounds (NMVOCs) as a result of higher surface temperatures and increased ultraviolet radiation on evaporative sources during the summer.

The NO_x emissions that were estimated were remarkably higher within the BMA than those estimated within the BRR because the BMA covers a highly populated area with a major road network as shown in Figure 4c and Table 3. The BC scenario estimated the total NO_x emissions for February 11th to be 45.63 t day⁻¹. The BAU scenario exhibited emissions that were 55% lower than the emissions in the BC scenario. The emissions were

reduced by 68% for the SB scenario and by 70% for the SBR scenario because of the mobility measures that were implemented in the BRR domain.

Power generation and industry. The Energy Plan for Catalonia (Generalitat de Catalunya, 2006) was used to estimate the emissions derived from power generation. This plan addresses the closure of coal and gasoil conventional power plants by installing new natural gas combined-cycle power plants, where the locations of the new power plants are shown in Figure 1c. Within the BRR region, there are two new installations, the Besos V and the Besos VI plants. These installations also belong to the parent domain BMA, which has two new power plants, the Puerto BCN I and the Puerto BCN II plants. Each of these four new combined-cycle power plants will have a potency of 400 MW, which implies the installation of 1 600 MW in the BMA.



The HERMES emission model works with real data provided by the on-line network for the measurement of emissions maintained by the Catalonia Government, which allows for a better reproduction of real conditions. However, the real data are subject to eventual changes in demand, as the daily emissions on June 18 were higher than the emissions on February 11 because two power plants were not operating during the winter of 2004.

The introduction of the new power plants leads to an emissions increase of 266% in the BRR domain and 532% in the BMA domain. The percentage increase was extremely large because there were no significant sources of power generation in the BC scenario.

Despite the fact that the new combined-cycle plants were less polluting than conventional power plants, new strategies have to be developed to counteract this increase in emissions. The EU energy strategy addresses the need to increase the renewable energy share and the need to improve energy efficiency (EC, 2010).

The emissions from the industrial sector are assumed to be constant for future scenarios. The slight differences in the emissions of the two days analysed are caused by the temporal factors implemented in the emission model, and a further discussion has been provided by Baldasano et al. (2008).

Domestic-commercial and solvents. The emissions from both the domestic-commercial and solvent sectors are directly related to the population; hence, a proportionality ratio was applied to the BC scenario of 2004 from the population estimations described in IDESCAT (2008) for use in future scenarios. The population scenario that was considered was the Medium-High Growth scenario because it best fit the period from 2002–2010. Therefore, the demographic values reflect a population increase of 6.5% in 2015 for the BMA (3 127 315 and 3 331 716 inhabitants in the years 2004 and 2015, respectively) and a population increase of 0.7% in the BRR (a population of 1 609 771 and 1 621 499 in the years 2004

and 2015, respectively). Hence, the variation in future emissions of domestic-commercial and solvents can be directly correlated to an increase in the population.

Within the domestic-commercial sector, substantial differences were observed between the two days that were analysed. During winter, there was a heavy utilisation of different fuels in heating systems, primarily natural gas, while the use of air conditioning in summer increases the consumption of electric power significantly. The solvent emissions comprise only the non-methane volatile organic compounds. The estimated solvent emissions in winter are higher than the estimated emissions in summer because the HERMES model assumes that painting activities are more common during the spring and summer seasons. Other activities, including the use of rubber, adhesives, cleaning products, hygiene products, propellants and the maintenance of vehicles, are considered to be invariant throughout the year.

Biogenic emissions. No changes in the biogenic emissions were considered for the different future scenarios, similar to the assumption that was made for the industrial sector. The land use and meteorological conditions were also assumed to be constant, which suggests that the biogenic emissions were constant as well. These emissions are higher during the summer than the winter because there is increased vegetation activity as a result of a higher air temperature and more solar irradiation. A more detailed description of the calculation of biogenic emissions for the area being analysed was conducted by Parra et al. (2004) and Parra et al. (2006).

Airports and ports. The HERMES emission model considers all the airports in the Iberian Peninsula, but only the Barcelona-El Prat airport is located within the area of concern (Figure 1c). The emissions from the Barcelona-El Prat airport were projected according to the data provided by AENA (2008), where the number of passengers served in 2004 was 24 558 138, and an increase in 69% was estimated for the year 2015.

Table 3. Nitrogen oxides (NO_x) emissions for the different scenarios and sectors included in the BMA and inside BRR domain for a typical winter and summer day

BRR NO _x (t day ⁻¹)	Winter day (February, 11 th)				Summer day (June, 18 th)			
	BC	BAU	SB	SBR	BC	BAU	SB	SBR
Traffic	16.05	10.30	4.28	3.48	17.02	11.09	4.60	3.74
Power generation	1.75	6.40	6.40	6.40	2.35	7.00	7.00	7.00
Industry	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
Dom.–Commercial	3.28	3.31	3.31	3.31	1.45	1.46	1.46	1.46
Solvents	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biogenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Airports	0.04	0.07	0.07	0.07	0.05	0.08	0.08	0.08
Ports	0.54	0.71	0.71	0.71	0.70	0.92	0.92	0.92
Total NO _x	23.49	22.62	16.60	15.80	23.38	22.37	15.88	15.03
Total PM ₁₀	2.21	1.91	1.46	1.41	2.17	1.89	1.40	1.35
Total PM _{2.5}	1.98	1.61	1.29	1.25	1.93	1.56	1.23	1.18
Total CO	101.34	38.27	22.81	20.67	98.34	43.74	27.20	24.92
Total SO ₂	3.45	3.14	3.12	3.12	2.18	1.78	1.76	1.76
Total NMVOC	42.92	35.94	30.51	29.89	52.34	42.26	35.55	34.79
BMA NO_x (t day⁻¹)	BC	BAU	SB	SBR	BC	BAU	SB	SBR
Traffic	45.63	20.45	14.45	13.68	46.38	21.75	15.29	14.46
Power gen	1.75	11.06	11.06	11.06	2.86	11.66	11.66	11.66
Industry	23.74	23.74	23.74	23.74	23.72	23.72	23.72	23.72
Dom.–Com	6.38	6.79	6.79	6.79	2.81	2.99	2.99	2.99
Solvents	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biogenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Airports	3.97	6.71	6.71	6.71	4.49	7.59	7.59	7.59
Ports	3.78	5.06	5.06	5.06	4.89	6.56	6.56	6.56
Total NO _x	85.24	73.80	67.80	67.04	85.15	74.26	67.80	67.00
Total PM ₁₀	12.39	11.55	11.09	11.05	12.26	11.46	10.98	10.93
Total PM _{2.5}	8.14	7.02	6.71	6.68	7.99	6.88	6.55	6.51
Total CO	223.94	95.76	80.94	79.43	222.37	106.01	90.16	88.56
Total SO ₂	21.58	20.47	20.45	20.45	19.51	17.84	17.82	17.82
Total NMVOC	107.62	88.49	83.12	82.55	129.11	105.92	99.30	98.61

The Barcelona port is the largest Spanish port for international traffic and the 41st largest in the world; therefore, the port is an important source of emissions in the Barcelona region (Villalba and Gemechu, 2011). The perspectives for the evolution in the activity of the Barcelona port are based on data provided by the Barcelona Port Authority, which more precisely encompasses the targeted number of vessels to be served and the amount of cargo being loaded or unloaded. Finally, the directive related to the sulphur content in fuels has limited its content to 0.1% by mass (Directive 2005/33/EC; EC, 2005).

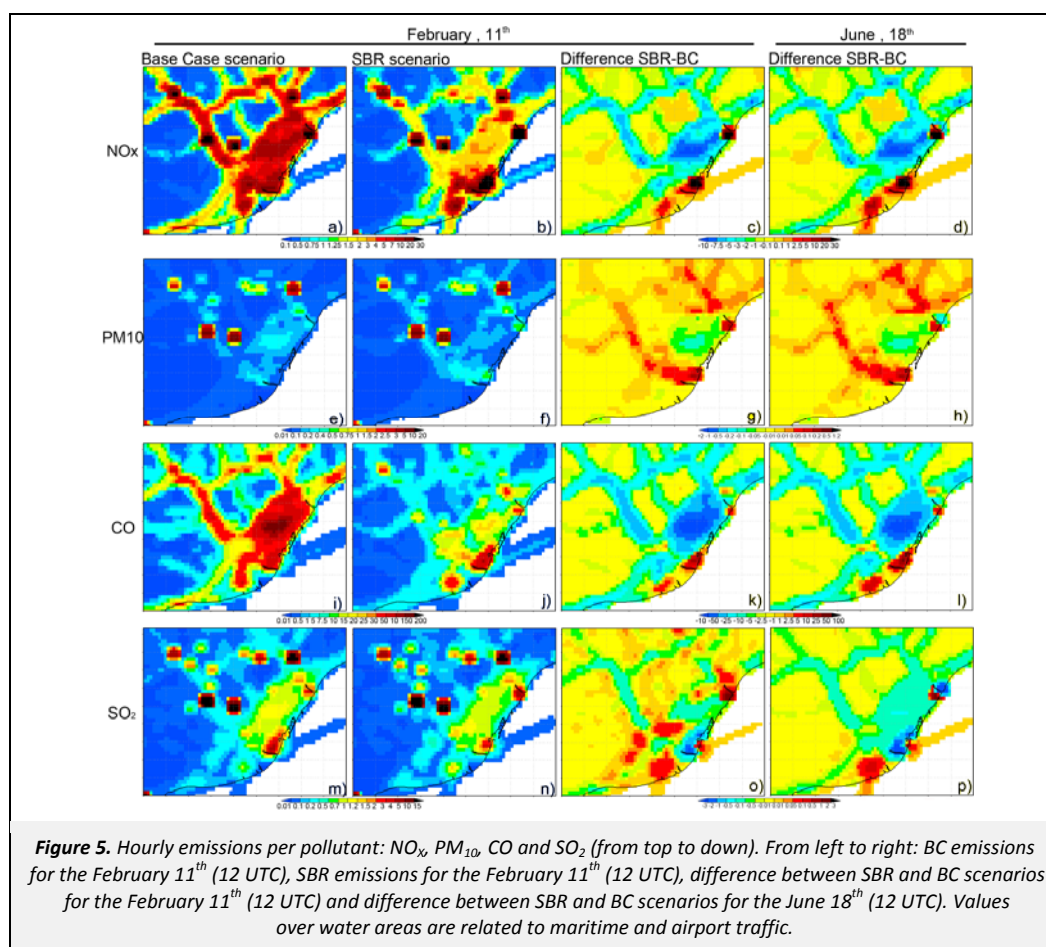
The emissions of CO, NMVOCs and NO_x from the port of Barcelona were estimated to increase by 33–34% in comparison with the emissions from 2004. The increase in particulate matter emissions was only projected to be 18% because the loading and unloading of liquefied natural gas (LNG) does not involve any mass transfer of such particulates. Finally, there is a significant decrease in SO₂ by 68–75% because the sulphur content in the fuels used by the vessels in the port is reduced and as a result of LNG loading and unloading.

4.2. An analysis of the emissions according to the pollutants analysed

This section evaluates the emissions by each pollutant in the different scenarios during the winter, which allows for the analysis

of the relative weight of the pollutants released from different sectors in the BMA and the BRR domains, as well as their evolution in future scenarios. The winter day was chosen to minimise the influence of biogenic emissions and to focus on the anthropogenic pollution sources.

The emissions of nitrogen oxides (NO_x). The reduction in the emissions derived from on-road traffic causes a decrease in the total NO_x that was estimated to be emitted in future scenarios as shown Table 3, even though there was a projected increase in the NO_x emissions from the power generation plants, the port and the airport. Figure 5a depicts the spatial distribution of NO_x emissions at 12 h UTC for the February 11, 2004 in the BC scenario based on 1 × 1 km² cells. The high emissions rates that were greater than 30 kg h⁻¹ km⁻² were related to point sources such as industries and power plants, while the road network emits NO_x at a rate that is greater than 5 kg h⁻¹ km⁻² throughout the BRR, with the emissions exceeding 10 kg h⁻¹ km⁻² at some locations. In the SBR scenario, the on-road emissions were significantly reduced to a rate that was less than 5 kg h⁻¹ km⁻² as shown in Figures 5b, 5c and 5d, especially in the BRR region as a result of mobility measures. In the future scenarios, the increases were focused on the two power stations (which exhibited increases of 30 kg h⁻¹ km⁻²), the port and the airport.



The emissions of particulate matter (PM₁₀ and PM_{2.5}). The on-road traffic measures also led to an overall reduction in the PM₁₀ emissions within the BRR. The total emissions determined from the BC scenario were reduced in the future scenarios by 14%, 34% and 36%, as shown in Table 3. The observed reductions for the three future scenarios were proportionally lower in the BMA and were 7%, 10% and 11%, respectively.

The emissions pattern of PM_{2.5} was very similar to the emissions pattern of PM₁₀. Within the BRR domain, the emissions from the BC scenario were reduced by 19% (BAU), 35% (SB) and 37% (SBR), while in the BMA domain they were reduced by 14% (BAU), 18% (SB) and 18% (SBR). There were greater reductions in PM_{2.5} emissions in comparison with the PM₁₀ emissions because PM_{2.5} is the main type of particulate matter that is emitted from combustion engines used for on-road transport.

In Figure 5e, the PM₁₀ emissions that were greater than 10 kg h⁻¹ km⁻² were a result of industrial activity, mainly from the concrete factories. The mobility measures led to a slight decrease in the total PM₁₀ emissions in the future scenarios, as shown in Figures 4f, 4g and 4h. The PM₁₀ emissions were reduced in the city centre of Barcelona from 0.4 kg h⁻¹ km⁻² in the BC scenario to 0.2 kg h⁻¹ km⁻² in the SBR scenario due to a reduction in on-road traffic. The new power stations produced local increases of 1 kg h⁻¹ km⁻² outside the city of Barcelona.

The emissions of carbon monoxide (CO). There were significant differences observed when the BC scenario was compared with the future scenarios regarding the emissions of CO: (1) the main source of CO emissions was from on-road traffic (EEA, 2009) and (2) mobility management measures and the vehicular fleet projection could reduce the emissions from on-road traffic feasibly. Within the BRR domain, the emissions based on the BC scenario were reduced by 62%, 77% and 80% based on the BAU, the SB and the

SBR scenarios, respectively, as shown in Table 3. In the BMA domain, the reduction of CO was also significantly high at 65% when the BC and the SBR scenarios were compared.

Figure 5i shows how the emissions of CO were derived from the on-road traffic network and how the emissions were reduced in the future SBR scenarios, as shown in Figures 4j, 4k and 4l, with a reduction rate of more than 25 kg h⁻¹ km⁻² within the BRR domain. Slight increases were observed that could be related to the emissions from the new power stations (25 kg h⁻¹ km⁻²) and the airport (5 kg h⁻¹ km⁻²).

The emissions of sulphur dioxide (SO₂). The differences in the SO₂ emissions between the future scenarios and the BC scenario were not very significant. For the BRR domain, the SBR scenario exhibited a reduction of 10% with respect to the BC scenario and a reduction of 5% for the BMA domain, as shown in Table 3. The reasons for these smaller differences include the following: (1) the main emissions sources were industrial activities that were kept constant for 2015, and (2) the SO₂ emitted from on-road traffic was of a small quantity; therefore, the significant reductions in SO₂ emissions from the on-road traffic sector in the future scenarios based on the use of less polluting fuels (EC, 2011) did not significantly affect the total SO₂ emissions.

Similar to NO_x and PM₁₀ emissions, the high SO₂ emissions shown in Figure 5m were found to emanate from point sources at rates that were greater than 15 kg h⁻¹ km⁻², and they were also related to the port activity and the sulphur content of the fuels used by the vessels in the port. In the future SBR scenario shown in Figure 5n, port emissions were projected to be reduced as a result of the limitation placed on the sulphur content in fuels (Directive 2005/33/EC; EC, 2005). On the other hand, the airport emissions were observed to increase with an increased number of passengers served by the airport. In the city centre of Barcelona,

the implemented mobility measures led to a reduction in SO₂ emissions to rates ranging between 0.1 and 0.5 kg h⁻¹ km⁻², as shown in Figures 4o and 4p.

Non-methane volatile organic compounds (NMVOCs). The NMVOCs originate mainly from biogenic sources (vegetation) and anthropogenic sources (human activity), as shown in Table 3. The analysed day corresponds to a winter period, where the biogenic emissions are noticeably lower than the anthropogenic emissions, allowing for an easier detection of the changes within the anthropogenic sources. Within the BRR domain, there was an observed reduction in the total emissions in the future scenarios because of the implementation of technological changes in new vehicles (a decrease of 16% when comparing the EB scenario with the BAU scenario). The implementation of the mobility measures within the BRR domain caused the total emissions to decrease by 29% in the SB scenario and 30% in the SBR scenario.

5. Conclusions

The evaluation of detailed emission abatement strategies is crucial for the improvement of air quality conditions in large cities. On-road traffic is the main source of emissions in the south-western Mediterranean area, especially in urban areas like Barcelona. In this paper, three future scenarios have been projected for 2015 by implementing traffic mobility measures in the city centre of Barcelona. To better define the future scenarios, a comprehensive projection of emissions from each sector has been considered.

The results of the HERMES model show the efficacy of the vehicle fleet renewal in reducing on-road traffic emissions. The mobility measures introduced in the city centre of Barcelona (the BRR domain) could also considerably reduce the on-road traffic in this area. As a result, the NO_x emitted by on-road traffic is projected to decrease by approximately 75% when the base case scenario is compared with the more ambitious SBR scenario.

Despite the reduction in on-road traffic emissions, the specific emissions that are projected for each sector exhibit several increases because of the introduction of new power plants and increased activity in the port and the airport. Therefore, the application of this comprehensive emission estimation will reduce current emissions in most of the city centre of Barcelona. However, the study also shows that more efforts are needed to mitigate the emissions with respect to the port, the airport and the power generation sources; otherwise, the emissions from those sources will increase and consequently lighten any reductions in emissions achieved by the measures in the on-road traffic sector. The main measures that should be considered to reduce the power generation sources are defined by EU entail increasing the renewable energy share and improving the energy efficiency. In port and airport areas the connection to the electric power system will allow to reduce the consumption of fossil fuels of ships and aircrafts during their activities.

The overall emission reductions for the BRR domain were estimated to be 35% for NO_x. Similar reductions were observed in relation to particulate matter and NMVOC emissions. In the case of CO, a higher emissions reduction of 80% was estimated. On-road traffic is the main contributor to CO emissions, and the application of on-road measures would affect the overall CO emissions the most significantly. However, lower SO₂ reductions to the order of 10% were observed based on the increased emission rates from the main emission sources, namely, the port, the airport and the power generation sectors.

Finally, we conclude that the HERMES emission model proves to be a suitable tool for the management and assessment of urban emissions. However, more effort is needed in the future to increase the size of the current databases for obtaining emission

factors that are associated with new technologies. These databases would need to reflect the changes in vehicular fleet composition that are already taking place, especially in urban areas.

Acknowledgments

The authors gratefully acknowledge the RACC and the Environmental Department of the Catalonia Government (Spain) for the information provided. Dr. Pedro Jiménez-Guerrero acknowledges the Ramón y Cajal Programme of the Spanish Ministry of Science and Technology.

Supporting Material Available

The supporting material contains a comparison between the HERMES inventory and the Spanish National Inventory (SNIE) for a validation of the HERMES model (Table S1). Figure S1 shows the emissions for the Catalan domain February 11th 2004 12 h UTC (NO_x kg h⁻¹ km⁻²). This information is available free of charge via Internet at <http://www.atmospolres.com>.

References

- AENA, 2008. Spanish Airports and Aerial Navigation, Annual Report, <http://www.aena.es/csee/Satellite?pagename=Estadisticas/Home>.
- Baldasano, J.M., Goncalves, M., Soret, A., Jimenez-Guerrero, P., 2010. Air pollution impacts of speed limitation measures in large cities: the need for improving traffic data in a metropolitan area. *Atmospheric Environment* 44, 2997-3006.
- Baldasano, J.M., Guereca, L.P., Lopez, E., Gasso, S., Jimenez-Guerrero, P., 2008. Development of a high-resolution (1 km x 1 km, 1 h) emission model for Spain: the High-Effective Resolution Modelling Emission System (HERMES). *Atmospheric Environment* 42, 7215-7233.
- Bandeira, J.M., Coelho, M.C., Sa, M.E., Tavares, R., Borrego, C., 2011. Impact of land use on urban mobility patterns, emissions and air quality in a Portuguese medium-sized city. *Science of the Total Environment* 409, 1154-1163.
- Brady, J., O'Mahony, M., 2011. Travel to work in Dublin. The potential impacts of electric vehicles on climate change and urban air quality. *Transportation Research Part D-Transport and Environment* 16, 188-193.
- Caserini, S., Giugliano, M., Pastorello, C., 2008. Traffic emission scenarios in Lombardy region in 1998-2015. *Science of the Total Environment* 389, 453-465.
- Chin, A.T.H., 1996. Containing air pollution and traffic congestion: transport policy and the environment in Singapore. *Atmospheric Environment* 30, 787-801.
- Cirillo, M.C., De Lauretis, R., Del Ciello, R., 1996. Review Study on European Urban Emission Inventories. European Environmental Agency, Copenhagen, 35 pages.
- Cohen, J.T., Hammitt, J.K., Levy, J.I., 2003. Fuels for urban transit buses: a cost-effectiveness analysis. *Environmental Science and Technology* 37, 1477-1484.
- Colville, R.N., Hutchinson, E.J., Mindell, J.S., Warren, R.F., 2001. The transport sector as a source of air pollution. *Atmospheric Environment* 35, 1537-1565.
- Crabbe, H., Beaumont, R., Norton, D., 1999. Local air quality management: a practical approach to air quality assessment and emissions audit. *Science of the Total Environment* 235, 383-385.
- DGT, 2008. Spanish Department of Transportation, Statistical data in the number of vehicles and fuel used. http://www.dgt.es/portal/es/seguridad_vial/estadistica/, accessed in August 2012.
- DGT (Spanish Department of Transportation), 2008. http://www.dgt.es/portal/es/seguridad_vial/estadistica/, accessed in August 2012.
- EC (European Commission), 2011. Quality of Petrol and Diesel Fuel Used for Road Transport in the European Union, COM (2011) 116, Brussels, 15 pages.

- EC (European Commission), 2010. Energy 2020 A Strategy for Competitive, Sustainable and Secure Energy, COM (2010) 639, Brussels, 21 pages.
- EC (European Commission), 2009. Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 Amending Directive 98/70/EC as Regards the Specification of Petrol, Diesel and Gas-Oil and Introducing a Mechanism to Monitor and Reduce Greenhouse Gas Emissions and Amending Council Directive 1999/32/EC as Regards The Specification of Fuel Used by Inland Waterway Vessels and Repealing, Directive 93/12/EEC, Official Journal of the European Union, L 140/88, 26 pages.
- EC (European Commission), 2007. Regulation 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, Official Journal of the European Union, L 171/1, 16 pages.
- EC (European Commission), 2005. Directive 2005/33/EC of the European Parliament and of the Council of 6 July 2005 amending directive 1999/32/EC as regards the sulphur content of marine fuels, Official Journal of the European Union, L 191/50, 11 pages.
- EC (European Commission), 2003. Directive 2003/17/EC of the European Parliament and of the Council of 3 March 2003 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels, Official Journal of the European Union, L 76/10, 10 pp.
- EC (European Commission), 2001a. Communication of the European Commission of 07/11/2001 on an Action Plan and Two Proposals for Directives to Foster the Use of Alternative Fuels for Transport, Starting with the Regulatory and Fiscal Promotion of Biofuels, COM (2001) 547, Brussels, 47 pages.
- EC (European Commission), 2001b. White paper. European Transport Policy for 2010: Time to Decide, Commission of the European Communities, COM (2001) 370, Brussels, 124 pages.
- EEA (European Environmental Agency), 2009. EMEP/EEA Air Pollutant Emission Inventory Guidebook, EEA Technical Report No. 9/2009, Copenhagen, 21 pages.
- EEA (European Environmental Agency), 2005. Environment and Health, Report 10/2005, European Environment Agency, 40 pp.
- EPA (Environmental Protection Agency), 2002. A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report, EPA420-P-02-001, United States Environmental Protection Agency, 126 pages.
- Generalitat de Catalunya, 2011. Assessment of the air quality of Catalonia: year 2010, Generalitat de Catalunya, Barcelona, 23 pages.
- Generalitat de Catalunya, 2006. Energy Plan for Catalonia 2006-2015, Generalitat de Catalunya, 462 pages.
- Ghose, M.K., Paul, R., Banerjee, S.K., 2004. Assessment of the impacts of vehicular emissions on urban air quality and its management in Indian context: the case of Kolkata (Calcutta). *Environmental Science and Policy* 7, 345-351.
- Goncalves, M., Jimenez-Guerrero, P., Baldasano, J.M., 2009. Emissions variation in urban areas resulting from the introduction of natural gas vehicles: application to Barcelona and Madrid Greater Areas (Spain). *Science of the Total Environment* 407, 3269-3281.
- Guo, H., So, K.L., Simpson, I.J., Barletta, B., Meinardi, S., Blake, D.R., 2007. C-1-C-8 volatile organic compounds in the atmosphere of Hong Kong: overview of atmospheric processing and source apportionment. *Atmospheric Environment* 41, 1456-1472.
- IDESCAT, 2008. <http://www.idescat.cat/en/poblacio/poblrecomptes.html>, accessed in August 2012.
- Jimenez-Guerrero, P., Jorba, O., Baldasano, J.M., Gasso, S., 2008. The use of a modelling system as a tool for air quality management: annual high-resolution simulations and evaluation. *Science of the Total Environment* 390, 323-340.
- Jorba, O., Perez, C., Rocadenbosch, F., Baldasano, J.M., 2004. Cluster analysis of 4-day back trajectories arriving in the Barcelona area, Spain, from 1997 to 2002. *Journal of Applied Meteorology* 43, 887-901.
- Kouridis, C., Gkatzoflias, D., Kioutsioukis, I., Ntziachristos, L., Pastorello, C., Dilara, P., 2010. Uncertainty Estimates and Guidance for Road Transport Emission Calculations, Publications Office of the European Union, EUR 24296 EN, Luxembourg, 165 pages.
- Larive, J.-F., 2007. The future composition of the EU road fuel pool. *CONCAWE Review* 16, 3-7.
- Lumbreras, J., Valdes, M., Borge, R., Rodriguez, M.E., 2008. Assessment of vehicle emissions projections in Madrid (Spain) from 2004 to 2012 considering several control strategies. *Transportation Research Part A-Policy and Practice* 42, 646-658.
- MMA (Ministerio de Medio Ambiente y Medio Rural y Marino), 2006. Green Book on Urban Environment, http://www.magrama.gob.es/es/calidad-y-evaluacion-ambiental/temas/movilidad-urbana/Libro_Verde_de_Medio_Ambiente_Urbano_Partes_1%2C2_Y_3_tcm7-88515.pdf, accessed in August 2012 (in Spanish).
- Moriarty, P., Honnery, D., 2008a. Low-mobility: the future of transport. *Futures* 40, 865-872.
- Moriarty, P., Honnery, D., 2008b. The prospects for global green car mobility. *Journal of Cleaner Production* 16, 1717-1726.
- Ntziachristos, L., Samaras, Z., 2005. Background Document to the Workshop on EU Policies to Improve the Contribution of Urban Buses and Other Captive Fleets to Air Quality, Brussels, 41 pages.
- Oduyemi, K.O.K., Davidson, B., 1998. The impacts of road traffic management on urban air quality. *Science of the Total Environment* 218, 59-66.
- Ozan, C., Haldenbilen, S., Ceylan, H., 2011. Estimating emissions on vehicular traffic based on projected energy and transport demand on rural roads: policies for reducing air pollutant emissions and energy consumption. *Energy Policy* 39, 2542-2549.
- Palmgren, F., Berkowicz, R., Ziv, A., Hertel, O., 1999. Actual car fleet emissions estimated from urban air quality measurements and street pollution models. *Science of the Total Environment* 235, 101-109.
- Palmgren, F., Berkowicz, R., Hertel, O., Vignati, E., 1996. Effects of reduction of NO_x on the NO₂ levels in urban streets. *Science of the Total Environment* 189, 409-415.
- Parra, R., Jimenez, P., Baldasano, J.M., 2006. Development of the high spatial resolution EMICAT2000 emission model for air pollutants from the north-eastern Iberian Peninsula (Catalonia, Spain). *Environmental Pollution* 140, 200-219.
- Parra, R., Gasso, S., Baldasano, J.M., 2004. Estimating the biogenic emissions of non-methane volatile organic compounds from the North Western Mediterranean vegetation of Catalonia, Spain. *Science of the Total Environment* 329, 241-259.
- Soret, A., Jimenez-Guerrero, P., Baldasano, J.M., 2011. Comprehensive air quality planning for the Barcelona Metropolitan Area through traffic management. *Atmospheric Pollution Research* 2, 255-266.
- Stephens-Romero, S., Carreras-Sospedra, M., Brouwer, J., Dabdub, D., Samuelsen, S., 2009. Determining air quality and greenhouse gas impacts of hydrogen infrastructure and fuel cell vehicles. *Environmental Science and Technology* 43, 9022-9029.
- Villalba, G., Gemechu, E.D., 2011. Estimating GHG emissions of marine ports-the case of Barcelona. *Energy Policy* 39, 1363-1368.
- Wang, G.H., Ogden, J.M., Sperling, D., 2008. Comparing air quality impacts of hydrogen and gasoline. *Transportation Research Part D-Transport and Environment* 13, 436-448.