Air Quality Model and Sensibility Analysis for Barcelona City

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1. Introduction

In the framework of the *PECQ 2011-2020*, acronym in Catalan of the Energy, Climate Change and Air Quality Plan for Barcelona 2011-2020 (Energy Agency of Barcelona, 2011), an air quality model for the Barcelona city was developed in order to help decision makers implement actions aimed to improve the air quality.

In the first stage, a real inventory of vehicles was performed, recording over 90,000 vehicle plates and also measuring 42,000 tailpipe emissions via Remote Sensing Device. Main conclusions are that the vehicles on the road are newer than the city census vehicles, and that the real-world vehicle NO_X emissions are 16.2% higher than EMEP/EEA emissions factors. A geographical emissions inventory of high resolution was compiled including all the emission sources inside the city and the surroundings.

The base-year results show that 65.6% of NO_2 concentration levels come from vehicles, 8.6% from residential and commercial sources, 4.8% from industry, including heat and power production close to the city, 2.1% from Barcelona Port, and 0.1% from Barcelona Airport. The local background contribution was calculated as 10.1% and the regional background accounts for 8.6%.

This paper will focus on the NO_2 air quality model for the Barcelona city, we will show the methodology and results, as well as a sensibility analysis in which various emission scenarios were modelled in order to determine the sensitivity of NO_2 concentrations to changes in emissions rates.

2. Barcelona air quality

Like many other cities, Barcelona exceeds the annual average NO_2 concentration thresholds established by the EU to protect human health (EEA, 2012). This means that cities, regions and countries must adopt new strategies, on various levels, aimed at improving air quality in metropolitan areas. This includes vehicle manufacturers, legislators, citizens, companies, and so on.

For years, Barcelona City Council and other public bodies have been working to improve air quality through various measures involving industry and power plants and by promoting renewable energy. Examples of this include the Solar Thermal Bylaw of 1999 (BOP, Butlletí Oficial de la Provincia de Barcelona, 2006) or the application of the Barcelona Energy Improvement Plan (2001-2010) (Barcelona Regional and Barcelona City Council, 2002).

Knowing that the main source of pollutants is road transport, Barcelona metropolitan area has made remarkable efforts to achieve a modal split change. This has included promoting the integration of public transport fares and the improvement of public transport networks (bus, metro, trams). Barcelona has also expanded the city's bicycle network and created "Bicing" – a public bicycle-rental service with a very low-cost flat rate. Another measure was to increase the roll-out of parking meters for surface parking, in order to make private transport systems less competitive.

Despite all the policies designed to make public transport more attractive and to stimulate the modal split change from private vehicles to the public system, there is still some way to go, since the city does not yet fall within the all air-quality standards set by Europe. So, new initiatives are required.

3. Barcelona urban air-dispersion model

Within the PECQ, in order to focus the Action Plan most effectively, it was essential to determine what activities and sectors are responsible for high NO_2 concentration levels. A detailed inventory of emissions by sectors has been developed for the base case year 2008. This emission inventory was one of the key inputs of the Barcelona Air-Dispersion Model, a tool that helps decision-makers know what is happening with air quality and what needs to be done in order to improve it.

3.1. Methodology

The high resolution air quality model, ADMS-Urban (Carruthers et al., 1998 and UK Air quality Expert Group 2004), has been used. It is a transport and advanced Gaussian dispersion model with an integrated street canyon model. The entire model is fully integrated in a Geographical Information System (GIS) database of emission sources, terrain configurations and other relevant aspects.

The main features of the dispersion model used are:

- Specific dispersion model for urban and metropolitan areas with resolution down to street level.
- Includes a meteorological pre-processing model.
- Uses the “FlowStar” module, a processing module designed for hourly flows and turbulence for high-resolution complex plots (Hunt et al., 1981).
- Can use hourly, daily and monthly input profile schedules for each source emission.
- Works with the OSPM model, specifically to assess the "Street Canyon" effect resulting from the recirculation of air turbulence among buildings (Hertel et al., 1990).
- Uses the GRS chemistry scheme, a semi-empirical photochemical model which includes the reactions of NO, NO_2, O_3 and many organic compounds.

After gathering the data and in order to map an air-quality model, a high-resolution grid was created with up to 150,000 virtual grid points across the territory, plus 50,000 points next to roads using "intelligent gridding” software capability. The result was a mean grid resolution of 35.2 metres in outlying parts of the city and an estimated mean grid resolution of 17.6 metres in the city centre in order to ensure higher accuracy. More than twelve processors were used, working constantly for 30 days. Figure 6 shows the map of NO_2 concentration levels after model calibration for 2008. Keep in mind that reality is more complex than the “typical profiles” or mean behaviours introduced in the model. Therefore, unusual traffic jams, fires, construction work, unknown emissions, and other situations can cause deviations between the model and reality.

Hourly data from the monitoring sites was compared with modelling results with virtual point detectors. Table 1 shows a comparison of annual mean values and Figure 5 contains a monthly example of hourly comparison.

3.2. Characteristics and emissions of vehicles in Barcelona

Since the road transport sector is the main emitter of pollutants, the PECQ established a clear difference with previous studies of vehicle emissions. A real-world characterisation of traffic was developed in order to find out what types of vehicles are driven around the city, as well as their emissions. It is important to mention that previous studies used the vehicle census of the city (Barcelona Statistics Department). We will show below that there is a major “gap” between the traffic on the streets and what is listed in the city census via road tax. This is a key point for drawing up effective policies and calculating related NO_X reductions. It is also important to have a better idea of actual emissions in order to obtain a better estimate in the air-dispersion model.

Since it is a diffuse sector, traffic emissions must be determined indirectly, based on vehicle km/year, total number of vehicles, average speed, and methodologies based on emission factors (EF) by vehicle characteristics (fuel type, engine size, weight and technology of the vehicle), such as EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2009)

To improve EF methodology, Barcelona City Council conducted an ad-hoc study (Barcelona Regional, Technet, 2010) over 32 days in May and June 2009, setting up 16 roadside points for measuring vehicle exhaust emissions, with a detector system called “RSD” - Remote Sensing Device (Technet) -. This technology can detect pollutant emissions from vehicle exhaust pipes instantly and in a non-intrusive manner, using infrared and ultraviolet light according to the Lambert-Beer law. This means that vehicles do not have to modify their normal driving patterns and thousands of vehicle license plates and exhaust vehicle emission data can be gathered in just a few hours. The emission data shows the actual emissions of the vehicles, unlike other methodologies based on standard emission factors, and the license plate shows the vehicle type. This makes it possible to know the brand, vehicle model, technical characteristics (power, weight, fuel, age, etc.), and city of residence (census). We gathered 90,000 vehicle license plates and emissions data for more than 42,000 vehicles after RSD exhaust data validation.

This study revealed some important aspects:

- The average age of all vehicles is 5.66 years.
- The cars driving around the city are newer (with an avg. age of 5.53 years) than the city vehicle census (9.13 years). This does not mean that the census does not work properly. This difference shows that people who use more often their car tend to have newer vehicles.
- Petrol cars are older (7.58 years) than diesel cars (4.43 years) due to a social trend. In Spain, it is typical to buy a diesel car if your annual mileage is very high, so daily car users buy more diesel cars than weekend car users.
- The pre-EURO class displays an interesting behaviour pattern. 20% of the cars in the city vehicle census are pre-EURO; by contrast, the EURO class only represents 8% of cars driven daily in the city streets.
- The taxi fleet has an average age of 3.4 years, and the average age of trucks is 6.5 years.
- The most common fuel used by vehicles in the city is diesel at 55.1%, followed by petrol at 44.1%, biodiesel at 0.6% and, finally, natural gas at 0.3%.
- 52% of the vehicles come from outside Barcelona city (they are not included in the municipal census). As for cars, 51% come from outside the city. In this group, 41% are petrol cars and 56% are diesel cars, since it is more cost-efficient to own a diesel car if your annual mileage is very high, as diesel is cheaper and more efficient than petrol. This makes sense considering that 62% of daily car trips in Barcelona are made by people that live outside the city and commute in to work (or vice-versa) (Serveis Mobilitat Aj. de Barcelona, 2008).

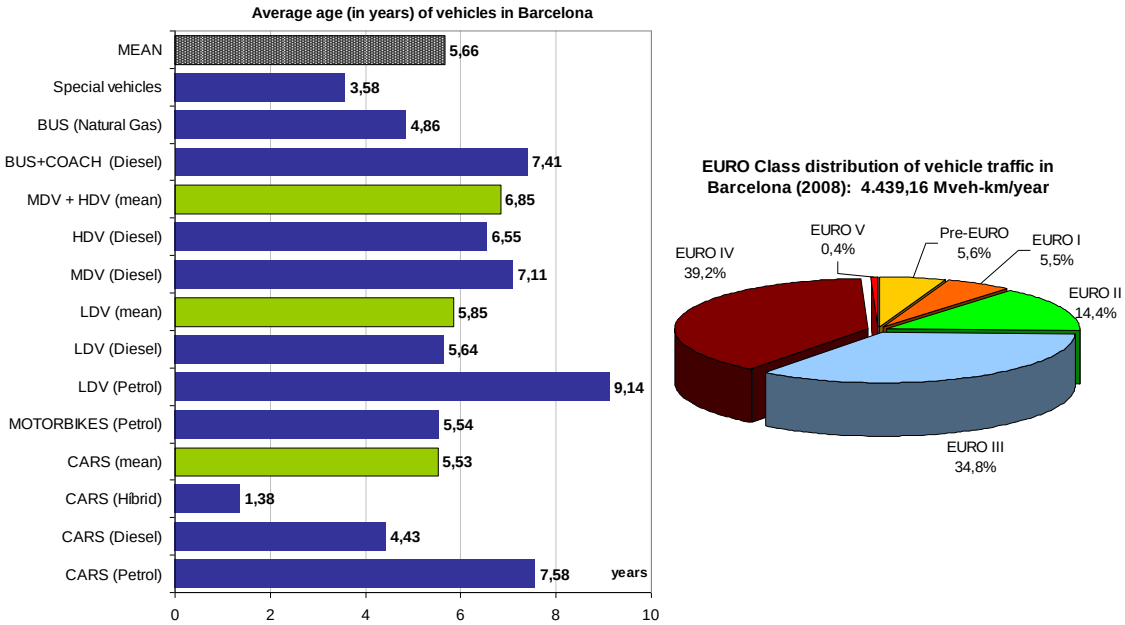


Figure 1: Average age of different categories of vehicles (left) and EURO class distribution of vehicles driving around city streets (right).

In the same study the exhaust pipe emissions from 42,000 vehicles were analysed and we compared the emissions from the "RSD" system with the COPERT methodology. The average result was that RSD measured 16.2% higher NO_X emissions than COPERT considering the same number of vehicles in city driving mode, with an average speed of 21.3 km/h and the weather conditions for May/June – the months when the detection survey was done –.

Using the annual share of vehicular traffic (Serveis de Mobilitat, 2008) with the RSD emission data it is calculated that 34.2% of vehicle NO_X emissions are from cars (29.3% from diesel cars and 4.9% from petrol cars), followed by vans (LDV) 17.4%, medium and heavy trucks (MDV and HDV) 15.7%, motorcycles and mopeds 12.3% – in Barcelona, 22.8% of all private transport is by motorbike –, private buses and coaches 12.2%, and local public buses 8.2%. The average emission factor for total traffic was 1.1297 grams of NO_X per kilometre. Figure 2 shows total emissions and emission ratio by vehicle class, and Figure 3 contains the distribution according to mobility, vehicle emission and trips.

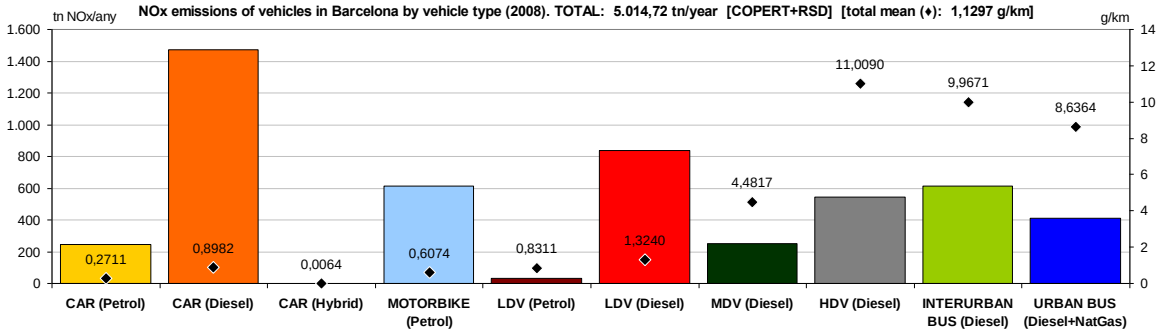


Figure 2: NO_X emissions and emission ratio by vehicle type for Barcelona.

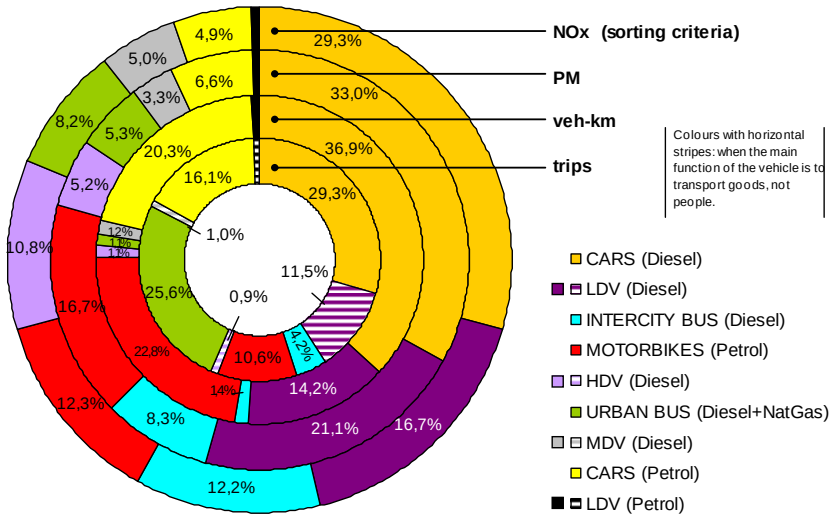


Figure 3: Related share of NO_X emissions (sorting criteria), PM_{10} emissions, mobility (veh-km) and trips.

3.3. Barcelona 2008 emissions inventory

Database quality is one of the most important aspects of air-quality modelling. All the emission sources input into the air-dispersion model are shown below. The base-case year for the emissions inventory is 2008.

- Road transport: we used the COPERT emission model plus the XTRA RSD recorded exhaust emission factors in order to include actual emissions from vehicles. Hourly, daily, weekly and monthly traffic profiles were also used.

- Residential and commercial: we used the CORINAIR emission factor to estimate NO_X emissions from natural gas and LPG. Hourly and monthly profiles were also implemented for this sector.
- Industry and power plants: Actual emissions data for stack emission sources with continuous environmental control was used. Other industrial emissions were estimated using CORINAIR methodology.
- Port: Land traffic, sea traffic and auxiliary vehicles in Barcelona's Port were taken into account using the COPERT+XTRA RSD system for the first, and the CORINAIR methodology for the second and third. Monthly profiles were implemented for this sector.
- Airport: Barcelona Airport is 12 km from the city centre (outside the city limits). NO_X emissions were estimated using CORINAIR methodology and considering auxiliary vehicles and LTO cycle for airplanes. Hourly and monthly profiles were used for the airport.

All these data provide an inventory of NO_X emissions for Barcelona and surroundings covering 1,476 km^2, of which Barcelona makes up only 7%, with 102 km^2. Air-quality modelling involves studying a larger area, since pollution does not respect municipal boundaries. Thus, total NO_X emissions for the entire area covered were 34,186 tonnes in 2008, while NO_X emissions for Barcelona city were 10,413 tn/y.

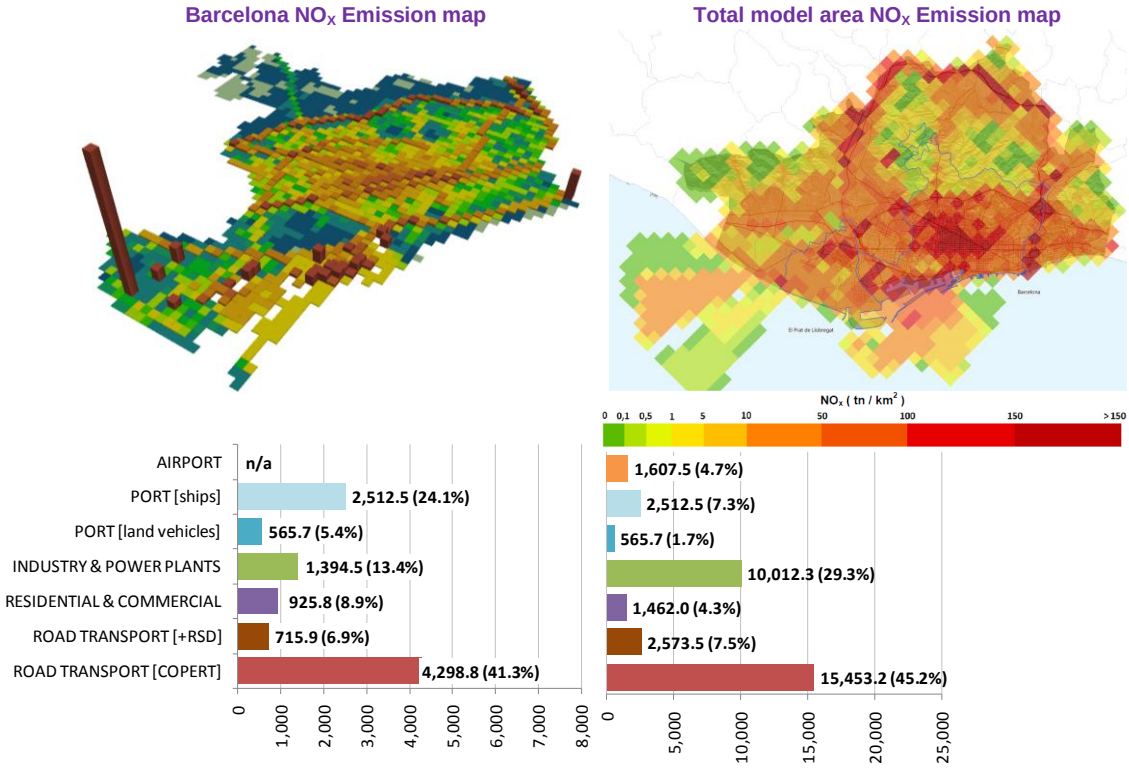


Figure 4: NO_X emissions map and source apportionment for Barcelona city (left) and for model area (right).

As regards Barcelona emissions, vehicle are responsible for 5,015 tn/y (4,299 according to COPERT plus 716 according to RSD), making up 48.2% of the city emissions. The second source of emissions was Barcelona Port, with 3,078 tonnes or 29.5% (2,512.5 for sea traffic plus 565,7 for land activity). The third source was industry and power plants, with 1,394 tn/y or 13.4%. And the residential and services sectors, with 926 tn/y or 8.9%. Figure 4 shows the geo-referenced emissions inventory.

3.4. Structural inputs for the model

Certain structural and meteorological inputs were also required in order to model air quality. This is described briefly below:

- Meteorological data: actual hourly weather data for 2008 was used, taken from an urban weather station located in the city.
- Cartography: the topography and surface features of the area were taken from the database of the Catalonian Institute of Cartography.
- Road infrastructure: city network, highway network and bus network for Barcelona city and surrounding municipalities were introduced in the model with AAWT (annual average weekday traffic).
- 3-D building model: the 3-D Barcelona building model was used to model the street canyon effect.
- Background concentration levels were based on hourly data from a specific background concentration station located on the coast in the north of Catalonia (Cap de Creus, Girona), 140 km from Barcelona. The annual average concentration levels for 2008 were 4.26 µg/m3 for NO2, 0.30 µg/m3 for NO, and 74.4 µg/m3 for O3 (AEMET, 2008).

3.5. Modelling results and validation process

By running the ADMS-Urban model for Barcelona with the geo-referenced emissions inventory and the structural inputs of the modelled area, we obtained an annual average NO_2 concentration of 14% below actual concentration levels for virtual point receptors representing real measurement stations. Therefore, 5 µg/m3 of NO_2 was added in order to calibrate the model – called "local background concentrations" – and the model was re-run.

After the calibration process, a very good estimate was obtained for all station measurement points. Table 1 shows the actual concentration levels for 2008 compared with the modelled values. We also obtained a very good model estimate for hourly concentration levels, as can be seen in Figure 5.

Table 1: Mean annual concentration levels of NO_2 by monitoring site. Modelled vs. real data.

Monitoring sites	Type of location	2008 Real data NO_2 (µg/m^3)	2008 Modelled NO_2 (µg/m^3)	Model/real data (%)
Ciutadella	Urban background	**42.3**	**46.2**	**109%**
Vall d'Hebrón	Urban background	**36.5**	**37.7**	**103%**
Eixample	High traffic site	**65.4**	**63.2**	**97%**
Gràcia	High traffic site	**62.6**	**57.9**	**93%**
Poblenou	Moderate traffic site	**47.4**	**41.8**	**88%**
Sants	Moderate traffic site	**45.3**	**50.0**	**110%**
Average value	---	**49.9**	**49.5**	**99%**

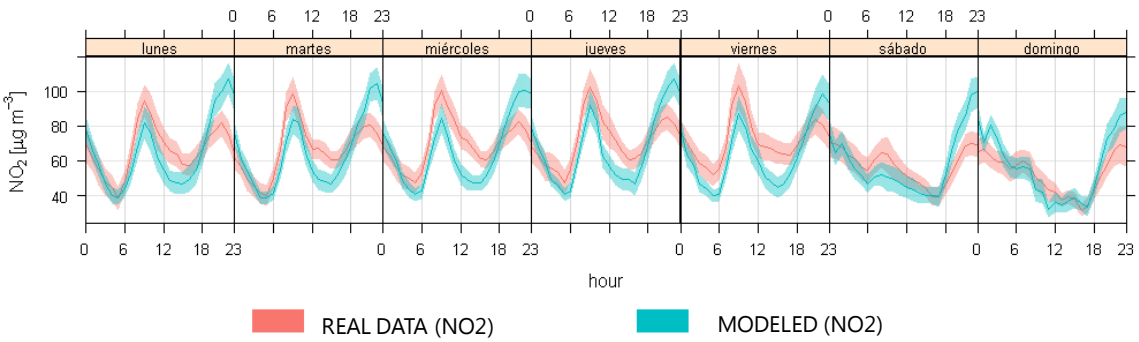
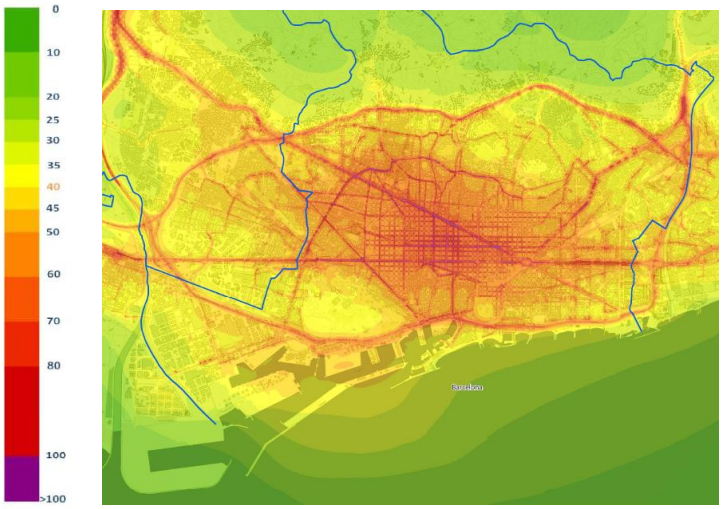


Figure 5: Real and modelled hourly and weekly NO_2 concentration levels.

The air-dispersion model for Barcelona revealed that 65.6% of the average annual NO_2 concentration level is due to traffic, the residential and service sector contributes to 8.6%, the industry and power generation to 4.8%, the Barcelona Port to 2.1%, and the Barcelona Airport contributes to 0.1%. In addition, 8.6% is due to the background pollution and local background contributes to 10.1%.

Figure 6: Annual average NO_2 concentration map of Barcelona, year 2008 and source apportionment.



NO_2 source sectors (2008)	
Road Transport	65,6%
Residential & commercial	8,6%
Industry	4,8%
Harbour	2,1%
Airport	0,1%
Regional Background	8,6%
Local Background	10,1%

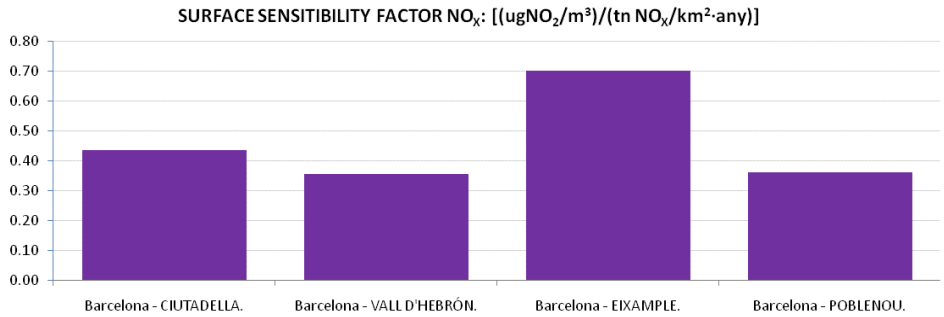
4. Sensibility analysis

Using the validated air quality model, different sensibility analysis have been performed, in this paper we present the results of the sensibility in variations of the traffic emissions. Several scenarios have been performed varying the emission factors for the all streets and calculating the NO_2 concentrations in the representing monitoring sites of the city and surroundings.

In the study we realized that the concentration levels are very sensible to variations of the traffic emissions. It was also demonstrated that not all the monitoring sites have the same response, it depends quite a lot of the location of the monitoring site, the nearby to busy roads, the shape of the street and its specific fluid dynamics.

Analysing the modelled data in the monitoring sites, we concluded that the NO_2 concentration level in Barcelona varies from 0.35 to 0.70 $\frac{\mu g/m^3}{tn/year/km^2}$. In other words, if we reduce the traffic emissions 1 tn/km^2·year of NO_X, we can expect an annual mean concentration reduction among 0.35 and 0.70 ug/m^3 of NO_2 for background and traffic sites respectively.

Figure 7: NO_X surface sensibility factor in different monitoring sites of Barcelona.



5. Discussion and conclusion

The Barcelona air-dispersion model was drawn up as part of the Barcelona PECQ 2011-2020 (acronym in Catalan of Barcelona's Energy, Climate Change and Air Quality Plan). As discussed in the paper, transport is the main culprit for current high NO_2 concentrations. This sector is responsible for 48.2% of NO_X emissions and produces 65.6% of the NO_2 concentration levels, on an annual average. An important study has been conducted in Barcelona to determine what kinds of vehicles use the city streets every day and their exhaust emissions.

The Barcelona air-quality model has been a very important tool for drawing up the PECQ, for understanding local dispersion and detecting main pollutant sectors during the diagnosis stage, and for helping to assess and predict the impact of the measures on the city's air quality during the policy-making process.

Focusing on the traffic emissions a sensibility analysis has been conducted to demonstrate that the NO_2 levels would decrease between 0.35 and 0.7 $\mu g/m^3$ per tn NO_X/km^2 that we avoid to emit annually.

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