
The challenge of improving urban air quality: effects of hybrid cars, introduction in Barcelona and Madrid (Spain)

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Abstract: WRF-ARW/HERMES/CMAQ modelling system is applied with high resolution (1 km², 1 h) to assess changes in Madrid and Barcelona (Spain) air quality due to hybrid cars introduction. The substitution of the oldest cars by hybrids is effective to reduce NO₂ and PM_{2.5} levels in the conurbations (up to 35%/12% in Madrid downtown, when 30% of cars are changed). In VOC-limited areas, as Barcelona, the NO_x emissions abatement locally increases tropospheric ozone concentration. Downwind, however, the precursors' emissions reduction leads to lower O₃ levels. Air quality models, applied with high resolution, prove to be useful tools to manage urban air quality.

Keywords: urban air quality; on-road traffic emissions; atmospheric modelling; environmental management.

Reference to this paper should be made as follows: Gonçalves, M., Jiménez-Guerrero, P. and Baldasano, J.M. (2011) 'The challenge of improving urban air quality: effects of hybrid cars, introduction in Barcelona and Madrid (Spain)', *Int. J. Environment and Pollution*, Vol. 47, Nos. 1/2/3/4, pp.70–78.

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1 Introduction

Improving urban air quality is nowadays an important environmental challenge. On-road traffic is the largest contributor to pollutant emissions in urban areas and remains a key target for public health action in Europe (Künzli et al., 2000). Therefore, air quality

management strategies and improvements in current vehicle technologies are being tested (Nagl et al., 2007). In the short term, the main options are the use of alternative fuels, such as biofuels or natural gas (COM (2001)347; COM(2006)845), and the introduction of new technology vehicles, such as hybrid vehicles (Demirdöven and Deutch, 2004). The quantitative evaluation of the effectiveness of these strategies is fundamental to help decision-makers. Air-quality modelling is the most suitable tool to assess air pollution changes, including secondary pollutants such as tropospheric O₃ (Sillman et al., 1998; Jiménez and Baldasano, 2004), and to obtain geographically distributed information in advance.

Hybrid vehicles usually combine an electric and an internal combustion engine. Braking energy recovery and the use of the electric motor lead to fuel savings, which peak in urban driving conditions (Christidis et al., 2005; Fontaras et al., 2008). Policies to encourage hybrid vehicles use and purchase have been introduced in Spain. Indirectly, measures like the European emission limits for vehicles (COM(2005)683) or the agreed objectives to reduce CO₂ emissions from transport (COM(2007)19) promote the introduction of hybrid vehicles.

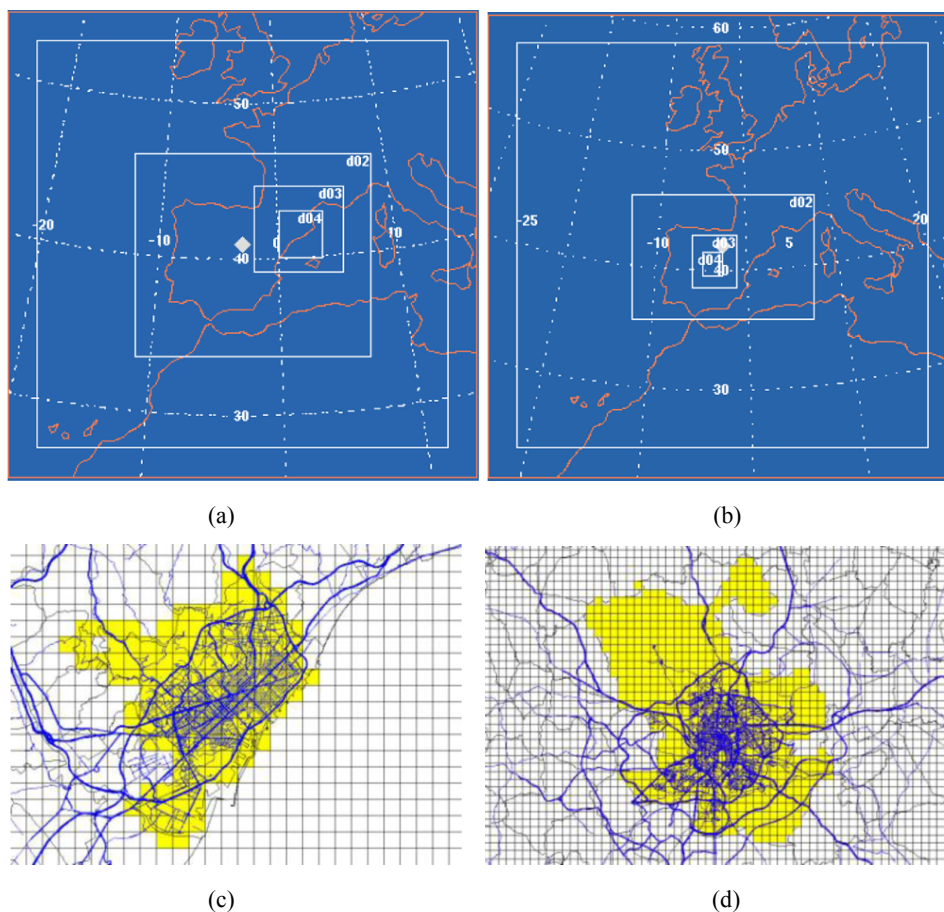
This work defines two scenarios of hybrid cars used in Barcelona and Madrid urban areas, the largest conurbations of Spain. A detailed assessment of the effects on air quality (O₃, SO₂, NO₂ and PM concentrations) is provided by means of the WRF-ARW/HERMES/CMAQ modelling system, applied with high resolution (1 km², 1 h) during a photochemical pollution episode of the year 2004 (Baldasano et al., 2008a, 2008b).

2 Methods

2.1 Modelling system description and selected episode

WRF-ARW mesoscale model (Michalakes et al., 2005) supplies the meteorological inputs for CMAQ model simulations (Byun and Schere, 2006). The domains are centred in Barcelona and Madrid cities; they cover larger areas to assess the evolution of the urban plume pollution: the North-Eastern Iberian Peninsula –NEIP– (322 × 259 km²) and the Central Iberian Peninsula –CIP– (181 × 214 km²), respectively (Figure 1(a) and (b)). The high temporal and spatial resolution (1 km²–1 h) allows detecting subtle changes in urban air quality and improves the air quality assessment in very complex terrains, such as those studied (Jiménez et al., 2005). A detailed description on the simulation settings is given in Gonçalves et al. (2009). HERMES model (Baldasano et al., 2008a, 2008b) estimates high-resolution emissions for the simulated domains. HERMES traffic module considers a bottom-up approach and accounts for 72 diesel and petrol vehicles categories according to EEA-EMEP/CORINAIR methodology (Ntziachristos and Samaras, 2000). The vehicle fleet composition is defined for Spain and specifically for Barcelona and Madrid urban areas for the year 2004.

Figure 1 Nested domains defined to perform the simulations (up). D1 Europe: 55×55 cells (54 km resolution), D2 Iberian Peninsula: 94×82 cells (18 km resolution), D3 Iberian Peninsula Area: 104×103 cells (6 km resolution): (a) D4 North-Eastern Iberian Peninsula (NEIP) domain (1 km resolution); (b) D4 Central Iberian Peninsula (CIP) domain (1 km resolution); (c) Barcelona and (d) Madrid urban areas; highlighted in yellow the areas where changes in emissions are defined and assessed (130 km^2 over Barcelona (c), and 373 km^2 over Madrid (d)) (see online version for colours)



The performance of the WRF-ARW/HERMES/CMAQ modelling system to predict air quality levels in the Iberian Peninsula meets the recommendations of the European Directives 1999/30/EC; 2002/3/EC and 2008/50/EC (Jiménez-Guerrero et al., 2008; Pay et al., 2010), and the specific evaluation for the selected episode, 17–18 June 2004, can be found in Gonçalves et al. (2009).

17–18 June 2004 corresponds to the worst air quality conditions in terms of O_3 , NO_2 and PM_{10} in Barcelona and Madrid areas for the year 2004, fitting also in a usual traffic circulation pattern (working days). The episode is characterised by a western recirculation in the synoptic scale: a frequent transport pattern over the Iberian Peninsula

(Jorba et al., 2004) usually associated with local-to-regional episodes of air pollution related to high levels of O₃ during summer (Gonçalves et al., 2009).

2.2 Definition of scenarios

The planned scenarios include: (H1) the introduction of 10% of gasoline–electric hybrid cars instead of the oldest gasoline and diesel private cars in Madrid and Barcelona and (H2) the introduction of 30% of gasoline–electric hybrid cars instead of the oldest gasoline and diesel private cars and taxis. The prediction of future trends in hybrid vehicles market for Spain is beyond the scope of this work. Considering the vehicle fleet renewal in the study areas constant and equal to the averaged value for the last 5 years (2004–2009), H1 is in agreement with long-term predictions for hybrid vehicles use, around 12% in 2020 (Christidis et al., 2005). H2 would constitute a longer-term scenario and it is assumed as an evaluation of the possible effects of a paradigm shift in vehicle technology towards hybridisation.

Specific speed-dependent emission factors for CO, VOC and NO_x for hybrid cars are obtained from Samaras and Zierock (2007). Changes in fuel consumption allow deriving CO₂ and SO₂ emissions. Owing to the lack of specific data, PM_{2.5}, CH₄, N₂O and NH₃ emissions are estimated under a conservative approach, taking into account equivalent gasoline emission factors.

3 Results and discussion

3.1 On-road traffic fuel consumption and emissions

On-road traffic is the main source of NO_x (57%) emissions in the NEIP domain, contributing also by 32% to primary PM_{2.5}. It is also the main emitter of NO_x (74%) in the CIP domain, being responsible for 42% of the total emitted PM_{2.5}. Moreover, 31% of the equivalent CO₂ emitted (83998 t d⁻¹) in the NEIP and 48% (60326 t d⁻¹) in the CIP is attributed to on-road transport (global warming potential taken from Forster et al. (2007)).

The main benefit of using hybrid vehicles concerns fossil fuel savings. Barcelona fuel consumption is reduced by 2.7 and 9.7%, respectively, for H1 and H2 (Table 1). The higher number of vehicles and the specific vehicle fleet composition of Madrid compared with Barcelona (82% vs. 66% of cars) result in larger impacts for the same scenarios. H1 reduces the fuel consumption by 3.4% and H2 by 12.1% in Madrid (Table 1). As a consequence of the fossil fuel savings, NO_x, NMVOC, CO, SO₂ and PM emissions from on-road traffic decrease. Impacts on NO_x emissions are especially important. Reductions range from 1.7 t of NO_x d⁻¹ (7.9% of NO_x from traffic) in Barcelona in H1, up to 32.3 t d⁻¹ (48.4%) in Madrid in H2 (Table 1). Derived changes in air quality are discussed in Section 3.2. Positive effects in terms of GHG emissions are also accounted. H1 saves 107.1 t d⁻¹ of equivalent CO₂ (2.6%) in Barcelona and 388.9 t d⁻¹ (3.2%) in Madrid. H2 effects are larger saving up to 1388.9 t d⁻¹ equivalent CO₂ (11.5%) in Madrid (Table 1).

Table 1 On-road traffic emissions and fuel consumption ($t d^{-1}$) for the Barcelona and Madrid urban areas during the 18 June 2004. Comparison among the base case scenario (BC), the H1 scenario: introduction of 10% of petrol hybrid electric cars; the H2 scenario: introduction of 30% of petrol hybrid electric cars

	Primary pollutant emissions					Fuel cons. GHG emis.		
	BCN							
(18/06/2004)	NO_x	NM VOC	CO	SO_2	PM_{10}	$PM_{2.5}$	FC	$CO_2 eq$
BC ($t d^{-1}$)	21.3	88.1	104.4	0.7	2.0	1.8	1247.7	4181.1
BC-H1 ($t d^{-1}$)	1.7	2.3	13.2	0.02	0.1	0.1	33.5	107.1
BC-H2 ($t d^{-1}$)	7.0	9.3	36.2	0.05	0.2	0.2	120.6	388.2
BC-H1 (%)	7.9	2.6	12.6	2.6	4.7	5.3	2.7	2.6
BC-H2 (%)	33.1	10.6	34.6	7.4	9.3	10.6	9.7	9.3
MAD								
BC ($t d^{-1}$)	66.7	134.5	297.6	1.8	4.9	4.2	3607.4	12055.2
BC-H1 ($t d^{-1}$)	7.6	6.2	50.7	0.1	0.4	0.4	122.2	388.9
BC-H2 ($t d^{-1}$)	32.3	23.7	126.0	0.2	0.7	0.7	435.5	1388.9
BC-H1 (%)	11.4	4.6	17.1	3.8	8.3	9.5	3.4	3.2
BC-H2 (%)	48.4	17.6	42.3	9.5	13.9	16.1	12.1	11.5

3.2 Air quality in the urban areas

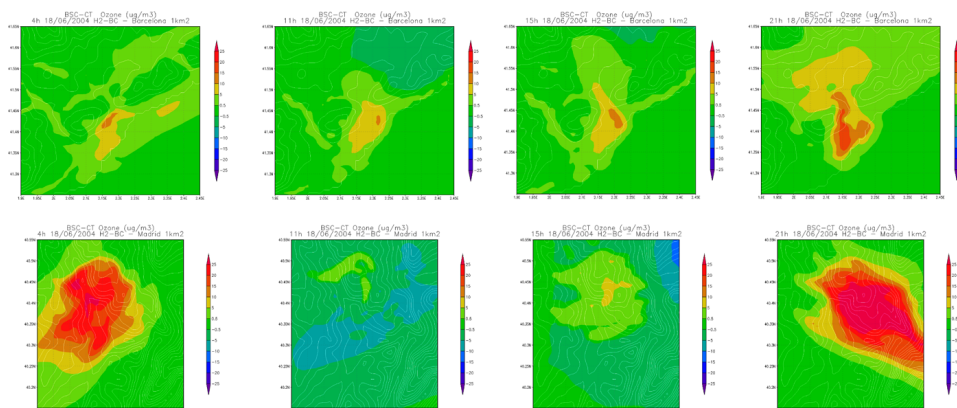
The introduction of hybrid vehicles seeks to benefit urban air quality, where major problems are related to NO_2 and PM concentrations. Madrid airshed, owing to its specific photochemical regime, also shows high O_3 levels. Nevertheless, O_3 peaks in downwind regions from the cities: the northern area of the NEIP and the southern area of the CIP. Differences in the origin of emissions, photochemical regime (NO_x -VOCs ratio) and atmospheric transport condition the final air quality levels. Therefore, those factors also affect the response to analogous management strategies.

Hybrid scenarios are positive in terms of NO_2 , SO_2 and PM concentrations in the conurbations. H1 reduces NO_2 24 h average concentration by 1.8% and $PM_{2.5}$ by 0.3% in the Barcelona Greater Area (BGA, defined as $40 \times 40 km^2$ over the urban region). Higher traffic intensity in downtown areas is reflected by larger reduction ratios. The finest fraction of particulates is mainly originated by fuel combustion processes or chemical production, therefore is the most affected by the fuel consumption savings. Maximum hourly $PM_{2.5}$ concentrations are 3.3% lower in Barcelona Downtown, BD (from $46.2 \mu g m^{-3}$ to $45.1 \mu g m^{-3}$). As aforementioned, the Madrid Greater Area (MGA, $40 \times 40 km^2$ area defined over the urban area) is more sensitive to changes in car fleet; therefore, the impact of hybrids scenarios is larger than in Barcelona. For instance, daily average NO_2 and $PM_{2.5}$ are 5.3% and 2.1% lower in H1 than in the base case. The emissions abatement in the urban areas affects the formation of NO_2 and secondary particulates in the urban plumes, decreasing NO_2 and $PM_{2.5}$ concentration in downwind regions from Barcelona and Madrid (not shown).

SO_2 concentration in the Barcelona has a main harbour-related origin, therefore remains almost unaffected by the hybrid scenarios. Madrid SO_2 levels are more sensitive to traffic emissions. SO_2 peaks decrease by 2.7% in H1 and by 6.9% in H2.

NO_x emissions can locally act as an O_3 sink. Therefore, the introduction of hybrid cars, with the consequent NO_x emission reduction, may increase local O_3 concentrations depending on the photochemical regime (NO_x -VOCs ratio). This is the case of Barcelona, where H1 and H2 propitiate an increase in O_3 levels by 0.3 and 0.7%, respectively (Figure 2 for H2). Nevertheless, maximum O_3 concentration in the area, $108.5 \mu\text{g m}^{-3}$, remains below the EU target for human health protection (Dir 2002/3/CE). On the contrary, Madrid is affected by higher O_3 levels than Barcelona (8-hr average concentration of $127.0 \mu\text{g m}^{-3}$), but the effects of H1 and H2 are positive during the maximum O_3 production period (from 11.00 UTC to 15.00 UTC, Figure 2). Urban O_3 levels are reduced because of the lower amount of NO_x available to react. Reductions in O_3 peak in Madrid downtown by 0.9% in H1 and by 2.0% in H2 are observed. Moreover, the reduction on O_3 precursors in both urban areas has positive effects in downwind O_3 concentrations (not shown).

Figure 2 Differences in O_3 hourly average concentration between the H2 and the BC scenario at 04.00 UTC, 11.00 UTC, 15.00 UTC and 21.00 UTC of 18 June, for the Barcelona area (up) and the Madrid area (down) (see online version for colours)



4 Conclusions

Air quality models, such as WRF-ARW/HERMES/CMAQ, applied with high resolution, provide a valuable tool to assess the effects of air quality management strategies in urban areas. The air quality responses depend on the particularities of the target areas. Therefore, it is fundamental to consider the specific vehicle fleet composition, the contribution of all activity sectors to total emissions, as well as the topography and meteorological conditions of the studied areas. Moreover, these particularities influence the chemical regime of the airshed, set by the specific NO_x -VOCs ratio, which directly affects O_3 production response to emissions abatement strategies. The WRF-ARW/HERMES/CMAQ, used in this work, takes into consideration all those factors, showing that Barcelona, a typically coastal city, and Madrid, a continental one, produce different responses to analogous scenarios.

The use of hybrid cars would help in reducing NO_2 and $\text{PM}_{2.5}$ levels, especially in Madrid, which is very sensitive to changes in the car fleet (e.g., NO_2 and $\text{PM}_{2.5}$ daily concentrations are 35%/12% and 9%/2% lower for H2 in Madrid/Barcelona downtown).

The photochemical regime conditions the O₃ production response to the NO_x emissions abatement. NO_x reduction in Barcelona slightly raises O₃ concentration within the conurbation, producing a decrease in O₃ levels downwind. On the contrary, Madrid, characterised by higher O₃ levels, could benefit from policies addressed to reduce NO_x, such as H1 and H2.

The advantages from hybrid cars use also arise in terms of GHG. H1 and H2 reduce equivalent CO₂ emitted by on-road traffic from 2.6% in H1 in Barcelona to 11.3% in H2 in Madrid. Benefits should be confirmed over the whole life cycle of the vehicles, since only the use phase is considered here.

Acknowledgements

This work was funded by the project CICYT CGL2006-08903 of the Spanish Ministry of Education and Science and CALIOPE project (www.bsc.es/caliope) of the Spanish Ministry of the Environment. Simulations were carried out in the MareNostrum supercomputer of the Barcelona Supercomputing Center – Centro Nacional de Supercomputación.

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