A Health Impact Assessment of Traffic Restrictions during Madrid NO$_2$ Episode

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Abstract. One of the first decisions to improve the urban air quality during an air pollution episode is to apply traffic parking and access restrictions to try to decrease the amount of private vehicles driving in the city but their the effectiveness of the decisions must be evaluated before taking them. The health impact assessment tool of this work can help to the decision makers because it examines the citizen’s health impacts of the applied measurements. The modelling system has been applied for a NO$_2$ episode in Madrid city during December, 2016. The core of the system is the EMIMO-WRF/Chem air quality modeling system that simulates the air quality concentrations every grid cell of 1 km by 1 km and traffic emissions are calculated using data from a microscopic traffic model. The pollutant concentrations are inputs to the health impact module, which uses concentration–response functions. Two simulations were designed: “REAL” including traffic restrictions and “BAU” representing what would happen if no action were taken. The differences between the two simulations (BAU-REAL) give us the contribution of traffic restriction measures to improve the citizen’s health. The results show that the measures taken in this specific case were not sufficiently effective compared to the effort to reduce traffic.

1. Introduction
In the last years the link between air pollution and the health of citizens has been increasing in relevance in society and policy makers have started to develop strategies to try to minimise the health impacts on the health of the population [1]. Epidemiological studies have evidenced relations between daily concentrations of outdoor air pollution to adverse health effects. Air quality is linked to rising mortality and morbidity in European cities. In the last few years, various epidemiological studies have shown associations between an increase in daily concentrations of ozone (O$_3$), particulate matter (PM) and nitrogen dioxide (NO$_2$) and an elevation in mortality and/or hospital admissions in the following days, which are predominantly caused by respiratory and cardiovascular problems. These short-term health effects have been well documented in multi-centre time series studies [2] [3] [4] [5]. Also there are health impact assessment studies which have reported on the long-term effects of air pollution [6]. Traffic is one of the most important sources of emissions in the cities, so recent studies try to investigate the scientific evidence for linking traffic emissions to negative health effects. The levels of pollution in a city involve sophisticated physical and chemical processes that affect both formation and atmospheric transport. All these atmospheric processes are modeled by chemical transport models can be used to know the expected air pollution concentrations and to estimate health impacts of policies. This type of air quality models takes into account the emissions, chemistry and
transport of the pollutants. Health impact assessment (HIA) is a methodology for quantifying and evaluating the impact of air pollution mitigation efforts on human health [7, 8]. Mortality and morbidity are the most significant criteria for measuring the impact on the health of the people exposed to air pollution [9]. The general principle for a health impact assessment is to use information on how a change on air pollution concentrations is expected to modify the risk of disease or death of the citizens. The relation between exposure to pollutants and specific health outcomes is supported by the consistency of epidemiological findings across different studies. The most often used exposure indicators in HIAs have been particulate matter (PM) and nitrogen dioxide (NO\textsubscript{2}) mass concentration for the effects of short-term exposure on mortality [10]. The methodology proposed in this work allows knowing a priori the benefits in the health of the citizens that would be expected after applying measures to reduce the exposure of the population to air pollution, such as traffic restriction measures in a city. The effectiveness of the measures to be taken can be evaluated before applying them and decide which may be the best solution for the health of citizens. The information produced by this kind of tools help managers and policy agents better assess the impact of theirs interventions.

The main objective of this study is to estimate the expected health benefits associated with traffic restrictions that produces mobility problems for the citizens. The work focuses on to investigate associations between short-term exposure to air pollutants daily mortality and morbidity in Madrid (Spain) during an important NO\textsubscript{x} episode on December 2016. The paper presents an integrated air quality modelling and health impact assessment tool, which can be used to evaluate the effectivity of decisions to reduce pollutant concentrations from a health point of view. Madrid is a city of about 3.5 million inhabitants with a population density of 5208 inhabitants/km\textsuperscript{2}. The city is surrounded by 4 ring roads, the M30 being the limit of the Central District. The road network in the city centre is dense with fairly high traffic volumes. In 2016, the city of Madrid approved a new protocol for high levels of nitrogen dioxide pollution.

Four scenarios are considered depending on the pollution concentration of the different measuring stations within the city. The scenarios added new traffic restriction measures as the alert level increased. Traffic restriction measures range from a reduction of the speed limit on the M30 and road access to the city to a complete traffic restriction in the city centre. Intermediate scenarios also consider a downtown parking restriction and a partial traffic restriction depending on the license plate.

2. Material and Methods

In this section we described the air pollution episode and the air quality modelling system which was run to simulate the describe episode. Results from the air quality modelling system has used by the health impact assessment module.

2.1. Episode

We have selected a 5 days long NO\textsubscript{x} episode in Madrid. It was a very interesting episode because it was the first time and unique at the moment that the Madrid city apply a restriction of access to the city centre for private vehicles in order to reduce air pollution. In December 2016, the levels of NO\textsubscript{2} in Madrid were so high that authorities restricted access to the city centre for half of the cars based on whether the number plate was even or odd. The episode occurred from December 26 to 30, 2016, during which NO\textsubscript{2} hourly concentrations reached 200 µg/m\textsuperscript{3} in several monitoring stations. On Wednesday, December 28, the city temporarily banned parking in the city center by non-resident car owners and restricted speed limits on the main highway (M30) to 70 km/h instead of 90 km/h. Non-residents were prohibited from parking from 9:00 a.m. local time until 9:00 p.m. within the regulated parking areas.

The restriction of access to the city centre for private vehicles was applied on Thursday 29th December, only the odd number plates could access the inner area delimited by the M30 road (city centre). It was activated between 6:30 a.m. and 9:00 p.m. The measure was activated when the previous day's nitrogen dioxide levels in the atmosphere exceeded 180 µg/m\textsuperscript{3} and predictions did not predict the weather conditions needed to improve air quality the next day.
Two scenarios were developed to examine associations between traffic restrictions (changes of traffic volume) and pollutant concentrations expressed as health impacts (changes on mortality and morbidity). The first scenario has considered the real traffic situation of those days that included traffic restrictions on Wednesday and Thursday, this simulation has been called "REAL" and includes traffic restrictions on Wednesday 28 (parking) and Thursday 29 (access). In the second scenario, we have deactivated the restrictions on Wednesday and Thursday, considering that those two days traffic followed a pattern similar to Wednesday and Thursday of the previous week in which there were no restrictions. Therefore, in this simulation, the same configuration and input data has been maintained except that the traffic emissions are different considering a “typical” Wednesday and Thursday traffic day, so this simulation has been called "BAU" (Business As Usual). Then the only difference between the "REAL" and "BAU" simulation is that there are no traffic restrictions applied in the BAU. The BAU simulation represents what would have happened if no traffic restriction measures had been taken on Wednesday and Thursday. The difference between the two simulations (BAU-REAL), gives us the contribution of traffic restriction measures to reduce concentrations of pollutants in the city of Madrid. This contribution may be either positive (traffic restrictions have reduced concentrations) or negative (restrictions have not improved air quality, but have aggravated pollution by increasing concentrations relative to BAU simulation).

2.2. Air quality modelling system
The EMIMO-WRF/Chem air quality modeling system has been used for calculating the emissions and concentrations for the Madrid area with 1 km of spatial resolution. We have run air quality simulations using the Weather Research and Forecasting and Chem model with version 3.8.1 (WRF-Chem) [11] to study the NO2 episode in Madrid with a spatial resolution of 1 km by 1 km. The Carbon Bonding Mechanism version Z (CMBZ) is the atmospheric chemical mechanism [12] used for gas phase chemistry. Aerosol chemistry is represented by the Model for Simulating Interactions and Aerosol Chemistry (MOSAIC) [13]. Dry aerosol deposition is simulated following the approach [14] and the wet deposition approach follows [15] and [16]. Photolysis rates are obtained from the photolysis scheme in Fast-J [17]. We include aerosol-radiant feedback in our simulation. The Rapid Radiative Transfer Model (RRTM) scheme [18] is used to represent both short-wave and long-wave radiation. We use [19] and the parameterization of the Grell-3d cumulus set [20]. This configuration was tested in phase 2 of the International Air Quality Assessment Model Assessment Initiative (AQMEII) [21]. The initial and lateral boundary conditions of the meteorological variables, every six hours, were taken from the 0.5º grid data of the Global Forecasting System (GFS) operated by the National Meteorological Service of the United States (NWS). The chemical conditions of the lateral boundaries for mother domain were taken from profiles.

TNO-MACC-II emission inventory [22] was processed using the EMIMO emission model [23]. Emission were speciated [24] and spatially and temporally to 1 km grid taking into account surrogate files. Biogenic emissions were calculated from the Guenther online scheme in the model [25]. Emissions are calculated for all important sectors but the difference in emissions in the two analyzed scenarios (BAU and REAL) are only due to differences in traffic emission because the traffic activity is different between the two scenarios. Traffic emissions were modeled taking into account changes in traffic situation of the two traffic scenarios (BAU, REAL). Traffic emissions were carried out using the Tier 3 method described in the EMEP/EEA 2016 Air Pollutant Emissions Inventory Guide - Update Dec. 2016 (Passenger cars, light commercial trucks, heavy vehicles including buses and motorcycles) that include specific emission factors and cover different engine conditions, following the COPERT methodology. [26]. Vehicle categories are divided by fuel type, vehicle weight, age of the vehicle and cubic engine capacity, each of which has its specific emission factors, defined according to traffic speed.

2.2.1. Traffic model
The traffic intensities and vehicle speeds are calculated by a traffic model. The microscopic SUMO traffic simulation [27] can be used to determine the large-scale effects of traffic management measures. The first entry to SUMO is the road network, which describes the part of a map related to traffic, roads...
and intersections that simulated vehicles travel. The road network has been obtained from OpenStreetMap. The road network consists of more than 100,000 streets and road segments. After you have generated a network, the next step is to put the vehicles in the network. SUMO allows you to use traffic detector data to generate traffic demand.

The information collected from traffic sensors can be used to construct vehicle quantities and routes. First, random traffic is generated for the Madrid network and then the detectors have been used as calibrators, which have been used to adapt traffic demand to a certain set of measures. Hundreds of traffic simulations have been carried out for each day, with different route configurations and the best of each day has been chosen. For the calibration of the SUMO model, data from more than 3,000 traffic counters were available, of which 2/3 were used for calibration and 1/3 for evaluation. Traffic simulation underestimated traffic flow (vehicles/hour) by 7.8%. The adjustment obtained in the model calibration process shows a good convergence between the actual traffic flow data and the results obtained with the corresponding R^2 of 0.97. The composition of the fleet was collected from vehicle registration information in Madrid for December 2016. In addition to the vehicle and fuel type, classification also takes into account the vehicle's engine type, vehicle technology (age of vehicles). More than 600 vehicle categories power the emissions model. In December 2016, Madrid had 43,97972 vehicles registered, depending on the composition of the Madrid car fleet, more than half of the vehicles circulating with diesel (57.74%) and 27.06% of the total number of vehicles in Madrid are more than 15 years old. Diesel vehicles and their ages are two important factors in air pollution problems. Most vehicles are passenger cars (78.34%) with about 10% of motorcycles and motorcycles.

2.3. Health impact assessment

Using the health impact assessment module we calculate the estimated change in human mortality and morbidity between BAU scenario and the REAL emission scenarios for each of the 1 km grid cells. For our analysis of health impacts and potential benefits, we base on the US EPA’s Benefits Mapping and Analysis Program (BenMAP) [28]. Our inputs to health impact module include modeled pollutant concentrations (daily averaged concentrations of NO\_2 and PM\_2.5) and the linkages between daily concentrations of some air pollutants and the risk of harmful effects on human health. The relationship between exposure variables and their effects on health can be modelled using log-linear (Poisson) regression and this function is called the exposure-response (ER) function. If we derive this function we get the equation (1) that allows us to estimate the change in mortality or morbidity as a result of a change in the respective exposure variable.

\[ \Delta y = y_0 (e^{\beta \Delta C} - 1) \]

where \( y_0 \) is the baseline incidence rate of the studied health effect, \( \beta \) is a parameter that gives us an estimate of the effect of mortality and that has been obtained from epidemiological studies, \( \Delta C \) is the change of the exposure variable (BASE minus REAL) [29].

The concentration-response functions used by the health impact module are published in international epidemiological studies of high scientific acceptability. Changes in concentrations are used as input to the log-linear relationship between changes in concentrations and changes in mortality or morbidity. These are the relationships between the mean/maximum daily concentrations of air pollutants and the risk of hazardous health effects on the same day or on days after exposure at these levels, also taking into account the meteorological conditions on those days. The concentration-response functions used in our tool are based on the relative risks (RR) found in scientific studies that have found correlations between decreased concentrations of PM\_2.5 and NO\_2 and health benefits. They provide relationships between mortality or hospital admissions from cardiovascular and respiratory causes and levels of exposure to air pollutants. The used RR values are recommended by the HRAPIE project (Recommendations for concentration-response functions for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide).
For the mortality and morbidity analysis the following exposure-response (E-R) relationships from studies were used: mortality all causes, RR=1.0027 (95% CI 1.0016 – 1.0038) for 10 µg/m³ increase of daily maximum NO₂ concentration; hospital admissions respiratory diseases, RR=1.0015 (95% CI 0.9992 – 1.0038) for 10 µg/m³ increase of daily maximum NO₂ concentration; mortality all causes, RR=1.0123 (95% CI 1.0045 – 1.0201) for 10 µg/m³ increase of daily mean PM2.5 concentration; hospital admissions cardiovascular diseases, RR=1.0091 (95% CI 1.0017 – 1.0166) for 10 µg/m³ increase of daily mean PM2.5 concentration; hospital admissions respiratory diseases, RR=1.0190 (95% CI 0.9982 – 1.0402) for 10 µg/m³ increase of daily mean PM2.5 concentration. The concentration-response functions have associated an uncertainty so that in epidemiological studies the data are published with a 95% confidence interval.

3. Results

The text of your paper should be formatted as follows. Traffic simulations of SUMO REAL and BAU show that on day 28 (parking restrictions) traffic was reduced by 10.24%, on day 29 (access restrictions) traffic was reduced by 16%, 75% and on day 30 (parking restrictions) traffic was reduced by 6.06% If we focus on the city centre (within the M30) on day 28 the reduction only reached 4%, but on day 29 it reached 20%. It seems clear that access restriction measures were more effective in reducing traffic in the city centre, while parking restrictions for non-residents affected more vehicles from outside the centre of Madrid, as they could not park and used other modes of transport to arrive to the city. The main differences between REAL and BAU simulations can be observed on day 29, especially during the early hours of the day when people go to work. On the 30th, which was Friday parking restrictions did not reduce traffic almost in the afternoon, but on the 28th (Wednesday) the reduction is maintained throughout the whole day (morning and afternoon). If we now compare Madrid's emissions for these days, we can see that on day 28 parking restrictions reduce the emission of NOx to -8.27%, on day 29 -10.28% and on day 30 the reduction is only -1.77%.

In this study we analyse the health impact for the change in the daily concentrations of PM₂.₅ and NO₂ between the two scenarios REAL and BAU. The impact of air pollution on mortality and morbidity was quantified in relative terms of the number of attributable deaths or hospital admissions. Figure 1 shows the calculated decrease in mortalities due to changes in NO₂ between the REAL scenario (traffic restrictions) and the base case BAU (without traffic restrictions) for the days 29 (traffic access restriction) and 30 (traffic parking restriction) of December, 2016.

![Figure 1](image-url)

**Figure 1.** Daily mean change (%) of number of natural deaths admissions for all causes for days 29 (left) and 30 (right), December 2016. Madrid domain 1km spatial resolution.
Figure 1 shows important differences in the spatial distribution of the health impacts. On day 29, the health benefits of traffic access restrictions are located in the center and south-west part of Madrid city. On day 30, center and North West appear to experience the highest level of benefit. On both days the center is the area where traffic restrictions are applied because that is where the air quality problems are most severe, but the health impacts are following the predominant wind directions (not showed). The highest health impact is found primarily in Madrid city center, where road transport density is highest. The mortality reduction is more important on day 29 (-0.39 %) that day 30 (-0.14 %). These reductions will result in 0.007 per 100,000 inhabitants fewer premature deaths on day 29 and 0.003 per 100,000 inhabitants on day 30 from traffic restrictions using NO2 as indicator.

4. Conclusions
This study demonstrates a methodology for analyzing the health impacts attributable to traffic restrictions. The modelling tool includes an emission model (EMIMO), which includes the SUMO model for traffic and a transport and pollutant chemistry model (WRF/Chem). The modelling system has been used to simulate an episode of high NO2 concentrations in the city of Madrid during December 2016 with high spatial resolution (1 km). The modeling system has been used to assess the effectiveness of the traffic restriction measures (parking restrictions at points 28 and 30; access limitations at point 29) taken by the Madrid City Council to try to reduce NO2 concentrations. The evaluation was carried out by comparing the REAL simulation (with traffic restrictions) with a BAU simulation (without traffic restrictions).

The results of the modelling of the estimated health impacts show that there would be insignificant reductions in mortality/morbidity due to the application of the proposed traffic restrictions. Therefore, the measures applied were not effective since the benefits for the health of the citizens were marginal. Using the health impact assessment methodology it is estimated that that less than one case of natural mortality will be avoided from the introduction of the traffic restrictions measurements. The expected change of NO2 by banning traffic from the Madrid city center is not associated with a considerable mortality or morbidity decrease. These results show that the measures taken were not sufficiently effective compared to the effort to reduce traffic. Other measures should be evaluated with less impact on citizens and with a greater capacity to reduce air pollution (transformation of diesel fuel into electric vehicles, prohibition of driving vehicles over 15 years old, reduction of traffic speed, etc.).

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