IDENTIFYING TRAFFIC EMISSIONS HOTSPOTS FOR URBAN AIR QUALITY
INTERVENTIONS: THE CASE OF MADRID CITY

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ABSTRACT

Since road traffic is the main source of NOx in urban areas, most cities in the world have designed and implemented transport policies to reduce them. Studies have reported associations between different health issues and residential proximity to high traffic roads. However, the environmental impact analysis included in the appraisal of transport projects do not usually take into account the local dimension of the air pollution problem; i.e. the fact that air pollution emissions has more severe consequences in high populated areas than in low populated areas.

Urban traffic in Madrid accounts for 83% of total NOx emissions and the city consistently fails to meet air pollutant limits set by European legislation. A controversial air quality protocol for high nitrogen dioxide pollution has been adopted including, among other traffic-related measures, a total restriction of private vehicles in the central district in extreme situations. This paper proposes a network air quality diagnosis of Madrid City Centre taking into account both transport exhaust emissions and population exposure levels. For this purpose, a macroscopic traffic model was extended to have the capability to simulate emissions on the basis of average vehicle speeds and traffic intensity at the link level. Two indicators will be compared; gross NOx emissions and population-weighted NOx exposure levels. The use of the later indicator is proposed as a ready-to-use tool to measure population exposure levels, to identify network air quality hotspots and to design transport emissions reduction actions in urban environments.
1. INTRODUCTION

Road traffic is a major source of GHG emissions and the largest contributor to air pollutant emissions in urban environments. According to the United Nations Environmental program (1), urban air pollution is responsible for up to 1 million premature deaths and 1 million pre-native deaths each year and has an estimated cost of 2 percent of GDP in developed countries and 5 percent in developing countries. Rapid urbanization, higher motorization rates and an increase of trip lengths has resulted in increasing urban air pollution in major cities, especially in developing countries. Consequently, governments and institutions across the world are taking actions to tackle air pollution impact on population.

There is a growing need to evaluate transport policies and initiatives taking into account the variable spatial impact of emissions and population exposure to air pollutants. Transport emissions assessment frameworks have been primarily developed to evaluate climate change mitigation strategies (2-5) and they do not consider GHG and air pollutant emissions varying spatial impacts (6). While GHG emissions have minimal local effects, air pollutant emissions have a major local impact directly affecting human health. Climate change is a global problem; GHG emissions emitted in any part of the world contribute to global figures and affect global warming. However, air pollutants concentrations fall off rapidly with increasing distance from roads and therefore they tend to affect areas where they are emitted (7,8). People who live, work or frequent locations near major roads appear to have an increased incidence and severity of health problems associated with air pollution exposures (9).

Despite this fact, studies analyzing environmental impacts of transport interventions usually report emissions reductions without considering where they are achieved (see e.g. 10-12). The same occur with the indicators used in transport projects appraisal methodologies (13) which do not take into account the amount of population exposed to air pollution emissions.

This is of particular importance when evaluating the impact of traffic management strategies at city level, since transport interventions in a delimited area of the city could affect in different ways other areas (14). For example, Hoogendoorn et al. (15) evaluate the air quality impact of a dynamic speed limit on a freeway near Rotterdam. Results shows that air quality deteriorate slightly along the stretch with a maximum increase of NOx emissions of 3.7%. This increase would be more harmful if it was produced in an urban highway crossing a high populated area. However, using gross air quality indicators this nuance cannot be considered. Another example can be found in Valdes et al. (16) that assess the impact at urban level of green navigation systems (in-vehicle tools that provide routing recommendations based on calculation of minimum fuel consumption and real-time traffic situation). Results shows an overall 8% GHG emission reduction concentrated in motorways and highways while urban streets experiment an increase due to traffic transfer to shorter routes. Although the measure presents benefits for climate change mitigation, authors question the suitability of this measure for urban air quality improvement. To correctly address emissions impact at urban level, assessment methodologies and indicators should consider the local spatial dimension of air pollutants.

This paper proposes the systematic use of a macroscopic air quality diagnosis tool based on the combination of transport, emission and population density GIS models to ensure the integrity of transport emission assessments. The interaction of these three elements results in an insightful and ready-to-use tool for measuring population local exposure levels to air pollutants, identifying air quality hotspots requiring interventions and assessing different emission reduction alternatives not only in the area directly affected by the interventions but also at a broader city level.

The proposed methodology is applied to Madrid case, evaluating its Central District air quality. The paper compares the standard traffic emission indicator that only takes into account the exhaust emissions produced by transport activity with a newly created population weighted emission indicator that measures citizens’ exposure levels to pollutants. The latter is used to highlight areas with higher pollutant impacts and propose customized transport related air quality interventions.
2. METHODOLOGICAL FRAMEWORK

The traffic-related network air quality diagnosis is composed of different elements (see Figure 1). A macroscopic traffic model is extended using an emission model to have the capability to simulate emissions on the basis of average vehicle speeds and traffic intensity at the link level. The Traffic Emissions Indicator (TEI), which represents the direct exhaust emissions provided by the joint model, is compared with a Population Exposure Indicator (PEI) to better explain the spatial impacts of air pollutants. PEI weights the exhaust emissions provided by the joint model by the population density previously assigned to each link in the traffic model. Finally, the information is exported to a GIS model that maps the spatial distribution of emissions across the network. The information provided by both indicators is analyzed for two different traffic periods: peak and off-peak hours applying a red (more polluted) to green (less polluted) scale.

![Methodological Framework flow chart](image)

Next paragraphs present a state of the art review on the interaction of the traffic and emissions models discussing their strengths and weaknesses for this study. The following subsection describes the indicator’s calculation process reasoning the need for including population exposure to air pollutant emissions and its correlation with population density. The final subsection explains the conventions using for mapping the indicators.

### 2.1. Traffic and emissions model interaction

A macroscopic traffic model is used to obtain traffic intensities and average speeds at link level. These models describe traffic at a high level of aggregation as a flow without distinguishing its constituent parts and using attributes as flow-rate, density, and velocity (17). They represent the steady-state behavior of network systems which is representative of average system conditions in the

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**Figure 1** Methodological Framework flow chart
simulation period adopted. For a recent review of traffic simulation models, see (18). Despite they are often computationally tractable and scalable; they fail to account for vehicle-specific attributes or detailed traffic dynamics (19). This makes them suitable for large scale, network-wide applications, which is the case of this analysis.

The model will include an additional link feature: population density. Macroscopic traffic models usually consider population density at zone level; nevertheless, in order to be able to develop a high resolution PEI, the population density of the administrative area crossed by the link will be added using a GIS as a new link characteristic. The level of disaggregation of these areas will depend on the information available for the city under study. When a link crosses more than one administrative area, the average population density of these areas will be considered.

Recently, some transport demand models have been linked with emission models for inventory studies and analysis of the environmental impacts of transport initiatives, e.g. (20) combines a microsimulation traffic model with an emission model to evaluate traffic emissions and air quality in a dense neighborhood, (21) investigates the effectiveness to reduce emissions of traffic signal control and variable message sign using again a microscopic transport model and an emissions model, (22) uses both a macroscopic transport model and a macroscopic emission model to assess the environmental impact of speed limits changes in urban motorways. The same approach is used in (23) evaluating the impact of a plate restriction policy on emission reduction. Finally, (3) quantifies the impact of different ITS on CO2 using different combinations of macroscopic and microscopic transport and emission models. However, those emissions models are useful to understand the overall impact of emissions but have limitations for evaluating impacts at local level, since they do not take into account population exposure levels.

There are different types of emission models that can be used at macro level: (a) average speed models like COPERT, MOBILE or EMFAC where emission factors are function of mean average speed; (b) traffic situation models, like HBEFA or ARTEMIS, where EF are determined by descriptions of particular traffic situations; (c) traffic variable models, TEE, NEMO or Matzoros, where EF are defined by traffic flow variables such as average speed or traffic density; (d) cycle variable models, like MEASURE or VERSIT+, where EF are function of different cycle variables such as idle time or positive kinetic energy and; (e) modal emissions models like MOVES, PHEM or CMEM, where EF are produced via engine or vehicle operating models at the highest resolution (24,25). These models need inputs provided by macroscopic transport models (average speed and traffic situation models), by microscopic transport models (cycle variable and modal models) or by both macroscopic and microscopic transport models (traffic variable models) (24).

The methodology used for this analysis is based on the one used in the ICT-Emissions project (www.ict-emissions.eu), which developed a methodology to assess transport emissions at macro scale level linking the widespread macroscopic emissions model COPERT (www.emisia.com/copert), to a macroscopic traffic model. The emissions model has been enhanced in two ways: first, it includes algorithms suitable for working at hourly time periods and for links length of hundreds of meters. As an innovative approach to customized urban emission assessment, the methodology also includes a subroutine to distribute the data among the hundreds type of vehicles subdivided by fuel type, age etc. needed to estimate emissions more accurately (26). The COPERT expression of speed may lead to uncertainties as similar average speeds can be reached with different speed patterns in each link and, therefore it may have limitations when traffic becomes congested and when link length is too short (27). A more detailed discussion about the limitations of the methodology can be found in (27).

2.2. Traffic Emission Indicator

The TEI is calculated using emissions factors (EFs) provided by the emission model and activity information provided by the traffic model. Emissions models estimate hot emissions from traffic multiplying EFs by appropriate traffic activity data for different vehicle classes. EFs express the mass of pollutant emitted per unit distance (g km⁻¹), time (g s⁻¹) or mass of fuel burned (g kg⁻¹) and the
corresponding activity data should be expressed following these units (i.e. vehicle kilometers travelled
(VKT), total time spent in particular driving conditions (e.g. idling), or total fuel consumption) (24). Start emissions and evaporation are seldom addressed using this method (28) and therefore there are not considered.

COPERT provides a straightforward expression for hot EF based on two or three speed ranges by vehicle category and uses for the calculation average speeds provided by the traffic model. Traffic emissions are the result of multiplying VKT, which are function of traffic intensity and link length also provided by the traffic model, with the corresponding emission factors. This methodology has been further developed for calculating emissions at link level in urban environments (29). The following equation represents the TEI calculation for each link:

\[
\text{TEI}_{i,p,k} = \text{EF}_{i,p,k} \times I_{i,p} \times l_i
\]

Where:
- \( \text{EF} \) is the emission factor provided COPERT which is directly related to the speed in the link and to vehicle type, vehicle fuel, engine type and technology.
- \( i \) is the links of the network
- \( p \) is an average hour of the time period considered (in this case will be peak hours and off-peak hours)
- \( k \) is the type of emission considered, in this case will be NOx
- \( I \) is the traffic intensity (vehicles/ hour) in a specific link of the network for an average hour of the time period considered
- \( l \) is the link length (km)

### 2.3. Population Exposure Indicator (PEI)

Traditionally, traffic emissions indicators take into account only transport activity; however, as explained before there is a need of indicators that also reflect population exposure to air pollution. Atmosphere and climate, together with urban form and population and street densities, influence the extent to which citizens are exposed to air pollutants (30). Variables such as buildings height, wind speed and direction or temperature should be also considered to develop accurate population exposure indicators that take into account pollutants dispersion.

Nevertheless, population density by itself could be deemed as a relevant proxy to consider population exposure levels, since:

- (i) exposure to local emissions from transport is largely a function not only of the amount of traffic activity, but also of population densities near large transportation corridors and the number of people who regularly work along these roadsides (30),
- (ii) numerous studies analyze air pollutants exposure levels at certain distance from a high traffic road (31,32) and associations between health effects and residential proximity to high traffic roads (33) have usually been reported,
- (iii) complex high resolution urban air quality modelling have limitations and uncertainties that remain unsolved (34),
- (iv) self-assessment character and macroscopic scope of the air quality diagnosis tool under development, do not advise for a highly complex indicator
Bearing in mind these considerations, PEI is calculated weighting transport exhaust emissions with population density as follows:

\[ \text{PEI}_i = \text{TEI}_{i,p,k} * D_i \]

Where:
- \( \text{TEI} \) is the Traffic Emission Indicator calculated above
- \( i \) is the links of the network
- \( p \) is an average hour of the time period considered (in this case will be peak hours and off-peak hours)
- \( k \) is the type of emission considered, in this case will be NOx
- \( D \) is the population density of the area the link crosses over

Due to the use of population density, this indicator is mainly residential focused and only partially reflects exposure to air pollution excluding the effect on working or tourist population.

2.4. Mapping air pollution indicators

Finally, both indicators obtained at link level will be mapped using a geometrical interval classification scheme provided by the GIS tool. It creates class breaks based on class intervals that have a geometric series, to create the red to green color scale. The algorithm creates geometric intervals by minimizing the sum of squares of the number of elements in each class in order to ensure that class ranges have approximately the same number of values and that the change between intervals is fairly consistent. The use of this algorithm produces cartographically comprehensive maps balancing the stress of changes in middle and extreme values (35).

3. CASE STUDY BACKGROUND

Madrid is a city of some 3.5 million inhabitants with a population density of 5,208 inhabitants/square km. The city is surrounded by 4 ring motorways being the M30 the limit of the Central District, which will be the focus of our study. M30 is a 32.5 km long urban motorway, except for about 1.5 km in the northern area –Illustracion– where it becomes a signalized urban boulevard. Its Annual Average Daily Traffic (AADT) varies widely throughout its layout, but is about 200,000 vehicles on average. The west section has the highest traffic volumes. The south-west section of the M30 is a tunnel section with a speed limit of 70km/h while the rest of the ring-road has a speed limit of 90km/h (except for the Illustration area which is 50km/h). The tunnel condition has not been taken into account in the evaluation; nevertheless, the effect of the different speed limit will be analyzed. The M30 as a whole contributes to 23.1% of Madrid’s city NOx emissions from traffic.

Figure 2 shows the distribution of population densities across the Central District (left side) next to its road network structure (right side) classified by traffic volumes. The north-west zone, which is home of the main green area of Madrid (El Pardo), and Castellana’s (the city’s north-south main avenue) adjacent areas are the ones with less population density in the Central District due to its predominantly crowded business and tourist orientation. The north area is less populated than the city center and the south except for the area next to the M30-Illustracion. Road network in the city center is dense with fairly high traffic volumes while in the northern and southern areas the network is lighter but with several high traffic volumes roads; those ones connecting city center and the metropolitan area.
Road transport in the city of Madrid accounts for almost 70% of total NOx emissions (36). Despite the variety of strategies considered to reduce emissions, including promoting the use of less polluting cars and fuels, public transportation, walking and cycling, the implementation of parking restrictions, the pedestrianization of historic zones, the restriction of private vehicles in densely populated areas and, the renovation of the inner ring-road completed in 2007 (37); the suburbanization process, which implies longer trips and greater car dependency had led to exceed the air pollutant limits set by the European Legislation (36).

In 2016, the city of Madrid approved a new Protocol for high nitrogen dioxide pollution levels (38). Four scenarios are considered depending on the pollution concentration of different measurement stations within the city. The scenarios added new traffic restriction measures as the level of alert increases. The traffic restriction measures range from a speed limit reduction in the M30 and the road accesses to the city to a complete traffic restriction in the city center. Intermediate scenarios consider also a parking restriction in the city center and a partial restriction of the traffic depending on the license plate. The protocol also considers measures to foster public transportation.

This paper aims to identify air pollution network hotspots in Madrid city center; i.e., discover the links with higher air pollution and exposure levels, in order to propose additional and more specific traffic management interventions to alleviate them. Traffic management strategies have proved efficiency, cost-effectiveness and feasibility reducing transport emissions (39) and different studies analyzed the impact on the links affected by e.g. speed reduction (22), variable speed limits (14), green-wave signal coordination (40) and real time control of signalized intersection (41).
3.1. Madrid’s traffic and emissions model attributes

The macro traffic model covers the whole region of Madrid - an area of 8,026 square km and home to 6 million inhabitants. The affection of the traffic from border regions is negligible compared with the internal traffic of the region. Results will be focus on Madrid Central District which is limited by the M30 ring road which functions as a local distributor road and it was recently renovated to improve traffic performance, reduce traffic emissions and create new public spaces (37).

The model has been developed for two different traffic periods: morning peak hours and off-peak hours. These periods have been determined after a detailed traffic analysis the metropolitan area using data from more than 340 traffic counts.

2012 OD matrices have been obtained updating the 2004 OD matrices which were based on the 2004 Madrid’s Household Mobility Survey (the latest available at the moment) with data from traffic flow counters. For the peak hour period, information of 325 traffic counters was used (89 from urban roads, 193 from urban highways, regional highways and toll motorways and 43 from periurban roads). For the off-peak hour period, information of 277 traffic counts was used for (32 from urban roads, 192 from urban highways, regional highways and toll motorways and 43 from periurban roads).

Following the recommendations of the ICT-Emissions project (27), the model assigns separately light vehicles and heavy vehicles in order to deliver better emission estimations. OD matrices for the heavy vehicles have been calculated as a percentage of the original OD matrices, according to the percentage heavy vehicles represented in each of the time periods previously defined (8.6% for peak hour and 8% for off-peak hour). Subsequently, they have been multiplied for the adjustment factor for heavy vehicles in urban environments specified in the Highway Capacity Manual. Finally, these matrices have been calibrated using 2012 traffic counts with heavy vehicles traffic information for the two periods defined for this model.

The fit obtained in the calibration process of the model shows a good convergence between the real data of traffic flow and the results obtained from assigning the new peak-hour and off-peak hour matrices, with corresponding R² of 0.73 and 0.71.

The National Statistical Institute provides maps with population by census district. It was used to create the new link feature of the traffic model: population density. The information of more than 850 districts was combined with the model network using a GIS. For those links that crossed more than one census area, it has been calculated as an average of the population density of the areas crossed.

Finally, Madrid’s fleet has been classified following COPERT guidelines. Besides the type of vehicle and fuel, the classification also considers the vehicle type of engine and vehicle technology (from conventional to Euro VI). The information about the fleet composition was provided by the Directorate-General of Traffic and enhanced with information about the circulating fleet provided by Madrid City Council. 292 vehicle categories feed the emission model, here and due to the limited length required by TRB papers, we only present the vehicle type classification and fuel the fuel type for the major class. Madrid’s fleet includes 0.5 percent of mopeds and motorcycles, 88 percent of cars (of which 26.3 are gasoline, 61.4 percent diesel and 0.3 percent others), 8.5 percent of light duty vehicles, 2 percent of heavy duty vehicles and 1 percent of buses.

4. IDENTIFICATION OF MADRID’S AIR QUALITY HOTSPOTS

Results are presented in two maps for an average hour of the peak (Figure 3) and off-peak (Figure 4) periods. TEI and PEI have been compared at link level for the two traffic periods under study. Red links represent very high values of the indicators while green links represent very low values. Three intermediate values are also considered: orange for high, yellow for moderate and light green for low values. The PEI is the indicator used for the identification of hotspots; nevertheless, the information provided by the TEI is also valuable and used to complete the analysis.

Consistency in the results of the peak and off-peak scenarios emphasizes the impact of air pollution, especially for the links with high values of the PEI, since it means more hours of high
exposure levels. The results for the two traffic scenarios are not directly comparable because of the
classification used for mapping the indicators; the highest and lowest value of the indicators for the
two scenarios are different, and therefore, same colors represent different indicator values in the two
scenarios. For example, we cannot state that a red link for the PEI off-peak scenario is more polluted
than the same yellow link for the peak scenario. Nevertheless, we can maintain that the same red link
in the two mentioned scenarios is subject of an urgent intervention, since it means that this link has the
highest levels of the indicator in the two scenarios. Independently of the specific values of the
indicator, this implies that the exposure levels next to this road link are at its highest levels during the
whole day.

FIGURE 3 TEI and PEI values for the peak hours scenario

At first sight, results for the TEI and PEI are quite different which is especially notorious for
the peak hour scenario. In the TEI map, the red is the predominant color for the M30 (except for the
south west area which is orange), its access roads and the Castellana while in City Center green
colored links are the most comment ones. This means that from the point of view of exhaust emissions,
not exposure, the whole ring-road and Castellana should be considered air quality hotspots.

Nevertheless, analyzing the PEI results different conclusions arise which changes potential
intervention priorities. M30 ring-road exposure levels range from low values in the north-west section
to high values in the Ilustracion Avenue and the east section. Exposure values along the Castellana are
predominant moderate due to the residential focus of the current state of the tool. Western accesses to
the M30 present low exposure values compared to TEI results; while southern and eastern accesses
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maintain high values in both indicators. Finally, City Center’s turn its low TEI values to moderate PEI values.

The comparison of the two indicators allows for identification of air quality particularities:

- **Road links with high values of TEI and moderate or low values of PEI**
  
  These areas highlight the relevance of the PEI indicator, since it reduces the weight of high congested links in low populated areas. For example, the north-west area of the Central District shows very high levels of TEI both for peak and off-peak hours. Nevertheless, since this is a low populated area, PEI values are definitively lower. Using the TEI for the air quality diagnosis could lead to a misinterpretation of the relative importance of these links in Madrid’s Central District network air quality and impact on population wellbeing. These should not been considered as air quality hotspots, i.e. they do not need urgent intervention.

- **Road links with low values of TEI and moderate to high values of PEI**
  
  A good example of these areas is the City Center, especially at the west side of Castellana. This high populated residential area shows low values of TEI which are consequence of moderate to low traffic intensities and low speed ranges. However, the PEI map shows moderate values, reflecting higher levels of exposure. Results are consistent for the two traffic periods analyzed. Exposure levels show that this area would need an early intervention. Taking into account its urban form and traffic conditions (high density,
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predominant narrow roads and low speed limits), traffic restriction policies, such as the
extension of the residential priority areas that include traffic calming measures, would be
recommended.

- Road links with high values of TEI and PEI
  This means that exhaust emissions are very high and occurs in high populated zones.
  This condition makes these areas subject of urgent action. This is the case of the east section of
  the M30 ring road. Results maps show a red color for TEI and PEI in both traffic scenarios,
  meaning that high levels of air pollution emission and exposure occurs for the most part of the
day. This section has the highest traffic volumes in the city center and belongs to the part of
the M30 with a 90km/h speed limit. A straightforward reduction strategy could be lowering the
speed limit in the section to 70km/h, as it is in the south-west section which presents slightly
lower TEI values. Since the M30 structures the traffic from the periphery towards the Central
District, traffic restriction policies are not recommended. Nevertheless, other traffic
management strategies could be also considered such as variable speed limits.

5. CONCLUSIONS, POLICY RECOMMENDATIONS AND FUTURE RESEARCH
The widespread use of this tool will improve decision making with regards to transport air pollution by
enhancing current standard methodologies with insights about the impact of relative variation of
pollutant exposure to population across urban road networks. This methodology is easy-to-implement
when limited information is available since the additional population density data points are easily
accessible and in most cases off-the-shelf. It will be very practical for evaluating policy making and
investment decisions for cities around the world, both in developed and emerging countries.

The tool allows for a quick identification of the links with the highest levels of pollution
impact on city inhabitants, making future transport interventions beneficial for larger shares of overall
urban population. Besides, the macroscopic scope of the methodology will allow evaluating the impact
of transport emission reduction strategies not only in the area directly affected by the designed
intervention, but also in the rest of the network.

Therefore, including the PEI in transport projects appraisal methodologies, such as cost-benefit
analysis or multicriteria analysis, will improve their environmental evaluation effectiveness since it
incorporates the impact of air pollution population exposure and contributes to maximizing the
marginal benefits to overall society of each transport decision and investment.

Future research will investigate the way to weight the PEI indicator by other socio-
demographic factors such as working population density, and hospitals, schools and parks locations.

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7. REFERENCES


