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Modelling the fuel consumption and pollutant emissions of the urban bus fleet of the city of Madrid

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ABSTRACT

An integrated methodology to estimate the emissions of automotive vehicles is proposed in this work, with application to the vehicle fleet of Madrid Municipal Transport Company. The fleet composed of 2000 buses and 20 different types, operating 167 routes providing a service to the whole of the city of Madrid, with 3.165 million inhabitants and over 404 million passengers in the year 2014. The results of the model have been validated by calculating the fuel consumption and comparing them with the actual consumption, as this is the only data that can be used by taking estimations that are external to the model. The errors found were small and acceptable. Thus, the approach of this work has two features: it uses both measured transport activity data and vehicle activity data with specific emissions models for the calculation of consumption and emissions for a bus fleet based on an urban area; it also has two outcomes: it provides useful information for understanding where and how air pollutants are originated and it is a tool for designing intervention measures.

1. Introduction

Various methodologies have been developed to estimate the emissions of automotive vehicles in a more or less comprehensive manner. In an initial approach they can be classified into two groups; an approach that is oriented to evaluating emissions in large geographical areas, countries, regions or others, taking into account the vehicle stock moving in these areas. It usually comprises a wide variety according to weight, the technology incorporated, particularly the powertrain, the fuels used and other variables that affect consumption and emissions. This kind of methodology that looks at the problem on a "macro" scale takes account of various infrastructures and does so at speeds, which among other variables, depend on the type of road, the terrain and the vehicles themselves. Estimations of this kind cannot be very precise and are based on the average values of variables of influence such as speed of the journeys of each group of vehicles according to the degree to which the available data can be broken down. Together with these weighted variables the emission factors of each vehicle group are also needed, usually from data bases that require the underlying emission factors to be adapted to local traffic situations and fleet composition, to reduce uncertainty in the calculations. If this is not done the results will give approximate values with a questionable error level. However, they may be acceptable for certain purposes such as emission inventories.

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The second approach is oriented to models that have been developed to provide more precise knowledge about the emissions of smaller vehicle stocks or vehicle fleets operating in easily identifiable environments. This provides the opportunity to obtain real data on vehicle emissions as well as on their operating conditions by using on-board measuring equipment. These are what are called "micro or local" scale models.

In both these micro and macro scale models two basic problem must be resolved: how to determine the emission factors of each of the vehicle types making up the fleet while taking account of the fuels corresponding to the driving cycles. The difference is that with the micro model experimental data can be obtained regarding the emissions and specific bus operation cycle of each route that each vehicle type is used for. Then, by taking both data, more exact estimates can be made. If the number of vehicles in the fleet and the types as well as the number of routes, is high, it is costly to experimentally determine each type of route. Therefore, the field work must be simplified by reducing it to samples of vehicles and routes that are chosen by applying the right statistical methods.

As pointed out previously, the "macro" models usually require data on the average driving speed of the different vehicle groups, such as the European model COPERT (Ntziachristos et al., 2009) and the MOBILE (MOBILE, MOVES, Naranjo et al., 2009; Ntziachristos et al., 2009; Ntziachristos et al., 2008; Philpot, 1993) - EMFAC models (Gammariello and Long, 1996; Hirschmann et al., 2010; Huang et al., 2013; IVE model, Ivani, 2007; Jiménez et al., 2011; Knörr et al., 2006; Kouridis et al., 2010; Kousoulidou et al., 2009; López et al., 2008a; López et al., 2008b; López et al., 2009; MEET, 1999; Mellios and Samaras, 2007; MOBILE, MOVES, Naranjo et al., 2009; Ntziachristos et al., 2009; Ntziachristos et al., 2008; Philpot, 1993; Proost et al., 2006; Rapone et al., 2007; Samaras et al., 2005; Smit et al., 2010; The CMEM model, The EMFAC model) developed in the USA, or information on the traffic conditions, such as HBEFA (HBEFA) and ARTEMIS (ARTEMIS, 2008), both European. The former group is named 'Average-speed' models while the latter is 'Traffic-situation' models in Smit et al. (2010).

HBEFA (HBEFA) has three important features: firstly it is the most widely used database for emission quantifications of road transport in Europe; secondly it is based on European emission measurement data of vehicles collected within the ERMES group (The PHEM model) and thirdly it is also the emission factor database for European models such as COPERT (Ntziachristos et al., 2009) and TREMOVE (Herbruggen and Logghe, 2005), as well as for national models (e.g. TREMOD in Germany (Knörr et al., 2006) or HBEFA Expert Version in Switzerland and Sweden (de Haan and Keller, 2004; EMEP/CORINAIR Emission Inventory Guidebook, 2008; EMEP/CORINAIR5, Environmental Protection Agency, 2002; FOEN, 2010). The Emission Factors (EFs) for different traffic situations are calculated by the Passenger Car and Heavy-Duty Vehicle Emission Model (PHEM) The PHEM model. Although HBEFA (HBEFA) is focused on emission factors, it also comprises tools for emission calculations at the city/regional and national level. COPERT (Ntziachristos et al., 2009), TREMOD (Knörr et al., 2006) and TREMOVE (Ntziachristos et al., 2008; Philpot, 1993; Proost et al., 2006; Rapone et al., 2007; Samaras et al., 2005; Smit et al., 2010; The CMEM model, The EMFAC model, The EMPA model, HBEFA, Smit, 2013; The PHEM model, Tong et al., 2000; Herbruggen and Logghe, 2005) are mainly used for emission inventories and policy scenarios for specific regions. Other examples of wider spatial resolution used as macro emission inventory models outside Europe are: MOVES (MOVES) as a road transport emission calculation tool in the USA, or EMFAC (Gammariello and Long, 1996) a trip-based macro emission inventory model specifically used in California and IVE (IVE model) an emission inventory model developed by the University of California Riverside, which has mainly been used to simulate vehicle emissions of air pollutants in developing countries.

Together with the above, models have been developed to provide more precise knowledge about the emissions of smaller vehicle stocks or vehicle fleets operating in easily identifiable environments. This provides the opportunity to obtain real data on vehicle emissions as well as on their operating conditions. The EMPA (The EMPA model) and PHEM (The PHEM model) models in Europe, PΔP in Australia (Smit, 2013) or CMEM (The CMEM model) and MOVES (MOVES) in the United States supply EFs measured on a test bench or roller bed in driving-type cycles under controlled laboratory conditions for urban environments. Integrating the factors of the PHEM (The PHEM model) and PΔP (Smit, 2013) with those available in the HBEFA (HBEFA) and COPERT (Ntziachristos et al., 2009) models has enabled estimations to be made on a regional and national level as reflected in developments such as TREMOD/HBEFA in Switzerland and Germany or HBEFA-COPERT or COPERT&PΔP in Australia. PHEM and CMEM are classified as 'Modal' models in the work of Smit et al. (2010).

It is clear that whatever the approach, the results from the models depend on how representative the EFs are: an adjusted description of vehicle type selected and driver cycles tested.

This is why, apart from the in-laboratory campaigns to find emission factors, measurements are also taken in real-world conditions such as tunnels, remote sensing, on-road and on-board measurements, all of which are possible due to the use of Portable Emission Measurement Systems (PEMS) (Huang et al., 2013; IVE model, Ivani, 2007; Jiménez et al., 2011; Knörr et al., 2006; Kouridis et al., 2010; Kousoulidou et al., 2009; López et al., 2008a).

The basic characteristics of emissions measurements in real cycles are:

- Real emissions are provided in the absence of a standard test cycle, and therefore it is an unrepeatable experiment.
- It includes all sources of variability, such as environmental conditions and traffic, driver behaviour, or highly transitory operation or the variable operating conditions of the vehicles.

A recent review of the strengths and weaknesses of the methods to find EFs can be consulted in Franco et al. (2013).

One mixed approach (micro and macro scale) can be seen in Corvalán et al. (2002). The authors developed an emission model in the city of Santiago de Chile, by taking the emission data factors of the light-duty gasoline route vehicles by exper-