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Application of supply chain considerations to estimate urban freight emissions

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A B S T R A C T

The estimation of pollutant emissions related to urban freight activities suffers from the same difficulty faced when trying to estimate the characteristics of individual urban freight routes or demand parameters. The great variety of urban freight practices forces to attain this objective only through strong hypotheses and simplifications. We propose here a methodology based on the generic characterization of urban freight routes, identifying the main features of each route type and the type of commercial activities typically served by each one of them. This results in an estimation of the overall urban freight route patterns in a city, which in turn can be used to derive aggregate emission indicators. The methodology is applied to the city of Seville, in the South of Spain, showing promising results.

1. Introduction

The analysis of urban freight deliveries is by definition a complex task, due to the multi-component systems involved and the diverse interactions between them (Dablanc, 2007). This is why the provision of urban freight solutions for a city should always start with an exhaustive view of the current scenario, from all the possible angles, given that the efficient management of urban freight transport should contribute to the economic, social and environmental sustainability of the area. This work focuses on one of those angles, namely the impact of urban freight on the environment, related to the use of fossil fuel vehicles, the subsequent energy consumption and the resulting levels of pollutant emissions.

The emissions of air pollutants and GHG are the most relevant indicators of urban transport sustainability (Haghshenas and Vaziri, 2012; Shiau and Liu, 2013). The estimation of urban-traffic-related emissions is a thoroughly covered research field, which has resulted in multiple alternative models, which differ in the type of input and output data they work with. Following Smit et al. (2010), these emission models may fall into one of these categories:

1. ‘Average-speed’ models, where emission factors are a function of the mean travelling speed. COPERT (Ekström et al., 2004; Ntziachristos et al., 2009), MOBILE (US EPA, 1993) or EMFAC (CARB, 1996) follow this approach.
2. ‘Traffic-situation’ models, where emission factors are determined by descriptions of a particular traffic situations (e.g. ‘stop-and-go-driving’, ‘freeflow motorway driving’), like HBEFA (Colberg et al., 2005) or ARTEMIS (André et al., 2009).
3. ‘Traffic-variable’ models, where emission factors are defined by traffic flow variables such as average speed, traffic density or queue length. TEE (Negrenti, 1996) or the Matzoros model (Matzoros and Van Vliet, 1992) are examples of this category.
4. ‘Cycle-variable’ models, in which emission factors are a function of various driving cycle variables (e.g. idle time, average speed, positive kinetic energy) at high resolution (seconds to minutes). These models typically require detailed information on vehicle movements (e.g. instantaneous data on speed, acceleration and road gradient). This is the approach chosen by MEASURE (Guensler et al., 1998) or VERSIT+ (Smit et al., 2007).
5. ‘Modal’ models, where emission factors are produced via engine or vehicle operating models at the highest resolution (one to several seconds), like PHEM (Hirschmann et al., 2010), CMEM (Barth et al., 1996) or VT-Micro (Rakha et al., 2004). They require similar inputs to cycle-variable models.

Other models focus on very specific emission factors, like McCormick et al. (2000) measuring emissions from different types of trucks and buses idling at high altitude, or take a more geographical approach, like Waygood et al. (2013) evaluating aggregate transport-related emissions for zones in a 5×5 km grid at 149 European cities. Other models are described and compared in Gokhale and Khare (2004), Smit et al. (2010) and Demir et al. (2011).

In order to estimate emission levels, emission models have to be

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combined with vehicle flow estimations, either macro- or microscopic, depending on the characteristics of the emission model. 'Average-speed', 'traffic situation' and 'traffic variable' models require macroscopic inputs, which makes them suitable for coupling with flow estimation models. Segalou et al. (2004), for instance, calibrate vehicle flows using data from specific surveys carried out in three French cities, and the subsequent emissions model is based on the COPERT guidelines, taking into account meteorological and topographical aspects. Kanaroglou and Buliung (2008) combine a vehicle emissions model with a set of OD matrices by vehicle type, and use a traffic assignment algorithm to obtain emission levels derived from vehicle flows, while Muñuzuri et al. (2010) apply a similar approach to estimate the ecological footprint for urban freight deliveries, basing their analysis on the estimation of freight vehicle flows, average speeds and stops. Also, Nuzzolo et al. (2014) combine a shopping model with a shop restocking model to estimate flows of freight quantities and vehicles in a city, then feeding those flows to the COPERT model to quantify the emissions associated both to freight deliveries and shopping trips. An interesting approach is the one followed by Andriankaja et al. (2015), comparing different urban delivery fleet configurations, including own and rented fleets, vehicle sharing and logistics pooling systems, and then measuring the subsequent impacts by life cycle impact assessment. Filippi et al. (2010) describe a methodology based on macroscopic simulation to estimate flows of commodities and vehicles, and to evaluate their impacts in terms of travel times and generalized transport costs, and also of air pollution and energy consumption, with emissions then calculated according to COPERT.

On the other hand, microscopic traffic models seek to determine the driving patterns of individual vehicles or routes, in order to feed them to 'traffic-variable', 'cycle-variable' or 'modal' emission models. As an example, Hwang and Ouyang (2015) plan urban freight routes taking into account a total travel cost composed of three components, including the total delivery time, emissions, and a penalty for late or early arrival. They follow a similar approach to Akçelik and Besley (2003), who consider operating costs, fuel consumption, and emissions in the route planning process, which is in turn affected by vehicle parameters and traffic and road parameters. Velickovic et al. (2014) combine traffic counts with roadside interviews to calibrate a shortest travel distance traffic assignment technique, used to calculate average trip lengths, while Figliozzi (2011), on the other hand, applies a more precise routing approach, combining vehicle routing techniques with an emissions model to estimate urban freight CO_2 emissions in Portland, Oregon. However, this last formulation is only applicable to determine the emissions caused by the delivery fleet of a single carrier, and requires precise knowledge about the location of the carrier's depot and of the customers' locations and demands.

Additionally, an intermediate approach, also widely present in the literature, consists of estimating average characteristics of individual routes, thus segmenting the overall urban freight delivery activity into different configurations. For example, Pluvinet et al. (2012) apply a GPS-based data collection method for urban freight route characterization using a Smartphone application, thereafter defining the characteristics of the overall routes as well as the environmental impacts linked with the categories of roads using the CMEM model. A similar approach is followed by Wygonik and Goodchild (2011), estimating the effect on cost and emissions of different delivery route configurations, defined by their time windows, customer density and fleet characteristics. The classification of urban freight routes has by itself generated much attention over the last few years, with examples like Cherrett et al. (2012), Nuzzolo et al. (2016) or Cattaruzza et al. (2017). Vaghi and Percoco (2011) incorporate the economic evaluation of emissions and the effect of city logistics policies, by means of a methodology based on the estimation of emissions for individual routes, determined by GIS software. Along this line, Russo and Comi (2016) review the environmental effect of several city logistics policies, obtaining the estimation of monthly reduction of air pollutants from different surveys, and Arvidsson et al. (2013) discuss the operative and environmental effects of measures incorporated by urban freight carriers. Zanni and Bristow (2010) analyse the effect of several policies to reduce urban freight emission levels, and obtain their emissions data from the 2008 London Freight Data Report (Transport for London, 2008), which identifies automatic traffic counts as its main source of information. Finally, Rizet et al. (2012) compare the transport activities and their associated energy consumption and CO_2 emissions for four types of supply chains covering a range of products in Belgium, France and UK, taking into account not only urban distribution, but also interurban and international transport, storage and shopping trips.

Our analysis, presented here, follows this third approach, seeking to determine the average characteristics of the different types of delivery routes operating in a city. The originality of the methodology lies in the consideration of supply chain characteristics, like vehicle type, delivery frequency, route length or number of stops, to segment delivery routes. Then these average values are used as inputs by a hybrid emissions models, which takes into account 'average-speed' correlations (similar to the COPERT approach) for typical driving conditions, but also incorporates 'cycle-variable' concepts to assess the effect of supply chain configurations (in terms of the number of stops in the route or the duration of those stops, for example) or urban design (in terms of traffic light stops). This approach results in a real decision-making tool, as it allows regulators and practitioners to assess to what extent the modification of specific urban delivery practices would have an effect on emission levels in the city. The remainder of the paper is as follows: Section 2 describes the analysis framework, while Section 3 provides the characteristics of the typical urban delivery vehicles and Section 4 shows the emission correlations for those vehicles under different operating conditions. Section 5 contains the details of the different delivery routes that can be found in a city for the main types of supply chains existing, and Section 6 applies the model to a case study. Finally, Section 7 concludes.

2. Framework description

According to Demir et al. (2014), the main factors affecting fuel consumption (and subsequently emissions) in commercial vehicle operations are distance covered, speed, road gradient, congestion, driver behaviour, engine type, and payload. However, the availability of detailed data concerning these factors when calculations need to cover an entire city is unfeasible. Some of the information may be available for individual vehicles, but the rest can only be estimated as average values for typical routes or for the entire network. We have thus grouped the relevant indicators in three categories, depending on whether they are specific to the vehicle, to the route or to the entire network:

- **Network indicators**: these are indicators that correspond to the network configuration, and are therefore independent of the operation of supply chains and specific delivery routes. They include the geometrical characteristics of the network (gradients, free-flow speeds, traffic lights) and its operational conditions (congestion, which has an effect on actual speed). The exact knowledge of these indicators for all the delivery vehicles operating in a city is impossible, but average values can be estimated for gradients, speed, or traffic light effects.
- **Route indicators**: the second set of indicators is related to the different delivery routes taking place in the city. Again, the acquisition of specific data for each individual route is not feasible, but average values can be estimated depending on the design of the supply chains operating in the city. This involves in the first place estimating the frequency with which the routes are operated (daily, weekly, twice a week, etc.), and also the average distance covered by the vehicle operating each route and the average number of customers visited by each vehicle, taking into account the average time spent at each customer for delivery.