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A framework for estimating traffic emissions: The development of Passenger Car Emission Unit

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ABSTRACT

In this study, we develop a Passenger Car Emission Unit (PCEU) framework for estimating traffic emissions. The idea is analogous to the use of Passenger Car Unit (PCU) for modeling the congestion effect of different vehicle types. In this approach, we integrate emission modeling and cost evaluation. Different emissions, typically speed-dependent, are integrated as an overall cost via their corresponding external costs. We then develop a normalization procedure to obtain a general trend that is applicable for all vehicle types, which is used to derive a standard cost curve. Different vehicle types with different emission standards are then mapped to this standard cost curve through their corresponding PCEUs that are to be calibrated. Once the standard cost curve and PCEUs have been calibrated, to estimate the overall cost of emission for a particular vehicle, we only need to multiply the corresponding PCEU of that vehicle type to the standard cost curve. We apply this PCEU approach to Hong Kong and obtain promising results. Compared with the results obtained by the full-blown emission model COPERT, the approach achieves high accuracy but obviates tedious inputs typically required for emission estimation.

Introduction

Traffic-related emissions are a major source of air pollution, especially in urban areas. For instance, in 2011 in Hong Kong, traffic emissions accounted for 67% of total Carbon Monoxide (CO), 29% of total Nitrogen Oxides (NO_X), 23% of total hydrocarbon (HC), and 19% of Respirable Suspended Particulates (RSP). Also, continuous growth in travel demand leads to increasing fuel consumption from road transport, a major source of carbon dioxide (CO_2), and damages in natural ecosystems through the greenhouse effect (Environmental Protection Department, 2011).

Due to their severe impact to the environment and human health, traffic emissions have been an important topic in recent transport studies. One area of research focuses on the relationship between vehicle emissions and traffic characteristics, such as speed, engine power and acceleration (Ahn et al., 2002; Corvalán et al., 2002; Int Panis et al., 2006; Mak and Hung, 2008). Most of these studies are based on specific emission models. Smit et al. (2010) classified them into five categories, namely, average-speed models, traffic-situation models, traffic-variable models, cycle-variable models, and modal models, with increasing complexity and more input variables, and stated that average-speed models are frequently used: MOBILE (18%), COPERT (16%) and EMFAC (9%). Fontes et al. (2015) divided emission models into instantaneous and average speed models, and listed up-to-date studies that include integration of traffic simulation models and emission models, most of

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which are average speed models. Csikós and Varga (2012) separated emission models into two categories: microscopic and macroscopic models. Microscopic models use detailed traffic data (e.g. speed, acceleration and idle time) to estimate instantaneous emission rates (e.g. CMEM, VERSIT+). Macroscopic models (COPERT, MOBILE) adopt aggregated traffic variables (average speed and Vehicle Kilometers Traveled) for large-scale estimation. Another area of research centers on the economic valuation of traffic emissions (Deng, 2006; Matthews et al., 2001; Mayeres et al., 1996; Santos et al., 2010). Evaluating the external cost of vehicle emissions is complicated and subject to uncertainty, and the estimates vary substantially (Maibach et al., 2008). Moreover, existing traffic control strategies typically evaluate vehicle emissions (CO, HC and NO_X) separately, without considering them collectively as a whole. Therefore, the effectiveness of different control strategies cannot be compared efficiently.

In general, modeling traffic emissions is an elaborate process, as it entails not only traffic characteristics (such as speed and acceleration), but also emission standards of the technology (such as EURO III, IV, and V) and vehicle types (e.g. passenger car, trucks, etc. with different engine sizes). This detailed process renders such modeling effort laborious, often encouraging studies to ignore certain parameters, which may severely hamper the accuracy of the results. To strike a balance between capturing the essence of the modeling effort and yet obviating the tedious process of coding the detailed parameters mentioned above, in this paper, we propose a framework for estimating Passenger Car Emission Unit (PCEU), analogous to the approach of Passenger Car Unit (PCU) which is commonly used for modeling the congestion effect of different vehicle types for traffic capacity or delay analysis.

Recent studies show that microscopic estimation of traffic emissions requires detailed vehicle trajectory data, for example, evaluating traffic signal strategies on emissions (e.g., Zhu et al., 2013). However, for planning studies, using average speed models for emissions estimation is common (Csikós and Varga, 2012). In this study, we also adopt an average speed model for developing the PCEU framework. With the average speed model, the key of the analysis here is to develop a standard curve expressed as a function of speed to represent the general trend of overall costs for different vehicle types. Subsequently, vehicles with different vehicle types and emission standards are mapped to this standard curve via their corresponding PCEU factors. Once the standard curve and PCEU factors are established, we simply need to multiply the PCEU factors to the standard curve to obtain the corresponding emission rates at different speeds for different vehicle types with different emission standards.

The framework of PCEU can notably simplify the process of estimating total traffic emissions without dropping parameters that are deemed important for macroscopic estimation. With the PCEU framework, the total external cost of emissions will be estimated by speeds and traffic volumes of different vehicle types; such information can be collected by standard traffic surveys. Moreover, the proposed framework can be extended for evaluating traffic control strategies targeted at reducing traffic emissions.

The outline of this paper is as follows: Section 'Methodology' describes the methodology for developing the PCEU framework, which can be divided into four parts: 1. Emission model; 2. Emission evaluation; 3. Cost Normalization; 4. PCEU determination. Section 'Numerical studies' first examines the performance of the proposed framework via simulations of different road types in Hong Kong, then conducts extensive simulations of the approach under different scenarios with different distributions of vehicle types and emission standards to investigate the applicability of the framework, and finally analyzes the influence of variations in external costs on the PCEU framework. Section 'Concluding remarks' provides some concluding remarks and future research directions.

Methodology

Among average-speed models, we choose COPERT 4 as the underlying emission model as it covers major air pollutants as well as greenhouse gases for a wide range of vehicle types. COPERT (Computer Programme to calculate Emissions from Road Transport) is a software to calculate vehicle emissions from road transport, widely adopted by European countries and regions to estimate road-side emissions and report national emission inventories. It is closely linked to modeling tools to inform policymaking around the world, such as GAINS, TREMOVE and TERM. Also, it is widely used in the academia (Corvalán et al., 2002; Ganguly and Broderick, 2008; Gokhale, 2012). To better illustrate the methodology, we select Hong Kong as the testbed whose emission standards follow the Euro standards, the same as those in COPERT. Although COPERT and Hong Kong are used to illustrate the approach, the methodology developed here is general, and can be adapted for other cities.

Fig. 1 schematically shows the PCEU framework, which can be divided into four modules: emission model, emission valuation, cost normalization and PCEU determination. In the first module, seven common vehicle types in Hong Kong are represented by their counterparts in COPERT, and each vehicle type has four emission standards. And six types of vehicle emissions (i.e. CO, NO_X, HC, $PM_{2.5}$, SO_2, and CO_2) for twenty-eight kinds of vehicles, i.e. seven vehicle types times four emission standards, are considered in the proposed framework. The relationships between different emission types and average speeds are plotted according to COPERT, denoted as emission factors, i.e. $EF_{i,j,m}(v)$, where m represents emission type, i for vehicle type, j for Euro emission standard, and v for mean traffic speed. Then, in emission valuation, the six vehicle emissions are combined into one monetary cost using the concept of external cost, with one external cost curve developed for each of the 28 vehicle kinds. Let's denote this cost curve depicting the relationship between monetary external cost and speed as $C_{i,j}(v)$. In cost normalization, these 28 cost curves, expressed as functions of speed, are normalized into the same scale