Transportation Research Part D 44 (2016) 78–92

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

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

Xuekai Cen, Hong K. Lo*, Lu Li

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

ARTICLE INFO

Article history:
Available online 1 March 2016

Keywords:
Emissions
External costs
PCEU framework
Standard cost curve

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

---

* Corresponding author.
E-mail address: cehklo@ust.hk (H.K. Lo).

http://dx.doi.org/10.1016/j.trd.2016.02.013
1361-9209/

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

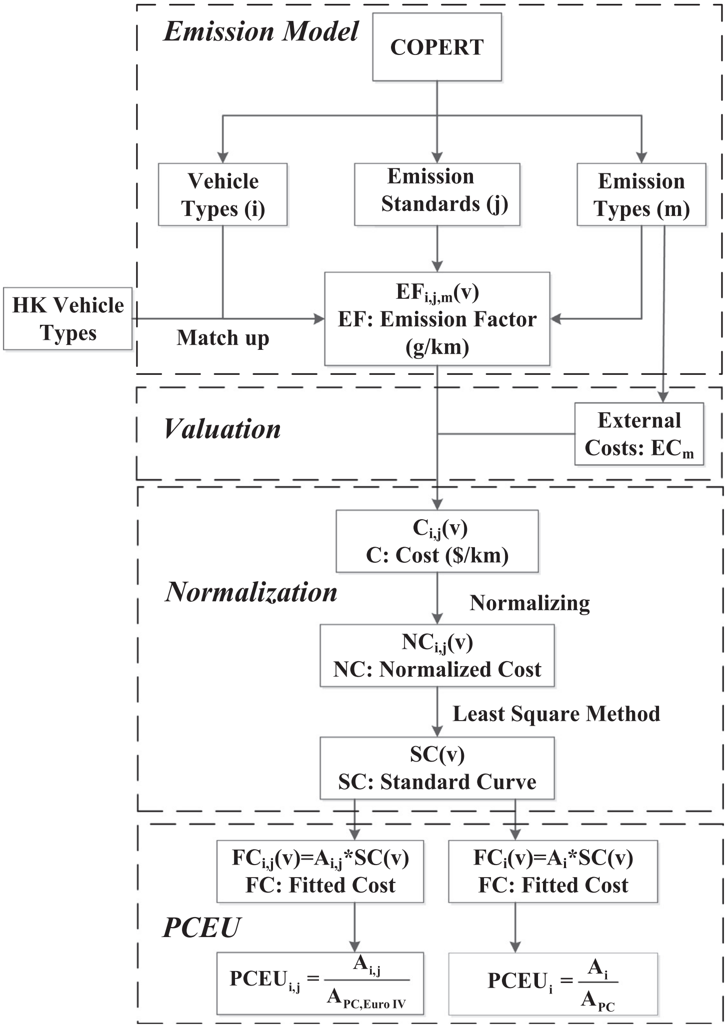

Fig. 1. The schematic of the methodology flowchart.

and subsequently calibrated or regressed into one standard curve, as will be discussed in detail later. In PCEU determination, two Schemes of the PCEU framework are developed based on the standard curve, Scheme 1 in terms of vehicle types and emission standards, and Scheme 2 in terms of vehicle types only. The following subsections will describe the four modules step by step.

Emission model

The methodology for COPERT to calculate emissions is described in the EEA Guidebook (Ntziachristos and Samaras, 2014). In this study, we directly refer to the EEA Guidebook, rather than relying on COPERT, for calculating emissions. In the EEA Guidebook, emissions estimation can be divided into three modes: hot emissions, cold-start emissions and non-exhaust emissions. In this study, only hot emissions are considered, a common practice of applying COPERT for emission estimation, as in Ahn et al. (2002), El-Shawarby et al. (2005), and Csikós and Varga (2012). In fact, the EEA Guidebook depicts the methodology of cold-start emissions estimation only for passenger car and light duty vehicle. In Appendix A, we compare cold-start and hot emissions for passenger car, and the results justify the use of hot emissions for passenger car. As for the estimation of non-exhaust emissions, the EEA Guidebook cautioned that the estimates are non-statistically significant based on a small set of measured data; and it does not cover buses. Due to the use of the EEA Guidebook as the underlying emission model, this study inherits its limitations. Nevertheless, if the methodology for calculating cold-start emissions or non-exhaust emissions for all vehicle types is available in the future version of the EEA Guidebook, the PCEU framework should and can cover them in future studies.

Pollutants

According to the Hong Kong Emission Inventory Report (Environmental Protection Department, 2011), five regulated emissions (CO, NO_X, HC, $PM_{2.5}$ and SO_2) and one greenhouse gas (GHG) CO_2 are included in the proposed framework.

Vehicle types

COPERT 4 covers over 240 vehicle categories, varied by vehicles types, fuel types, emission standards, engine capacity and maximum load. It is tedious and perhaps unnecessary for planning studies to calculate emissions for all vehicle categories. Moreover, including too many detailed vehicle categories will render its application impractical given that corresponding data about the proportions of these various vehicle categories in the traffic stream need to be identified and collected. Therefore, vehicle types should be chosen judiciously, which should cover the majority of vehicles in the traffic stream, and perhaps to the extent possible, match the vehicle categories for licensing purposes, which would facilitate ease of applications in the future. In Hong Kong, licensed vehicles are categorized into private cars, goods vehicles, motor cycles, taxis and buses (Transport Department, 2012). All vehicle types except motor-cycles are covered in our study, and are matched with their counterparts in COPERT 4, as shown in Table 1.

The categorization of vehicles in Hong Kong is not exactly the same as that in COPERT. Consequently, some assumptions are made during the matching process. First, medium (5.5t–24t) and heavy (>24t) goods vehicles in Hong Kong are matched with two subcategories (respectively 14t–20t and >32t) of heavy-duty vehicles in COPERT. Second, there is no double-deck bus in COPERT, which is represented by urban bus articulated with similar characteristics. Third, motor-cycles, consist less than 3% of the traffic in Hong Kong, are excluded due to their relatively small addition to total traffic emissions. Even though this vehicle categorization is defined based on the Hong Kong situation, the selected vehicle types are rather universal and can be adopted for other cities.

Emission standards

Emission standards are an important instrument in controlling vehicle emissions as the technology advances. For example, European Union has set up European emission standards (Euro standards) to regulate the acceptable limits of exhaust emissions for new vehicles sold in its member states, and it progressively introduces increasingly stringent standards to reduce vehicle emissions. Currently, Euro standards consist of Pre Euro, Euro I, Euro II, Euro IV and Euro V, and are widely adopted around the world including Hong Kong. Euro II to Euro V for all vehicle types are covered in this study for the following reasons. First, the proportion of pre-Euro and Euro I vehicles in HK is less than 9% (Environmental Protection Department, 2012). Also, Pre-Euro and Euro I vehicles are close to their legislated maximum lifespan of 17 years, and will be phased out in the near future, to be replaced by new vehicles with newer standards. Similar to vehicle types, emission standards selected here are mainly for illustration of the proposed framework. The methodology here is not restricted to specific vehicle types and emission standards in Hong Kong.

Emissions estimation

The core of emission estimation lies in the emission factors, which portray the emission performance of specific vehicle types, expressed as the mass of pollutant emitted per unit distance (g/km). In the proposed methodology, we make use of emission factors expressed as a function of speed according to generic inputs such as emission type, vehicle type and emission standard, leaving out factors that are context specific, such as road gradient or tons or number of passengers carried. For fuel types in Hong Kong, private cars use gasoline, taxi and a small proportion of light buses use LPG (Liquefied Petroleum Gas, treated as gasoline in COPERT), and others all use diesel. Therefore, it is safe to assume that PC uses gasoline and other vehicle types use diesel, i.e. taxi is treated as PC using gasoline and light buses use diesel. Road gradient is set to be zero. Also, to ensure consistency between different emission factors, the range of speed is taken to be 10–75 km/h.

In COPERT, CO, NOX, HC and $PM_{2.5}$ are calculated directly by their corresponding emission factors, while SO_2 and CO_2 are fuel-dependent emissions, calculated indirectly by emission factors of fuel consumption. For CO_2, it is supposed that the carbon contained in the fuel is fully oxidized through combustion, and hence can be determined by:

$$EF_{i,j,\mathrm{CO}_2}(v) = \frac{44.011}{12.011 + 1.008 * r_{H:C}} * EF_{i,j,Fuel}(v) \tag{1}$$

Table 1

Corresponding vehicle types between Hong Kong and COPERT.

Vehicle types in HK (t: tonne)	Counterparts in COPERT	Abbreviation
Taxi, private car	Passenger car	PC
Light goods vehicle (<5.5t)	Light-duty vehicle (<3.5t)	LGV
Medium goods vehicle (5.5–24t)	Heavy-duty vehicle (14–20t)	MGV
Heavy goods vehicle (>24t)	Heavy-duty vehicle(>32t)	HGV
Public and private light bus	Urban bus midi (<15t)	L bus
Single-deck bus	Urban bus (15–18t)	SD bus
Double-deck bus	Urban bus articulated (>18t)	DD bus

where $r_{H:C}$ is the ratio of oxygen to carbon atoms, 1.8 for gasoline and 2.0 for diesel. For SO_2, it is assumed that all the sulfur in the fuel is completely transformed to SO_2, which can be calculated by

$$EF_{i,j,SO_2}(v) = 2 * k_s * EF_{i,j,Fuel}(v) \tag{2}$$

where k_s is the sulfur content of gasoline and diesel, which is 0.001% in Hong Kong according to the Euro V fuel standard.

Overall, six emission types, seven vehicle types each with four emission standards are considered, i.e. a total of 168 emission factors are included in our study. It is cumbersome to directly work with so many emission factors; thus how to combine these emission factors into a single representative cost is imperative, which is discussed in emission valuation.

Emission valuation

To combine the six emission types collectively into a single representative cost, the concept of external cost is introduced. The external costs of vehicle emissions quantify the environmental impacts of traffic-related air pollutants incurred to society. In this paper, we choose the handbook from IMPACT (Maibach et al., 2008) as a main reference for estimating external costs, supplemented by the external cost of CO from (Matthews et al., 2001), as shown in Table 2.

The external costs of NOx, HC, SO_2 and $PM_{2.5}$ are assumed to be the same as those in the United Kingdom, and that of CO_2 comes from its central value in 2010; all of which are exchanged from Euro to US Dollar (USD). The external cost of CO refers to its mean value in Matthews et al. (2001). The largest difference between the aforementioned studies comes from the external cost of $PM_{2.5}$. Matthews et al. (2001) admitted that the external cost of $PM_{2.5}$ was an underestimate of its true value. Note that the external costs of CO, NO_X, HC, $PM_{2.5}$ and SO_2 are due to their impact on human health, while the external cost of CO_2 results from its impact on global warming; it is a common practice to add these two kinds of costs together to form one monetary cost (Lemp and Kockelman, 2008). The sensitivity or variations of external costs will be studied in the subsection of numerical studies.

Then, the speed-dependent emission factors of six emission types are combined by multiplying their corresponding external costs:

$$C_{i,j}(v) = \sum_m EF_{i,j,m}(v) * EC_m \tag{3}$$

where EC_m denotes the external cost of emission type m, and $C_{i,j}(v)$ denotes the speed-dependent overall cost of vehicle type i and emission standard j. Summarily, the 168 items of $EF_{i,j,m}$ are reduced to 28 items of $C_{i,j}(v)$ through their external costs, which greatly simplifies the procedure of data analysis in the next step for quantifying the impacts of different vehicle emissions for different vehicle types and emission standards.

Figs. 2 and 3 show the overall costs and respective emission costs, respectively, for PC Euro IV (PC4) and DD bus Euro II (DD bus2). For convenience, PC4 stands for PC, Euro IV, etc. Comparing the overall costs between them, the cost of DD bus2, i.e., $C_{DDbus2}(v)$, is at least twenty times larger than$C_{PC4}(v)$. Though differing in magnitude, the two speed-dependent overall costs decrease with speed, and roughly follow the same trend, such as percentage change over speed. This observation leads to the need for cost normalization.

Also, another observation is that the cost of CO_2 contributes to almost all the overall cost of PC4, whereas more than half of the overall cost of DD bus2 comes from $PM_{2.5}$. The reason is that diesel vehicles emit more $PM_{2.5}$ than gasoline vehicles, thus having higher proportions of $PM_{2.5}$ cost. Generally, CO_2 is the determining factor in overall emission costs for PC using gasoline, whereas $PM_{2.5}$, CO_2 and sometimes NO_X together constituting almost all the external costs in diesel vehicle types. The result is consistent with the trend that $PM_{2.5}$ and CO_2 become the main target pollutants for managing traffic emissions (Bigazzi and Figliozzi, 2012).

Cost normalization

After combining emission factors into overall cost curves for different vehicle types and emission standards, there still remain 28 cost curves to be analyzed, as shown in Fig. 4. A natural idea is to directly conduct regression analysis on all the cost curves. As observed in Fig. 4, the cost curves vary a lot with vehicle type i and emission standard j, which renders direct application of regression analysis inaccurate, as shown in Fig. 5; note the large discrepancy between the direct regression curve, and original cost curves of PC4, MGV3, DD bus2.

However, it can be observed that the trend, or percentage change of different cost curves, denoted as $\frac{dC_{i,j}(v)}{C_{i,j}(v)}$ are roughly the same, and that $C_{i,j}(v)$ can be expressed in percentage change. Thus, a normalization procedure is proposed to rescale all the costs into the same range (0, 1), in order to obtain a standard curve that represents percentage change of all cost curves

Table 2
External costs of different vehicle emissions.

Emissions	NO_X	$PM_{2.5}$	CO	CO_2	SO_2	HC
USD/kg	3.613	360.487	0.520	0.023	6.115	1.019

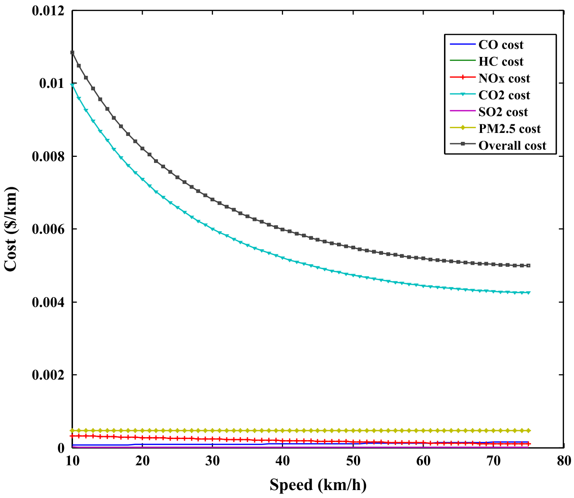

Fig. 2. Emission costs of PC, Euro IV.

through regression analysis. During the normalization procedure, the percentage changes of different cost curves are preserved.

$$NC_{i,j}(v) = \frac{C_{i,j}(v)}{\|C_{i,j}(v)\|} \tag{4}$$

$$\|C_{i,j}(v)\| = \sqrt{\sum_{v} [C_{i,j}(v)]^2}, \quad v = 10, 11, \ldots, 75 \tag{5}$$

$NC_{i,j}(v)$ is the normalized cost of vehicle type i and emission standard j at speed v, and $\|C_{i,j}(v)\|$ is the normalizing denominator of $C_{i,j}(v)$, as defined in (5). To obtain the value of $\|C_{i,j}(v)\|$, $C_{i,j}(v)$ is treated as a vector of 66 elements, i.e. average speed v is set to be integer. In this sense, $\|C_{i,j}(v)\|$ is the norm of vector $C_{i,j}(v)$, computed as the square root of the sum of the squared elements of the vector. After normalization, all $NC_{i,j}(v)$s falls within (0, 1).

In this process, the percentage change of $C_{i,j}(v)$ keeps intact because:

$$\frac{dC_{i,j}(v)}{C_{i,j}(v)} = \frac{d\|C_{i,j}(v)\| * NC_{i,j}(v)}{\|C_{i,j}(v)\| * NC_{i,j}(v)} = \frac{dNC_{i,j}(v)}{NC_{i,j}(v)} \tag{6}$$

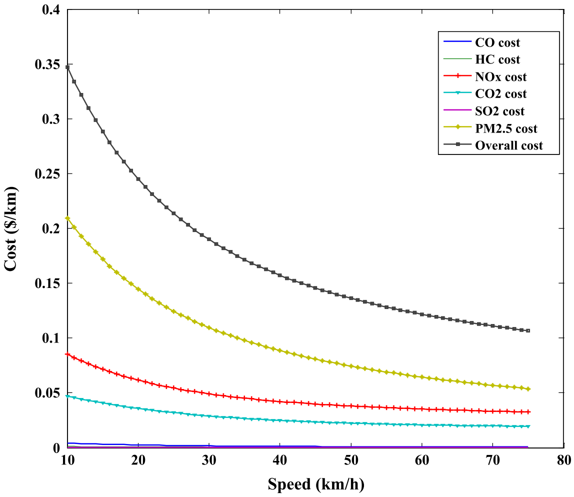

Fig. 3. Emission costs of DD bus, Euro II.

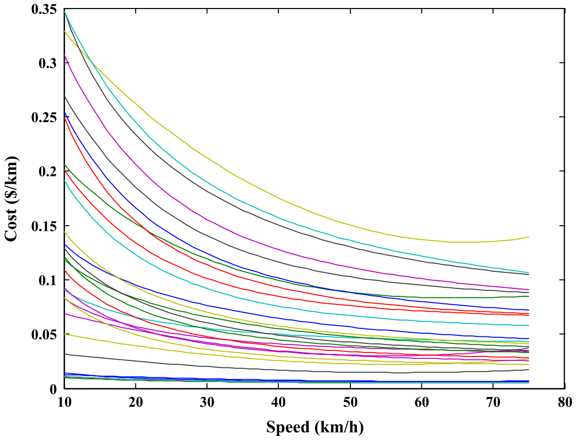

Fig. 4. Speed-dependent cost curves.

where $dC_{i,j}(v)$ is the differential of $C_{i,j}(v)$, and $\frac{dC_{i,j}(v)}{C_{i,j}(v)}$ is the percentage change of $C_{i,j}(v)$.

Comparing the cost curves before and after normalization from Figs. 4 and 6, the normalized costs are restricted to a much tighter range, making it possible to derive a general trend for different cost curves. Fig. 6 illustrates that all the normalized costs roughly follow the same trend over speed, which greatly facilitates the development of a standard cost curve covering different vehicle types and emission standards.

The standard curve is obtained by regressing all the normalized costs over speed. Several general forms of nonlinear expressions (e.g., exponential, power and polynomial) are compared in Table 3 and the exponential form is chosen because of its highest R-squared value and lowest root-mean-square error (RMSE). Note that though the power form has fewer coefficients, it is abandoned because the cost rapidly increases after speed exceeds 75 km/h, which does not fit the data well.

The standard cost curve is given as follows:

$$SC(v) = 0.2714 * \exp(-0.06408 * v) + 0.08542 * \exp(-0.0009178 * v) \tag{7}$$

where $SC(v)$ is the standard cost curve expressed the normalized cost over speed v, ranging from 10 km/h to 75 km/h.

PCEU determination

To make the PCEU framework convenient for use, two levels of simplification are further taken into account: Scheme 1 considers both vehicle types and emission standards; Scheme 2 considers only vehicle types (without explicitly capturing emission standards). With the standard cost curve developed in Section 'Cost Normalization' as the base, we then calibrate the multiplier, or PCEU, associated with each vehicle type and emission standard to best fit the original total cost curve of that specific vehicle type and emission standard. In Scheme 1, each multiplier PCEU is calibrated specific to the vehicle type and emission standard based on regression. Let's denote this multiplier as $A_{i,j}$. Fig. 7 shows that the fitted cost curves match

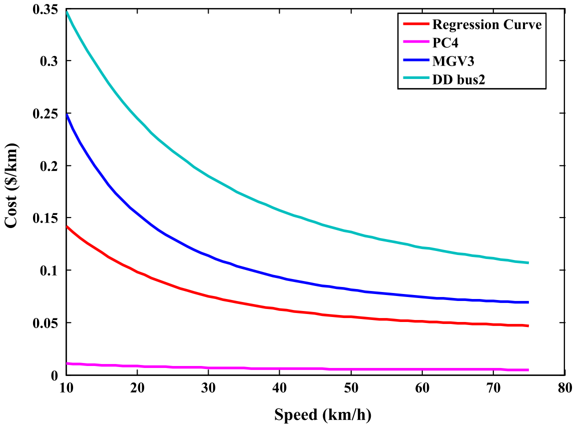

Fig. 5. Effect of direct regression curve.

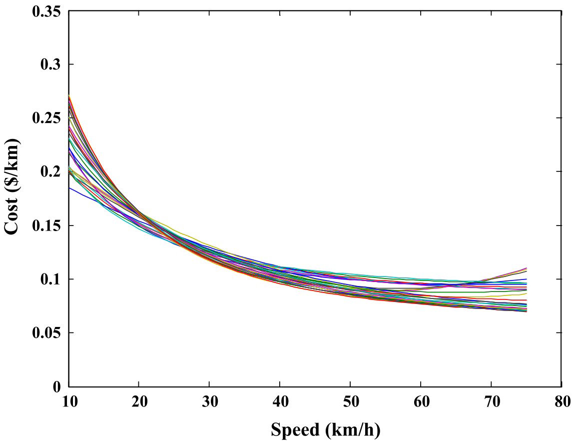

Fig. 6. Normalized speed-dependent cost curves.

closely the original cost curves of corresponding vehicle types and emission standards. Comparing Figs. 5 and 7, the results of direct regression versus regression after cost normalization, the improvement is significant.

In Scheme 2, the multiplier PCEU is calibrated only specific to the vehicle type based on regression. Let's denote this multiplier as A_i. Since emission standard is not explicitly captured in the regression, naturally the result will not be as good. But then since less information is used, without needing to collect information on the distribution of emission standards of the traffic stream, it will be easier to apply, at the expense of losing some accuracy. The question is whether savings in data collection justify the accuracy loss. To answer this question, we will conduct the analysis via simulation, as detailed later.

To be consistent with the PCU framework, we arbitrarily set the PCEU of PC4 in Scheme 1 to be one, i.e., $PCEU_{PC,4} = 1$, whereby the PCEUs of all the other vehicles are set relative to. Likewise, for Scheme 2, we arbitrarily set the PCEU of PC to be one, i.e. $PCEU_{pc} = 1$ whereby the PCEUs of all the other vehicles are set relative to, as expressed below:

Scheme 1:

$$FC_{i,j}(v) = A_{i,j} * SC(v) \tag{8}$$

$$PCEU_{i,j} = \frac{A_{i,j}}{A_{PC,4}} \tag{9}$$

$$FC_{i,j}(v) = PCEU_{i,j} * A_{PC,4} * SC(v) \tag{10}$$

$$FC_{i,j}(v) = PCEU_{i,j} * SUC_1(v) \tag{11}$$

Scheme 2:

$$FC_i(v) = A_i * SC(v) \tag{12}$$

$$PCEU_i = \frac{A_i}{A_{PC}} \tag{13}$$

$$FC_i(v) = PCEU_i * A_{PC} * SC(v) \tag{14}$$

$$FC_i(v) = PCEU_i * SUC_2(v) \tag{15}$$

where $SC(v)$ comes from (7), and $FC_{i,j}(v)$ is the fitted cost of vehicle type i and emission standard j; $A_{i,j}$ is the corresponding coefficient with respect to vehicle type i and emission standard j. $PCEU_{i,j}$ is the PCEU factor of vehicle type i and emission standard j. The terms in Scheme 2 are similar to those in Scheme 1. For the coefficients of the bases, $A_{PC,4}$ is equal to

Table 3
Comparison of different regressed forms of standard curve.

Form	Exponential	4th polynomial	Cubic	Power
Coefficient no.	4	5	4	3
R-squared	0.9535	0.9535	0.9514	0.9502
RMSE	0.0085	0.0085	0.0087	0.0088

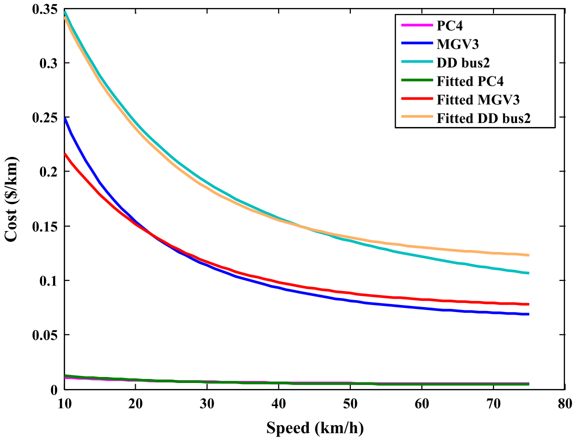

Fig. 7. Fitted cost curves in PCEU Framework.

0.0539 and A_{PC} is equal to 0.0557. For convenience, two standard unit curves are defined for Scheme 1 and Scheme 2, respectively: $SUC_1(v) = 0.0539SC(v)$ and $SUC_2(v) = 0.0557SC(v)$. And the fitted costs in the two Schemes can be calculated by multiplying the respective PCEU to standard unit curves as shown in (11) and (15).

The PCEUs of both Schemes are shown in Table 4. Their large variations manifest that vehicle types and emission standards have large impacts on vehicle emissions, particularly for vehicle types, e.g. $PCEU_{HDV}$ and $PCEU_{DDbus}$ are over seventeen times larger than $PCEU_{PC}$. Also, as emission technologies advance, all vehicles with newer standards have lower overall cost of emissions, except that $PCEU_{PC,4}$ is slightly higher than $PCEU_{PC,3}$. The reason is that from Euro III to Euro IV, $PM_{2.5}$ drops substantially for all vehicle types, while CO_2 for PC increases slightly due to higher fuel consumption and CO_2 is the dominant factor in the overall cost of PC. In Scheme 2 of the PCEU framework, it is assumed that the distribution of emission standards in each vehicle type is even, and the PCEU factors can be obtained directly by regression analysis, using the least square method. Intuitively, a Weighted Average Method (WAM) can be adopted to obtain PCEU factors of Scheme 2 based on Scheme 1, given that the distribution of emission standards in each vehicle type is known, expressed as:

$$Ave_i = \sum_j PCEU_{i,j} * r_{i,j} \tag{16}$$

$$PCEU_i = \frac{Ave_i}{Ave_{PC}} \tag{17}$$

Note that $PCEU_{PC}$ is set to 1 with the introduction of Ave_i, and the coefficient of the base becomes $A_{PC,4} * Ave_{PC}$, instead of A_{PC}. Assuming $r_{i,j}$ is equal to 0.25, i.e. evenly distributed in emission standards, the PCEU factors of Scheme 2 can be easily calculated from Scheme 1 using WAM. The two resultant PCEU factors of Scheme 2 are quite similar, as shown in Table 4. Therefore, the weighted average method can be applied to determine the PCEU factors of Scheme 2 in the road network, where the distribution of emission standards is roughly known. Actually, if the distribution of emission standards is deterministic, i.e. $r_{i,j}$ is given, Scheme 2 using WAM will have the same performance as Scheme 1.

Another observation worth noting is the large discrepancy between PCU (Transport Department, 2001) and PCEU, as presented in Table 4. For example, the PCEU of HGV is six times larger than its PCU factor. Generally, PCU, routinely in planning studies, is a simplifying way of converting heterogeneous vehicle types into passenger cars for modeling their effects on congestion and delay. Analogously, PCEU here is a way of simplifying the analysis of traffic flow on emissions; both are road transport externalities in transport economics (Santos et al., 2010). The PCEU approach allows for a convenient way of evaluating traffic management strategies for emissions reduction under heterogeneous traffic, which will improve past efforts that either assumed homogeneous traffic or estimated total emissions by multiplying traffic volumes to emissions of a single vehicle class (e.g., Coelho et al., 2005; Zhang et al., 2010).

Summary of methodology

To sum up, the core of the proposed methodology is to develop a simple PCEU framework from assimilating massive information from emission models. Taking Hong Kong as an example, 168 emission factors of six emission types, seven vehicle types and four emission standards are selected from COPERT 4. In emission valuation, 168 emission factors are combined into 28 cost curves via their external costs. In cost normalization, 28 cost curves are further reduced to a single standard cost curve, which preserves the general trend of all cost curves. In PCEU determination, using regression analysis, the whole PCEU framework is constructed by a standard cost curve and corresponding multipliers for specific vehicle types and emission

Table 4
PCEU factors for Scheme 1 and Scheme 2.

	PC	LGV	MGV	HGV	L bus	SD bus	DD bus
Scheme 1							
Euro II	1.2	6.3	17.7	30.0	15.6	21.2	27.9
Euro III	0.9	4.6	17.7	26.9	14.2	18.9	23.5
Euro IV	1.0	3.0	8.3	11.1	6.5	8.5	10.7
Euro V	1.0	1.3	7.0	9.6	5.7	7.5	9.3
Scheme 2							
Regression	1.0	3.6	12.3	18.8	10.2	13.6	17.3
WAM	1.0	3.7	12.4	18.9	10.2	13.7	17.4
PCU	1	1.5	2.0	2.5	1.5	3.0	3.0

standards, i.e. the tedious process of estimating vehicle emissions from emission model is simplified to making use of a standard cost curve and PCEU.

Numerical studies

In the previous section, the proposed methodology demonstrates the significant simplification of estimating traffic emissions from emission models due to the PCEU framework. The key question to address, of course, is whether the PCEU framework is accurate enough. In this section, two schemes of the PCEU framework are applied in estimating traffic emissions, and compared with the benchmark calculation by using the full-blown COPERT 4.

Simulations of three scenarios in Hong Kong

To validate the proposed framework, simulations are conducted on different road types in Hong Kong. Lantau Link, Cross Harbor Tunnel, and overall situation in Hong Kong are chosen as three scenarios (i.e. the distributions of different vehicle types follow those in Lantau Link, Cross Harbor Tunnel and Hong Kong). In each scenario, traffic emissions estimated from the two Schemes are compared with those calculated with COPERT 4 which are taken as the ground truth. To ensure comparability, several assumptions are made:

1. All the road lengths are 1 km long.
2. All scenarios follow the current overall distribution of emission standards of Hong Kong vehicles.
3. Actual traffic volumes of different vehicle types are represented by their corresponding proportions to total traffic volumes.
4. The speeds of all types of vehicles are assumed to be identical in all scenarios, ranging from 10 km/h to 75 km/h.

The distribution of vehicle types and emission standards in Hong Kong is shown in Table 5 (Environmental Protection Department, 2012), and the traffic volumes of different vehicle types are shown in Table 6 (Transport Department, 2012). From Tables 5 and 6, the traffic volumes in the three scenarios by different vehicle types and emission standards can be obtained by multiplying their corresponding ratios. Then, the total emission costs of all three scenarios can be calculated with the PCEUs and standard unit curves. Fig. 8 demonstrates that the two curves from the PCEU framework closely match with the COPERT 4 curve, i.e. the two Schemes do not lose much accuracy as compared with COPERT 4 in terms of total costs.

To quantify the performance of the two Schemes, we define the relative error as:

$$Error_i(v) = \frac{TC_i(v) - TAC(v)}{TAC(v)} \tag{18}$$

where i means Scheme i, $Error_i$ denotes relative error of Scheme i. $TC_i(v)$ denotes the total cost calculated by Scheme i at given speed v. TAC is the total COPERT 4 cost, or the ground truth. Based on their relative errors, three indices are introduced:

Table 5
Overall distribution of emission standards of Hong Kong vehicles.

	PC	LGV	MGV	HGV	L bus	SD bus	DD bus
Euro II	0.17	0.23	0.23	0.26	0.39	0.14	0.14
Euro III	0.28	0.32	0.33	0.15	0.22	0.37	0.37
Euro IV	0.49	0.39	0.29	0.29	0.22	0.29	0.29
Euro V	0.06	0.06	0.15	0.29	0.17	0.21	0.21

Note that the sum of ratios may not equal to 1 due to rounding.

Table 6
Proportions of traffic volumes by different vehicle types.

	PC	LGV	MGV	HGV	L bus	SD bus	DD bus
Hong Kong	0.812	0.098	0.053	0.006	0.004	0.013	0.013
Cross harbor tunnel	0.656	0.183	0.039	0.009	0.024	0.040	0.049
Lantau link	0.671	0.116	0.095	0.016	0.002	0.053	0.047

Note that the sum of ratios may not equal to 1 due to rounding.

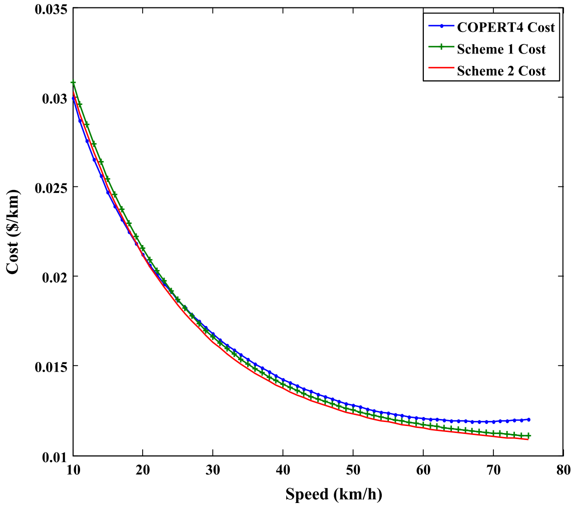

Fig. 8. Three different total costs of Hong Kong Scenario.

average absolute relative error, maximum and minimum relative errors, which are, respectively, represented by the average error, maximum error and minimum error. The average error is computed as follows.

$$AVError_i = \frac{\sum_{v=10}^{75} |Error_i(v)|}{66} \tag{19}$$

From Table 7, it is noticed that both Schemes of the PCEU framework achieve high accuracy as compared with COPERT 4, with the average errors being less than 0.04 in all three scenarios. To further illustrate their comparison, different total costs in terms of vehicle types are provided in Table 8. The relative errors of the total costs by vehicle types in all three scenarios are equal because all the three scenarios follow the same distribution of emission standards.

Comparing the two Schemes of the PCEU framework with regards to vehicle types, Scheme 1 performs better than Scheme 2 except for PC, which is reasonable because Scheme 1 takes the impact of emission standards into consideration.

Among the Scheme 2 indices, 0.172 is the largest maximum error and −0.322 is the smallest minimum error. Theoretically speaking, the relative error of the total cost estimated by Scheme 2 can never exceed this upper bound range from −0.322 to 0.172 in whatever proportion of vehicle types. In actual situation, due to positive and negative errors attributed from different vehicle types cancel each other, the combined error in a mixed traffic stream will be much smaller. In other words, though only considering the influence of vehicle types, Scheme 2 of the PCEU framework can be effectively applied to estimate traffic emissions in any type of roads in Hong Kong, on the condition that the current distribution of emission standards remains unchanged. Furthermore, even if the current distribution of emission standards varies a lot, rendering the distribution extreme (e.g. only Euro IV and Euro V vehicles exist), Scheme 2 can still be effective if it is redeveloped by WAM,

Table 7
Relative errors of different total costs in three scenarios.

	Hong Kong		Cross Harbor Tunnel		Lantau Link	
Scheme	1	2	1	2	1	2
Average	0.026	0.036	0.007	0.021	0.005	0.010
Maximum	0.032	0.014	0.010	−0.011	0.010	−0.001
Minimum	−0.076	−0.092	−0.038	−0.058	−0.016	−0.028

Table 8
Relative errors of total costs by vehicle types in the three scenarios.

	PC	LGV	MGV	HGV	L bus	SD bus	DD bus
Average[a]	0.081	0.050	0.007	0.030	0.040	0.061	0.053
	0.071	0.128	0.045	0.081	0.067	0.068	0.065
Maximum[a]	0.100	0.139	0.014	0.046	0.061	0.135	0.149
	0.130	0.017	−0.035	0.128	−0.037	0.148	**0.172**
Minimum[a]	−0.135	−0.240	−0.025	−0.046	−0.083	−0.095	−0.062
	−0.111	**−0.322**	−0.072	0.029	−0.168	−0.085	−0.043

Bold indicates the largest and smallest values in the table.

[a] Average: the two consecutive rows are, respectively, indices for Schemes 1 and 2.

using the new distribution of emission standards. In this sense, the PCEU framework can be conveniently applied to other cities if an approximate distribution of emission standards is available.

Simulations with varying distributions of emission standards

From the previous discussion, it is found that with a known distribution of emission standards, both Schemes of the PCEU framework have effective performance regardless of the proportions of vehicle types. To evaluate the robustness of the proposed framework, simulations with varying distributions of emission standards are conducted. For simplicity, we consider the scenario that the proportions of vehicle types follow the overall situation in Hong Kong. It is legislated in Hong Kong that newly registered vehicles should comply with Euro IV or newer standards, i.e. vehicles of Euro II and Euro III will be replaced by those of Euro IV and Euro V. Thus, it is assumed that vehicle types of Euro II and Euro III will be replaced by Euro IV and Euro V vehicles in four years, with 25% replacement in each year, equally shared by new Euro IV and Euro V vehicles. Table 9 demonstrates that the average errors of both Schemes increase as time goes on, especially for Scheme 2. Scheme 1 is still able to obtain high accuracy in year 4, while the average error of Scheme 2 almost reaches 0.4. Generally, changes in the distribution of emission standards have an impact on the performance of Scheme 2, but does not affect the performance of Scheme 1 as much, because Scheme 1 considers the effect of emission standards. The different influences on the two Schemes can be clearly illustrated in Fig. 9, where $\cos ti$ represents the corresponding cost in year i, and $\cos t0$ is the original cost. Note that the total cost in Scheme 2 does not change in different years because it does not consider the impact of emission standards. As more vehicles of older standards are replaced by vehicles of newer standards, the difference between the total COPERT 4 costs and the total Scheme 2 cost becomes larger, while Scheme 1 costs and COPERT 4 costs still match with each other quite well.

To sum up, Scheme 1 of the proposed framework produces good results even as the distribution of vehicle types and emission standards varies. If the distribution of emission standards is known beforehand, the PCEUs of Scheme 2 can be adjusted using WAM, which will then have identical performance with Scheme 1. Moreover, the differences in the PCEU between Euro IV and Euro V vehicles are small. As time moves on, when most vehicles will fulfill the requirements of either Euro IV or Euro V, Scheme 1 and Scheme 2 will have roughly the same performance.

Performance of the PCEU framework under varying external costs

Estimating the environmental externality of road transport is complicated and full of uncertainty. For air pollution costs, the preferred approach is broadly acknowledged, using values of statistical life based on willingness to pay. For the cost of greenhouse effect, the avoidance cost approach is widely adopted, given long-term reduction targets for CO_2 emissions in the handbook (Maibach et al., 2008). The external costs for traffic emissions vary a lot with locations. In fact, the handbook provides different air pollution costs for different European Union (EU) countries, and each country has different $PM_{2.5}$ costs for

Table 9
Relative errors of total costs in different years (Hong Kong Scenario).

	Year 0	Year 1	Year 2	Year 3	Year 4
Average[a]	0.026	0.033	0.040	0.048	0.057
	0.036	0.055	0.148	0.263	0.402
Maximum[a]	0.032	0.040	0.049	0.060	0.074
	0.014	0.117	0.233	0.377	0.558
Minimum[a]	−0.076	−0.087	−0.093	−0.099	−0.108
	−0.092	−0.019	0.067	0.170	0.294

[a] Average: the two consecutive rows are indices of Schemes 1 and 2.

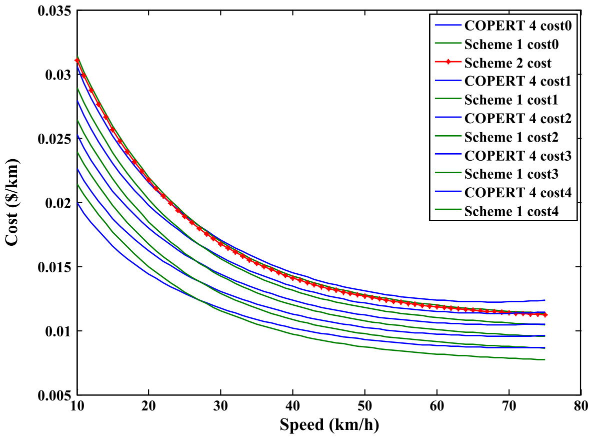

Fig. 9. Three different total costs in different years (Hong Kong Scenario).

Metropolitan, Urban and Outside built-up areas. Also, besides the average cost, often lower and upper bound estimates are given.

Based on the external costs provided in Table 2, CO_2, NO_X and $PM_{2.5}$ constitute more than 95% of the overall cost in all vehicle types. Therefore, several scenarios considering different external costs of CO_2, NO_X and $PM_{2.5}$ are constructed, together with scenarios according to the Germany and EU average. For each scenario, the standard curve and PCEU factors are recalculated, and the average error is computed according to the current distribution of vehicle types and emission standards in Hong Kong. The differences in external costs between the original scenario and the scenarios constructed here are highlighted in bold. The upper and lower CO_2 costs provided in the handbook are, respectively, chosen for the CO_2 Upper and CO_2 Lower bound estimates. 622.120 is the highest $PM_{2.5}$ cost in the handbook, and 116.086 is the $PM_{2.5}$ cost for Outside built-up areas in UK. 7.226 and 1.807 are, respectively, twice and half of the original NO_X cost.

Observing the average errors in Table 10, we find that the PCEU framework performs well in all the scenarios, with the average errors of all other scenarios similar to those of the original scenario. Also, the other indices including maximum and minimum errors are also quite similar. Actually, there are large variations in the external costs between the different scenarios, judging from the big distinctions between the numbers in bold. These results show that the PCEU framework is robust even as the external costs vary. Together with the abovementioned simulations in Sections 'Simulations of three scenarios in Hong Kong' and 'Simulations with varying distributions of emission standards', we can conclude that the PCEU framework can be adapted for other cities, given that local external costs and vehicle composition are available to develop the specific standard curve and PCEU factors.

Concluding remarks

In this study, we developed a framework of Passenger Car Emission Unit (PCEU) by integrating emission model and emission valuation, analogous to the concept of PCU but for capturing environmental externality of road transport. The emission factors of six major emissions were combined into an overall cost by multiplying their corresponding external costs. Then, the concept of a standard cost curve was proposed to represent the general trend of emission costs of different vehicle types and emission standards. A normalization process was introduced to obtain the standard cost curve, which was further used to derive the PCEUs of two different Schemes.

Table 10
Scenarios of different external costs of emissions.

Scenarios	NO_X	$PM_{2.5}$	CO	CO_2	SO_2	HC	Average error	
							Scheme 1	Scheme 2
Original	3.613	360.487	0.520	0.023	6.115	1.019	0.026	0.036
CO_2 Upper	3.613	360.487	0.520	**0.042**	6.115	1.019	0.025	0.032
CO_2 Lower	3.613	360.487	0.520	**0.006**	6.115	1.019	0.023	0.039
$PM_{2.5}$ Upper	3.613	**622.120**	0.520	0.023	6.115	1.019	0.028	0.041
$PM_{2.5}$ Lower	3.613	**116.086**	0.520	0.023	6.115	1.019	0.022	0.027
NO_X Upper	**7.226**	360.487	0.520	0.023	6.115	1.019	0.023	0.033
NO_X Lower	**1.807**	360.487	0.520	0.023	6.115	1.019	0.029	0.039
Germany	**8.894**	**356.225**	0.520	0.023	**10.191**	**1.575**	0.023	0.033
EU average	**3.862**	**272.821**	0.520	0.023	**4.850**	**0.821**	0.025	0.033

Bold indicates the largest and smallest values in the table.

In the numerical studies, it was demonstrated that the proposed PCEU framework was applicable for different regions, through the development of a localized standard cost curve and corresponding PCEUs. Specifically, Scheme 1 is more robust than Scheme 2 as the former can perform effectively even in various distributions of emission standards, while Scheme 2 is generally more applicable as it only requires vehicle type distribution which can be collected by a simple traffic survey. Also, if the distribution of emission standards by vehicle types is also known, Scheme 2 can be improved with the Weighted Average Method, which will then produce the same performance as Scheme 1. With this framework, estimating the total emissions only requires the average speeds and traffic volumes of different vehicle types, while avoiding the tedious individual emission calculation of different vehicle types, emission standards and speeds. The estimation is simplified to a standard cost curve and PCEU without losing much accuracy.

The PCEU framework provides a simplified way to calculate traffic emissions. Nevertheless, as it uses COPERT as the underlying emission model, the PCEU approach inherits the limitations of COPERT. One limitation is its use of average speed for emissions estimation, which may render the approach not applicable or at least not accurate for traffic conditions where the speed varies a lot, such as in the vicinity of signalized junctions. Also, the approach relies on external costs that should be updated over time and adjusted for different geographical regions. These limitations call for future extensions. The first and foremost is to combine the PCEU approach with microscopic emission models and consider the effect of different modes of traffic operations on emissions, such as acceleration, deceleration and idling. In this way, emissions can be more accurately estimated. But before that, the present PCEU factors offer a balanced compromise to work with heterogeneous traffic types for emissions estimation.

Acknowledgements

The study is supported by Research Grant SBI13EG04-B, General Research Funds #616113 and 16206114 of the Research Grants Council of the HKSAR Government and Strategic Research Funding Initiative SRFI11EG15.

Appendix A

In the EEA Guidebook, cold-start emissions are calculated as additional emissions over hot-emissions. Let $EF_{Cold;i,k}$ and $EF_{Hot;i,k}$ be, respectively, the cold-start and hot emission factors of pollutant i produced by vehicle technology k as classified by vehicle type and emission standard. The ratio of cold to hot emissions is expressed in (20), where $\beta_{i,k}$ denotes the fraction of mileage driven with a cold engine or the catalyst operated below the light-off temperature for pollutant i and vehicle technology k as expressed in (21); l_{trip} denotes the average trip length, taken to be 10 km in Hong Kong; and t_a, the ambient temperature, set to be 25 °C according to Hong Kong Observatory. And the parameter $e_{i,k}$ is given in Table 11 by the EEA Guidebook.

$$\frac{EF_{Cold;i,k}}{EF_{Hot;i,k}} = \beta_{i,k} * (e_{i,k} - 1) \tag{20}$$

$$\beta_{i,k} = 0.6474 - 0.02545 * l_{trip} - (0.00974 - 0.000385 * l_{trip}) * t_a \tag{21}$$

Making use of (20) and (21), Table 11 and Fig. 2, we calculate the ratios of $EF_{Cold;i,k}/EF_{Hot;i,k}$ and the corresponding proportions of external costs for different pollutants under different speeds, as shown in Table 12.

Table 11
$e_{i,k}$ for Euro 1 and later passenger cars.

Speed (km/h)	CO	NO$_X$	HC	CO$_2$	SO$_2$
10	1.00	1.41	1.99	1.25	1.25
20	1.00	1.87	2.47	1.25	1.25
30	1.04	2.71	2.94	1.25	1.25
40	1.54	3.19	3.42	1.25	1.25

Table 12
$EF_{Cold;i,k}/EF_{Hot;i,k}$ for Euro 1 and later passenger cars.

Speed (km/h)	CO		NO$_X$		HC		CO$_2$		SO$_2$	
10	0	(0.007)	0.1	(0.031)	0.24	(0.001)	0.06	(0.929)	0.06	(0.002)
20	0	(0.010)	0.21	(0.035)	0.36	(0.001)	0.06	(0.912)	0.06	(0.002)
30	0.01	(0.014)	0.42	(0.035)	0.48	(0.002)	0.06	(0.899)	0.06	(0.001)
40	0.13	(0.017)	0.54	(0.033)	0.59	(0.002)	0.06	(0.891)	0.06	(0.001)

Note: the bracketed numbers are the corresponding proportions of external costs for different emissions at different speeds.

Certain emissions, such as NO_X and HC, have a high ratio of $EF_{Cold;i,k}/EF_{Hot;i,k}$, up to 0.59 at high speed. However, their corresponding proportions of external costs are low (Table 12). As for CO_2, it constitutes the highest proportion of the overall external cost for passenger car, around 90% at various speeds; nevertheless, its low cold-start to hot emissions ratio, 0.06, does not have a major impact on the performance of the PCEU framework. If the methodology for calculating cold-start emissions for all vehicle types is included in the future version of the EEA Guidebook, the PCEU framework should and can cover cold-start emissions.

References

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. J. Transp. Eng. 128 (2), 182–190.

Bigazzi, Alexander Y., Figliozzi, Miguel A., 2012. Congestion and emissions mitigation: a comparison of capacity, demand, and vehicle based strategies. Transp. Res. Part D: Transp. Environ. 177, 538–547.

Coelho, M.C., Farias, T.L., Rouphail, N.M., 2005. Impact of speed control traffic signals on pollutant emissions. Transp. Res. Part D: Transp. Environ. 10 (4), 323–340.

Corvalán, R.M., Osses, M., Urrutia, C.M., 2002. Hot emission model for mobile sources: application to the metropolitan region of the city of Santiago, Chile. J. Air Waste Manag. Assoc. 52 (2), 167–174.

Csikós, A., Varga, I., 2012. Real-time modeling and control objective analysis of motorway emissions. Proc.-Soc. Behav. Sci. 54, 1027–1036.

Deng, X., 2006. Economic costs of motor vehicle emissions in China: a case study. Transp. Res. Part D: Transp. Environ. 11 (3), 216–226.

El-Shawarby, I., Ahn, K., Rakha, H., 2005. Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions. Transp. Res. Part D: Transp. Environ. 10 (1), 13–30.

Environmental Protection Department, 2011. Hong Kong Emission Inventory Report.

Environmental Protection Department, 2012. A breakdown of licensed vehicles in Hong Kong, from communication with L.Y. Pao.

Fontes, T., Pereira, S.R., Fernandes, P., Bandeira, J.M., Coelho, M.C., 2015. How to combine different microsimulation tools to assess the environmental impacts of road traffic? Lessons and directions. Transp. Res. Part D: Transp. Environ. 34, 293–306.

Ganguly, R., Broderick, B.M., 2008. Performance evaluation and sensitivity analysis of the general finite line source model for CO concentrations adjacent to motorways: a note. Transp. Res. Part D: Transp. Environ. 13 (3), 198–205.

Gokhale, S., 2012. Impacts of traffic-flows on vehicular-exhaust emissions at traffic junctions. Transp. Res. Part D: Transp. Environ. 17 (1), 21–27.

Int Panis, L., Broekx, S., Liu, R., 2006. Modelling instantaneous traffic emission and the influence of traffic speed limits. Sci. Total Environ. 371 (1), 270–285.

Lemp, J.D., Kockelman, K.M., 2008. Quantifying the external costs of vehicle use: evidence from America's top-selling light-duty models. Transp. Res. Part D: Transp. Environ. 13 (8), 491–504.

Maibach, M., Schreyer, C., Sutter, D., Van Essen, H.P., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., Bak, M., 2008. Handbook on Estimation of External Costs in the Transport Sector. Internalisation Measures and Policies for All external Cost of Transport (IMPACT), CE Delft.

Mak, K.L., Hung, W.T., 2008. Developing air pollutant profiles using routine monitoring data in road tunnels: a note. Transp. Res. Part D: Transp. Environ. 13 (6), 404–411.

Matthews, H.S., Hendrickson, C., Horvath, A., 2001. External costs of air emissions from transportation. J. Infrastruct. Syst. 7 (1), 13–17.

Mayeres, I., Ochelen, S., Proost, S., 1996. The marginal external costs of urban transport. Transp. Res. Part D: Transp. Environ. 1 (2), 111–130.

Ntziachristos, L., Samaras, Z., 2014. EMEP/EEA Emission Inventory Guidebook 2013. European Environment Agency.

Santos, G., Behrendt, H., Maconi, L., Shirvani, T., Teytelboym, A., 2010. Part I: Externalities and economic policies in road transport. Road Transp. External., Econ. Polic. Other Instrum. Sustain. Road Transp. 28 (1), 2–45.

Smit, R., Ntziachristos, L., Boulter, P., 2010. Validation of road vehicle and traffic emission models–a review and meta-analysis. Atmos. Environ. 44 (25), 2943–2953.

Transport Department, 2001. Transport Planning & Design Manual. Transport Department, Hong Kong.

Transport Department, 2012. Transport Digest. Transport Department, Hong Kong.

Zhang, Y., Lv, J., Ying, Q., 2010. Traffic assignment considering air quality. Transp. Res. Part D: Transp. Environ. 15 (8), 497–502.

Zhu, F.H., Lo, H.K., Lin, H.Z., 2013. Delay and emissions modeling for signalized intersection. Transp. B: Transp. Dyn. 1 (2), 111–135.