DEVELOPMENT OF EMISSION FACTORS FOR A URBAN ROAD NETWORK BASED ON SPEED DISTRIBUTIONS

by

Ming Li, Ph.D. Candidate
MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University
Haidian District, Beijing 100044, P.R. China
Tel: 86-10-51688570, Fax: 86-10-51688570, Email: limzlxs@gmail.com

Lei Yu, Ph.D., P.E.
Professor of Texas Southern University
Yangtze River Scholar of Beijing Jiaotong University
College of Science and Technology, Texas Southern University
3100 Cleburne Avenue, Houston, Texas 77004
Tel: 713-313-7007, Fax: 713-313-1853, E-mail: Yu_lx@tsu.edu

Zhiqiang Zhai, Graduate Research Assistant
MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University
Haidian District, Beijing 100044, P.R. China
Tel: 86-10-51688570, Fax: 86-10-51684022, Email: 13120926@bjtu.edu.cn

Weinan He, Project Manager of Assessment and Modelling
Beijing Transport Energy & Environment Center
FengTai District, Beijing 100073, P.R. China
Tel: 86-10-57078267 Fax: 86-10-57078266, Email: heweinan314@163.com

and

Guohua Song, Ph.D., Associate Professor
(Corresponding author)
MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University
Haidian District, Beijing 100044, P.R. China
Tel: 86-10-51684022, Fax: 86-10-51688570, Email: GhSong@bjtu.edu.cn

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ABSTRACT

Average speeds are widely used in emission models to develop emission factors for emission estimations. However, using speed distributions instead of simply average speeds may improve the accuracy of the emission estimations because speed distribution represents speed profiles better in a real-life network. To investigate the feasibility of incorporating speed distributions instead of average speeds, the research for this paper collects massive emission and traffic activity data. First, the relationship between emission factors and average speeds was developed. Second, the speed distributions during daytime hours (6:00 to 21:00) for classified roads were analyzed and found speed distribution on the expressway followed the bimodal distribution, while that on arterials and collectors followed the same distribution pattern, but with a single peak. Third, the research developed emission factors for the road network based on speed distributions, then compared with those using traditional average-speed-based method. The comparative analysis showed that even though both emission factors by these two distinguished methods presented a similar variation trend, the results from the average-speed-based method were lower. Although the relative differences of two methods were less than 10%, they tended to increase during peak hours. Finally, the research identified two reasons for those increased differences. First, speed distributions are more scattered during peak hours, and secondly the relationship between average speeds and emission factors is nonlinear in nature, so the relative differences in the low speed fraction increased more significantly during peak hours.

Keywords: Vehicle Emissions; Speed Distribution; Emission Factors;
INTRODUCTION

Due to the rapid increase in vehicle population, traffic emissions have become a bottleneck for further sustainable transportation development in China. According to the research (1), vehicle exhaust emissions CO, HC, and NOx account for 86%, 38%, and 58%, respectively, of total pollutants in Beijing. In response, numerous traffic management policies have been implemented in Beijing, such as the vehicle restriction rule, bus priority system, and increase in parking fees. In September 2013, the Five-Year Clean Air Action Plan (2013-2017) was released. It unveiled a package of measures designed to improve both traffic conditions and air quality. Given this background, developing a method that can accurately evaluate the effects of different traffic management policies on emission reductions is an imperative need.

The emission factor has long been a key parameter in emission estimations. It is defined as the amount of vehicle emissions per unit distance (e.g. g/km or g/mile) (2). Existing literature has shown that the traditional method used to estimate emission factors is generally based on average speed. However, the use of a single average speed for all vehicles on a road network is not sufficient to represent actual traffic conditions, a factor that can lead to errors in emission predictions. In this context, the research in this paper developed emission factors based on speed distributions instead of a single average speed, as it is reasonable that speed distribution will provide more detailed information than a single speed for characterizing a real speed profile so essential to emission estimations (3). First, the research collected massive traffic activity data in Beijing for which hourly speed distributions from 6:00 to 21:00 on weekdays were then analyzed. Then, it generated hourly emission factors of CO, HC, and NOx based on speed distributions for classified roads as well as for the entire road network. Finally, the emission factors that resulted were compared to those generated by the traditional average-speed-based method.

AN OVERVIEW OF EXISTING STUDIES

An accurate and detailed account of actual speed characteristics is fundamental to produce emissions estimations. That speed is defined as a distance change of an individual vehicle per unit time. Generally, the speed is classified into both instantaneous speed and average speed (4). When estimating fuel consumption and emissions of an individual vehicle, the instantaneous speed can produce a more reliable evaluation (5). In any network-wide emission modelling, however, average speed is commonly used. Eggleston et al. (6) calculated the emission factors for Europe Community member states to set up an emission inventory. Barlow et al. (7) established the functions for average speed and the emission factor for different pollutants. The average speed based emission models generate emission factors as a
function of average speed in practical applications (8).

According to these modeling approaches, emission factor models can be broadly classified into modal operating models and average speed models (9). In a modal operating model, such as the Comprehensive Modal Emissions Model (CMEM), the entire fuel consumption and emissions process is broken down into components that correspond to the physical phenomena associated with vehicle operation and emissions production, so it is often applied to evaluate the emissions benefits of project-level or corridor-specific traffic control measures (e.g. HOV lanes). In the average speed model, emission factors are generated and adjusted based on average speed. Examples of the average speed model include COPERT (11) (12), MOBILE (13) and EMFAC (14). Other emission models, such as MOVES (15), IVE (16), HBEFA (17), and EMIT (18), have their own specific advantages and disadvantages when developing emission factors.

Based on these studies, average speed is an important variable in emission estimations because traffic emissions are highly dependent on an average speed. Therefore, in traditional applications, the average speed for a network should be as accurate as possible; otherwise, inaccurate speed predictions may have a negative effect on the calculation of emissions (19). What's more, a single average speed for all vehicles on a road network is not sufficient to represent all traffic conditions because trips with different vehicle operation characteristics can produce the same average speed. Therefore other research has focused on improving the estimates of emission factors.

Song et al. (20) developed speed correction factors based on speed-specific VSP distributions. Yu et al. (21) developed driving cycles for classified roads, incorporating a vehicle’s driving activities as well as its emission characteristics derived from the PEMS data. In particular, speed distribution was introduced in the emission calculating. Trozzi et al. (22) analyzed the influence of speed on emissions and conducted a study that concluded that different speed distributions with a given average speed would have different emissions. Smit et al. (3) developed a method to predict such speed distributions using the data from a dynamic macroscopic traffic model and concluded that emissions of CO, HC, NOx, PM_{10} and CO_{2} generally increase when applying the speed distribution method.

Today, emission factors can be developed by using speed distributions versus using a single average speed for the entire network. However, the existing studies have not investigated the differences between the two methods based on real world traffic data. With the rapid development of advanced data collection technologies, massive traffic activity data can be readily collected and that data can be used to generate speed distributions. By connecting speed distributions to emission models, it becomes possible to derive more accurate emission factors that are associated with various actual traffic conditions.
METHODOLOGY

In order to obtain the emission factors for the road network in Beijing, this research designed a four-step approach using the existing data. To begin, two types of data were collected. The first was the proportions of vehicles that meet certain emission standards and VKT distributions on different road classes. The second was massive vehicle emission rates and activity data collected from typical light duty vehicles on real roads. Then, by analyzing the vehicle emission data and the activity data, emission factors at different speeds for the classified roads were calculated through a statistical analysis. By connecting speed distributions to emission factors at different speeds, the research then generated emission factors for different road classes and the entire network. Finally, the research applied the traditional method for developing emission factors based on average speed, which were then compared to those developed using the proposed approach.

Data Source and Preparation

Data Preparation of Basic Traffic Information

At present, there are 5.51 million motor vehicles in Beijing. According to a sample survey launched in 2013, gasoline vehicles account for more than 92% of each road class (23). Taking this situation into consideration, this paper simplified the analysis by assuming that all vehicles on the roads were gasoline-powered light vehicles.

Applying the field survey and the traffic model, the proportion of vehicles meeting certain emission standards and VKT distributions on different road classes are shown in Table 1 (1). It should be noted that for this paper, urban roads were classified into three classes, in which the expressway is the same as the Urban Restricted Access Roadways defined in MOVES. Vehicles were further classified into 5 groups based on the emission standards in China, China 0 (pre China I), I, II, III, and IV.

<table>
<thead>
<tr>
<th>ROAD CLASS</th>
<th>Proportion of vehicle fleet meeting certain emission standards</th>
<th>VKT Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>China 0</td>
<td>China I</td>
</tr>
<tr>
<td>Expressway</td>
<td>1.3%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Arterial</td>
<td>1.0%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Collector</td>
<td>1.1%</td>
<td>6.3%</td>
</tr>
</tbody>
</table>

Data Preparation for Speed Distributions

In 2006, the Beijing Transportation Research Center established a floating car system (24). It includes a data center and about 66,000 taxis. Each taxi is equipped with a GPS device and sends real time activity data to the data center, including its speed and location. Because taxis are extensively distributed over the road network and have a
high market penetration rate of around 10%, real traffic operation conditions can be well characterized using floating car system. This research collected a month of continuous data (at 15-minute intervals) on weekdays based on the floating car system, where the time ranged from 6:00 A.M. to 9:00 P.M., and the area examined covered the entire urban road network in Beijing. It should also be noted that in Beijing, the speed limit on the arterial is 70km/h, and on the collector is 60km/h (25), so speed distribution was normalized after clearing out any unreasonable data. The result was 35,090 records of valid data for this study.

It should also be noted that the speed distribution in this study was generated on the basis of VKT, i.e., the speed-specific VKT distribution. In the floating car system, speeds are divided into bins at 5 km/h intervals, and the average speed of each link is updated based on the average speed of taxis equipped with a GPS on the link.

\[ VKT_{l,j,k} = \sum_l Q_{l,j,k,l} \times L_l \]
\[ VKT \text{ Fraction}_{i,j,k} = \frac{VKT_{i,j,k}}{\sum_k VKT_{i,j,k}} \quad (1) \]

where \( Q_{l,j,k,l} \) is the traffic volume on the link \( l \) at hour \( i \), road class \( j \), speed bin \( k \), and \( L_l \) is the length of link \( l \). The speed distribution is then developed based on the VKT fractions, shown in the following part of this paper.

Data Preparation for Emission Factors

Beijing Jiaotong University has collected massive on-road emission data of CO, HC, and NOx since 2003. Using the Portable Emission Measurement Systems (PEMS), 152 light duty vehicles have been tested and 689,410 records have been collected. Further, by using GPS devices, massive second-by-second vehicle activity data could be collected, including 424,426 records from expressways, 185,570 records from arterials, and 140,806 records from collectors.

Based on these collected emission and vehicle activity data, the research analyzed the relationship between the speed and emission factors using the VSP-based emission modelling approach (20). For each record, the VSP value was calculated using Equation (2):

\[ VSP = v \times [1.1 \times a + 9.81 \times grade + 0.132] + 0.000302 \times v^3 \quad (2) \]

where \( v \) is the speed in the unit of m/s, \( a \) is the acceleration in the unit of m/s\(^2\), and \( grade \) is the vehicle vertical rise divided by the slope length, which is assumed to be zero in the study because the data were not collected on gradient ramps or bridges. Since objects of the study were vehicles of the same weight class and fuel type, and identical coefficients were chosen for the Equation (2). Second, by defining the 60-second continuous speed records as a trajectory and calculating the average speed in each trajectory, the research was able to classify every trajectory into a speed-specific trajectory pool based on average speed. Third, it used the VSP distribution in each pool to describe the driving behavior of different road classes (expressway, arterial and collector) based on the vehicle activity data. Fourth,
emission rates (gram/second) for different emission standards in each VSP bin were calculated by analyzing the PEMS emission data. Finally, by using VSP as an intermediate variable, the emission factors at different speeds were calculated using Equation (3):

\[
\text{Emission Factor} = 3600 \times \frac{\sum (VSP \text{ Distribution}_i \times \text{Emission Rate}_i)}{\text{Average Speed}} \quad (3)
\]

where the Emission Factor is at a specific speed, emission standard and road class in the unit of g/km, VSP Distribution\(_i\) is the VKT fraction in VSP bin \(i\), Emission Rate\(_i\) is the emission rate in VSP bin \(i\), and Average Speed is the average speed of the speed-specific trajectory pool in the unit of km/h.

**Development of Emission Factors**

*Development of Emission Factors for Classified Roads*

In order to develop emission factors for the road network (\(EF_{\text{net}}\)), the research first calculated emission factors for different road classes (\(EF_{\text{road}}\)). Based on the data discussed earlier, including traffic activity data, emission rates, and the proportion of vehicles meeting a certain emission standard on each road class, the research derived emission factors for each road class at a specific speed. These results are shown in Figure 1, where the relationship between emission factors on different road classes and average speed is described by corresponding regression curves.

![Emission Factor of CO at Different Speeds](image)

- **Expressway**: \(EF = 13.318v^{-0.43}\)  \(R^2 = 0.9765\)
- **Arterial**: \(EF = 13.305v^{-0.435}\)  \(R^2 = 0.9949\)
- **Collector**: \(EF = 13.265v^{-0.403}\)  \(R^2 = 0.9609\)

- a) CO
FIGURE 1 Emission factors of different pollutants at different average speeds.

As shown in Figure 1, emission factor \( EF \) decreases with an increase in average speed, mainly because when a vehicle is at a lower speed, it will take longer to pass one unit of distance. Further, these trends can be fitted statistically. For all the pollutant types, a power function can clearly describe the trends with all \( R^2 \) above 0.9. Another finding was that emission factors on expressways and arterials are very close, especially for CO and HC pollutants.

Then, based on the power functions in Figure 1, two methods can be used to calculate hourly \( EF_{road} \). One is the average-speed-based method as shown in Equation (4), and the other is based on speed distributions as shown in Equation (5).

\[
EF_{road} = EF(\bar{v}) = EF(\int_0^{v_{max}} v \times P_v \, dv) \tag{4}
\]

\[
EF_{road} = \int_0^{v_{max}} EF_v \times P_v \, dv \tag{5}
\]
where $\bar{v}$ is the average speed, $v_{\text{max}}$ is the speed limit on the road, and $P_v$ is the proportion at the speed $v$ based on the mentioned speed distribution mentioned.

**Development of Emission Factors for a Road Network**

In order to develop hourly $EF_{\text{net}}$, this research strived to determine the weighted sum of $EF_{\text{road}}$. On the basis of the VKT distribution shown in Table 1, the weight of emission factors on expressways, arterials, and collectors was 0.41, 0.21, and 0.38, respectively. Further, methods for calculating hourly $EF_{\text{net}}$ were then revised from Equations (4) and (5) to Equations (6) and (7).

$$EF_{\text{net}} = EF_{\text{expressway}}(\bar{v}_1) \times 0.41 + EF_{\text{arterial}}(\bar{v}_2) \times 0.21 + EF_{\text{collector}}(\bar{v}_3) \times 0.38$$  \hspace{1cm} (6)

$$EF_{\text{net}} = 0.41 \times \int_0^{v_{1\text{max}}} EF_{\text{expressway}} v \times P_v \, dv + 0.21 \times \int_0^{v_{2\text{max}}} EF_{\text{arterial}} v \times P_v \, dv + 0.38 \times \int_0^{v_{3\text{max}}} EF_{\text{collector}} v \times P_v \, dv$$  \hspace{1cm} (7)

where $EF_{\text{expressway}}(\bar{v}_1)$ is the emission factor at the average speed $\bar{v}_1$ on the expressway, $EF_{\text{arterial}}(\bar{v}_2)$ is the emission factor at the average speed $\bar{v}_2$ on the arterial, $EF_{\text{collector}}(\bar{v}_3)$ is the emission factor at the average speed $\bar{v}_3$ on the collector, and $v_{1\text{max}}$, $v_{2\text{max}}$, and $v_{3\text{max}}$ are the speed limits on expressways, arterials, and collectors.

**RESULTS AND DISCUSSION**

**Speed Distributions for the Classified Roads**

**Hourly Speed Distribution for the Classified Roads**

Based on the 35,090 records of speed distribution data collected, this research analyzed hourly speed distributions on weekdays during daytime hours (from 6:00 to 21:00). According to the surveys and analyses, Beijing Traffic Management Bureau defines peak hours as 7:00 to 9:00 and 17:00 to 19:00. The results are shown in Figure 2.

![Speed Distribution](image)

a) Expressway
As shown in Figure 2, there is an apparent difference in the patterns of speed distributions between the expressway and the other two road classes, the shapes of which are like the letter “W” (the black lines). Thus, the analyses were divided into two segments, one for the expressway and the other for the arterial and the collector. On the expressways, the distribution ranged from 15 km/h to 75 km/h, while the main fractions ranged around 60 km/h during off-peak hours (the red blocks). During peak hours, the speed distributions were scattered (the green blocks).

On the arterials and collectors, the speed distribution demonstrated a unimodal distribution pattern. The main fractions were concentrated in the low speed areas during peak hours, and the speed was higher at noon and at night. Generally, the red region was under 45 km/h on the arterials, and under 40 km/h on the collectors.

\textit{Speed Distribution for Peak and Off-peak Hours}

In order to offer a comparison of the speed distributions, this research broke the daytime hours into peak hours and off-peak hours, as shown in Figure 3.
In Figure 3(a), there is a clear characteristic that shows that the speed distribution on expressways follows a bimodal distribution. However, during the off-peak hours, the fraction of 60 km/h was the single peak, which reached 16%. During peak hours, the fractions on the two peaks have a similar value at around 8%. It was noted that speed distributions of 9h and 7h on the expressways (dotted line with black points) showed distinct characteristics, but the average speeds were nearly identical (48.0km/h for 9h and 47.8km/h for 7h). This result implies that traffic scenarios with the same average speed may indeed have different speed distributions.

In Figures 3(b) and 3(c), speed distributions on the arterials and collectors show the same pattern with a single peak, regardless of whether during peak or off-peak hours. However, the speed distribution range on the arterials was wider than that on the collectors, and the fraction at the high speed on the arterials was also higher. Taking 50 km/h as an example (the dotted line), the fraction on the arterial is around 7% and 5% during the off-peak and peak hours, but around 5% and 4% on the collectors.

**FIGURE 3 Speed distributions for peak and off-peak hours.**

By applying Equation (5), this research developed emission factors for different road classes. Those calculations and the results are shown in Figure 4.
As shown in Figure 4, the emission factors on the expressway were the lowest, and those on the collectors were the highest. During peak hours, all emission factors increase, because low speed bins have higher fractions at that time, and emission
factors will increase rapidly with a decrease in the average speed. In addition, these curves illustrate the similarities in the variation tendency between different road classes, and the NOx curve is much smoother than the other two pollutants.

**Hourly Emission Factors for the Entire Road Network Using Speed Distributions**

Based on the emission factors for each road class, the emission factors for the entire road network were calculated by Equation (7).

**FIGURE 5 Emission factors on the road network using speed distributions.**

As shown in Figure 5, the emission factors of HC and CO have two peaks during peak hours. Especially at 17:00, the emission factor is much higher than at other hours. However, the curve for the NOx emission factors changed only slightly. Thus, the NOx emission factor is less sensitive to speed variations than the CO and HC.

**Comparison and Analysis**

In order to compare two different methods for generating emission factors, one based on average speed, and the other based on speed distributions, this research calculated emission factors by the average-speed-based method using Equation (6), as shown in Figure 6.
FIGURE 6 Emission factors on the road network using average speeds.

Comparing Figure 6 to Figure 5, the research noted a similar variation trend. The research further calculated the relative difference between the two methods. It should be noted as well that many of the relative differences were negative, which means that the results using the traditional average-speed-based method were lower than those using the method based on speed distributions.

a) For classified roads
b) For the road network

FIGURE 7 Relative Differences in Emission Factors for classified roads and road network.

As shown in Figure 7, for each road class (Figure 7(a)) and the entire road network (Figure 7(b)), the relative differences of HC are the highest, and those of NOx are the lowest. Moreover, in Figure 7(a), the relative differences in the emission factors on the arterial are all higher; while those on the expressway are fluctuate more. In Figure 7(b), the highest relative difference in the emission factors on the road network is 7.6%, and the lowest is 1.3%. Relative differences in the emission factors of CO and HC are similar and their variation trends remain close.

There was another interesting finding as well, which is that the curves of relative differences also had two peaks during the peak hours. There are two possible reasons. First, during peak hours, the speed distribution is more scattered, and thus the average speed is not able to describe the traffic conditions correctly. Especially on expressways, speed shows a bimodal distribution pattern (Figure 3(a)). Second, the relationship between the emission factors and the average speed is nonlinear in nature, as shown in Figure 1, so during peak hours, the relative differences in the fraction for low speed increased more significantly.

SUMMARY AND RECOMMENDATION

By collecting massive vehicle activity and emissions data, this research derived the relationship between emission factors and average speeds based on the intermediate parameter of VSP. Then, based on the developed relationship and the speed distributions, two different approaches for deriving emission factors for classified roads and the entire road network are provided. The main findings of this research can thus be summarized as follows:

1) The relationship between emission factors and average speeds for classified roads can be well modelled by using the power function.
2) Speed distributions on classified roads, however, have different patterns. On expressways, speed distribution follows the bimodal distribution pattern during peak hours. There are two peaks at speeds of 20 km/h and 55 km/h. On arterials and collectors, the speed distribution is much more concentrated and has only a single peak.

3) Emission factors on expressways are the lowest, while those on collectors are the highest.

4) The traditional average-speed-based method generates systematic relative differences of emission factors for an urban road network. Relative differences in the two methods were negative and less than 10%. During peak hours, the speed distribution is much more scattered and has higher percentages in the low speed ranges, so the relative differences increase during peak hours.

The above findings will help traffic engineers better understand traffic emissions on urban road networks. Advanced traffic data collection technologies, such as smartphones, on-board navigation systems, and Google's location APIs, provide greater opportunities to generate detailed speed distributions for a road network. Further studies will focus on the influences of different link lengths and time intervals at the granularity level and examine the differences in the resulting emissions between the two methodologies.

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