A VALIDATION OF TEMPORAL AND SPATIAL CONSISTENCY OF
FACILITY- AND SPEED-SPECIFIC VSP DISTRIBUTION FOR EMISSIONS
ESTIMATION: A CASE STUDY IN BEIJING

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ABSTRACT
The Vehicle specific power (VSP) distribution (or OpMode distribution in the MOVES model) is the determinant parameter in estimating emissions. The existing research and MOVES model developed specific VSP distributions for the restricted/unrestricted access road types and various average speeds. However, the question raised that if the VSP distribution are consistent temporally and spatially? For instance, are the facility- and speed-specific VSP distributions developed in the city CBD area applicable to its suburb area? Is it necessary to update periodically the database of the VSP distributions in the emission model like MOVES? In this context, this study examined the temporal and spatial consistency of the facility- and speed-specific VSP distributions in Beijing. The VSP distributions in different years and the ones in different areas are developed, based on the massive second-by-second vehicle activity data. The indicators of Pearson correlation coefficient and root mean square error (RMSE) are employed to quantify the differences between the VSP distributions. The results indicate that a very strong consistency exists between the facility- and speed-specific VSP distributions in different years or areas, with all the correlation coefficients approximately to be "1". In addition, the maximum differences of the VSP distributions in different years or areas are approximately 1/5 of that for different road types. By analyzing the facility- and speed-specific emission factors, it is found that the temporal and spatial differences of the VSP distributions have no significant impact on vehicle emissions estimation.

Keywords: VSP Distribution; Operating Mode Distribution; Temporal and Spatial Consistency; Emission Estimation
INTRODUCTION AND LITERATURE REVIEW

In recent years, emission modeling approaches have been evolving from basing on the average speed associated with the fixed driving cycle to basing on the vehicle specific power (VSP) (1), such as the Motor Vehicle Emissions Simulator (MOVES) model. VSP has been widely accepted as an important explanatory variable with respect to emissions. It is defined as the instantaneous tractive power per unit vehicle mass, in the unit of kW/ton. The MOVES provides the method to calculate VSP (2), as shown in the following Equations.

\[ a_t = v_{t+1} - v_t \]  
\[ VSP_t = (A \cdot v_t + B \cdot v_t^2 + C \cdot v_t^3) / m + (a_t + g \cdot \sin \theta) \cdot v_t \]

where 
- \( v_t \) and \( v_{t+1} \) are the vehicle speeds at time \( t \) and \( t+1 \), in the unit of m/s;
- \( a_t \) is the acceleration in the unit of m/s^2;
- \( g \) is the acceleration due to gravity, which is 9.8 m/s^2;
- \( \sin \theta \) is the road grade;
- \( A, B, C \) are road load coefficients, representing rolling resistance, rotational resistance and aerodynamic drag, in the units of kW·s/m, kW·s^2/m^2 and kW·s^3/m^3, respectively; and
- \( m \) is the vehicle weight, in the unit of metric ton.

In the VSP based emission models, both the emission rates and vehicle activities are derived by using a VSP binning approach, in which the VSP values are categorized into various VSP bins (3, 4). The VSP distribution, or operating mode (OpMode) distribution in the MOVES, is defined as the time (or time fraction) spent in each VSP bin (2, 5). In the MOVES, a total of 23 operating modes are defined for the running-exhaust process on the basis of VSP, speed and acceleration. The running exhaust emissions are estimated basically by multiplying the emission rates with the VSP distribution (6), as shown in Equation (3).

\[ emission = \text{running time} \times \sum_{VSP\text{bin}} \text{emission rate} \times \text{VSP distribution} \]  

The emission rates in various VSP bins represent the vehicle emissions under different power demands, which are obtained from vehicle emission tests by using chassis dynamometers or portable emissions monitoring systems (PEMS). Emission rates are fixed for a specific type of vehicle (regulation class, fuel type, model year, weight etc.). Thus for a specific vehicle fleet, the VSP distribution determines the emissions in a traffic network.

Extensive efforts have been made towards the characteristics of the VSP distributions. Frey et al. (3) examined the speed profiles of thirteen runs on different links with average speed 30-40 km/h and found a surprising consistency in the VSP distributions of different runs. Yu et al. (7) employed the root mean square error (RMSE) to assess the difference between two VSP distributions. Song et al. (8) compared the VSP distributions of the expressway and non-expressway, peak hour and non-peak hour in Beijing and found their significant differences both in terms of road type and time. For the expressway, applicable mathematical models were developed to describe the VSP distributions based on the average travel speed higher than 20 km/h and lower than 20 km/h respectively (5, 9). Chamberlin et al. (10, 11)
compared the VSP distributions obtained from the MOVES with those measured on a vehicle instrumented with the Total On-Board Tailpipe Emissions Measurement System (TOTEMS) and calibrated a microsimulation package to real-world vehicle operating characteristics for the purposes of emissions estimates. Qi et al. (12) developed the VSP distributions for both freeway and arterial facilities under different traffic conditions to evaluate the impacts of Advanced Traveler Information Systems (ATIS) on vehicle emissions under incident conditions. Wang et al. (13) investigated the VSP distribution characteristics of different freeway weaving configurations and their effects on vehicle emissions based on VISSIM.

Three methods have been proposed to generate VSP distributions: (i) based on drive schedules. For example, the MOVES2010 employs 47 drive schedules, mapped to specific source types and road types, to develop VSP distribution for light duty vehicles (LDVs) according to the input of average speed for the national default case (14). (ii) based on the output speed file of a microscopic traffic simulation model, which has long been questioned because of higher fractions of aggressive acceleration than real-world data (15). (iii) based on the second-by-second field activity data collected in the real world (3, 8), which characterizes the dynamic traffic and thus is more accurate and more representative. With the advancement of GPS technology, a large amount of second-by-second vehicle activity data become available, making this real-data-based method widely used.

The MOVES model employs the VSP binning method to calculate emission rates and to incorporate second-by-second vehicle performance characteristics for various VSP distributions. Default databases for the facility- and speed-specific VSP distributions are built. Though it is recommended to collect the local VSP distribution for emission estimation particularly for project-level applications (14), the VSP distributions derived from the default driving schedules are commonly used in different years and areas. Consequently, the questions raised: if the characteristics of the facility- and speed-specific VSP distributions are consistent temporally and spatially?

In this context, the primary objective of this study is to analyze the consistency of the VSP distributions developed in different years and different areas respectively in order to answer the following two questions:

(i) Is it needed to update the database of the VSP distributions in the emission model periodically?

(ii) Is it feasible to use the facility- and speed-specific VSP distribution developed in one area of the city (such as the city center) to represent the vehicle operation mode in another area (such as the suburb or other cities)?

The rest of this paper is organized as follows. The next section describes the study’s methodology, in which the facility- and speed-specific VSP distributions in different years and different areas are developed and compared by employing the RMSE. Then the emission differences caused by the temporal and spatial differences of the VSP distributions are evaluated. Finally, major findings are summarized along with recommendations.

**METHODOLOGY**

In this study, VSP distribution is defined as the time fractions spend in each VSP bin for a specific traffic condition of a combination of different road types and average speeds. General methodology in this study includes three parts: (i) the facility- and speed-specific VSP distributions in different years and different areas are developed
respectively based on massive second-by-second LDV activity data. (ii) the RMSE is employed in order to quantify the differences of the VSP distributions. (iii) facility- and speed-specific emission factors of CO₂, CO, HC and NOₓ are calculated to evaluate the impact of the temporal and spatial differences of the VSP distributions on the vehicle emissions.

**Data Sources**

The data sources in this study includes two parts: (i) second-by-second vehicle activity data of the LDVs; (ii) second-by-second emissions data of the light duty gasoline vehicles (LDGVs). A total of 7,547,355 records of second-by-second real-world activity data of LDVs were collected with portable GPS devices in Beijing in the past decade and stored in the database in Beijing Jiaotong University. The data are composed of 11,305 trips, provided by 178 LDVs. Other details about the data are listed as follows:

- Collection Date, from April 25th, 2004 to April 16th, 2013
- Collection Time, from 5:00 a.m. to 11:00 p.m.
- Longitude and Latitude
- Instantaneous Speed, from 0 to 133 km/h

Details about the emissions data of the LDGVs will be described in later part of this paper. The VSP values are calculated by using Equation (1) and (2). In Equation \( \sin \theta \) is assumed to be zero where roads are generally flat and is 0.04 on the bridges of the interchanges in Beijing (16); and for LDVs, the recommended values of \( A, B, C \) and \( m \) are 0.156461, 0.0020002, 0.000493 and 1.4788 respectively (2).

In order to analyze statistically the quantitative correlations between the VSP distribution and average speed, the VSP values are categorized into various VSP bins (4). VSP bins are defined by using an equal VSP interval of 1 kW/ton, as shown in Equation (4). It is found that over 98.8 percent of the VSP values are between -20 and 20 kW/ton, so in this paper, VSP bins in each distribution are analyzed within this range for the convenience of displaying VSP distributions (5).

\[
\forall: VSP \in [n-0.5, n+0.5), \quad VSP \text{ bin } = n \quad (n \text{ is an integer from } -20 \text{ to } 20) \quad (4)
\]

**VSP Distributions in Different Years**

Since there are significant differences in VSP distribution patterns for different facility/road types (i.e. expressway vs. non-expressway) (8), the VSP distributions on the expressway and non-expressway are developed separately. A digital map of the road network of Beijing, in the form of connecting links, and a map-matching algorithm are employed to match the GPS latitude and longitude in each record of the vehicle activity data to the corresponding road link. The coordinates, road type, length, etc. for each link in the map are available in its database. After the processing of map matching, each record of the data has an attribute field of "Facility Type", which is either expressway or non-expressway.

In order to analyze the temporal consistency of the facility- and speed-specific VSP distributions, the data are divided into two year groups with approximately equal numbers of records:

- "Before 2012", for the Collection Date before 2012
- "After 2012", for the Collection Date in 2012 or after
For each year group, the speed-specific VSP distributions on the expressway and non-expressway are developed separately. First, the activity data are divided into pieces of "trajectories", each of which consists of 180 seconds of continuous speed data. The trajectories are partitioned to consist of 180-seconds continuous speed data because: (i) a long speed profile, like a driving cycle over 10 minutes, contains too many traffic patterns to produce stable and representative VSP distributions at a certain travel speed, which is why the fixed driving cycle is questioned to represent the dynamic nature of the real-world traffic; and (ii) on the non-expressways, the average length is about 800 meters and the average travel speed is about 20 km/h, besides, the red time of the signal cycle in an intersection is usually 20-90 seconds. Therefore, the VSP distributions based on the temporal resolution of 180 seconds include both the driving characteristics on the basic road segments and at the intersections.

For each trajectory, the average speed is calculated, according to which this trajectory is put into a facility- and speed-specific trajectory pool (5). The trajectories are grouped into 35 speed intervals on the expressway and 21 intervals on the non-expressway with a result that each speed interval consists of at least 20 trajectories (3,600 records of VSP). The speed interval is 2km/h for both expressway and non-expressway. Then, VSP is calculate for each second of record by using Equations (2) and (3), and VSP distribution is calculated for each facility- and speed-specific trajectory pool by applying Equation (4). Figure 1 illustrates the facility- and speed-specific VSP distributions of Before 2012 and After 2012.

As can be seen, in each speed interval, the VSP distributions of the expressway and non-expressway are significantly different in pattern. The fraction of VSP bin=0kW/ton of the VSP distribution on the non-expressway is significantly higher because of the longer idling mode at the intersections.

However, The VSP distributions of different years are quite similar in pattern on both the expressway and non-expressway. It is observed that the facility- and speed-specific VSP distributions are temporally consistent. A quantitative consistency analysis will be presented later.
VSP Distributions on expressways.
Zhai, Song, Lu, He, and Yu

VSP bin (kW/ton)

(b) VSP Distributions on non-expressways.

Figure 1 Facility- and speed-specific VSP distributions of different years.

VSP Distributions in Different areas

In order to analyze the spatial consistency of the VSP distributions, the vehicle activity data are divided into different area groups. This study uses two methods to divide the data:

(i) the first method is to divide the data into four "sector area" groups, namely "Area 1", "Area 2", "Area 3" and "Area 4", as can be seen in Figure 2 (a);

(ii) the other method is to divide the data into four "annular area" groups:

- "Inside 2nd Ring Area", for the area inside (and including) 2nd Ring Road
- "2nd-3rd Ring Area", for the area from 2nd to (and including) 3rd Ring Road
- "3rd-4th Ring Area", for the area from 3rd to (and including) 4th Ring Road
- "Outside 4th Ring Area", for the area outside of 4th Ring Road

As can be seen in Figure 2 (b). The blue points are the example of GPS records of the vehicle trajectories.
Figure 2 Methods for area division.

(a) Sketch of four sector areas.

(b) Sketch of four annular areas.

Note: Road names in red are expressways and the ones in black are non-expressways.
For each area group, the facility- and speed-specific VSP distributions are developed. Figure 3 illustrates the comparison of VSP distributions between "Inside 2nd Ring" and "Outside 4th Ring" on the expressway and non-expressway. The VSP distributions of other areas in the annular area division follow the similar patterns. It is observed that the facility- and speed-specific VSP distributions are spatially consistent. The VSP distributions of areas in the sector area division are compared and their consistency can also be observed. A quantitative consistency analysis will be discussed later.

(a) VSP distributions on expressways.
Temporal and Spatial Consistency of Facility- and Speed-specific VSP Distribution

Correlation Coefficient of VSP Distributions

The consistency of the facility- and speed-specific VSP distributions in different years and different areas is tested with the Pearson correlation coefficient (17), termed as $r$ in Equation (5).

$$r = \frac{\sigma_{\varphi_A} \varphi_B}{\sigma_{\varphi_A} \sigma_{\varphi_B}}$$  \hspace{1cm} (5)$$

where

- $\varphi_A$ is the fraction in the VSP distribution of $A$;
- $\varphi_B$ is the fraction in the VSP distribution of $B$;
- $\sigma_{\varphi_A} \varphi_B$ is the covariance of the VSP distribution of $A$ and $B$; and
- $\sigma_{\varphi_A}$, $\sigma_{\varphi_B}$ are the standard deviations of the VSP distribution of $A$ and $B$ respectively.

The correlation coefficients of the facility- and speed-specific VSP distributions between different years and different areas are calculated, as listed in Table 1. As can be seen, a very strong linear correlation exists between the VSP
distributions of different years or different areas, with all the correlation coefficients approximately to be "1".

Table 1 Correlation Coefficient of Facility- and Speed-specific VSP Distributions between Different Years and Areas

<table>
<thead>
<tr>
<th>Speed Interval (km/h)</th>
<th>Between Years</th>
<th>Between Areas</th>
<th>Speed Interval (km/h)</th>
<th>Between Years</th>
<th>Between Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>1.000</td>
<td>1.000</td>
<td>38-40</td>
<td>0.995</td>
<td>0.994</td>
</tr>
<tr>
<td>2-4</td>
<td>1.000</td>
<td>1.000</td>
<td>40-42</td>
<td>0.992</td>
<td>0.998</td>
</tr>
<tr>
<td>4-6</td>
<td>1.000</td>
<td>0.999</td>
<td>42-44</td>
<td>0.995</td>
<td>0.993</td>
</tr>
<tr>
<td>6-8</td>
<td>0.999</td>
<td>1.000</td>
<td>44-46</td>
<td>0.991</td>
<td>0.991</td>
</tr>
<tr>
<td>8-10</td>
<td>0.999</td>
<td>0.999</td>
<td>46-48</td>
<td>0.995</td>
<td>0.994</td>
</tr>
<tr>
<td>10-12</td>
<td>0.998</td>
<td>0.998</td>
<td>48-50</td>
<td>0.997</td>
<td>0.990</td>
</tr>
<tr>
<td>12-14</td>
<td>0.996</td>
<td>0.999</td>
<td>50-52</td>
<td>0.996</td>
<td>0.996</td>
</tr>
<tr>
<td>14-16</td>
<td>0.994</td>
<td>0.997</td>
<td>52-54</td>
<td>0.997</td>
<td>0.993</td>
</tr>
<tr>
<td>16-18</td>
<td>0.991</td>
<td>0.999</td>
<td>54-56</td>
<td>0.998</td>
<td>0.994</td>
</tr>
<tr>
<td>18-20</td>
<td>0.987</td>
<td>0.994</td>
<td>56-58</td>
<td>0.997</td>
<td>0.997</td>
</tr>
<tr>
<td>20-22</td>
<td>0.999</td>
<td>0.999</td>
<td>58-60</td>
<td>0.997</td>
<td>0.991</td>
</tr>
<tr>
<td>22-24</td>
<td>0.998</td>
<td>0.998</td>
<td>60-62</td>
<td>0.990</td>
<td>0.994</td>
</tr>
<tr>
<td>24-26</td>
<td>0.997</td>
<td>0.997</td>
<td>62-64</td>
<td>0.994</td>
<td>0.995</td>
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<tr>
<td>26-28</td>
<td>0.998</td>
<td>0.999</td>
<td>64-66</td>
<td>0.991</td>
<td>0.987</td>
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<td>28-30</td>
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<td>0.994</td>
<td>66-70</td>
<td>0.997</td>
<td>0.992</td>
</tr>
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<td>30-32</td>
<td>0.997</td>
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<td></td>
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<tr>
<td>32-34</td>
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<td>0.992</td>
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<tr>
<td>34-36</td>
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<tr>
<td>36-38</td>
<td>0.996</td>
<td>0.991</td>
<td></td>
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</table>

Root Mean Squared Error of VSP Distributions

In order to quantify the differences of the facility- and speed-specific VSP distributions in different years or areas, the indicator of root mean squared error (RMSE) is employed (7). A higher value of RMSE means a higher level of difference between two VSP distributions. The RMSE is calculated using Equation (6).

\[
RMSE_{A,B} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\varphi_{A,i} - \varphi_{B,i})^2}
\]  (6)

where

\[
RMSE_{A,B} \text{ is the RMSE of the VSP distribution of } A \text{ and } B;
\]

\[
\varphi_{A,i} \text{ is the fraction of the } i^{th} \text{ VSP bin in the VSP distribution of } A;
\]

\[
\varphi_{B,i} \text{ is the fraction of the } i^{th} \text{ VSP bin in the VSP distribution of } B; \text{ and}
\]

\[
n \text{ is the number of VSP bins in each VSP distribution, which is 41 in this study.}
\]

Figure 4 illustrates the RMSEs of the VSP distributions in different years or areas on the expressway and non-expressway. The RMSEs of the VSP distributions between different road types are illustrated as a reference of comparison.
As can be seen in Figure 4, the RMSEs of the VSP distributions between different years or different areas are significantly lower than those between different road types. The maximum RMSE of the VSP distributions of "Expressway vs. Non-expressway" is as high as 30.3*10^{-3}, while the one between different years or areas is 5.9*10^{-3} (2.3*10^{-3} in average) on the expressway and 6.1*10^{-3} (2.4*10^{-3} in average) on the non-expressway. The maximum temporal and spatial differences of the facility- and speed-specific VSP distributions are approximately 1/5 of the differences related to road type.

**Impact of Temporal and Spatial Differences of VSP Distributions on Emissions**

In VSP based microscopic emission models, like the MOVES, emissions for road links are estimated as the product of the time spent in each VSP bin (i.e. VSP distribution or OpMode distribution) multiplied by the corresponding emission rate. The VSP distribution determines the emissions per unit time, and further, the combination of VSP distribution and the average travel speed determines the emissions per unit distance, i.e. the emission factor (3, 18). This paper employs the emission factor in order to evaluate the impact the temporal and spatial differences of the facility- and speed-specific VSP distributions on the emissions.
The emissions data were collected on a chassis dynamometer 2014 in Beijing. Eight LDGVs, including three Citroen c-Elysees and five Hyundai Elantras, were tested based on the New European Driving Cycle (NEDC). The basic parameters of the tested vehicles are listed in Table 2. For each vehicle, 1,180 records of the mass emissions of Carbon Dioxide (CO₂), Carbon Monoxide (CO), Hydrocarbons (HC) and Nitrogen Oxides (NOx) from the tailpipe exhaust, and the corresponding vehicle speed are reported in a second-by-second basis.

### Table 2 Basic Parameters of Tested Vehicles

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Year</th>
<th>Displacement (L)</th>
<th>Curb Weight (kg)</th>
<th>Transmission Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Elysee</td>
<td>2008</td>
<td>1.6</td>
<td>1485</td>
<td>Manual</td>
</tr>
<tr>
<td>Elantra</td>
<td>2008</td>
<td>1.6</td>
<td>1240</td>
<td>Manual</td>
</tr>
</tbody>
</table>

By employing the VSP binning method, the mean emission rates (in the unit of g/s) of CO₂, CO, HC and NOx in various VSP bins are calculated, as well as the data frequency, as illustrated in Figure 5.

![Figure 5 Mean emission rate and data frequency in each VSP bin.](image)

The facility- and speed-specific emission factors are calculated by using Equation (7).

\[
EF_v = 3600 \cdot \frac{1}{v} \sum_i ER_i \cdot VSP \text{ bin} \\
\]

where

- \(EF_v\) is the emission factor in the average speed of \(v\), in the unit of g/km;
- \(v\) is the average speed in the unit of km/h;
- \(ER_i\) is the mean emission rate of the \(i\)th VSP bin in the unit of g/s; and
- \(VSP \text{ bin}_i\) is the time fraction in the \(i\)th VSP bin.

The facility- and speed-specific emission factors of CO₂, CO, HC and NOx between different years are compared, as well as those among different areas. Figure 6 illustrates the absolute value of the relative differences (%) of the emission factors between different years and among different areas. The one between different road types is illustrated as comparison.
For different road types, the maximum of the absolute value of the relative differences for the CO$_2$, CO, HC and NOx emission factors are 11.6%, 8.4%, 4.9% and 20.0% respectively; while for different years, are 2.4%, 2.5%, 1.9%, and 2.5% on the expressway, and 2.2%, 2.2%, 1.8% and 2.6% on the non-expressway respectively; for different areas are 2.3%, 2.5%, 2.0% and 3.0% on the expressway, 2.1%, 1.4%, 0.8%, and 2.3% on the non-expressway respectively.

The maximum relative differences of the emissions caused by road type differences are as high as twenty percent, while approximately two percent by year or
Since the emission rate in each VSP bin is fixed in this study, all the differences of the emissions could be explained with the differences of the VSP distributions. The temporal and spatial differences of the VSP distributions have no significant impact on vehicle emission estimation. Therefore, it implies that it is unnecessary to update the database of the VSP distributions in the emission model regularly. And it is feasible to use the facility- and speed-specific VSP distribution developed in one area in other areas or cities for emission estimation of LDVs.

CONCLUSIONS AND RECOMMENDATIONS

This study develops and compares the facility- and speed-specific VSP distributions of different years, as well as those in different areas in Beijing. The RMSE is employed to indicate the temporal and spatial consistency of the VSP distributions. Main findings are summarized as follows:

(iii) The characteristics of the facility- and speed-specific VSP distributions are highly consistent temporally and spatially. A very strong linear correlation exists between the VSP distributions between different years or different areas, with all the correlation coefficients approximately to be "1". The result of the case study in Beijing shows that the maximum difference of the VSP distributions among different years or areas is approximately 1/5 of that among different road types.

(iv) The temporal and spatial differences of the facility- and speed-specific VSP distributions have no significant impact on vehicle emissions estimation. The differences of CO₂, CO, HC and NOₓ emissions caused by temporal and spatial differences of the VSP distributions are less than 3%.

(v) The study in Beijing implies that it is unnecessary to update the database of the VSP or OpMode distributions regularly for developing regional emission inventory. And it is feasible to use the facility- and speed-specific VSP distribution developed in one area to represent the vehicle operation mode in other areas or cities for emission estimation of LDVs.

VSP or OpMode distribution is a critical parameter in emission estimation. This paper focuses on the temporal and spatial consistency of the VSP distributions in Beijing within a decade. The differences of the VSP distributions over decades might be significant, further study is needed to confirm or deny this assumption. It is recommended that other factors that may affect the consistency of VSP distributions, such as driver’s gender or aggressiveness, vehicle loads of freight trucks or transit buses, should be further investigated for the purpose of emission estimations.

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