Applications of Speed Variance in Measuring Freeway Level of Service and in Air Emissions Evaluation

11/15/2013
Resubmitted for presentation at 2014 TRB Annual Meeting

Word count: 7,150
Words = 5,400
Figures 5 * 250 = 1,250
Tables 2 * 250 = 500

Chih-Lin Chung*
Department of Transportation Management,
Tamkang University
New Taipei City, Taiwan
Tel: +886-2-2621-5656 ext. 2518
E-mail: cchung@mail.tku.edu.tw

Will Recker
Institute of Transportation Studies,
University of California, Irvine
4000 Anteater Instruction and Research Bldg (AIRB)
Irvine, CA 92697-3600
Tel: (949) 824-5642, Fax: (949) 824-8385
Email: wwrecker@uci.edu

* Corresponding author
ABSTRACT

Speed variance is an important, but overlooked, parameter in traffic studies. This paper examines the use of statistical relationships between speed variance and the fundamental parameters—density, average speed, and flow—to support applications of speed variance via those fundamental parameters to two important aspects of traffic operations. First, it is proposed that speed variance be used to measure freeway level of service from A through E in the context of “no more \( x \)% of the vehicles with travel time up to \( y \)% greater than the free flow condition.” It is argued that such a measure not only reflects mobility (\( y \)%), reliability (\( x \)%), and potentially safety, but also avoids the vague descriptions associated with each service level in the current HCM. Second, the relationships are applied to estimate speed distribution for the MOVES mobile source air emission model. A revised approach is developed and compared to that in the current model. It is argued that the MOVES model’s approach limits the distribution in two speed bins, results in unsupported speed variance, and may cause identical distributions under various average speeds. The proposed revised approach based on speed variance generates specific spread-out distributions consistent with empirical data. The findings of these two applications bring new concepts to the current practice. Suggestions are made to fix the deficiencies of the existing and proposed approaches in the applications.

Keywords: speed variance, coefficient of variation of speed, standard deviation of speed, freeway operations, air emissions
INTRODUCTION

Speed variance, a parameter that assesses differences among individual speeds, typically is measured by the coefficient of variation of speed (CVS) or standard deviation of speed (SDS). Wardrop (1952) derived CVS as the square root of time mean speed (TMS) over space mean speed (SMS) minus one, or $CVS = \sqrt{(TMS / SMS)} - 1$. Rakha and Zhang (2005) indicated that 0.1 to 0.3 differences between TMS and SMS are not uncommon when traffic is congested. Based on Wardrop as well as Rakha and Zhang, CVS could be as high as 0.55. Alternatively, May (1990) indicated that CVS might range from approximately zero to something on the order of the reciprocal of the square root of the mean speed, and typically ranges from 0.08 to 0.17 in empirical studies. This range, however, has been shown to be somewhat conservative. Del Castillo and Benitez (1995) set CVS 0.15 or less, as a rule of thumb, as the boundary between stationary and non-stationary traffic regimes. Based on empirical data from a Dutch motorway, Treiber et al. (1999) report CVS values from 0.09 to 0.25. Wang et al. (2007) collected data from two Chinese urban highways with CVS between 0.07 and 0.32. More recently and more extensively, Chung and Recker (2010) analyzed nearly a quarter million individual speeds on the 10-lane Interstate 80 in northern California, and found CVS that ranged from 0.08 to more than 0.5. As for SDS, the range is about from 2 to 16 mph with a majority between 4 and 13 mph (Sharnar and Mannering 1998, Wang et al. 2007, Chung and Recker 2010).

Studies focused on relating speed variance to the fundamental traffic-stream parameters likely have been undertaken because, while important for certain studies, direct measurement of speed variance is inaccessible to most traffic management centers that capture only the fundamental parameters. Sharnar and Mannering (1998) applied regression analysis to explain standard deviation of speed (SDS), another common measure for speed variance as CVS multiplied by average speed. They found that the lane-by-lane SDS is correlated with SDS of the adjacent lanes, average speed, various dummy variables of time, and truck-to-passenger car flow ratio. Those data were collected from a rural section of the Interstate 90 in Washington State. The associated overall $R^2$ values were 0.31 to 0.33 with large sample sizes over 2,000. Treiber et al. (1999) approximated the square of CVS as a hyperbolic tangent function of density. Such approximation displays positive correlation between the square of CVS and density during the stationary regime. Under specific average speed levels, Wang et al. (2007) proposed flow as an exponential equation of SDS with $R^2$ from 0.26 to 0.74, given small sample sizes less than 15. They also estimated traffic density as an exponential equation of CVS with an $R^2$ of 0.34 using a sample size of about 40. Notable deficiencies in the above studies include small sample size (less than 30), low $R^2$ (less than 0.35), and uncommon relationships (hyperbolic tangent function).

Although not abundant, there are examples of the potential for CVS to be a useful measure to guide traffic management policy decisions. For example, safety studies have identified that not
only speed, but speed variance kills (Baruya 1997; TRB 1998). Speed variance has also been applied to pricing high-occupancy toll lanes and to deriving value of reliability (Chung and Recker 2011; Brownstone and Small 2005). Nonetheless, studies on speed variance are relatively incomplete compared to those focused on the fundamental traffic-stream parameters—density, average speed, and flow. The objectives of this research are to: 1) review and verify the relationship between speed variance and the fundamental traffic parameters, 2) present two applications of speed variance on freeway operations and air emissions, and 3) foster greater attention to the potential uses of speed variance as the subject of future studies.

**METHODOLOGY**

We here provide more comprehensive relationships between speed variance and each of the individual fundamental parameters (flow, density, speed) as the basis for succeeding applications. Raw data from the loop detectors on California Interstate 80 in Berkeley were collected for two weekdays in November 2008. Each direction has one high-occupancy vehicle (HOV) lane during 5-10 A.M. and 3-7 P.M., and four lanes for general purpose traffic. The HOV hours, that already cover off-peak, transitional, and peak periods, are analyzed to exclude the non-HOV-hour effects. We exogenously calculate $CVS$ and $SDS$ from individual speeds since the detectors do not produce speed variance. Occupancy from the detectors is converted to density by a multiplier (the $g$ factor) of 2.1. Datasets containing $CVS$, $SDS$, density, flow, and average speed are compiled on a 5-min basis with the sample size of 206 observations.

Figure 1(a) plots the observations and exhibits commonly recognized relationships between the fundamental parameters: wilder fluctuations in the congested state, a gap around the critical point (queue discharge regime), and a stable speed during light traffic. The scatter plots in Figure 1(b) do not support any valid relationships between $SDS$ and the fundamental parameters, other than the obvious conclusion that $SDS$ in the congested state is generally greater than in the uncongested state.

Focus is given to $CVS$ for which—are analyzed. Figure 2, which displays results that $CVS$ is highly significantly correlated with the three fundamental parameters. First, the results indicate that $CVS$ fits a negative exponential function of average speed with an $R^2$ of 0.91. Second, $CVS$ can be explained by an exponential form of density at $R^2$ of 0.83. This finding is the reverse of that due to Wang et al. (2007), who suggested density be exponential of $CVS$. Given that the dataset used here is larger and that the $R^2$ here is more significant than the study of Wang et al., we suggest $CVS$ more properly be an exponential function of density. Third, flow and $CVS$ hold a two-phase linear relationship that respectively corresponds to the congested and uncongested states. The two lines tend to intersect at around the lane capacity and the median $CVS$ of the uncongested state. These case specific relationships between $CVS$ and the fundamental

TRB 2014 Annual Meeting

Paper revised from original submittal.
parameters are expressed by Eqs. (1) ~ (3), which were shown valid for general traffic patterns by approximating the enumerated situations to the proposed forms within an acceptable level (Chung 2010).

Figure 1 Standard Deviation of Speed (SDS) and the Fundamental Parameters

- \( CVS \) and average speed \((S)\): \( CVS = \alpha \exp(\beta S) \)
  where \( \gamma \) is positive and \( \delta \) is negative. \hspace{1cm} (1)

- \( CVS \) and density \((D)\): \( CVS = \gamma \exp(\delta D) \)
  where \( \alpha \) and \( \beta \) are positive coefficients. \hspace{1cm} (2)

- \( CVS \) and flow \((F)\):
  \( CVS = \lambda F + \eta \) (congested state); \( CVS = c \) (uncongested state) \hspace{1cm} (3)
  where \( \lambda \) is negative, and \( \eta \) and \( c \) are positive.
Figure 2 Coefficient of Variation of Speed (CVS) vs. the Fundamental Parameters

(a) CVS-speed

(b) CVS-density

(c) CVS-flow
In summary, CVS is favored over SDS when relating speed variance to the fundamental parameters. CVS can be explained by average speed, occupancy, or flow, albeit flow is least suggested due to its insensitivity to CVS in the uncongested state. The relationships in Figure 2 will apply to succeeding applications as the default models. The use of location-specific coefficients, if available, is encouraged to reflect area disparity.

ALTERNATE LOS MEASURE FOR FREEWAY OPERATIONS

One potential application of speed variance is the freeway level of service (LOS). The Highway Capacity Manual (HCM) defines LOS as a quality measure describing operational conditions within a traffic stream, generally in terms of speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, but not safety (TRB, 2000). LOS of basic freeway segments can be evaluated based on the fundamental traffic parameters. These measures, either in aggregation (like flow) or averages (like density and speed), neglect the impact of traffic variation and present only partial images of the real freeway operations.

HCM-related Approach

An alternative, argued for here, is to develop measures based on speed variance. Such an approach can be advanced from different perspectives. For example, by setting density criteria for LOS A through E, the HCM derives the speed and flow criteria from the density-speed-flow relationships under the “base condition,” as shown in the lower diagram of Figure 3. In a similar fashion, we can construct CVS–density criteria via the default relationship built earlier, as shown in the upper diagram of Figure 3. If the corresponding speed is available, SDS-based criteria can be created through CVS multiplied by speed.

Another approach is through HCM’s speed criteria for LOS and the default CVS-speed relationship to get CVS-based criteria. The speed variance criteria, however, are not obtainable via flow measurements to which CVS is not sensitive.
Mobility- and Reliability-related Approach

In contrast to the HCM-related approaches, use of CVS to characterize LOS allows joint consideration of travel mobility and reliability via a single speed variance measure. This can be accomplished by defining LOS \( i \) as determined by the \( k \)th percentile travel time \( t_t^{k\text{th}} \) no greater than \( m_i \) times the free flow travel time \( t_f \), where \( m_i \) is a multiplier greater than 1 and increases with LOS \( i \). Such measurement relates mobility to \( m_i t_f \) and reliability to \( t_t^{k\text{th}} \), as expressed in Eq. (4) for travel time \( t_t \), or in Eq. (5) for standardized travel time \( T_T \) by setting \( t_f \) as 100.
LOS $i$: $tt^{k\%ile} \leq mttf$, for $i$ from A to E numbered as from 1 to 5  

(4)

LOS $i$: $TT^{k\%ile} \leq M_i$  

(5)

where $M_i = 100m_i$ and $TT^{k\%ile}$ is the $k$th percentile of standard travel time.

As generally recognized (see, e.g., May. 1990; McShane and Roess; 1990; Chung, 2010), speeds can be assumed normally distributed. Such assumption and the default CVS-speed relationship ($CVS = 0.9318e^{-0.036S}$ or $SDS = S \times 0.9318e^{-0.036S}$) can generate the speed distribution and its cumulative probability, as shown in Figures 4(a) and 4(b), and expressed in Eqs. (6) and (7). Figure 4(c) displays the cumulative probability of standardized travel time with respect to average (mean) speed $S$, as expressed in Eq. (8).

$$f(v) = \frac{1}{\sqrt{2\pi}SDS} e^{\frac{(v-S)^2}{2SDS^2}}$$

(6)

where $f(v)$ is the probability density function of speed $v$ that is normal distribution with average speed $S$ and standard deviation $SDS$.

$$P(v) = \text{prob}(v \leq r) = \int_{v=0}^{r} \frac{1}{\sqrt{2\pi}SDS} e^{\frac{(v-S)^2}{2SDS^2}}$$

(7)

where $P(v)$ is the cumulative probability of speed $v$ less than a certain level $r$.

$$P(tt) = \text{prob}\left( tt \leq \frac{L}{q} \right) \equiv P(TT) = \text{prob}\left( TT \leq 100 \frac{L}{q/ff} \right),$$

where $P(tt)$ ($P(TT)$) is the cumulative probability of (standardized) travel time less than a certain level, and $L$ is the travel length, then

$$P(TT) = P(tt) = \text{prob}\left( \frac{L}{v} \leq \frac{L}{r} \right) = \text{prob}(v \geq r) = \int_{v=r}^{\infty} \frac{1}{\sqrt{2\pi}SDS} e^{\frac{(v-S)^2}{2SDS^2}} = 1 - P(v)$$

(8)
Figure 4: Speed and Travel Time Distribution with respect to Average Speed

(a) Probability Density of Speed with respect to Average Speed

(b) Cumulative Probability of Speed with respect to Average Speed

(c) Cumulative Probability of Travel Time with respect to Average Speed
We can turn Eq. (5) into:

\[ \text{LOS } i: \quad TT^{k\%ile} = 100 \left( \frac{t^{k\%ile}}{t_f} \right) = \frac{100 ffs}{v^{(100-k)\%ile}} = \frac{100 ffs}{S + Z(100-k)SDS} \leq M_i \quad (9) \]

where \( ffs \) is free flow speed, and \( Z \) is the standardized unit in the normal distribution. By setting

free flow speed of 70 mph, \( k \) of 60 (that corresponds to \( TT^{60\%ile} \), \( Z(40) \approx -0.25 \), and \( P(TT) = 0.6 \)), and \( M_i \) of 102, 110, 120, 140, and 180, respectively, for LOS A through E, for example, we can determine the following criteria for LOS:

**LOS A:** No more 60% of the vehicles with travel time up to 2% greater than the free flow condition:

\[
\frac{7000}{S - 0.25SDS} \leq 102 \implies \text{(average) speed} \geq 70.0 \text{ mph, } SDS \leq 5.3 \text{ mph, and } \]

\[ CVS \leq 0.08 \]

**LOS B:** No more 60% of the vehicles with travel time up to 10% greater than the free flow condition: speed \( \geq 65.1 \text{ mph, } SDS \leq 5.9 \text{ mph, and } [CVS \leq 0.09] \)

**LOS C:** No more 60% of the vehicles with travel time up to 20% greater than the free flow condition: speed \( \geq 60.0 \text{ mph, } SDS \leq 6.5 \text{ mph, and } [CVS \leq 0.11] \)

**LOS D:** No more 60% of the vehicles with travel time up to 40% greater than the free flow condition: speed \( \geq 51.9 \text{ mph, } SDS \leq 7.5 \text{ mph, and } [CVS \leq 0.14] \)

**LOS E:** No more 60% of the vehicles with travel time up to 80% greater than the free flow condition: speed \( \geq 41.1 \text{ mph, } SDS \leq 8.8 \text{ mph, and } [CVS \leq 0.21] \)

The results can also be derived from Figure 4(c) by projecting the standardized travel time onto the plain of the cumulative probability and average speed. Given the above pre-set situation, each criterion is simply the intersection of the projected travel time curves and the line of \( P(TT) = 0.6 \), as shown in Figure 5.

Instead of fixing \( k \) and varying \( M_i \), the other potential settings are \( k \) of 99, 85, 60, 25, and 5 for LOS A through E, and \( M_i \) of 120. The respective \( CVS \) criteria become 0.07, 0.09, 0.11, 0.14, and 0.19, which can also be generated from the curve of standardized travel time of 120 (i.e., \( TT = 120 \)) with respect to different cumulative probability of \( TT \) in Figure 5.
Discussion

The results of the two HCM-related approaches are compiled in Table 1, which shows the speed variance criteria through density and those through speed are, as expected, not the same. This is because the dataset used to construct the \( CVS \)-density-speed relationships does not have an identical density-speed pattern as the one that HCM adopts. Also, use of the \( g \) factor to convert occupancy to density is likely responsible for the difference. The \( g \) factor may be location-specific and needs to be determined with caution; here, we arbitrarily employ one value for illustrative purpose. Although both HCM approaches are acceptable, we suggest choosing the speed variance criteria derived from density that is more sensitive to a broad range of traffic conditions than from speed and flow (TRB 2000; ITE 1999). \( CVS \) is also favored over \( SDS \) for two reasons. First, \( CVS \) substantially considers both speed and speed variance and is more sensitive to the change of traffic conditions. Second, \( SDS \) is indirectly related to the fundamental parameters through \( CVS \).

The mobility- and reliability-related approach allows LOS expressed as “no more \( x \)% of the vehicles with travel time up to \( y \)% greater than the free flow condition.” Such expressions are specific and quantified, unlike the current definition of LOS B that represents \textit{reasonably} free flow, LOS C that provides for flow with speed at or \textit{near} free flow speed, LOS D that speeds begin to decline \textit{slightly} and density begins to increase \textit{somewhat more quickly}, and so on.
The concept of the mobility- and reliability-related approach is distinct from that of the HCM, whereas these two approaches do share some things in common. As shown in Table 1, both display a consistent trend—speed variance thresholds increasingly rise as LOS drops from A to E. The criteria values are somewhat similar for the uncongested state. Also, both approaches result in the general recognition, as mentioned by Del Castillo and Benitez (1995), that \( CVS \) of 15% serves as a transitional point from the uncongested to congested states.

Adoption of either the HCM or the mobility and reliability approach will depend on the data availability, decision makers’ concerns, motorists’ perception, etc. We do not suggest replacing the existing density-based LOS criteria by the speed variance. Rather, such a measure provides an alternative view that the conventional measure is missing. For example, the density criterion for LOS C is 26 pc/mi/ln—a somewhat uncongested traffic—which correspond to \( CVS \) of 0.14, and 60% (25%) of the vehicles can finish their trips within 40% (20%) more than the free flow travel time—less favorable LOS D in terms of reliability and mobility, as shown in Table 1. The same condition is presented on different aspects with distinct images.

Table 1 Speed Variance-based LOS Criteria for Basic Freeway Segments

<table>
<thead>
<tr>
<th>Approach</th>
<th>LOS Criteria</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM-related</td>
<td>Max density</td>
<td>11</td>
<td>18</td>
<td>26</td>
<td>35</td>
<td>45</td>
<td>The HCM density criteria in pc/mi/ln</td>
</tr>
<tr>
<td></td>
<td>Max ( CVS )</td>
<td>0.09</td>
<td>0.11</td>
<td>0.14</td>
<td>0.19</td>
<td>0.27</td>
<td>Figure 2(b): ( CVS = 0.0618e^{0.0327D} )</td>
</tr>
<tr>
<td></td>
<td>Min speed</td>
<td>70.0</td>
<td>70.0</td>
<td>68.2</td>
<td>61.5</td>
<td>53.3</td>
<td>The HCM speed criteria in mph</td>
</tr>
<tr>
<td></td>
<td>Max ( CVS )</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
<td>0.10</td>
<td>0.14</td>
<td>Figure 2(a): ( CVS = 0.9318e^{-0.036S} )</td>
</tr>
<tr>
<td></td>
<td>Max SDS</td>
<td>4.9</td>
<td>4.9</td>
<td>5.5</td>
<td>6.2</td>
<td>7.5</td>
<td>( SDS = CVS \times S ) (( SDS ) in mph)</td>
</tr>
<tr>
<td>Mobility &amp; reliability-related</td>
<td>Reliability</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>% of vehicles within the travel time criteria</td>
</tr>
<tr>
<td></td>
<td>Mobility</td>
<td>102</td>
<td>110</td>
<td>120</td>
<td>140</td>
<td>180</td>
<td>Free flow travel time = 100</td>
</tr>
<tr>
<td></td>
<td>Max ( CVS )</td>
<td>0.08</td>
<td>0.09</td>
<td>0.11</td>
<td>0.14</td>
<td>0.21</td>
<td>Figure 2(a): ( CVS = 0.9318e^{-0.036S} )</td>
</tr>
<tr>
<td></td>
<td>Max SDS</td>
<td>5.3</td>
<td>5.9</td>
<td>6.5</td>
<td>7.5</td>
<td>8.8</td>
<td>( SDS = CVS \times S ) (( SDS ) in mph)</td>
</tr>
<tr>
<td>Reliability</td>
<td>99%</td>
<td>85%</td>
<td>60%</td>
<td>25%</td>
<td>5%</td>
<td></td>
<td>% of vehicles within the travel time criteria</td>
</tr>
<tr>
<td></td>
<td>Mobility</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>Free flow travel time = 100</td>
</tr>
<tr>
<td></td>
<td>Max ( CVS )</td>
<td>0.07</td>
<td>0.09</td>
<td>0.11</td>
<td>0.14</td>
<td>0.19</td>
<td>Figure 2(a): ( CVS = 0.9318e^{-0.036S} )</td>
</tr>
<tr>
<td></td>
<td>Max SDS</td>
<td>5.2</td>
<td>5.9</td>
<td>6.4</td>
<td>7.3</td>
<td>8.3</td>
<td>( SDS = CVS \times S ) (( SDS ) in mph)</td>
</tr>
</tbody>
</table>

Note: The rounded \( CVS \) may correspond to slightly different \( SDS \) (enlarged by average speed).

In addition to the consideration of mobility and reliability, \( CVS \) simultaneously contains average speed and standard deviation associated with the prior research findings that “speed and speed variance kill.” As noted in the HCM, safety is not included in the current LOS measures.
Use of CVS alone or jointly with other measures for LOS could potentially cover such aspects as safety, mobility, and reliability. Because safety involves many factors and could be location-specific, we simply point out such potentiality and suggest this issue for future study.

Speed variance-based criteria result from the equations (relationships) between the fundamental parameters and CVS. More investigations are required to obtain generally recognized equation coefficients; albeit our default settings comply with the common observations and the exponential forms were verified to be general. The original LOS criteria from the HCM were determined by the professional judgment (TRB, 2000). Likewise, those settings of $TT^{1-k\%}$ and $M_i$ under the mobility- and reliability-related approach are proposed through some simple judgment for illustrative purpose; in-depth analysis and evaluation on these settings are needed to properly reflect each service level.

Another issue is the area disparity. The HCM applies the universal diagrams by free-flow speed to all urban areas (see the lower ones in Figure 3). It may not be the case for CVS due to various regional driving cultures. Such driving cultures (e.g., the percentages of aggressive and conservative motorists, and how they drive on the road) are likely neutralized by the fundamental parameters that are either an aggregation or average. But those driving cultures could be highlighted by speed variance that reveals the individual differences. It is suggested that each urban area conduct the CVS investigations and build up its own CVS diagrams.

REVISED SPEED/VHT DISTRIBUTION FOR AIR EMISSION MODELS

A second potential application of speed variance is in the area of mobile source emissions modeling. MOVES (MOtor Vehicle Emissions Simulator), a model designated by the U.S. Environmental Protection Agency (EPA) to estimate air pollution emissions from mobile sources in official State Implementation Plan and for certain transportation conformity analyses outside of California, supersedes MOBILE that had been used since 1978. One of the input items for MOVES is the vehicle hours traveled (VHT) distribution assigned to sixteen speed bins. The first bin is for speeds less than 2.5 mph, followed by 5-mph increments until speeds greater than 72.5 mph. The average speeds of each bin are accordingly 2.5, 5, 10, ..., 65, 70, and 75.

EPA’s Approach

There are several ways to obtain the speed distribution. One, recommended by EPA (2010), is to post-process the output from local travel demand network models that estimate speed primarily as a measure of impedance to travel. However, no further illustrations are given on how to properly post-process the modeled speed for input to MOVES. When only a single average speed is available for a particular road type, EPA (2010) provides a general formulation
that inversely splits the distribution (probability) by the difference between the single average speed $\mu$ and the adjacent speed bins $A$ and $B$ in a scale of $d$ mph, i.e.,

$$\begin{align*}
\text{The value for bin } A \text{ or } P_A &= \frac{B - \mu}{d}, \\
\text{The value for bin } B \text{ or } P_B &= \frac{\mu - A}{d},
\end{align*}$$

where $B - A = d = 5$ \hspace{1cm} (10)

Such a split has some characteristics: 1) It is analogized to the lever principle, where $\mu$ is the fulcrum, $B - \mu$ and $\mu - A$ are the lengths of the lever arms, and $P_A$ and $P_B$ are the forces. The longer the arm length is, the smaller the force will be to balance a lever with the same torque on each end. 2) A single average speed $\mu$ leads to the same split in its adjacent speed bins as $\mu \pm 5n$ does, where $n$ is an integer. 3) The average speed will be split only into the adjacent two bins. Should the single average speed be $5n$, the distribution will be completely assigned to the $5n$ bin. 4) Such a speed split can represent the VHT distribution.

**Revised Approach**

As noted earlier, individual speeds have been found to be normally distributed. Given a normal distribution with average speed $S$ and standard deviation $SDS$, the speeds will primarily fall within the range of $S \pm 2SDS$ that may span more than two bins. Also, the speed distribution is not VHT-based without certain transformations. Given the average speed of 53.7 mph for a freeway, for example, we could apply the default CVS-speed relationship for the VHT distribution, as shown in the following six steps:

1. $CVS = 0.1348 = 0.9318e^{-0.036S}|S = 53.7; \quad SDS = 7.2 \text{ mph.}$

2. 97.7% of the individual speeds fall within $S \pm 2SDS$, or from 39.2 to 68.2 mph that covers seven bins of 40, 45, 50, 55, 60, 65, and 70. The remaining 2.3% of the speeds are proportionally grouped into each bin.

3. Looking up the normal distribution table results in the speed distribution $P^{spd}_i$.

4. Each bin does not follow a uniform distribution. Speed bin $i$ should be represented as

$$S_i + Z_i\left(\frac{p[Z_i + p[Z_{hi}]]}{2}\right)SDS \text{ instead of as } \left(\frac{s_{li} + s_{hi}}{2}\right) = S_i,$$

where $s_{li}$ and $s_{hi}$ are the two bounds of bin $i$ that respectively correspond to the standardized $Z_{li}$ and $Z_{hi}$ while $P[Z_{li}]$ and $P[Z_{hi}]$ are the cumulative probabilities given the $Z$ values. These two values are very close
after the speed distribution is divided into multiple bins more than five. We thus use the simple averages, the same way used in MOVES, to represent the speed bins.

5. Although MOVES mixes the speed distribution $P_{i}^{spd}$ with the VHT distribution $P_{i}^{vht}$, these two are not identical but convertible through Eqs. (11) and (12).

$$VHT_{i} = \frac{VMT_{i}}{S_{i}} = \frac{q_{i}L}{S_{i}} = \frac{P_{i}^{spd} Q L}{S_{i}} \tag{11}$$

$$P_{i}^{vht} = \frac{VHT_{i}}{\sum_{i} VHT_{i}} = \frac{P_{i}^{spd} / S_{i}}{\sum_{i} P_{i}^{spd} / S_{i}} \tag{12}$$

where $VMT_{i}$ is the vehicle miles travels in speed bin $i$, $L$ is the trip length, and $q_{i}$ is the volume in speed bin $i$. $q_{i}$ is the volume $Q$ multiplied by the corresponding speed distribution.

6. In the case that the given data are for individual freeway stretch $j$ in a sub-hourly period $t$, we can expand the VHT distribution to be hourly-based, as required by MOVES, and to the freeway corridor for air emission studies in a similar fashion by temporal and spatial aggregations, as shown in Eq. (13).

$$P_{i}^{vht} = \frac{VHT_{i}}{\sum_{i} VHT_{i}} = \frac{\sum_{j} \sum_{i} P_{ij}^{spd} Q_{ij} L_{j} / S_{ij}}{\sum_{i} \sum_{j} \sum_{t} P_{ij}^{spd} Q_{ij} L_{j} / S_{ij}} \tag{13}$$

Discussion

Vehicle speed and acceleration have a significant effect on vehicle emissions (EPA, 2010). Although EPA provides a formula to develop average speed distribution via a single average speed, it should be used only when underlying speed distribution data are not available. For illustrative purpose, we apply Eqs. (11) and (12) to the VHT distribution calculation under the average speed of 53.7 mph, along with two additional scenarios of 43.7 and 60.0 mph in contrast. The results are compared to those from the EPA’s approach.

As shown in Table 2, the EPA’s approach leads to the same distribution for 53.7 and 43.7 mph in their adjacent bins, and the average speed of 60 mph entirely falls into the 60 bin. The simple split somewhat diminishes EPA’s intent of dividing the speed into sixteen bins. We may regard such a split as the “all-or-nothing assignment” borrowed from a technique used in the route choice since the adjacent bins are assigned all, while non-adjacent ones are assigned nothing.
Alternatively, the revised approach results in “spread-out assignment” among the speed bins. One average speed will generally span more than five bins based on the given CVS-speed relationship. For the selected average speeds of 53.7 and 43.7 mph, their distributions are different and respectively span seven and eight bins. The central bins have higher values than the side bins as a result of normal distribution. The single average speed of 60 mph will span multiple bins that reflect the speed variation. Also, the VHT distribution weights slow speed more heavily, making $P_{i}^{vht}$ greater (less) than $P_{i}^{quad}$ in the lower (higher) bins.

Due to the all-or-nothing assignment, if the speed bins were in a scale smaller (bigger) than 5 mph, the EPA’s approach would incur a sharper (flatter) distribution that still falls into the two adjacent bins. The proposed revised approach would also be affected by the change of scale but to a less significant level because of the spread-out assignment. To be specific, both approaches have the same average speed, but the EPA’s approach shown in Eq. (10) leads to standard deviation of $d\sqrt{P_{i}P_{B}}$, which could be somewhere between 0 and 0.5$d$ or 2.5 mph, while the revised approach obtains standard deviation from the field CVS-speed relationship which appears primarily around 5 to 9 mph. With the range of standard deviation much larger than the EPA’s, the revised approach is expected to generate greater air emission estimates.

Instead of making impetuous judgment on which approach is proper, it is better to think about an issue of the adequacy of the speed bins measured by $d = 5$ mph. The scale has a direct and dominant influence on standard deviation of speed for the EPA’s approach, in which the interrelationship between average speed, standard deviation of speed, and $d$ is not explained. Should $d$ of 5 be adopted due to its popularity, 10 or 15 could also be an option that results in standard deviation of $10\sqrt{P_{i}P_{B}}$ or $15\sqrt{P_{i}P_{B}}$. In this case, the EPA’s approach with speed bins by $d = 15$ mph will produce air emission estimates closer to the revised approach.

As mentioned earlier, urban areas may have their own driving cultures that correspond to different CVS-speed relationships. Such differences will not be reflected by the EPA’s approach with a fixed bin scale $d$ but by the revised one through the location-specific CVS-speed relationship that alters the speed (VHT) distribution in the air emission model. It is suggested that the EPA’s approach adopt location-specific $d$ like 5, 10, or 15 that fits the local speed variance characteristics.

Change of scale $d$ will affect the number of bins which an average speed will span. Such a scale as 15 mph will eliminate the number to as few as two or three, making the approach no longer spread-out. As a result, it is suggested that the revised approach remain the fixed and small scale of 5 mph.
### Table 2 Speed and VHT Distribution for Various Average Speeds

<table>
<thead>
<tr>
<th>Speed bin (i) by MOVES ((v_{li} - v_{hi})) in mph</th>
<th>Range of the (Z) values (Z_{li} \sim Z_{hi})</th>
<th>Speed Distribution (P_{i}^{spd}) (Total = 1)</th>
<th>VHT Distribution (P_{i}^{vht}) (Total = 1)</th>
<th>VHT Distribution by MOVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S = 53.7) (SDS = 7.2)</td>
<td>1. 40 (37.5 ~ 42.5)</td>
<td>(-2.24 ~ -1.55)</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>2. 45 (42.5 ~ 47.5)</td>
<td>(-1.55 ~ -0.86)</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>3. 50 (47.5 ~ 52.5)</td>
<td>(-0.86 ~ -0.17)</td>
<td>0.24</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>4. 55 (52.5 ~ 57.5)</td>
<td>(-0.17 ~ 0.52)</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>5. 60 (57.5 ~ 62.5)</td>
<td>(0.52 ~ 1.22)</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>6. 65 (62.5 ~ 67.5)</td>
<td>(1.22 ~ 1.91)</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>7. 70 (67.5 ~ 72.5)</td>
<td>(1.91 ~ 2.60)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>(S = 43.7) (SDS = 8.4)</td>
<td>1. 25 (22.5 ~ 27.5)</td>
<td>(-2.51 ~ -1.92)</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>2. 30 (27.5 ~ 32.5)</td>
<td>(-1.92 ~ -1.33)</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>3. 35 (32.5 ~ 37.5)</td>
<td>(-1.33 ~ -0.73)</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>4. 40 (37.5 ~ 42.5)</td>
<td>(-0.73 ~ -0.14)</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>5. 45 (42.5 ~ 47.5)</td>
<td>(-0.14 ~ 0.45)</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>6. 50 (47.5 ~ 52.5)</td>
<td>(0.45 ~ 1.04)</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>7. 55 (52.5 ~ 57.5)</td>
<td>(1.04 ~ 1.63)</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>8. 60 (57.5 ~ 62.5)</td>
<td>(1.63 ~ 2.23)</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>(S = 60) (SDS = 6.4)</td>
<td>1. 45 (42.5 ~ 47.5)</td>
<td>(-2.71 ~ -1.94)</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>2. 50 (47.5 ~ 52.5)</td>
<td>(-1.94 ~ -1.16)</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>3. 55 (52.5 ~ 57.5)</td>
<td>(-1.16 ~ -0.39)</td>
<td>0.23</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>4. 60 (57.5 ~ 62.5)</td>
<td>(-0.39 ~ 0.39)</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>5. 65 (62.5 ~ 67.5)</td>
<td>(0.39 ~ 1.16)</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>6. 70 (67.5 ~ 72.5)</td>
<td>(1.16 ~ 1.94)</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>7. 75 (72.5 &lt; )</td>
<td>(1.94 &lt; )</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

Speed variance can be obtained from its relationships with the fundamental traffic stream parameters commonly available to researchers and traffic management centers. It was found that \(CVS\) can be well explained by average speed, density, and flow in the negative exponential, exponential, and two-phase linear forms, respective. Such relationships enable different applications of speed variance.
One is to establish speed variance-based criteria that LOS A through E can be quantitatively gauged as “no more $x\%$ of the vehicles with travel time up to $y\%$ greater than the free flow condition.” $y\%$ serves as a mobility indicator and $x\%$ is a reliability indicator. This approach avoids the vague expressions of LOS and assesses such aspects as mobility, reliability, and potentially safety not considered by the current measures. In the selected case, the density criterion for LOS C is 26 pc/mi/ln—somewhat uncongested traffic—which correspond to “no more 60% (25%) of the vehicles with travel time up to 40% (20%) greater than the free flow condition”—less favorable LOS D in terms of reliability and mobility.

The other application revises the approach of EPA’s MOVES to estimating speed distribution through a single average speed. The EPA’s approach limits the distribution in two speed bins and results in unsupportive standard deviation. The revised approach leads to a spread-out distribution with standard deviation varying with the average speed. In the selected case, the EPA’s approach undervalues speed variance and is expected to result in underestimated air emissions. While the framework of this study should be valid without area disparity, it is suggested that more investigations be conducted for more accurate and location-specific speed variance values.

**ACKNOWLEDGEMENT**

This research is supported by the National Science Council, Taiwan (NSC 102-2221-E-032-034).

**REFERENCES**

Baruya, A. (1997) A Review of Speed-Accident Relationship for European Roads, Transportation Research Laboratory, Crowthorne, UK.


