Characteristics of Speed Dispersion and Its Relationships with the Fundamental Traffic Flow Parameters in Urban Freeways: A Case Study in Northern California

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Abstract

This research reveals statistical characteristics of speed dispersion and its relationships with fundamental traffic flow parameters in northern California. Nearly a quarter million vehicle observations of a five-lane urban freeway are examined individually by lane and aggregately for a total of seven categories. Speed dispersion is measured by coefficient of variation of speed (CVS) and standard deviation of speed (SDS). CVS displays an exponential form of occupancy or space mean speed, and is two-phase linear to flow. Variation of CVS is stable and similar across lanes during light traffic, and afterward increases and diverges into three groups. SDS in contrast does not present any simple equation of the fundamental parameters. Both CVS and SDS of the all lane mix are greater than those of other categories given fixed occupancy or mean speed.

Keywords: Speed Dispersion, Mean Speed, Flow, Density, Fundamental Diagram

1. INTRODUCTION

Speed dispersion plays a key role in such aspects as traffic safety, travel reliability, operating efficiency, air emission, etc. Unlike the fundamental traffic flow parameters (*flow*, *density*, and *mean speed*), research on the characteristics of speed dispersion is relatively sparse and incomplete. The effects of speed dispersion would be more easily understood by clarifying the relationships between speed dispersion and the fundamental parameters enabling speed dispersion to be estimated via fundamental parameters that are available from standard traffic monitoring equipment. This would not only benefit studies in the associated aspects mentioned above, but also help identify how these parameters affect traffic operations, both individually and collectively.

Among the indicators of speed dispersion, standard deviation of speed (*SDS*) and coefficient of variation of speed (*CVS*), a normalized standard deviation as *SDS* divided by mean speed, are widely used. 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 normally ranges from 8% to 17% in the empirical studies, which is shown to be somewhat conservative in Section 3. Del Castillo and Benitez (1995) set *CVS* 15% or less to filter off the non-stationary regime, but the relationship between *CVS* and the fundamental parameters was not mentioned. Wang et al. (2007) proposed *flow* as an exponential function of *SDS* and *density* as an exponential function of *CVS* that distribute from 7% to 32%. Treiber et al. (1999) adopted *CVS* square as a hyperbolic tangent function of *density*; such adoption displays positive correlation between *CVS* square and *density* during the stationary regime. Sharnar and Mannering (1998) explained lane-by-lane *SDS* by *SDS* of adjacent lanes, mean speed, various dummy variables of time, and truck-to-passenger car flow ratio. We note that not every study referenced above specifies *CVS* and *SVS* with respect to either space mean speed or time mean speed, but rather to a general term “average speed”—such findings are still valuable but should be used with caution.

This paper is organized as follows: Section 2 illustrates how the dataset used to analyze the relationships between speed dispersion and the fundamental parameters is obtained from double loop detectors. A comparison is made between the observed speed dispersions and those reported in the literature. Section 3 describes empirical data collection and time-of-day traffic patterns; Sections 4 and 5 analyze the characteristics of speed dispersion by regression and descriptive statistics. Finally, conclusions are made together with suggestions for future applications.

2. MATHEMATICAL DESCRIPTION

Double loop detectors do not directly produce speed dispersion. Raw data that record on and off time of loop occupancy are used to exogenously compute individual speeds and speed dispersion. The procedure for populating the complete dataset used in this study is illustrated below.

- Apply equation (1) for individual speeds, as suggested by the Traffic Detector Handbook (2006),

$$v_i = \frac{1}{2}\left(\frac{d}{Td_{i:on} - Tu_{i:on}} + \frac{d}{Td_{i:off} - Tu_{i:off}}\right) \times \frac{60^3}{5280} \qquad (1)$$

  where v_i (in mph) is the speed of individual vehicle *i*, $Td_{i:on/off}$ (in 1/60 seconds) is time that the downstream detector is on/off and $Tu_{i:on/off}$ (in 1/60 seconds) is the time that the upstream detector is on/off with respect to vehicle *i*, and *d* is the distance between the center points (20 ft in this application).

- Within a given time interval (an interval of 5 minutes is used here as it is a basic interval unit of the California Freeway Performance Measurement System), ***space mean speed*** and ***time mean speed*** are simply the harmonic mean speed and arithmetic mean speed, respectively.

$$SMS = \frac{n}{\sum_{i=1}^{n} \frac{1}{v_i}}; \qquad TMS = \frac{\sum_{i=1}^{n} v_i}{n} \qquad (2)$$

  where *SMS* is space mean speed (in mph), *TMS* is time mean speed (in mph), *n* is the vehicle count during the time interval, and the hourly ***flow*** (in vph) is 12*n*.

- Wardrop (1952) verified equation (3) that obtains ***speed dispersions*** for given *TMS* and *SMS*.

$$TMS = SMS + \frac{SD_{sms}^2}{SMS} = SMS\left(1 + CV_{sms}^2\right) \qquad (3)$$

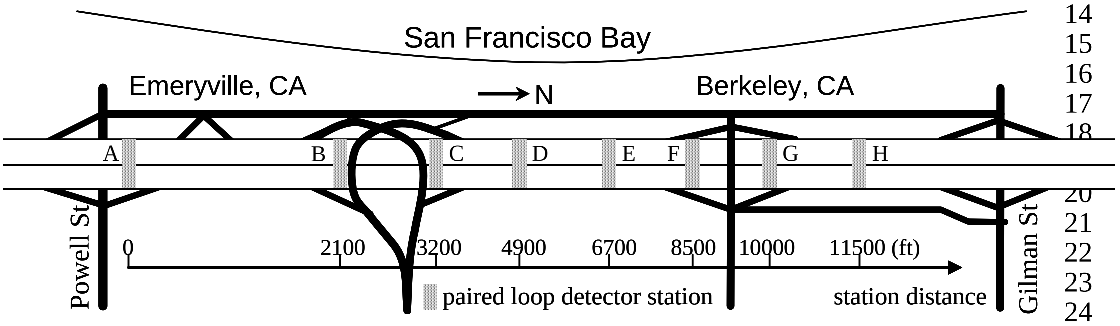
$$\Rightarrow \begin{cases} SD_{sms} = \sqrt{SMS(TMS - SMS)} & (3a) \\ CV_{sms} = \left(\sqrt{\frac{TMS}{SMS}} - 1\right) \times 100\% & (3b) \end{cases}$$

  where SD_{sms} (in mph) is the standard deviation with respect to space mean speed; CV_{sms} (in %) is the coefficient of variation with respect to space mean speed.

- To complete the dataset, 5-minute mean ***occupancy*** (in %) is calculated as the average over its 30-second components. Although *occupancy* is commonly used as a surrogate for the *density* of the traffic over a link, this study neither uses density nor tries to impute density from occupancy.

3. DATA COLLECTION

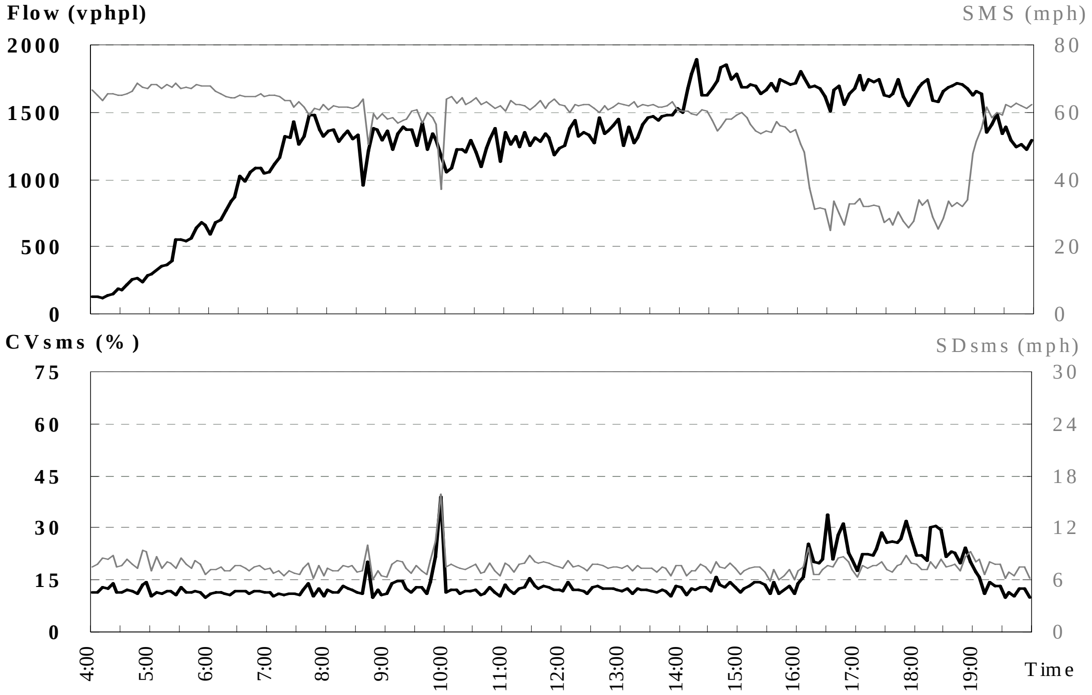
The Berkeley Highway Laboratory provided raw data from eight inductive loop detector stations along a 2-mile freeway testbed on I-80 in Berkeley and Emeryville, California, as shown in FIGURE 1. Station A consists of double loop detectors embedded in 12 lanes while all other stations are comprised of 10 lanes. To maintain consistent lane geometry and to avoid sampling vehicles within a short distance, data only from Stations B and H were selected for analysis. Data were collected for the November 17th (Monday) A.M. and 18th (Tuesday) P.M. periods in 2008. The directional five lanes from the innermost (leftmost) to outmost (shoulder) are numbered 1 to 5, where Lane 1 is a continuous-access HOV2+ lane during 5-10 A.M. and 3-7 P.M. and lanes 2 to 5 are open to general purpose traffic. The speed limit is 65 mph for both lane types. Individual lanes have 422 filtered out of 432 observations (=12 intervals per hour × 9 HOV hours × 2 directions × 2 stations). The total vehicle count is 233,026.



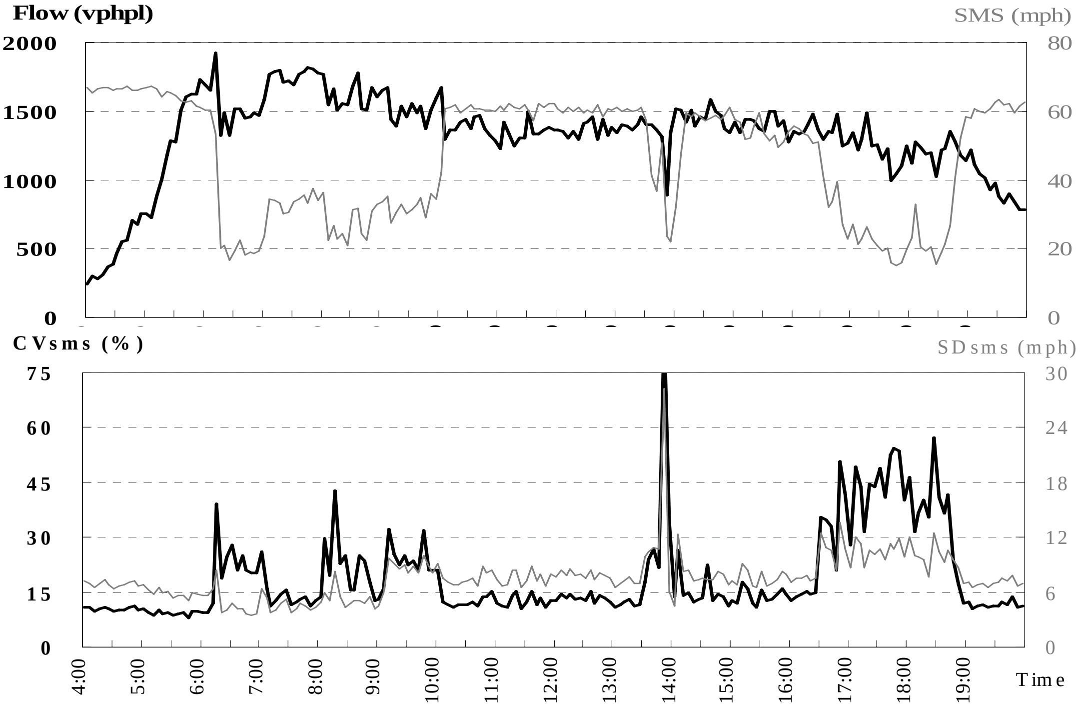
Note: I-80 is an east-west bound highway but geographically north-south bound in this section. The geographical directions are used hereinafter.

FIGURE 1 Configuration of the study site

FIGURE 2 shows that A.M. and P.M. peak periods unsurprisingly have higher flow, lower speed, and greater speed dispersion. With few exceptions, SD_{sms} ranges from 6 to 10 mph northbound and 4 to 12 mph southbound, while CV_{sms} ranges from 10% to 35% northbound and 10% to 55% southbound. The CV_{sms} range of the northbound is close to the observation by Wang et al (2007) from 7% to 32% while that of southbound is broader than the proposal by May (1990) from 0 to $\sqrt{1/SMS}$, which implies that the value of *TMS* based upon equation (3a) is about within 0 to 1 mph greater than *SMS*. In fact, large differences between *TMS* and *SMS* (10% to 30%) are not uncommon when traffic is congested (Rakha and Zhang, 2005), which corresponds to CV_{sms} up to 65%. From this point of view, the CV_{sms} range found in this study is reasonable as the dataset covers a massive amount of observations. In addition, the individual speeds generally comport to normal distributions that comply with McShane and Roess (1990) and May (1990).



(a) I-80 Northbound



(b) I-80 Southbound

FIGURE 2 Time-of-day traffic variation at detector station H (HOV hr: 5-10, 15-19)

4. RELATIONSHIPS BETWEEN PARAMETERS

The matrix below is used to succinctly identify the relationships between the parameters that are considered here. The lower triangle of the matrix can be reflected from the upper one, of which the 4th to 9th relationships are the main concerns of this study and the 1st to 3rd are briefly inspected as background information for the succeeding analysis. The relationships will be based upon regression analysis using ordinary least square (OLS) method.

X \ *Y*	*Occupancy*	*SMS*	*Flow*	CV_{sms}	SD_{sms}
Occupancy	—	1	2	**4**	**7**
SMS		—	3	**5**	**8**
Flow			—	**6**	**9**
CV_{sms}				—	—
SD_{sms}				—	—

Relationships 1, 2, and 3: *Occupancy*－*SMS*－*Flow*

FIGURE 3 shows the "all lane mix" as representative (individual lanes present similar scatter plots). The well-known Greenshields equations are depicted for reference, albeit more complex forms may better fit the fundamental diagrams. The plots match the general recognitions: wilder fluctuations in the congested regime, a gap around the critical point, stable mean speed during light traffic, etc.

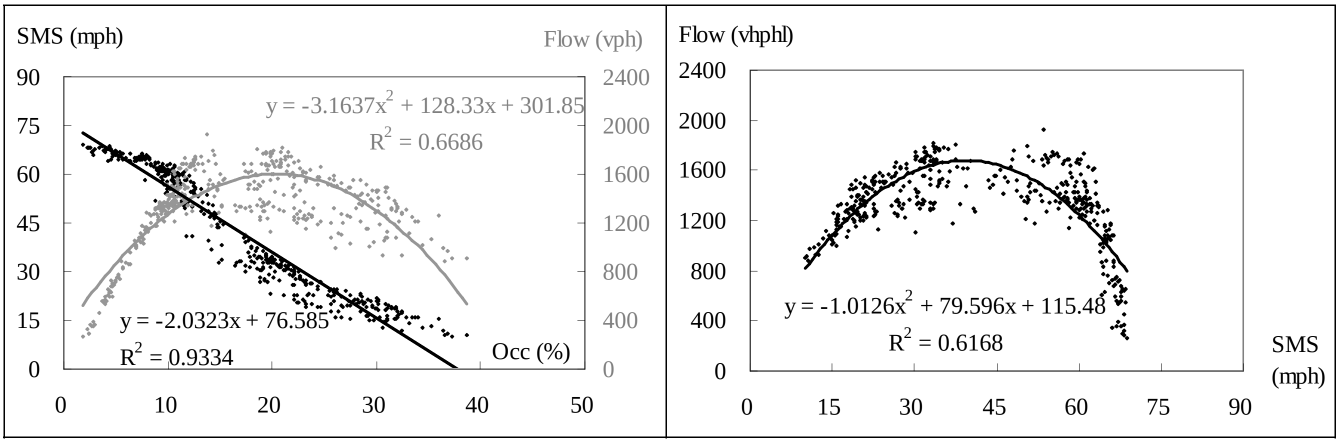


FIGURE 3 Relationships between *Occupancy*, *SMS*, and *Flow* (all lane mix)

Relationship 4: *Occupancy* vs. CV_{sms}

FIGURE 4 displays estimated relationships between *occupancy* and CV_{sms} in both exponential and quadratic forms; the former is judged a better fit for two reasons. First, the quadratic form results in a smaller coefficient of determination than do the exponentials except for Lane 1, and it secondly leads to an open bottom parabola for Lane 2 that misestimates CV_{sms} in the free flow condition. It is noted that the exponential forms in FIGURE 4 are the reverse of those of Wang et al. (2007) who suggested *density* be an exponential form of CV_{tms} based on around 40 observations and with a coefficient of determination of 0.34 We examined their suggestion by fitting *occupancy* as an exponential form of CV_{sms} , but the coefficient of determination associated with the "all lane mix" drops from 0.75 to 0.55. Also given that the dataset and coefficients of determination in FIGURE 4 are more significant than the study of Wang et al., we suggest CV_{sms} more properly be an exponential form of *occupancy*.

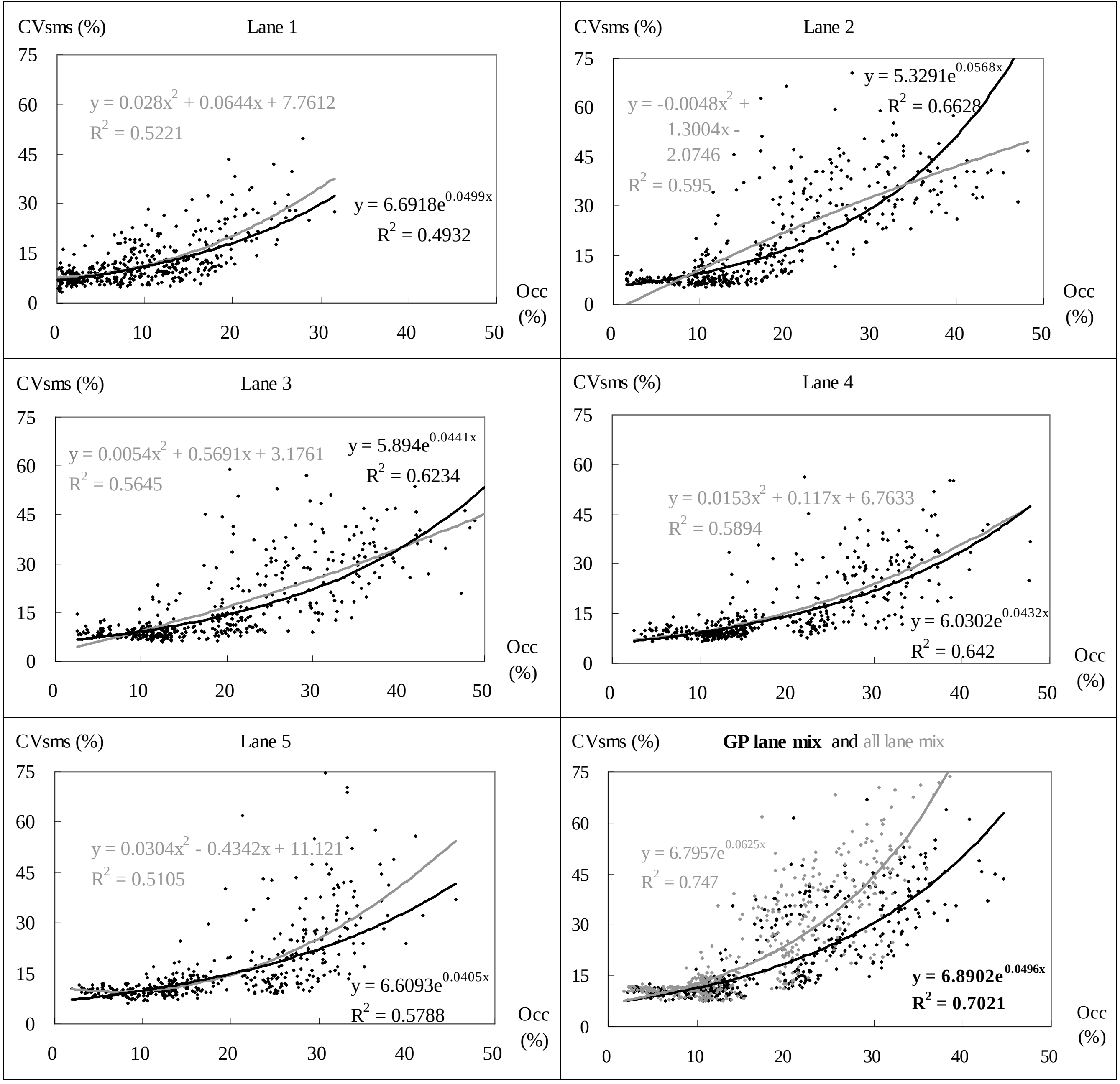


FIGURE 4 Relationships between *Occupancy* and CV_{sms}

The HOV lane (Lane 1) is less congested than the general purpose (GP) lanes, resulting in some “missing” observations, which potentially account for data points in upper right of the Lane 1 diagram in FIGURE 4; it is likely responsible for the smallest coefficient of determination among all categories. Similar CV_{sms} across lanes are found in the free flow state, beyond which diverge into three groups: group 1 (all lane mix), group 2 (Lanes 1 and 2, and GP lane mix), and group 3 (Lanes 3 to 5). Group 1 has the largest speed dispersion with respect to fixed occupancy, followed by group 2 and then group 3, as shown in FIGURE 5. We can further generalize FIGURE 4 into the following $occupancy - CV_{sms}$ relationship.

$$CV_{sms} = aExp(bOcc) \tag{4}$$

$a = cv_f$ when $Occ \approx 0$

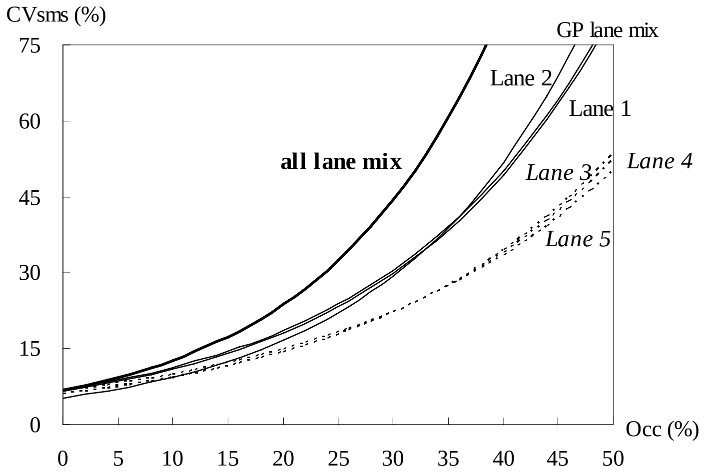
$$b \approx \frac{0.078 + 0.017D_{1,2,G} + 0.042D_{all}}{ln(cv_f)}$$

where $D_{1,2,G} = \begin{cases} 1, & \text{Lanes 1, 2, and GP lane mix} \\ 0, & \text{Otherwise} \end{cases}$; $D_{all} = \begin{cases} 1, & \text{All lane mix} \\ 0, & \text{Otherwise} \end{cases}$

$$\Rightarrow CV_{sms} = cv_f\,Exp\left(\left(\frac{0.078 + 0.017D_{1,2,G} + 0.042D_{all}}{ln(cv_f)}\right)Occ\right) \tag{4a}$$

or $$ln(CV_{sms}) = \left(\frac{0.078 + 0.017D_{1,2,G} + 0.042D_{all}}{ln(cv_f)}\right)Occ + ln(cv_f) \tag{4b}$$

where cv_f (in %) is the free flow CV_{sms} and varies by lane; its observed variation is from about 7 to 11 and its estimated variation is from about 5 to 7, as shown in TABLE 1. Coefficient *b* varies by the above lane groups.



Note: Diagrams correspond to equations in FIGURE 4.

FIGURE 5 Three lane groups by *Occupancy* $-$ CV_{sms} relationships

TABLE 1 CV_{sms}, SD_{sms}, and SMS in the Free Flow Condition

	Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	GP lane mix	All lane mix
cv_f -est (in %)	6.69	5.33	5.89	6.03	6.61	6.89	6.80
cv_f -obs (in %)	7.53	7.32	8.76	9.78	9.77	10.78	10.89
sd_f -obs (in mph)	5.43	5.35	5.94	6.23	6.20	7.26	7.37
SMS_f -obs (in mph)	72.79	73.23	68.62	65.61	62.88	67.33	67.62
# of observations	141	29	14	11	21	18	31

Note: 1. -est means estimated, and –obs means observed.
2. Observed values are based upon the free flow condition set as occupancy less than 5%. The medians of those CV_{sms}, SD_{sms}, and SMS are the cv_f, sd_f and SMS_f.

Relationship 5: SMS vs. CV_{sms}

CV_{sms} would be expected to be an exponential form of *SMS* as, in general, CV_{sms} is exponential to *occupancy* (FIGURE 4) and *occupancy* is linear to *SMS* (FIGURE 3 left). FIGURE 6 verifies this expectation by resulting in coefficients of determination about 0.6 or greater. Quadratic forms are slightly worse than the exponential forms and are not listed. Similar to the *occupancy* $- CV_{sms}$ relationship, the all lane mix has the best fit among the seven categories, but on the contrary, $SMS - CV_{sms}$ displays downward curves.

As shown in FIGURE 7, the seven categories can be divided into: group 1 (all lane mix), group 2 (Lane 2 and GP lane mix), and group 3 (Lanes 1, 3, 4, and 5). Compared to FIGURE 5, Lane 1 is grouped with outer lanes (Lanes 3, 4, and 5) if *SMS* is used to explain CV_{sms}, but is grouped with Lane 2 if *occupancy* is used to explain CV_{sms}. The relatively low coefficient of determination of Lane 1 is likely the reason for the grouping difference. Nevertheless, under fixed occupancy or mean speed, both figures are consistent in the all lane mix with the greatest CV_{sms}, Lanes 3 to 5 with the least CV_{sms}, and Lane 2 and the GP lane mix in between. We can further generalize FIGURE 6 into the following $SMS - CV_{sms}$ relationship.

$$CV_{sms} = cExp(dSMS) \quad (5)$$

$c \approx cv_j$ when $SMS \approx 0$

$d \approx -0.024 - 0.06D_{2,G} - 0.07D_{all}$

where $D_{2,G} = \begin{cases} 1, & \text{Lane 2 and GP lane mix} \\ 0, & \text{Otherwise} \end{cases}$; $D_{all} = \begin{cases} 1, & \text{All lane mix} \\ 0, & \text{Otherwise} \end{cases}$

$$\Rightarrow CV_{sms} = cv_j Exp((-0.024 - 0.006D_{2,G} - 0.007D_{all})Occ) \quad (5a)$$

$$\text{or } ln(CV_{sms}) = (-0.024 - 0.006D_{2,G} - 0.007D_{all})Occ + ln(cv_j) \quad (5b)$$

where cv_j (in %) is the jam CV_{sms} and varies greatly by lane; its estimated range is from 36 to 73 and observed range is from 28 to 72, as shown in TABLE 2. Coefficient *d* varies by the above lane groups.

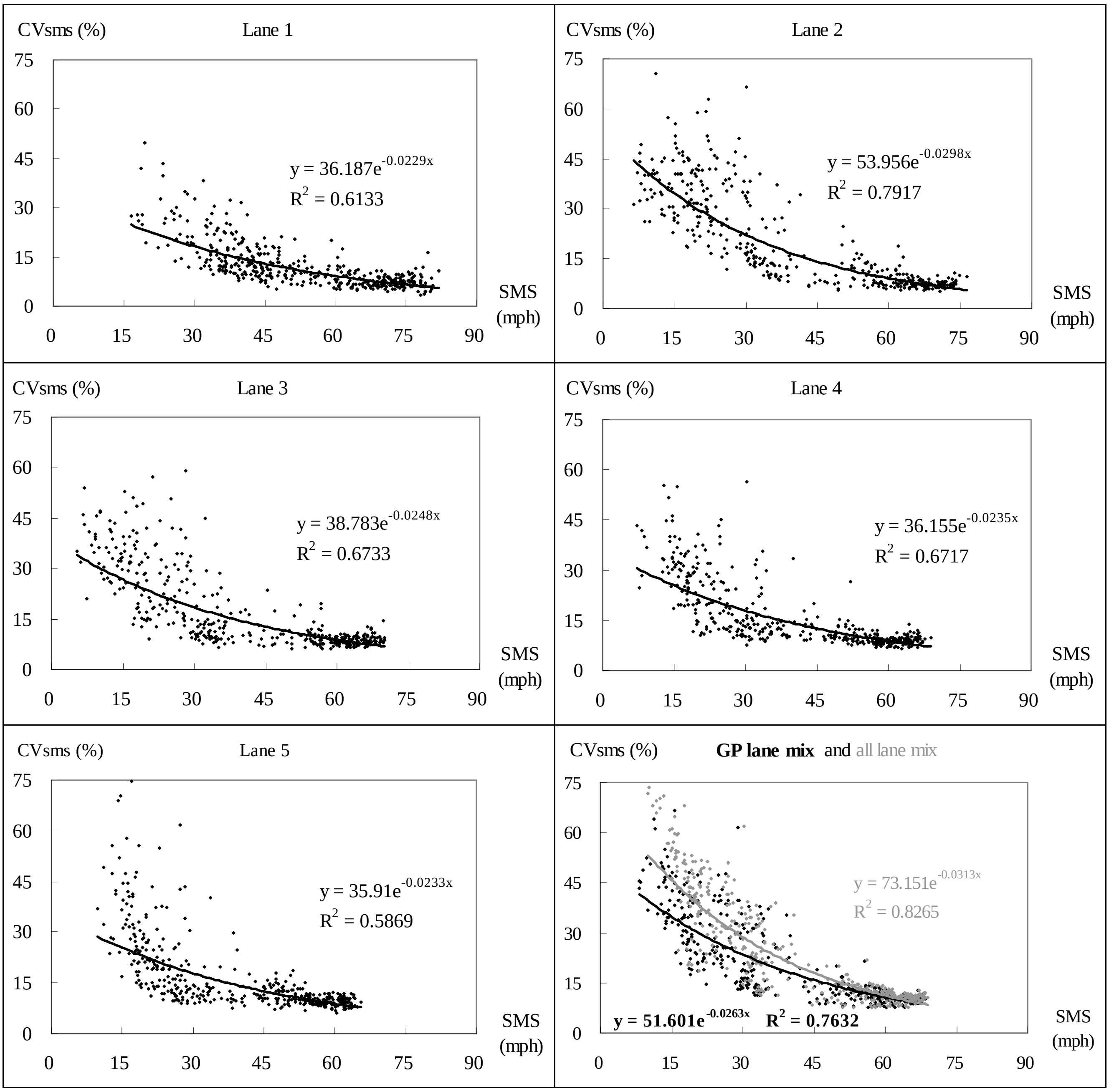


FIGURE 6 Relationships between *SMS* and CV_{sms}

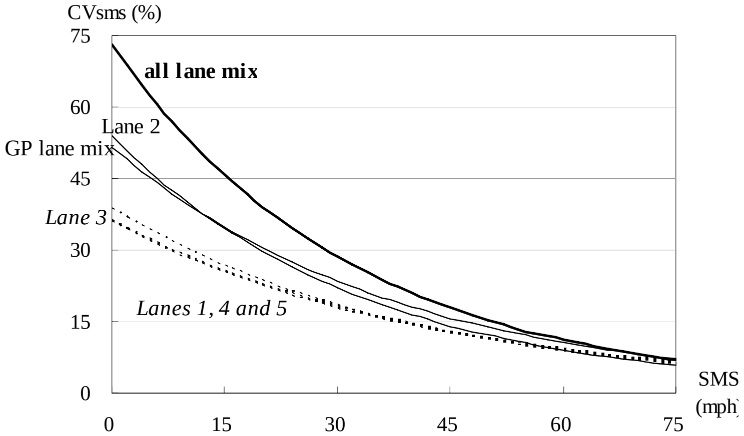


FIGURE 7 Three lane groups by $SMS - CV_{sms}$ relationships

TABLE 2 CV_{sms} and SD_{sms} in the Jam Condition

	Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	GP lane mix	all lane mix
cv_j-est (in %)	36.19	53.96	38.78	36.16	35.91	51.60	73.15
cv_j (in %)	27.54*	38.83	38.73	38.32	36.90	45.03	71.83*
sd_j (in mph)	4.60*	3.09	3.13	3.25	3.62	3.78	7.27*
# of observations	0	14	15	6	1	5	0

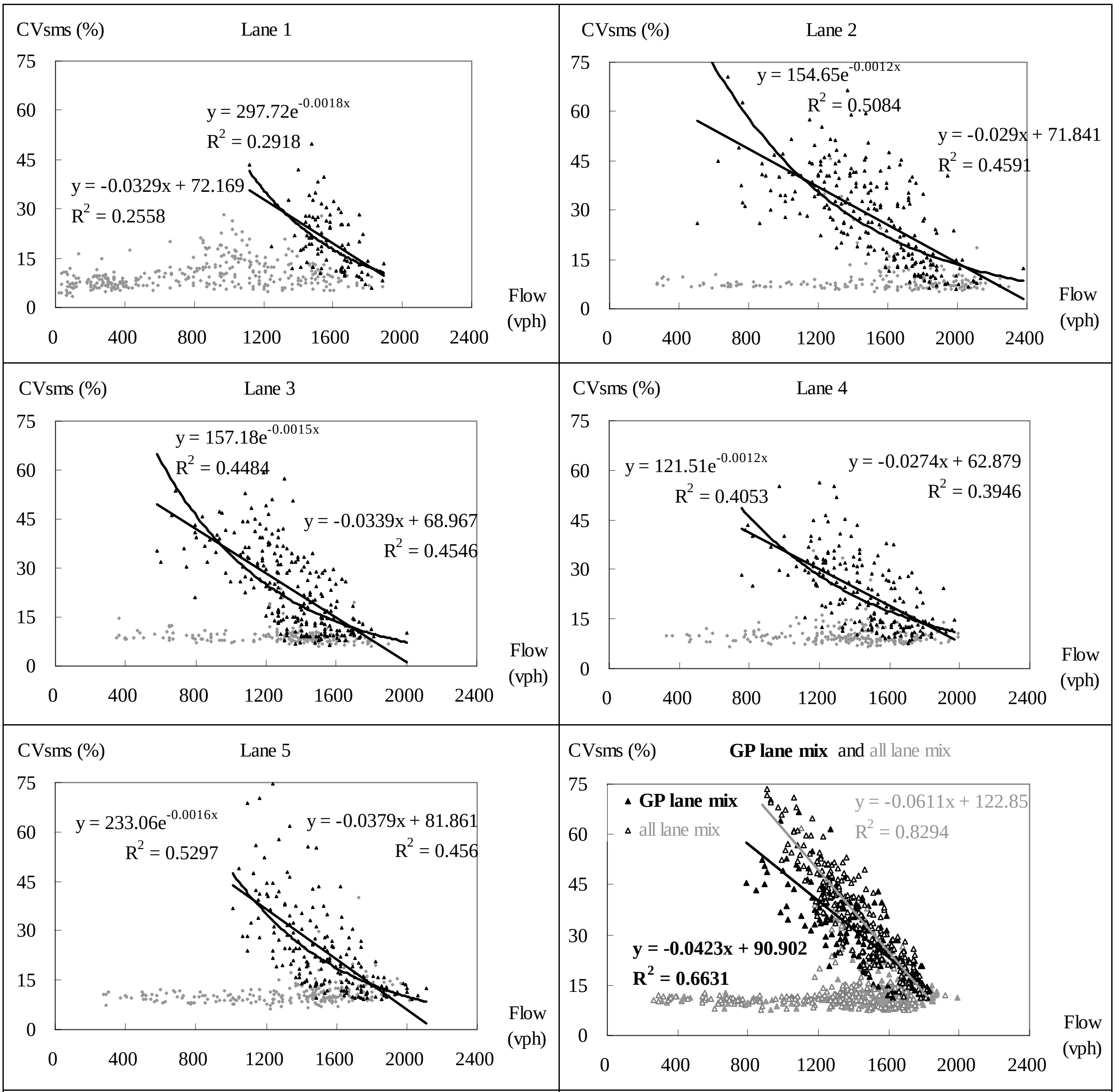
Note: 1. cv_j-est is the estimated values from FIGURE8. The other two are observed values.

2. Observed values are based upon the jam condition set as *SMS* less than 10 mph. The medians of those CV_{sms} and SD_{sms} serve as cv_j and sd_j.

3. Lane 1 and all lane mix have no observations with *SMS* less than 10 mph. The cv_j and sd_j is the observations with their least *SMS* of 16.69 and 10.12 mph, respectively.

Relationship 6: *Flow vs.* CV_{sms}

Flow and CV_{sms} hold a two-phase linear relationship that respectively corresponds to the congested and uncongested states. As recognized in FIGURE 8, the two states intersect at around the lane capacity and the mean CV_{sms} of the uncongested state. Although CV_{sms} during congestion (black dots in FIGURE 8) could be explained by either a linear or an exponential form of *flow*, the linear relationship is preferred for its simplicity. Consistently, the all lane mix has the highest coefficient of determination and Lane 1 has the least. Individual lanes are not grouped as they are in relationships 3 and 6 because of poor fitness scores. For uncongested conditions (grey dots in FIGURE 8), CV_{sms} varies within a small range while *flow* changes from 0 to over 2,000 vphpl. As shown in TABLE 3, mean CV_{sms} is about 9% to 11% for the individual lanes, and is about 12% to 14% for the lane mixes. These results are consistent with those of Del Castillo and Benitez (1995) that set CVS of 15% or less for the uncongested state.



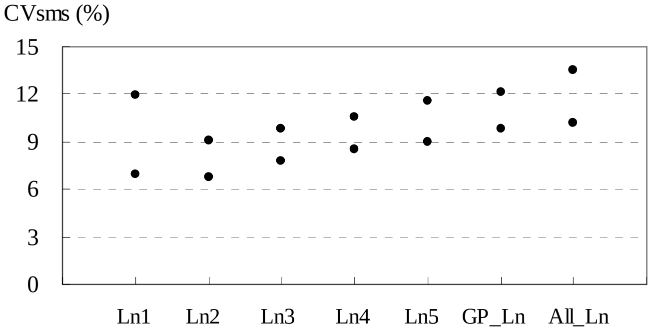
R^2	Exponential	Linear
Lane 1	**0.2918**	0.2558
Lane 2	**0.5084**	0.4591
Lane 3	0.4484	**0.4546**
Lane 4	**0.4053**	0.3946
Lane 5	**0.5297**	0.4560
GP lane mix	0.6604	**0.6631**
All lane mix	0.7949	**0.8294**

Note 1. The black dots are those observed in the congested state, and the grey ones are in the uncongested state.

2. Based on the corresponding flow-occupancy scatter plots, the congestion thresholds are set as occupancy of 15% for Lanes 1 to 3, 18% for Lane 4, GP lane mix, and all lane mix, and 20% for Lane 5.

FIGURE 8 Relationships between CV_{sms} and *Flow*

TABLE 3 Descriptive Statistics of CV_{sms} by Lane in the Uncongested State

	Mean CVsms (%)	σ_{CVsms} (%)	number of observation	Range of the majority of *CVsms* (75%tile – 25%tile)
Lane 1	9.96	4.28	330	
Lane 2	9.07	4.96	187	
Lane 3	9.24	2.63	189	
Lane 4	10.15	3.39	231	
Lane 5	10.83	3.38	239	
GP lane mix	11.94	4.56	214	
All lane mix	13.53	7.10	224	

Relationships 7, 8, and 9: *Occupancy*, *SMS*, and *Flow* vs. SD_{sms}

No simple equations are found valid for $occupancy - SD_{sms}$, $SMS - SD_{sms}$, and $flow - SD_{sms}$, as shown in FIGURE 9 that takes the all lane mix as a representative. The figure, however, reveals SD_{sms} during congestion to be more spread out and to be greater on average than that during uncongested conditions.

From equation (4) in relationship 4, *occupancy* along with *SMS* may be expected to jointly explain SD_{sms}, as shown in equation (6).

$$SD_{sms} = cv_f SMS \times Exp\left(\left(\frac{0.078 + 0.017D_{1,2,G} + 0.042D_{all}}{ln\left(cv_f\right)}\right)Occ\right) \tag{6a}$$

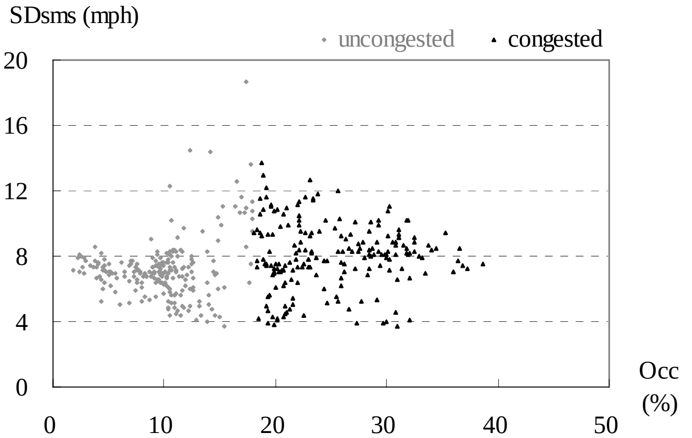
$$\text{or } ln\left(SD_{sms}\right) = \left(\frac{0.078 + 0.017D_{1,2,G} + 0.042D_{all}}{ln\left(cv_f\right)}\right)Occ + ln\left(SMS\right) + ln\left(cv_f\right) \tag{6b}$$

From equation (5) in relationship 5, another "complicated" form between *SMS* and SD_{sms} may be expected as follows:

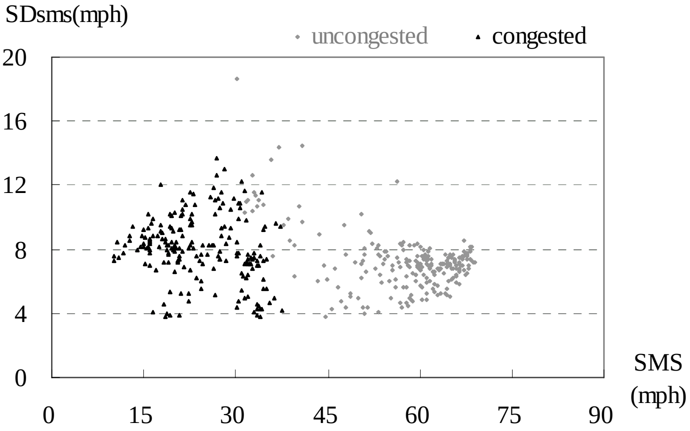
$$SD_{sms} = cv_j SMS \times Exp\left(\left(-0.024 - 0.006D_{2,G} - 0.007D_{all}\right)SMS\right) \tag{7a}$$

$$\text{or } ln\left(SD_{sms}\right) = \left(-0.024 - 0.006D_{2,G} - 0.007D_{all}\right)SMS + ln\left(SMS\right) + ln\left(cv_j\right) \tag{7b}$$

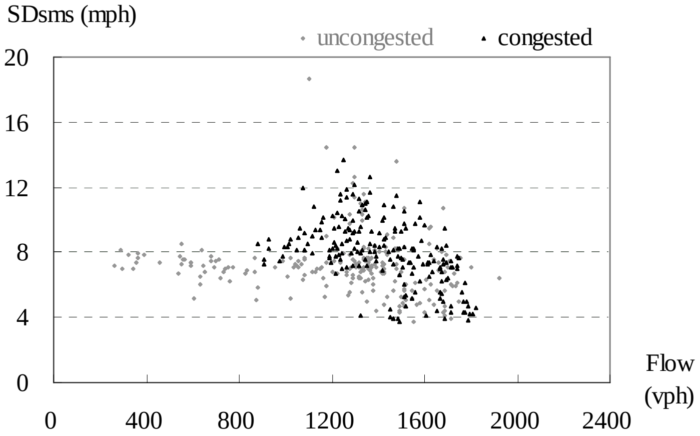
Finally, although Wang et al. (2007) proposed *flow* as an exponential form of SD_{tms}, we may expect *flow* and *SMS* to jointly explain SD_{sms} because of relationship 6.



(a) *Occupancy*－ SD_{sms}



(b) *SMS*－ SD_{sms}



(c) *Flow*－ SD_{sms}

FIGURE 9 Scatter plots of the fundamental parameters and SD_{sms} (all lane mix)

5. DESCRIPTIVE CHARACTERISTICS OF SD_{sms}

As shown in FIGURE 10, SD_{sms} under median to heavy traffic (*occupancy* between 9% and 27%) distributes expansively, but at light (*occupancy* less than 9%) and overflow (*occupancy* greater than 27%) traffic, SD_{sms} mainly locates within 6 to 8 and 7 to 9 mph, respectively. Also, mean SD_{sms} initially increases with traffic but stays around 8 mph in the congested state. These untamed variations may be the reason for difficulties in explaining SD_{sms} by a simple equation of a fundamental parameter.

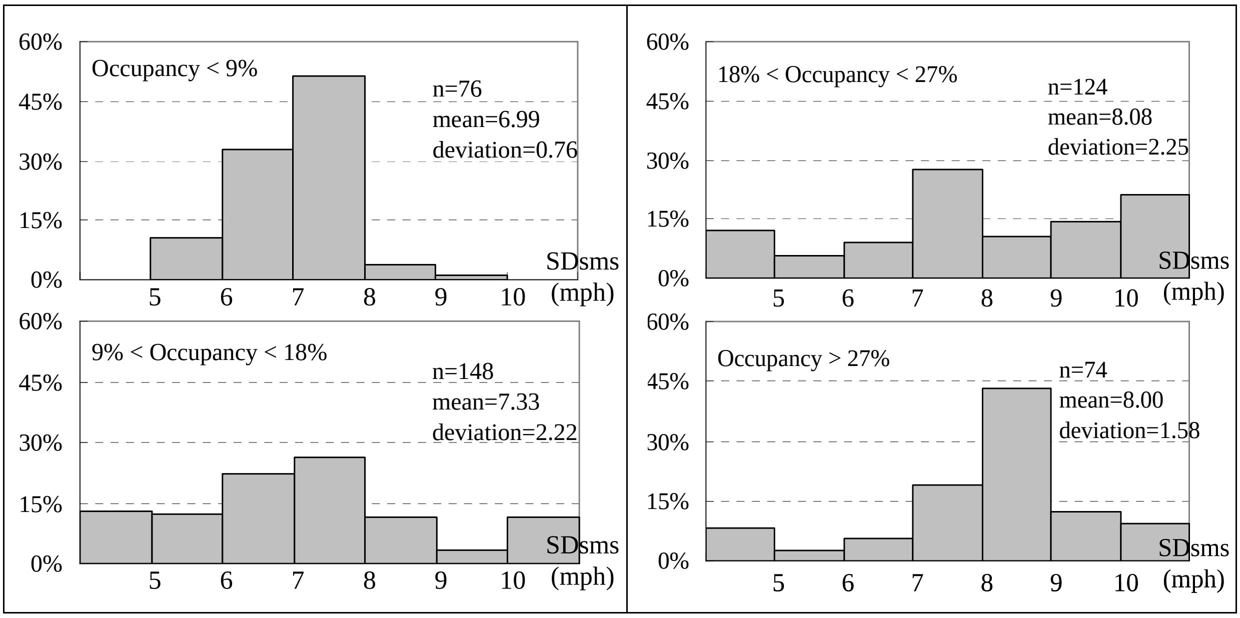


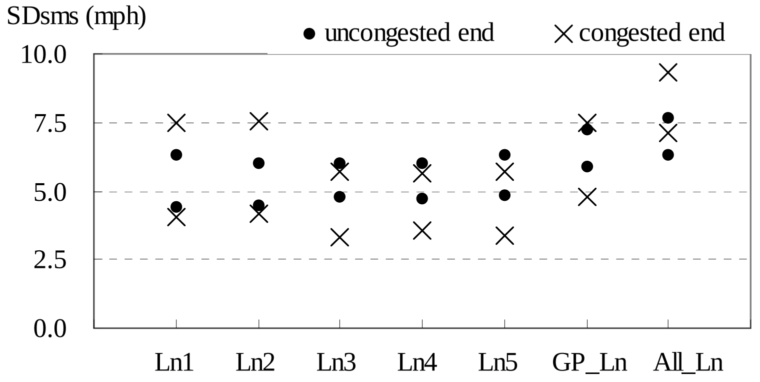
FIGURE 10 Histograms of SD_{sms} by occupancy level (all lane mix)

TABLE 4 reveals some characteristics of SD_{sms}. First, the SD_{sms} values of individual lanes stay steady during light traffic. Specifically, the mean values are within 5.57 ± 0.07 mph and the majority fall within 4 to 6 mph. When traffic becomes congested, SD_{sms} fluctuates more, which might be caused by lane changing that leaves gaps for the following vehicle to speed up, and/or by stop-start waves that happen only in congestion. Second, speed dispersions in Lanes 1 and 2 during congestion are on the average greater than those associated with uncongested conditions. This may be explained by the supposition that when congestion in the adjacent GP lane (Lane 2) deteriorates, violators are more likely to rush into and out of the HOV (Lane 1) for short time intervals with increasing frequency. This factor is proposed by Varaiya (2007) to justify capacity loss of HOV lanes with respect to GP lanes. On the other hand, an HOV lane operates as a one-lane highway, so its speed is governed by the low speed vehicles—the 'snails' (Varaiya, 2007). As traffic worsens, a faster HOV vehicle may be eager to pass the 'snail' in front of it by darting into and out of Lane 2 more frequently. These two factors force drivers (not only in the HOV but also in the adjacent GP lanes) to adjust speeds, causing greater speed dispersions in Lanes 1 and 2 in congestion. Third, speed dispersions in Lanes 3 to 5 under uncongested conditions are on the average greater than those in congestion. This may be due to the outer lanes that usually have higher percentages of trucks and conservative motorists who tend to stay in lane when traffic worsens as it is more difficult to find a gap large enough in comparison to the uncongested state.

TABLE 4 Descriptive Statistics of SD_{sms} by Lane and Congestion Level

	Uncongested state			Congested state		
	Mean SD_{sms} (mph)	σ_{SDsms} (mph)	number of observation	mean SD_{sms} (mph)	σ_{SDsms} (mph)	number of observation
Lane 1	5.50	1.62	330	6.13	2.27	92
Lane 2	5.52	1.74	187	6.10	2.71	235
Lane 3	5.57	1.26	189	4.97	2.28	233
Lane 4	5.54	1.28	231	4.86	1.97	191
Lane 5	5.64	1.25	239	4.92	2.25	183
GP lane mix	6.68	1.44	214	6.42	2.30	208
All lane mix	7.22	1.86	224	8.05	2.03	198

Range of the majority SD_{sms} (75%tile – 25%tile)



Note: See note 2 of FIGURE 8 for the occupancy-based congestion thresholds.

6. DISCUSSION

TABLE 5 compiles the coefficients of determination of the suggested regression equations in FIGURE 4, 6, and 8. The results conclusively indicate that CV_{sms} would be better explained by *SMS* than by either *occupancy* or *flow*. In the case that *SMS* is not available—for instance, single loop detectors do not record speed—*occupancy* can be a substitute of *SMS*. *Flow* is not suggested to be used to explain CV_{sms} except for non-individual lanes during congestion. CV_{sms} is favored over SD_{sms} when using speed dispersion to link to the fundamental traffic flow parameters, albeit SD_{sms} and CV_{sms} have at least two similarities. First, both indicators in the all lane mix are greater than they are in the individual lanes. This is understandable as the all lane mix contains more varieties of vehicle types, driving behaviors, lane restrictions, speed limit, etc. Second, individual lanes can be grouped by inner two lanes and outer three lanes for both SD_{sms} and CV_{sms} with respect to the congestion level, of which the possible causes are discussed in Section 5. One of the contrasts between SD_{sms} and CV_{sms} is that due to a deeper drop of SMS than SD_{sms}, CV_{sms} in the outer three lanes increases with traffic while SD_{sms} does not.

Although *SMS* can be theoretically connected to *flow*, *density*, and *average travel time*, time mean speed (*TMS*) is commonly employed in traffic practice as an approximation of *SMS*. Equations (8), (5) and (3) can make conversions between *TMS* and *SMS*, and their speed dispersions. As shown in Table 6 (that takes the all lane mix, for example), differences between *TMS* and *SMS* are as much as 3 mph; CV_{tms} and CV_{sms} is within 10% deviation if *TMS* is above 35 mph; SD_{tms} and SD_{sms} is within 10% deviation if *TMS* is above 20 mph. During light traffic, TSM and SMS, and their speed dispersions are very likely exchangeable for practical purposes.

$$SD_{tms}^2 = E(v - TMS)^2 = E\left(v - SMS - \frac{SD_{sms}^2}{SMS}\right)^2 = SD_{sms}^2 - \frac{SD_{sms}^4}{SMS^2} \qquad (8)$$

where *v* is individual speeds.

TABLE 5 Coefficients of Determination between CV_{sms} and the Fundamental Parameters

Parameter	Relationship	Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	GPL mix	All lane mix
Occupancy	Exponential	0.49	0.66	0.62	0.64	0.58	0.70	0.75
SMS	Exponential	**0.61**	**0.79**	**0.67**	**0.67**	**0.59**	**0.76**	**0.83**
flow (congested)	Linear	0.29	0.46	0.45	0.39	0.46	0.66	**0.83**

TABLE 6 Mean Speeds and Speed Dispersions Lookup Table

TMS (mph)	SMS (mph)	CV_{tms}	CV_{sms}	SD_{tms} (mph)	SD_{sms} (mph)	$TMS - SMS$ (mph)	$\frac{CV_{tms}}{CV_{sms}}$	$\frac{SD_{tms}}{SD_{sms}}$
70	69.52	8.22%	8.30%	5.75	5.77	0	99%	100%
65	64.39	9.61%	9.75%	6.25	6.28	1	99%	100%
60	59.22	11.24%	11.46%	6.74	6.79	1	98%	99%
55	54.02	13.13%	13.49%	7.22	7.29	1	97%	99%
50	48.77	15.31%	15.90%	7.65	7.75	1	96%	99%
45	43.47	17.80%	18.76%	8.01	8.16	2	95%	98%
40	38.12	20.61%	22.18%	8.25	8.46	2	93%	98%
35	32.74	23.70%	26.25%	8.29	8.60	2	90%	96%
30	27.36	26.93%	31.07%	8.08	8.50	3	87%	95%
25	22.03	30.09%	36.71%	7.52	8.09	3	82%	93%
20	16.86	32.82%	43.16%	6.56	7.28	3	76%	90%
15	11.97	34.69%	50.29%	5.20	6.02	3	69%	86%
10	7.49	35.35%	57.86%	3.53	4.33	3	61%	82%
5	3.50	34.65%	65.56%	1.73	2.29	1	53%	76%

7. CONCLUSION

Speed dispersion is an important traffic factor, but is often overlooked. Through empirical data analysis, we found some characteristics of speed dispersion: CV_{sms}, rather than SD_{sms}, displays an exponential form of *occupancy* or *SMS*, and is two-phase linear to *flow*. These statistical equations fit fairly well for the all lane mix and GP lane mix, and should be carefully used for certain individual lane(s). There is no evidence to indicate that the speed dispersion of the continuous-access HOV lane is unique vis-a-vis the individual GP lanes. Although the dataset collected from the study site matches generally recognized patterns, it is suggested that generalization of the relationships between speed dispersion and the fundament traffic flow parameters would rely on more extensive empirical cases and theoretical development.

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