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**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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**1 Abstract**

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

12

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

## 1 1. INTRODUCTION

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

11 Among the indicators of speed dispersion, standard deviation of speed (*SDS*) and  
12 coefficient of variation of speed (*CVS*), a normalized standard deviation as *SDS* divided by mean  
13 speed, are widely used. May (1990) indicated that *CVS* might range from approximately zero to  
14 something on the order of the reciprocal of the square root of the mean speed, and normally  
15 ranges from 8% to 17% in the empirical studies, which is shown to be somewhat conservative in  
16 Section 3. Del Castillo and Benitez (1995) set *CVS* 15% or less to filter off the non-stationary  
17 regime, but the relationship between *CVS* and the fundamental parameters was not mentioned.  
18 Wang et al. (2007) proposed *flow* as an exponential function of *SDS* and *density* as an  
19 exponential function of *CVS* that distribute from 7% to 32%. Treiber et al. (1999) adopted *CVS*  
20 square as a hyperbolic tangent function of *density*; such adoption displays positive correlation  
21 between *CVS* square and *density* during the stationary regime. Sharnar and Mannering (1998)  
22 explained lane-by-lane *SDS* by *SDS* of adjacent lanes, mean speed, various dummy variables of  
23 time, and truck-to-passenger car flow ratio. We note that not every study referenced above  
24 specifies *CVS* and *SVS* with respect to either space mean speed or time mean speed, but rather to  
25 a general term “average speed”—such findings are still valuable but should be used with caution.

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

33

## 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),

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

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.

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

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  $12n$ .

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

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

$$\Rightarrow \begin{cases} SD_{sms} = \sqrt{SMS(TMS - SMS)} \end{cases} \quad (3a)$$

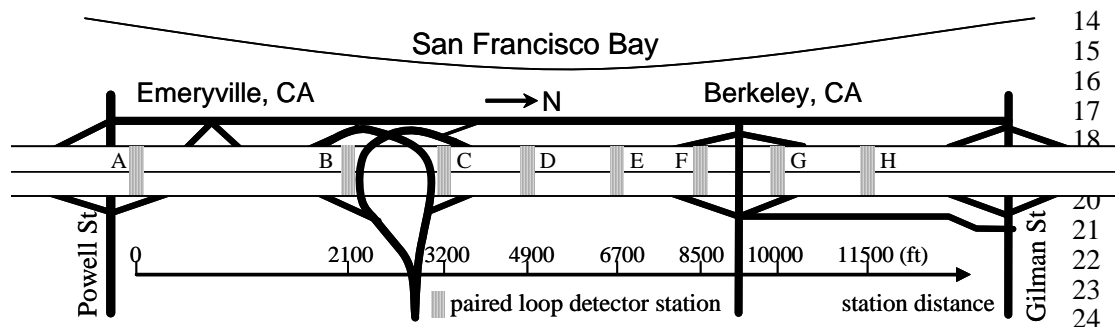
$$\Rightarrow \begin{cases} CV_{sms} = \left( \sqrt{\frac{TMS}{SMS}} - 1 \right) \times 100\% \end{cases} \quad (3b)$$

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 17<sup>th</sup> (Monday) A.M. and 18<sup>th</sup> (Tuesday) P.M. periods in 2008. The directional five lanes from the innermost (leftmost) to outermost (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.

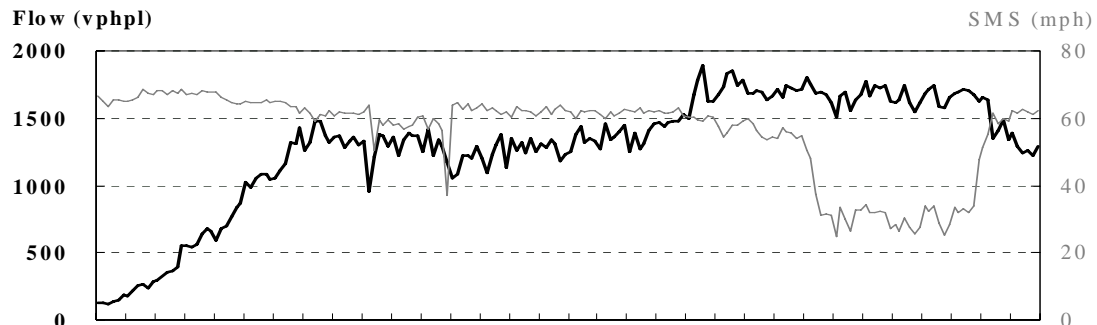


Note: I-80 is an east-west bound highway but geographically north-south bound in this section. The geographical directions are used hereinafter.

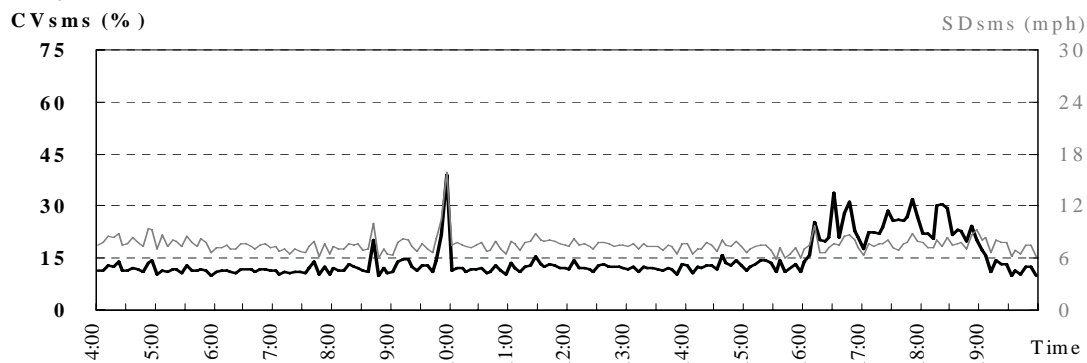
**FIGURE 1 Configuration of the study site**

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).

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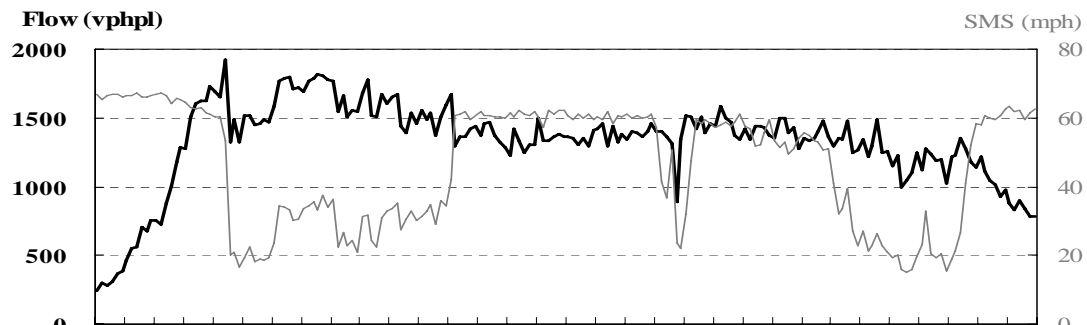
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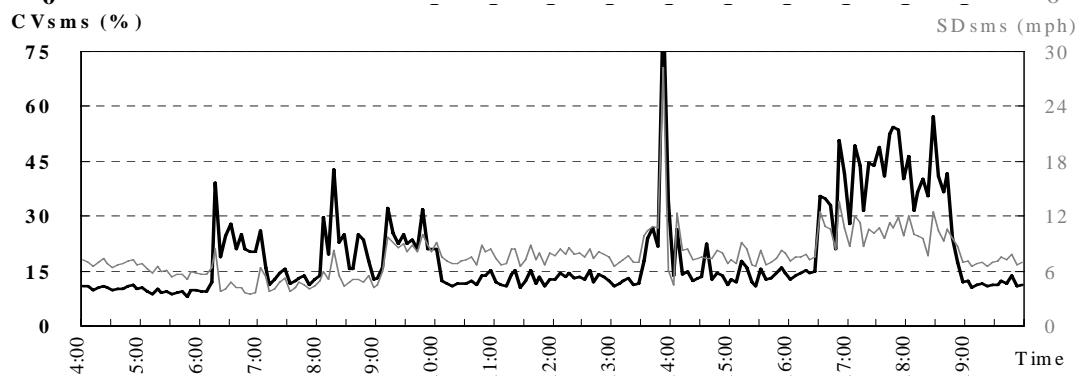
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(a) I-80 Northbound

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(b) I-80 Southbound

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

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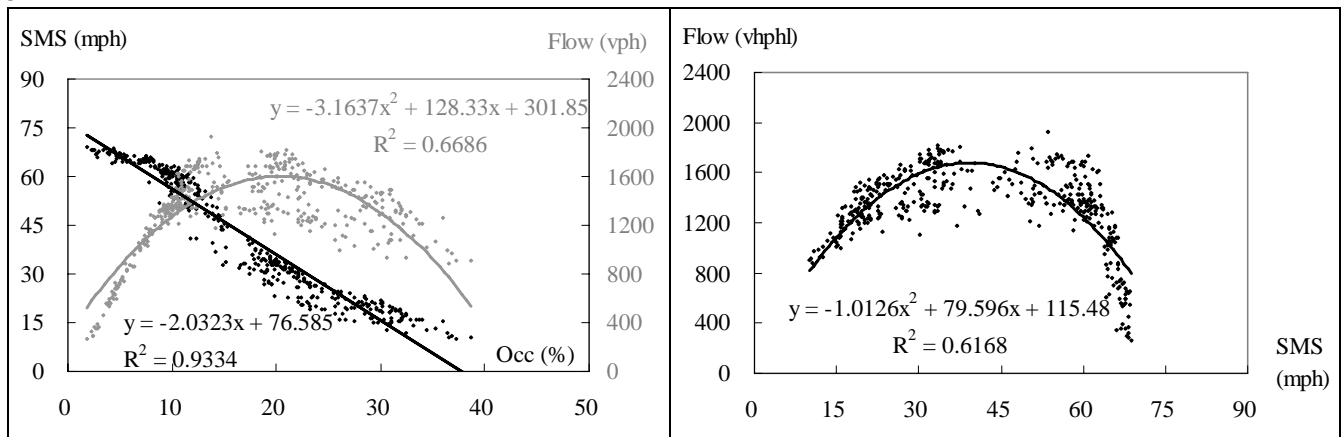
1 **4. RELATIONSHIPS BETWEEN PARAMETERS**

2 The matrix below is used to succinctly identify the relationships between the parameters that are  
 3 considered here. The lower triangle of the matrix can be reflected from the upper one, of which  
 4 the 4<sup>th</sup> to 9<sup>th</sup> relationships are the main concerns of this study and the 1<sup>st</sup> to 3<sup>rd</sup> are briefly  
 5 inspected as background information for the succeeding analysis. The relationships will be based  
 6 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
$CV_{sms}$				—	—
$SD_{sms}$					—

7 **Relationships 1, 2, and 3: Occupancy – SMS – Flow**

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



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

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

16 FIGURE 4 displays estimated relationships between occupancy and  $CV_{sms}$  in both exponential  
 17 and quadratic forms; the former is judged a better fit for two reasons. First, the quadratic form  
 18 results in a smaller coefficient of determination than do the exponentials except for Lane 1, and it  
 19 secondly leads to an open bottom parabola for Lane 2 that misestimates  $CV_{sms}$  in the free flow

1 condition. It is noted that the exponential forms in FIGURE 4 are the reverse of those of Wang et  
 2 al. (2007) who suggested *density* be an exponential form of  $CV_{tms}$  based on around 40  
 3 observations and with a coefficient of determination of 0.34 We examined their suggestion by  
 4 fitting *occupancy* as an exponential form of  $CV_{sms}$ , but the coefficient of determination  
 5 associated with the “all lane mix” drops from 0.75 to 0.55. Also given that the dataset and  
 6 coefficients of determination in FIGURE 4 are more significant than the study of Wang et al., we  
 7 suggest  $CV_{sms}$  more properly be an exponential form of *occupancy*.

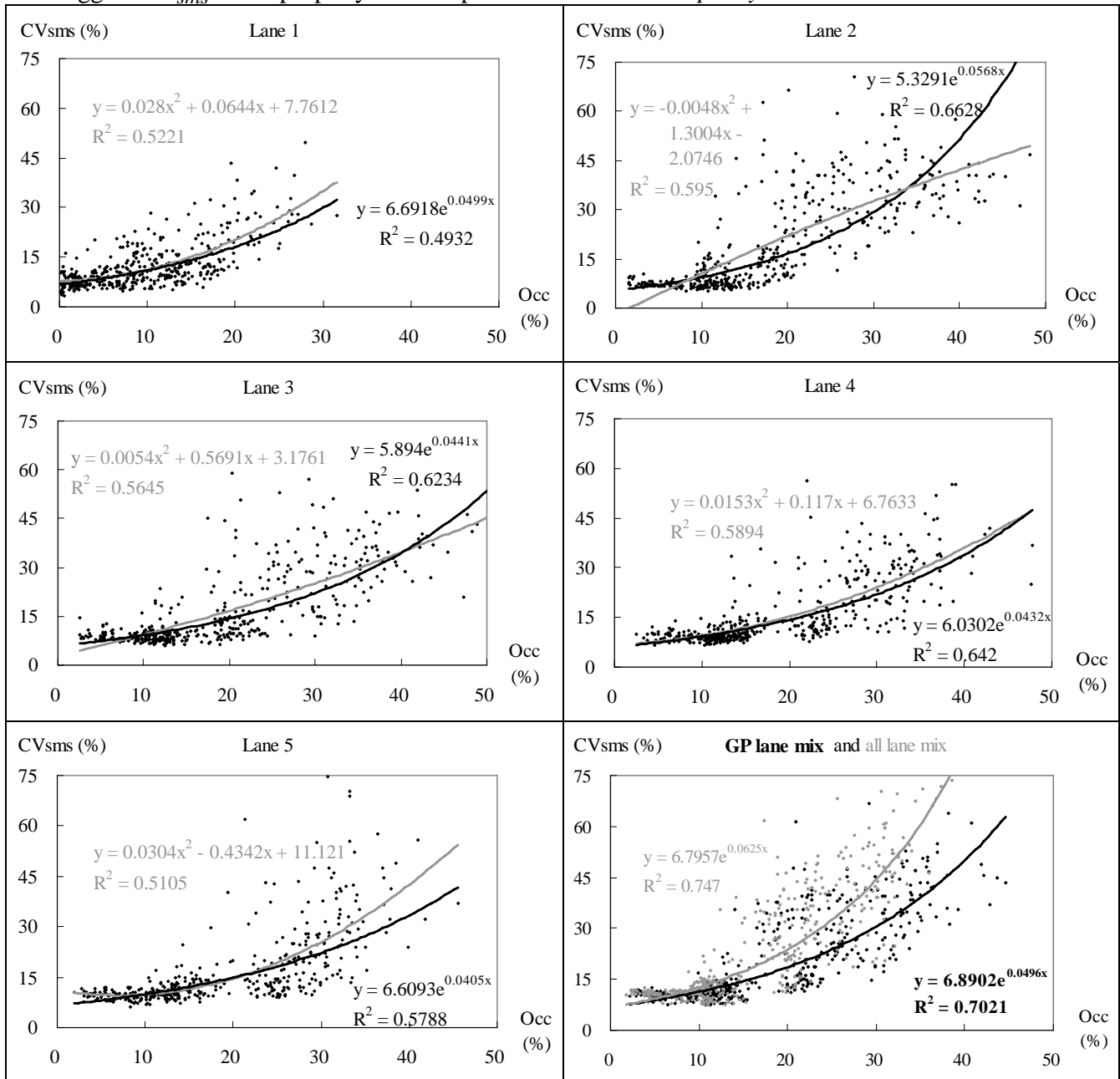


FIGURE 4 Relationships between *Occupancy* and  $CV_{sms}$



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

9  $CV_{sms} = aExp(bOcc)$  (4)

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

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

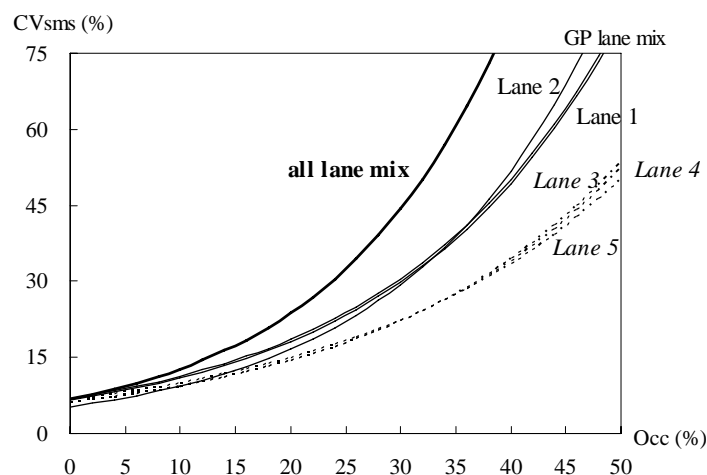
12 where  $D_{1,2,G} = \begin{cases} 1, & \text{Lanes 1, 2, and GP lane mix} \\ 0, & \text{Otherwise} \end{cases}$ ;  $D_{all} = \begin{cases} 1, & \text{All lane mix} \\ 0, & \text{Otherwise} \end{cases}$

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

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

15 where  $cv_f$  (in %) is the free flow  $CV_{sms}$  and varies by lane; its observed variation is from about  
 16 7 to 11 and its estimated variation is from about 5 to 7, as shown in TABLE 1. Coefficient  $b$   
 17 varies by the above lane groups.

18



19

20

21

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.

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

$$c \approx cv_j \text{ when } SMS \approx 0$$

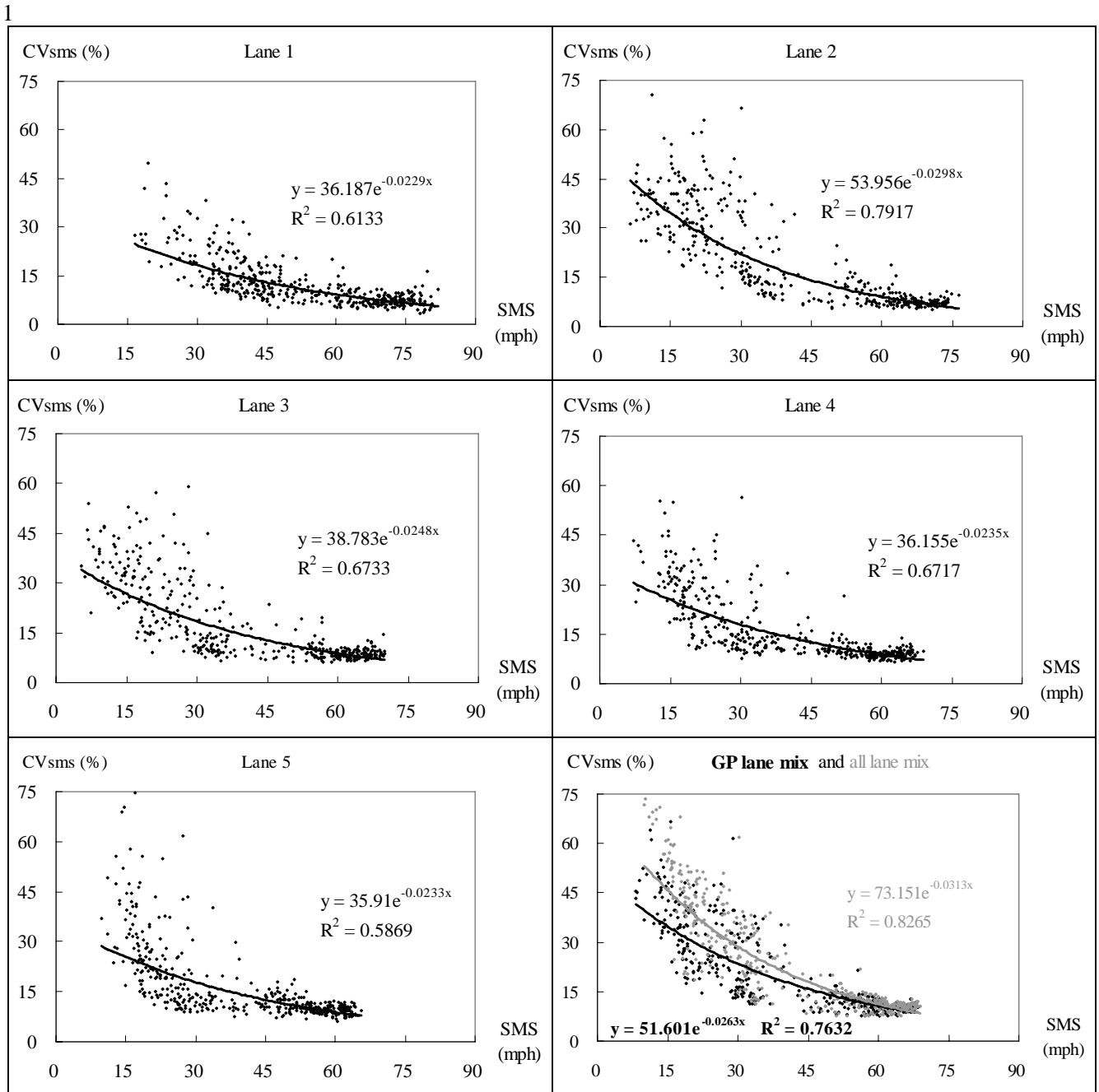
$$d \approx -0.024 - 0.06D_{2,G} - 0.07D_{all}$$

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

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

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

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.



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

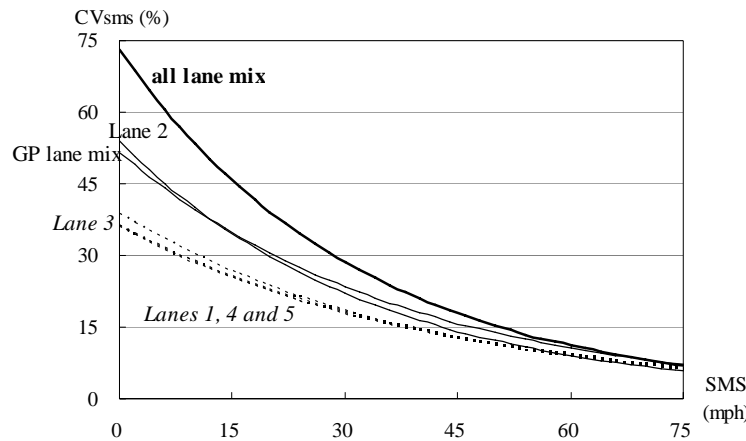


FIGURE 7 Three lane groups by SMS— $CV_{sms}$  relationships

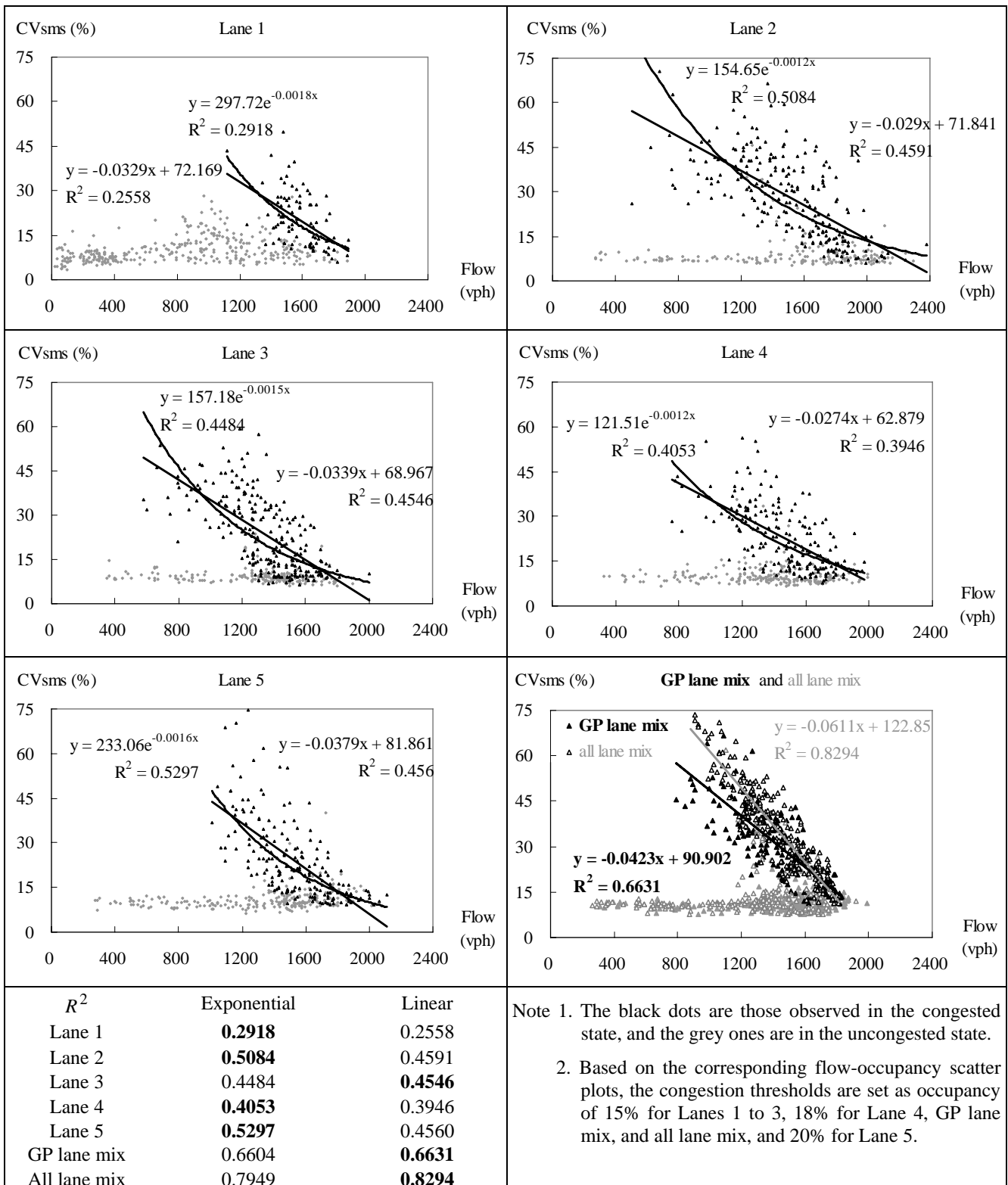
TABLE 2  $CV_{sms}$  and  $SD_{sms}$  in the Jam Condition

	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 FIGURE 8. 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.



1

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

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

	<i>Mean CV<sub>sms</sub></i> (%)	$\sigma_{CV_{sms}}$ (%)	number of observation	Range of the majority of <i>CV<sub>sms</sub></i> (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	

2

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

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

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

10 
$$SD_{sms} = cv_f SMS \times Exp\left(\left(\frac{0.078 + 0.017D_{1,2,G} + 0.042D_{all}}{\ln(cv_f)}\right)Occ\right) \tag{6a}$$

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

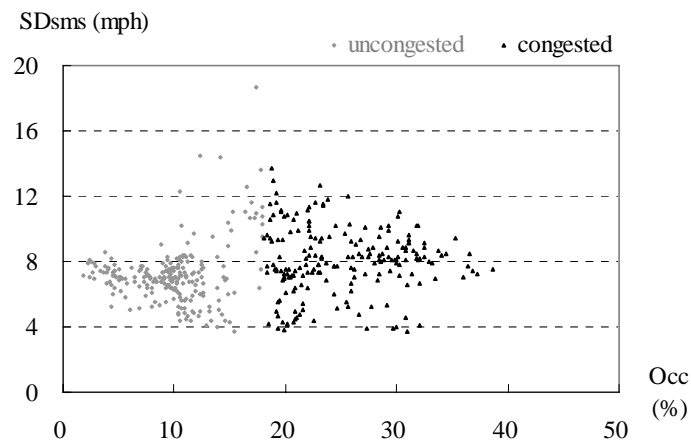
12 From equation (5) in relationship 5, another “complicated” form between *SMS* and  
 13  $SD_{sms}$  may be expected as follows:

14 
$$SD_{sms} = cv_j SMS \times Exp((-0.024 - 0.006D_{2,G} - 0.007D_{all})SMS) \tag{7a}$$

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

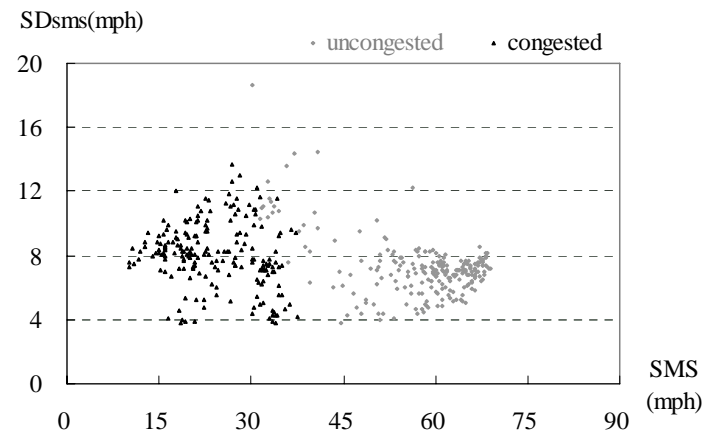
16 Finally, although Wang et al. (2007) proposed *flow* as an exponential form of  $SD_{tms}$ , we  
 17 may expect *flow* and *SMS* to jointly explain  $SD_{sms}$  because of relationship 6.

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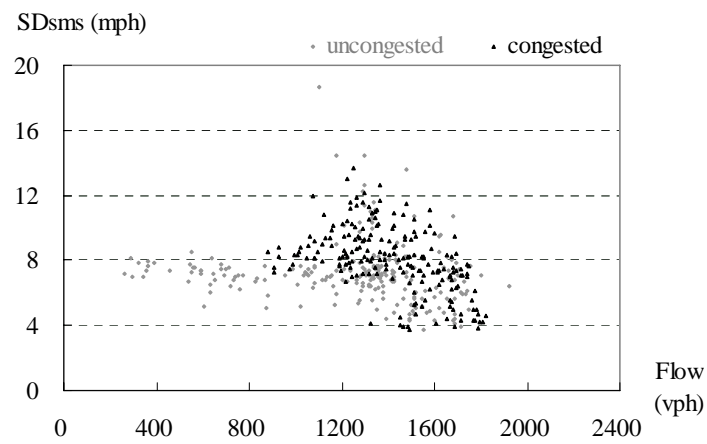
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(a) *Occupancy* —  $SD_{sms}$



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(b) *SMS* —  $SD_{sms}$



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(c) *Flow* —  $SD_{sms}$

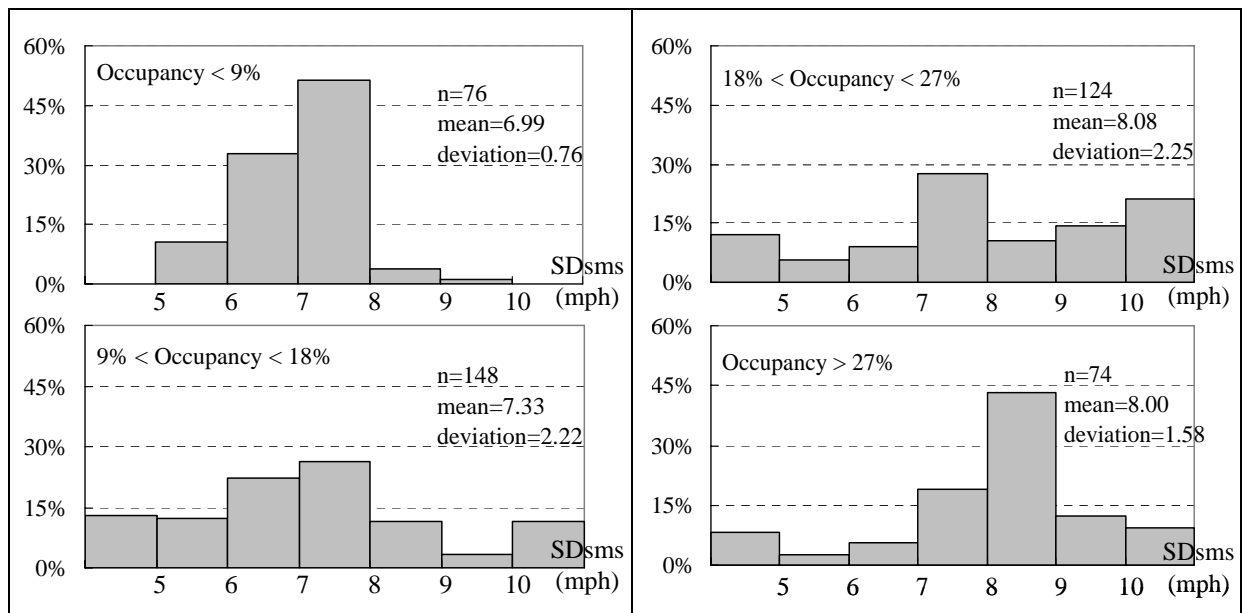
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**FIGURE 9** Scatter plots of the fundamental parameters and  $SD_{sms}$  (all lane mix)

9

**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  $5.57 \pm 0.07$  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



1 into and out of Lane 2 more frequently. These two factors force drivers (not only in the HOV but  
 2 also in the adjacent GP lanes) to adjust speeds, causing greater speed dispersions in Lanes 1 and  
 3 2 in congestion. Third, speed dispersions in Lanes 3 to 5 under uncongested conditions are on the  
 4 average greater than those in congestion. This may be due to the outer lanes that usually have  
 5 higher percentages of trucks and conservative motorists who tend to stay in lane when traffic  
 6 worsens as it is more difficult to find a gap large enough in comparison to the uncongested state.

7  
 8 **TABLE 4 Descriptive Statistics of  $SD_{sms}$  by Lane and Congestion Level**

	Uncongested state			Congested state		
	Mean $SD_{sms}$ (mph)	$\sigma_{SD_{sms}}$ (mph)	number of observation	mean $SD_{sms}$ (mph)	$\sigma_{SD_{sms}}$ (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)

● uncongested end      × congested end

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

10  
 11 **6. DISCUSSION**

12 TABLE 5 compiles the coefficients of determination of the suggested regression equations in  
 13 FIGURE 4, 6, and 8. The results conclusively indicate that  $CV_{sms}$  would be better explained by  
 14  $SMS$  than by either *occupancy* or *flow*. In the case that  $SMS$  is not available—for instance, single  
 15 loop detectors do not record speed—*occupancy* can be a substitute of  $SMS$ . *Flow* is not  
 16 suggested to be used to explain  $CV_{sms}$  except for non-individual lanes during congestion.  
 17  $CV_{sms}$  is favored over  $SD_{sms}$  when using speed dispersion to link to the fundamental traffic  
 18 flow parameters, albeit  $SD_{sms}$  and  $CV_{sms}$  have at least two similarities. First, both indicators in

1 the all lane mix are greater than they are in the individual lanes. This is understandable as the all  
 2 lane mix contains more varieties of vehicle types, driving behaviors, lane restrictions, speed limit,  
 3 etc. Second, individual lanes can be grouped by inner two lanes and outer three lanes for both  
 4  $SD_{sms}$  and  $CV_{sms}$  with respect to the congestion level, of which the possible causes are discussed  
 5 in Section 5. One of the contrasts between  $SD_{sms}$  and  $CV_{sms}$  is that due to a deeper drop of  
 6  $SMS$  than  $SD_{sms}$ ,  $CV_{sms}$  in the outer three lanes increases with traffic while  $SD_{sms}$  does not.

7 Although  $SMS$  can be theoretically connected to *flow*, *density*, and *average travel time*,  
 8 time mean speed ( $TMS$ ) is commonly employed in traffic practice as an approximation of  $SMS$ .  
 9 Equations (8), (5) and (3) can make conversions between  $TMS$  and  $SMS$ , and their speed  
 10 dispersions. As shown in Table 6 (that takes the all lane mix, for example), differences between  
 11  $TMS$  and  $SMS$  are as much as 3 mph;  $CV_{tms}$  and  $CV_{sms}$  is within 10% deviation if  $TMS$  is above  
 12 35 mph;  $SD_{tms}$  and  $SD_{sms}$  is within 10% deviation if  $TMS$  is above 20 mph. During light traffic,  
 13  $TMS$  and  $SMS$ , and their speed dispersions are very likely exchangeable for practical purposes.

$$14 \quad SD_{tms}^2 = E(v - TMS)^2 = E\left(v - SMS - \frac{SD_{sms}^2}{SMS}\right)^2 = SD_{sms}^2 - \frac{SD_{sms}^4}{SMS^2} \quad (8)$$

15 where  $v$  is individual speeds.

16 **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	<b>0.61</b>	<b>0.79</b>	<b>0.67</b>	<b>0.67</b>	<b>0.59</b>	<b>0.76</b>	<b>0.83</b>
flow (congested)	Linear	0.29	0.46	0.45	0.39	0.46	0.66	<b>0.83</b>

17  
18

**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%

19

## 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 fundamental traffic flow parameters would rely on more extensive empirical cases and theoretical development.

## REFERENCES

1. Del Castillo, J. M. and Benitez, F. G. (1995), On the Functional Form of the Speed-Density Relationship, Part Two: Empirical Investigation, *Transportation Research B*, 29, pp 391-406.
2. Federal Highway Administration (FHWA, 2006), *Traffic Detector Handbook: Third Edition*, Publication No. FHWA-HRT-06-108, McLean, VA, USA.
3. May, A. D. (1990), *Traffic Flow Fundamentals*, Prentice Hall, Englewood Cliffs, NJ, USA.
4. McShane, W. R. and Roess, R. P. (1990), *Traffic Engineering*, Prentice Hall, Englewood Cliffs, NJ, USA.
5. Rakha H. and Zhang W. (2005), Estimating Traffic Stream Space Mean Speed and Reliability from Dual- and Single-Loop Detectors, *Transportation Research Record*, 1925, pp 38-47.
6. Shankar, V. and Mannering, F. (1998), Modeling the Endogeneity of Lane-mean Speeds and Lane-speed Deviations: a Structural Equations Approach, *Transportation Research A*, 32, pp 311-322.
7. Treiber, M., Hennecke, A., and Helbing, D. (1999), Derivation, Properties, and Simulation of a Gas-kinetic-based, Nonlocal Traffic Model, *Physical Review E*, 59, pp 239-253.
8. Varaiya P. (2007), Effectiveness of California's High Occupancy Vehicle (HOV) System, UCB-ITS-PRR-2007-5, California PATH Research Report.
9. Wang, H., Wang, W., Chen, X., Chen, J., and Li, J. (2007), Experimental Features and Characteristics of Speed Dispersion in Urban Freeway Traffic, *Transportation Research Record*, 1999, pp150-160.
10. Wardrop J. G. (1952), Some Theoretical Aspects of Road Traffic Research, *Proceedings of the Institute of Civil Engineers*, 1-2, pp. 325-378.