Effectiveness of High Occupancy Vehicle (HOV) Lanes in the San Francisco Bay Area

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ABSTRACT

The San Francisco Bay Area is well-suited for studying the effectiveness of high occupancy vehicle (HOV) lanes because the HOV restrictions are time-actuated: lane 1 is restricted to 2+ or 3+ vehicles on weekdays, 5-9 AM and 4-7 PM; at other times it is a general purpose lane. Thus traffic on the same lane can be compared with and without the HOV restriction. Analysis of the data for 2001-2005 shows: (1) HOV actuation imposes a 20% *capacity penalty*: the maximum flow at 60 mph on an HOV-actuated lane is 1,600 vehicles/hour, compared with 2,000 vehicles/hour when it is not HOV-actuated; (2) The HOV restriction significantly increases demand on the other lanes causing a net *increase* in overall congestion delay; (3) HOV actuation does *not* significantly increase person throughput; and (4) Both short-term (daily) and long-term (yearly) carpooling responses are *insensitive* to travel-time savings. The first conclusion implies that although HOV lanes will seem underutilized, there is little 'excess capacity' to permit toll-paying or hybrid vehicles access to HOV lanes in order to raise revenue or promote fuel efficiency. The fourth conclusion implies that HOV use will not increase as congestion worsens. Together, these conclusions threaten belief in the effectiveness of HOV lanes as a means to mitigate congestion or reduce pollution in the Bay Area.

Keywords: HOV effectiveness; carpooling; HOT lanes; San Francisco Bay Area; congestion

1. INTRODUCTION

California promotes HOV facilities. The State spent $2.3 billion by 2000 for 925 HOV lane-miles (1.9% of the system's total), with plans to double the HOV system by 2020. Studies of HOV effectiveness usually support its expansion, largely based on the obvious conclusion that HOV travelers benefit from lower travel times, see e.g. (*1*, *2*).

There are skeptical views, however. The 2000 California Legislative Analyst's Report (*3*) emphasizes several cautionary statistics: 24 percent of HOV lanes carried fewer than the mandated minimum 800 vehicles per hour or vph; HOV usage did not generally increase over time; and HOV lanes generally operated at two-thirds of capacity. The 2003 American Community Survey finds the proportion of work-commute trips in California that are carpooled declined from 13.12% in 2001, to 12.67% in 2002, to 12.60% in 2003 (*4*). In the SCAG region, with more than 660 miles of HOV lanes—the largest in the nation—carpooling declined from 14.3% to 11.4% between 2000 and 2004, and the share of drive-alone commuting increased from 73% to 76.7%. The decline is widespread: carpooling declined from 16.5% to 12.1% in San Bernardino County and from 15.6% to 14.1% in Riverside County experienced between 2003 and 2004 (*16*, p. 69, 70).

Underutilization of HOV lanes provides grounds for suggestions to permit toll-paying or hybrid vehicles access to HOV lanes in order to raise revenue or promote fuel efficiency. Virginia allows hybrid vehicles access to I-95. But a January, 2005 *Washington Post* editorial claimed that as a result "traffic in I-95's HOV lanes is starting to slow to the crawl associated with the regular lanes." The editorial concludes, "Whatever the idea's original logic, it has outlived its usefulness and ought to be dropped" (*5*). The Virginia DOT Task Force reportedly has recommended that the exemption for hybrid single occupancy vehicles (SOVs) be allowed to expire in July 2006 (*6*).

A Los Angeles telephone survey found 88% supporting carpool lanes; 42% said carpool lanes were underutilized; and 57% claimed 'travel-time savings' as their motivation for carpooling (*2*, pp.29-31). This last claim may be weighed against the fact that nationally in 2001, 83% of carpools consisted of people from the same household, 97% of whom had only household members (*7*, p.29).

These observations raise four questions:

1. HOV excess capacity: How much additional flow can an HOV lane support while maintaining free flow speed of 60 mph?
2. Overall congestion: If an HOV lane were to be opened to general traffic, would the overall congestion be decreased?
3. Person throughput: Does an HOV lane increase the total throughput in persons per hour?
4. Carpooling response to travel-time savings: How many SOV drivers would switch to carpooling if travel time on non-HOV lanes doubled?

This paper addresses these questions by analyzing data from the San Francisco Bay Area during 2001-2005. These data are well-suited for studying these questions because the Bay Area's HOV lanes are time-actuated: On designated freeway segments, lane 1 (the leftmost, fast lane) is restricted to high-occupancy vehicles (2+ or 3+ persons) during 5:00-9:00 AM and 3:00-7:00 PM on weekdays; at other times it is a general-purpose lane. This allows comparison of traffic on the same lane when it is HOV-actuated with when it is not. The analysis arrives at unorthodox answers.

First, the maximum flow at 60 mph on an HOV-actuated lane is 1,600 vph, compared with 2,000 vph when it not HOV-actuated. Thus HOV actuation imposes a 20% *capacity penalty*. The penalty is inflicted by the 'snails': An HOV lane becomes a one-lane highway whose speed is determined by the slow vehicles—the snails. Common sense, which suggests an 'excess' HOV capacity of 400 (= 2,000 – 1,600) vph, is mistaken.

Second, the HOV restriction significantly increases traffic on the other lanes; the net result is an *increase* in overall congestion delay.

Third, the calculation of the impact of HOV actuation on total person throughput uses unreliable estimates of average vehicle occupancy (AVO) of non-HOV vehicles. For a 2+ HOV lane, the lowest (non-HOV) AVO estimate of 1.25 implies a small increase in person throughput, but the higher AVO estimates of 1.3 or 1.4 imply a significant decrease in person throughput. Thus, HOV actuation does *not* significantly increase person throughput.

Fourth, travel-time savings is *not* a factor in the decision to carpool. This is the case whether one examines short-term (daily) or long-term (yearly) response.

The next section reviews the data used in the analysis; the subsequent sections consider in turn the four questions noted above.

2. DATA

Bay Area HOV segments occupy 274.5 lane-miles out of a total of 2,868 direction-miles of highway. On each HOV segment, lane 1 is HOV-actuated on non-holiday weekdays, generally from 5-9 AM and 3-7 PM, although the times vary slightly. During HOV actuation, the lane is restricted to vehicles with 2+ or 3+ persons (*8*, p. 9).

Loop detector data are obtained from the California Freeway Performance Measurement System or PeMS database. PeMS collects 30-second loop detector data, and processes the data to produce information about speed, congestion, travel time, and demand (VMT). PeMS data are available from its website (*9*). Loops are indexed by their VDS (vehicle detector station) ID. Bay Area data are available starting mid-2001. The paper analyzes several HOV segments.

Consider an HOV segment with n VDSs located at postmiles $x_1 < x_2 < \ldots < x_n$. With the VDS at x_i is associated the section of the freeway midway between x_i and the adjacent VDSs at x_{i-1} and x_{i+1}, i.e., from $(x_{i-1}+ x_i)/2$ and $(x_i + x_{i+1})/2$. This section is $L_i = (x_{i+1} - x_{i-1})/2$ miles long. Let $t = 1, 2, \ldots, T$ be the 5-minute intervals comprising the peak period. From PeMS one obtains $v_k(x_i, t)$ and $q_k(x_i, t)$, the average speed (mph) and total volume (count) in lane k at x_i during interval t, for the HOV lane $k = 1$ and the adjacent non-HOV lane $k = 2$. Define

$$VMT_k = \sum_i \sum_t q_k(x_i, t) \times L_i \text{ (veh-miles)}, \quad (1)$$

$$VHT_k = \sum_i \sum_t \frac{q_k(x_i, t) \times L_i}{v_k(x_i, t)} \text{ (veh-hours)}, \quad (2)$$

$$Q_k = VMT_k / ((\sum_i L_i) \times (T/12)) \text{ (vehicles per hour or vph)}, \quad (3)$$

$$V_k = \frac{VMT_k}{VHT_k} \text{ (mph), and} \quad (4)$$

$$S = \frac{VMT_1}{VMT_1 + VMT_2} \quad . \quad (5)$$

VMT_k is the daily peak period demand in lane k measured in vehicle-miles traveled, and VHT_k is the corresponding vehicle-hours traveled. Q_k is the volume (vph) in lane k averaged over the entire study segment and peak period. (The factor 12 in formula (3) converts 5-minute time durations into hours.) V_k is the average speed in lane k during the peak period. Lastly, S is the HOV lane's *share* of *VMT* demand in lanes 1 and 2. These aggregate quantities are computed for each day in 2001-2005 for the analysis in section 6. The analysis in sections 3-5 uses the 5-minute average speed and flow at individual VDS.

3. HOV EXCESS CAPACITY

Figure 1 shows two scatter plots of speed vs. flow in lane 1. Each point represents a 5-minute average on weekdays in August 2004 from VDS 400488 on 880-N. The *y*-axis is speed in mph; the *x*-axis is flow in vehicles per 5-minutes. The plot on the left is for time samples during 4-7 PM, when the HOV restriction is actuated. The plot on the right is for 7-9 PM, when HOV is de-actuated.

After de-actuation, traffic moves at a nearly constant speed above 70 mph, with a maximum flow of 160 veh/5-min or 1,920 vph. By contrast, during HOV actuation speed declines as flow increases, with a maximum flow at 70 mph of 120 veh/5-min or 1,440 vph. Thus at this location, HOV actuation imposes a (1920-1440)/1920 or 25% capacity penalty at free flow (70 mph).

The phenomenon in Figure 1 occurs everywhere. For example, the plots in Figure 2 from VDS 400172 on 101-S imply a capacity penalty of 18% at 60 mph. By examining many locations we find that, in free flow conditions (nominally 60 mph), the maximum flow during HOV actuation is 1,600 vph and during HOV de-actuation it is 2,000 vph. *Thus HOV actuation imposes a capacity penalty of 400 vph or 20%*.

The HOV capacity penalty may be explained as follows. The HOV lane operates as a one-lane highway, so its speed is governed by the low speed vehicles—the 'snails'. As lane 2 is even slower, a faster HOV vehicle cannot pass the slower snail in front of it. However, as soon as HOV is de-actuated, slower drivers move to the outer lanes and the faster drivers move to (what was) the HOV lane, with a dramatic increase in speed as seen, for example, in Figure 3.

Three factors may account for the snails: A certain fraction of HOV drivers may prefer to be slow; others may be slow because of the perceived danger from very slow vehicles in the adjacent lane 2; lastly, as congestion in lane 2 worsens, violators may dart into and out of the HOV for short time intervals with increasing frequency, forcing HOV drivers to slow down (*10*). Because HOV flow at 60 mph is below 1,600 vph, common sense may conclude that there is an 'excess capacity' of 400 vph. Common sense would be wrong, because any significant increase in HOV flow (by, say, tolled or hybrid vehicles) would rapidly reduce HOV speed as Figures 1 and 2 indicate.

4. OVERALL CONGESTION

Figure 3 is used to assess the impact of HOV actuation on overall congestion. During 3-7 PM, HOV actuation removes one general purpose lane. As seen in Figure 3, this plunges all non-HOV lanes into congestion, slightly reduces overall flow (maximum flow is at 2:50 PM), and greatly reduces speed in both the HOV lane and lane 2. When HOV is de-actuated at 7 PM, speed increases dramatically in both lanes. (To prevent clutter, plots for lanes 3 and 4 are not shown; they behave similarly to lane 2.) The speed reduction in all lanes during HOV actuation causes a large increase in congestion delay. This example and others (see (*15*, Figure 8)) raise the question, "Would overall congestion be reduced by eliminating the HOV lane?"

The answer would certainly be 'yes', but for two qualifications: one having to do with freeway management, the other with mode choice. A bad management strategy with no HOV lane and poor or no metering at on-ramps may cause more congestion than a less bad strategy with one HOV lane and poor or no metering, merely because HOV actuation serves as a very crude metering mechanism. But if a proper ramp metering is in place that guarantees a reasonably high *vehicle* flow in non-HOV lanes, total vehicle flow and average speed without an HOV lane will be significantly larger.

The second qualification is based on two claims about mode choice: (1) HOV lanes move significantly more people overall (even if they don't move more vehicles), (2) HOV lanes induce enough drivers to carpool to compensate for both the larger congestion in non-HOV lanes and the capacity penalty imposed on the HOV lane. These claims are dubious, as seen next.

5. PERSON THROUGHPUT

We calculate persons per hour (PPH) by multiplying vehicle flow and AVO at VDS 400486 in 880-S. Because AVO estimates are unreliable (*11*), we use a range of estimates. According to (*12*, p. 66), in the section of 880-S that includes VDS 400486, during the afternoon peak the HOV lane AVO is 2.1 and the AVO on the three non-HOV lanes is 1.1. We use these estimates for the HOV actuation period. (The HOV AVO rate should be reduced by the HOV violation rate estimated at 5.8% on July 5, 2002, but we do not make this correction.)

AVO estimates during HOV de-actuation are not available, and we have several alternatives. The *Household Travel Survey* (*13*, Table B) gives an AVO of 1.5 for all trips and 1.1 for home-to-work trips; for the Bay Area, the Metropolitan Transportation Commission gives an AVO of 1.4 for all trips and 1.1 for home-to-work trips (*13*, Table 8.10); lastly, the California Life-Cycle Benefit/Cost Analysis Model uses a default of 1.38 for peak period AVO (*14*, p.2-12). We use 1.25, 1.3 and 1.4 for AVO during HOV de-actuation.

From the plot on the left in Figure 4 we see that for the two higher AVO estimates, HOV actuation *reduces* the throughput of persons per hour (PPH). With the lowest AVO estimate of 1.25, HOV actuation *slightly increases* PPH, compared with the pre-actuation period 2-3 PM. Thus, HOV actuation does *not* significantly increase throughput in persons per hour.
The HOV AVO estimates might be inappropriate if vans and buses comprised a significant portion of HOV vehicles. However, the AVO estimates in (*12*) *do* take vans and buses into account. In any event, the percentage of persons traveling by van or bus in the HOV segments considered here are (*12*): 80-E (28%); 101-S (8%); 101-N (4%), 880-N (3%); and 880-S (8%).

Knowing the speed and volume, and taking AVO=1.25 during HOV de-actuation, we can determine a cost index—the time taken by one person or one vehicle to travel one mile. The two indexes are plotted in the right of Figure 4. Evidently, the *average* person (on *all*, including HOV, lanes) pays a travel-time cost during HOV actuation (5-7 PM) that is two-and-a-half times higher. If we view travel time as the cost of freeway operation, we must conclude that HOV actuation increases this cost. This is a better measure of productivity *loss* than the productivity *gain* measured as the ratio between HOV AVO and non-HOV AVO in (*1*, pp. 6, 8). The latter merely reflects the fact that HOV actuation causes carpools to move into the HOV lane.

6. CARPOOLING RESPONSE

It is believed that travel-time savings cause people to shift from traveling alone to carpooling (*1*, p. 14, *2*, p. 29). We estimate how much carpooling increases with travel-time savings in the four complete HOV freeway segments listed in Table 1 during 2001-2005.

For each HOV segment and each weekday, we calculate the HOV lane's share S of the vehicle-miles traveled in lanes 1 and 2, using formula (5). To measure travel-time savings, we calculate V_2, the speed in lane 2, averaged over the HOV segment and actuation duration, using formula (4).

HOV share S is expected to increase as lane 2 speed V_2 decreases. Figure 5 gives a scatter plot of HOV share vs. lane 2 speed for the four study segments. Each point represents the average over the HOV actuation AM or PM peak period (indicated in Table 1) for one day. The solid straight line is the least-squares fit to the linear regression $S = \alpha + \beta V_2$. Table 2 lists the regression coefficients.

Consider the plot for 101-S, PM for now. In agreement with the prior expectation, there is a (small) downward trend in the scatter plot: As lane 2 speed decreases from 60 to 30 mph, the HOV share increases from 0.40 to 0.44. That is, *as travel time in the non-HOV lane increases by 100%, the HOV share increases by only 10%*. But even this tiny 10% increase in HOV share is illusory.

The number of HOV-*qualified* vehicles or carpools (which is what we *want* to measure) differs from the number of HOV-*using* vehicles (which is what we *can* measure) in two ways. When speed in lane 2 is high, say 60 mph or more, there is less incentive for an HOV-qualified driver to use the HOV lane, and so the number of HOV-using vehicles *underestimates* the number of HOV-qualified vehicles. On the other hand, when speed in lane 2 is low, say 30 mph or less, the number of HOV lane violators will increase, and so the number of HOV-using vehicles *overestimates* the number of HOV-qualified vehicles. We adjust the share *S* of HOV-using vehicles to obtain $\hat{S}$, the share of HOV-qualified vehicles.

Violation rates in different HOV segments in the Bay Area vary (see *8*, p.19, and Table 2). (The California Department of Transportation considers a 10 percent violation rate acceptable (*1*, p.5).) We assume a 5 percent violation rate when speed in lane 2 is 30 mph. We also assume that 5 percent of HOV-qualified drivers do not move into the HOV lane when lane 2 speed is 60 mph. The adjusted share $\hat{S}$ is shown in Table 2. Figure 5 also shows the adjusted regression line for $\hat{S}$. Evidently, *carpooling is unresponsive to short-term (daily) changes in travel- time savings*. This finding runs counter to general opinion.

It may be that it takes a long time to make carpooling arrangements and so one should not expect an elastic short-term response. We estimate long-term (annual) response. Figure 6 gives box plots of average speeds in lanes 2 and share of demand in HOV lane in each year. Consider the segment in 101-N, AM peak. The lane 2 speed decreases steadily over 2001-2005 but the yearly median *S decreased* over 2001-2004 as well! Similarly, there is no close correlation between V_2 and S observable in the other study sites. This finding also repudiates the hypothesis that long term increases in travel-time savings encourages carpooling.

7. CONCLUSION

HOV plans for the San Francisco Bay Area seek to increase its current 270 lane-miles by an additional 230 lane-miles (*1*, Table 1), at a cost of $3.7 billion. The DKS study of the Bay Area's HOV plan (*1*) builds on the premise, "Carpooling, vanpooling and express bus services have become increasingly more important to meeting the mobility needs of the region…"

This premise seems false. The analysis presented here suggests that in the Bay Area, instead of improving mobility, HOV lanes *exacerbate* the congestion problem: HOV lanes suffer a capacity drop of 400 vehicles/hour; they increase congestion overall; they do not significantly increase the throughput of people; and they do not encourage carpooling.

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TABLE 1 Summary of Study HOV Segments

Route	Limits	Length (miles)	Min. Occ	HOV actuation
I-80E	Powell St to Rte 4	14.1	3	5-10AM, 3-7PM*
I-880N	Mission Blvd to South of Rte 237	16.9	2	5-9AM, 3-7PM*
SR-101S	San Mateo Co. Line to Cochrane Rd	34.8	2	5-9AM, 3-7PM*
SR-101N	Cochrane Rd to San Mateo Co. Line	34.0	2	5-9AM*, 3-7PM

* peak hours considered

TABLE 2 Coefficients and selected values of $S = \alpha + \beta V_2$

Freeway	α	β	**S for V_2 = 30**	**S for V_2 = 60**	**Violation rate (%)**	**S_{adj} for V_2 = 30**	**S_{adj} for V_2 = 60**
I-80E	0.4933	-0.00093	0.465	0.437	6.5(PM)	0.442	0.459
I-880N	0.5024	-0.00112	0.469	0.435	4.4(PM)	0.445	0.457
SR-101S	0.4608	-0.00086	0.435	0.409	3.0(PM)	0.413	0.429
SR-101N	0.4468	-0.00103	0.416	0.385	4.5(AM)	0.395	0.404

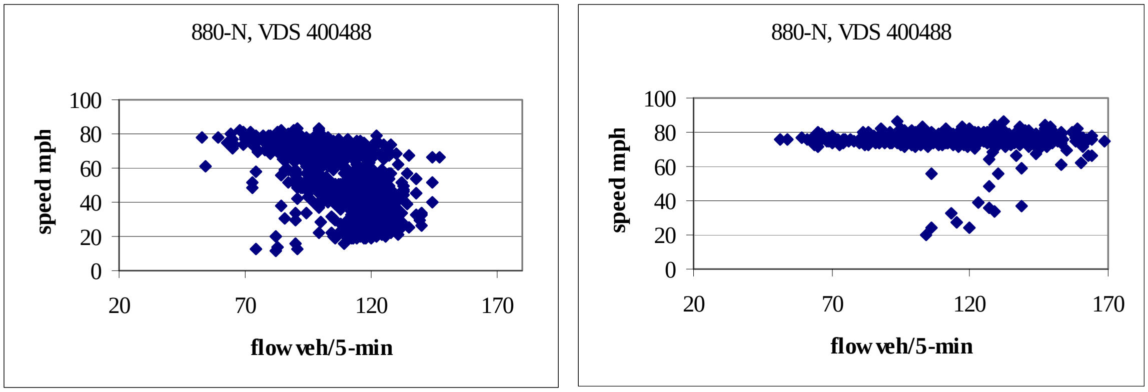

FIGURE 1 Flow vs. speed during HOV actuation, 4-7 PM (left), and after HOV actuation, 7-9 PM (right), at VDS 400488 on 880-N, August 2004.

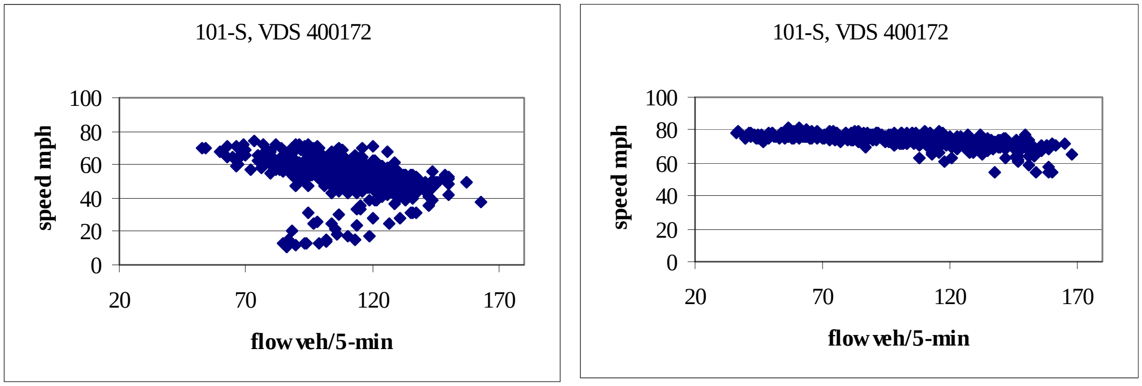

FIGURE 2 Flow vs. speed during HOV actuation, 4-7 PM (left), and after HOV actuation, 7-9 PM (right), at VDS 400172 on 101-S, August 2004.

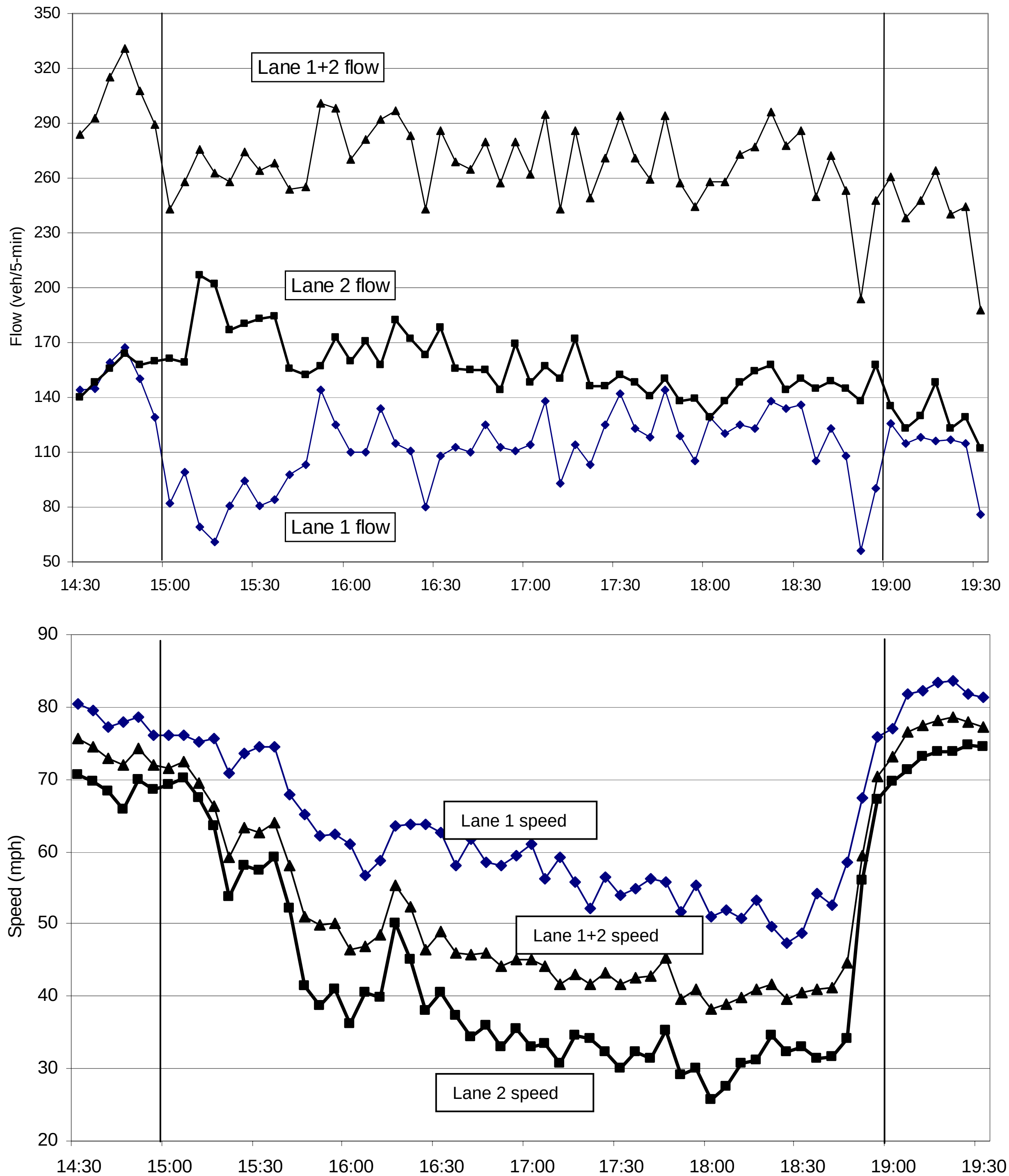

FIGURE 3 Flows in vehicles/5-min (top) and speeds (bottom) in lanes 1 and 2 at VDS 400352 on 880-S, August 4, 2004. Speed in all lanes drops during HOV actuation, 3-6:45 PM, increasing congestion delay. Speed increases dramatically at 7 PM. Maximum flow is reached at 2:45 PM.

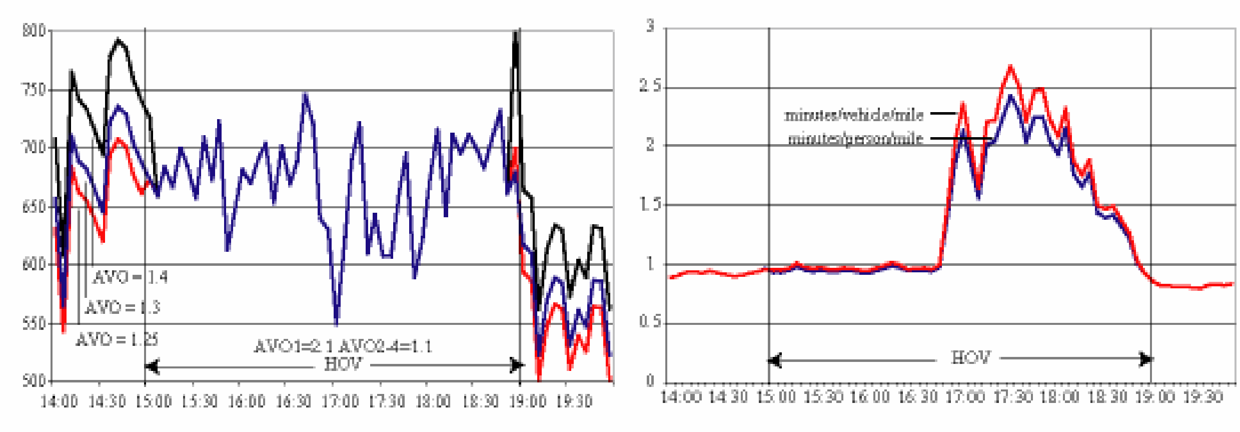

FIGURE 4 Flow in persons per 5-min using the indicated AVO values (left), and time spent per person-mile and per vehicle-mile, 2-8 PM, at VDS 400486 on 880-S, August 18, 2004.

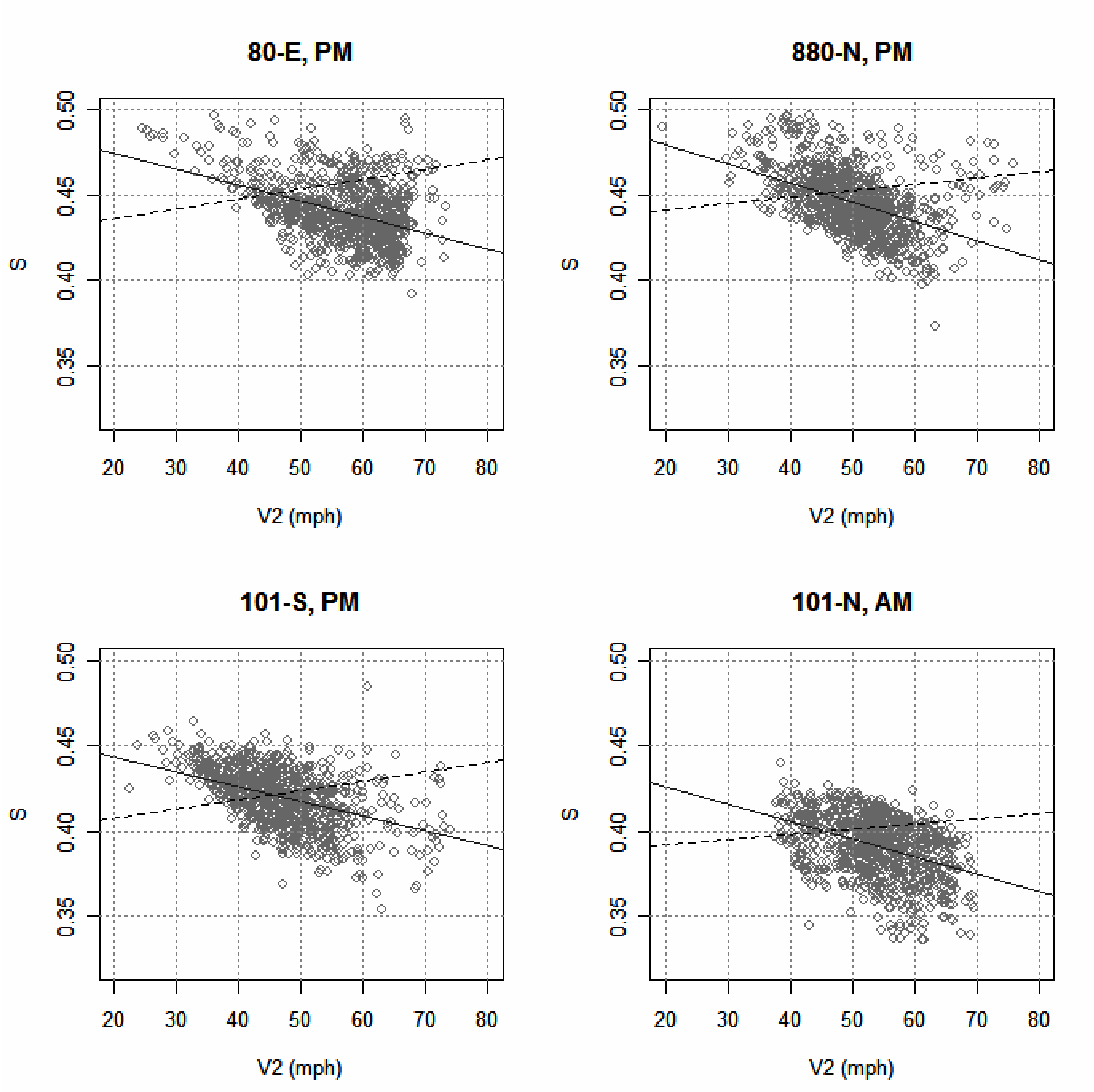

FIGURE 5 Share of demand in HOV lane vs. average speed in lane 2 in four HOV segments, for 2001-2005. Each point represents the AM or PM peak for one weekday. Also shown are least squares linear regression lines through data points (solid lines) and adjusted lines (dashed lines).

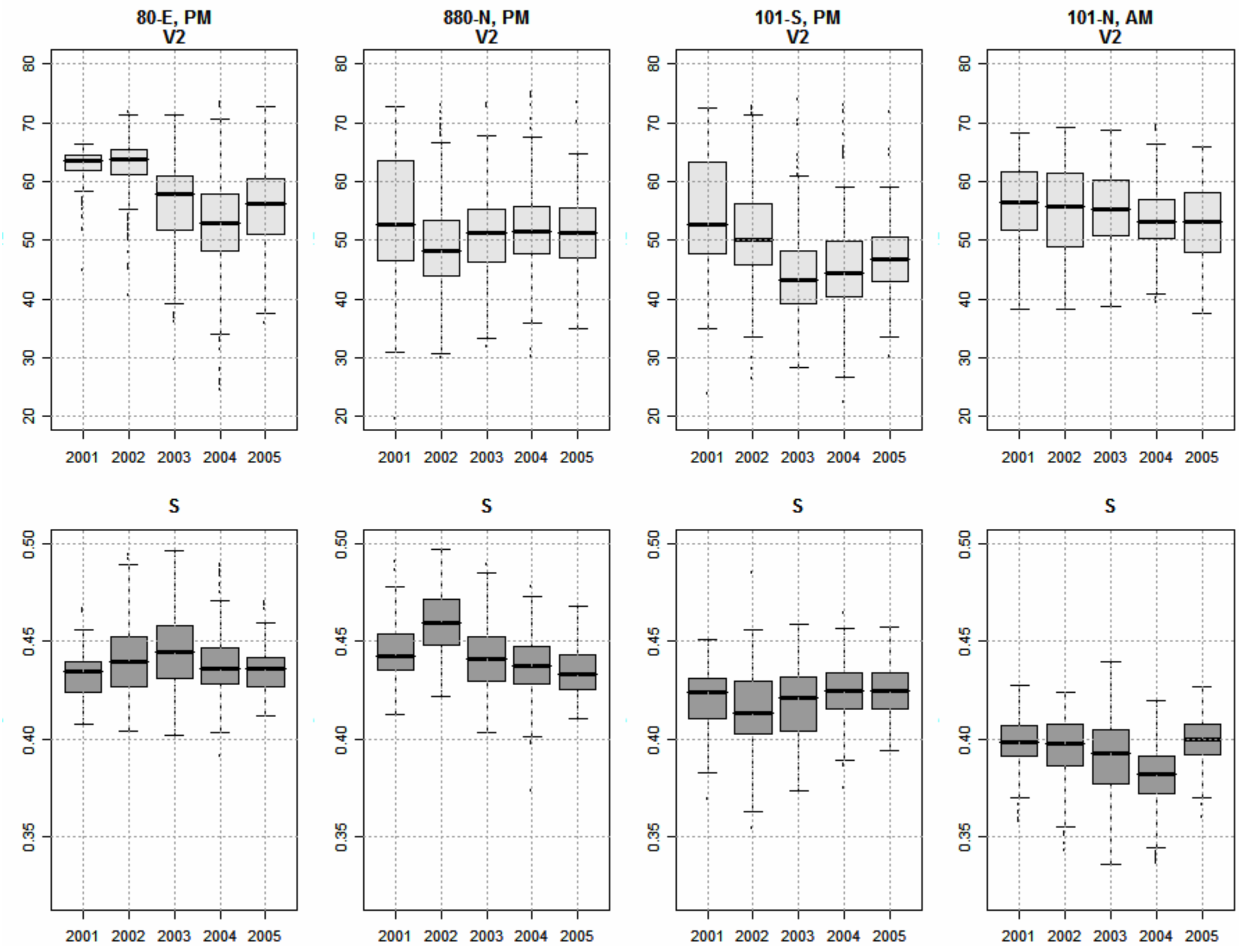

FIGURE 6 Average speed in lane 2 (top) and share of demand in HOV lane (bottom) for 2001-2005 for the four study segments. Boxplots show each year's distribution of daily *S* or V_2.