Operational Assessment of Speed Priority for High-Occupancy Vehicle Lanes over General-Purpose Lanes

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ABSTRACT

Current guidelines arguably do not properly address how much high-occupancy vehicle (HOV) lanes should be prioritized over general-purpose (GP) lanes. This study develops two schemes for HOV and GP lanes by utilizing the concept of "speed equilibrium," which determines whether HOV lanes are under-prioritized, over-prioritized, or well-prioritized. The first scheme incorporates average vehicle occupancy with speed priorities, reflecting the HOV core value of carrying more persons in fewer vehicles; HOV lanes maintain higher equilibrium speeds than GP lanes, but the differences decrease as traffic speeds decrease from free flow to jam states. The second scheme is a revision of the existing HOV principle: equilibrium built upon the principle of time saved leads to increasingly greater HOV speeds relative to GP lane speeds, as traffic volumes increase. Both schemes are visualized in three-dimensional data plots to illustrate the effects of individual traffic variables. Using only a single measure, i.e., speed, ensures inferior HOV priority with respect to mobility and reliability. Observed freeway data were applied to the two schemes, and the results can be used to determine the necessity of HOV policy adjustment. The schemes are complimentary to current HOV operational assessments.

Keywords: high-occupancy vehicle lane, average vehicle occupancy, travel time saving, freeway operational assessment.

INTRODUCTION

Performance evaluations are essential to monitor the operation of high-occupancy vehicle (HOV) facilities. Based on specific volume or speed criteria, such evaluations analyze how well HOV facilities achieve different goals. The state-of-the-practice performance criteria for HOV facilities relative to general-purpose (GP) lanes have been documented over a long period of time under various guidelines. For example, the Transportation Research Board (TRB, 1998) suggests that the HOV lane should carry more people in fewer vehicles than adjacent GP lanes, which is identical to the guideline provided in the Washington State's policy (WS DOT, 1991). The TRB (1998) also proposed a minimum threshold of 400 to 800 vehicles per peak hour per lane (vphpl), and 1,200 to 1,500 vphpl for the degrading thresholds on concurrent HOV facilities. In contrast, the American Association of State Highway and Transportation Officials (AASHTO, 2004) set the high end of the maximum volume ranges for most HOV facilities at 1,600 vphpl. The California Department of Transportation (Caltrans, 2003) gauges HOV facilities with desired volume utilization between 800 and 1,650 vphpl, for a minimum of 1,800 persons per peak hour per lane (pphpl). In addition, speed and time saved are commonly used performance measures. The "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users" (SAFETEA-LU, 2005) considers that HOV facilities' effectiveness is degraded if the average vehicle speed is less than 45 mph in one or both of the peak hours, for more than 18 out of 180 days, which is similar to the WS DOT guideline (1991). The TRB (1998) and Caltrans (2003) suggest that HOV facilities save at least 1 min per mile and a total of 5-10 min compared to GP lanes.

The above criteria, however, are insufficient for evaluating freeway operations. First, the "1 min saved per mile" principle is not applicable for extensive traffic conditions. For instance, to comply with this principle, a speed of 40 mph in a GP lane will require an impossibly high HOV lane speed of 120 mph. Essentially, the principle should only be used for GP lane speeds of less than 35 mph, with corresponding HOV speeds less than 80 mph, which is a legitimate maximum speed. Second, consider two speed pairs for HOV and GP lanes reported on a highway: (65, 64) mph and (65, 55) mph. The (65, 64) mph pair presents good traffic conditions, but the HOV lane barely offers any time saving incentive compared to the (65, 55) mph pair. The HOV lane users would think that the (65, 55) mph pair is an adequate condition, whereas the GP lane users would expect that the (65, 64) mph pair is more reasonable. The existing guidelines do not provide an explanation for this discrepancy.

The objective of this study was to address the above issues by clarifying how much HOV lanes should be prioritized over GP lanes. HOV priority is presented based on speed because for operational aspects, it measures mobility and time saved, and for monitoring aspects, speed is accessible to motorists and most traffic management centers. Two schemes regarding vehicle occupancy and time saved were developed via mathematical derivation to complement the existing guidelines. These schemes can determine (1) under-prioritized HOV, which implies that the HOV speed is too slow, (2) well-prioritized HOV, which implies that the HOV and GP lanes are at a "speed equilibrium," and (3) over-prioritized HOV, which implies that the GP lane speed is too slow.

VEHICLE OCCUPANCY SCHEME

The person throughput of HOV facilities is a major concern for transportation authorities (Chang et al., 2008). Ideally, HOV speed priority is secured because of higher person movement capacity, via greater average vehicle occupancy (*AVO*) relative to GP lanes. In this scenario, speed priority increases with *AVO*, or more specifically, is proportional to *AVO*, as given by the following equation:

$$P_{ln}^{s} = AVO_{ln} \cdot f(X) \propto AVO_{ln} \tag{1}$$

where P_{ln}^{s} is the speed priority and *ln* denotes HOV and GP lanes respectively. P_{ln}^{s} is a function of the lane-related variable, AVO_{ln}, and the lane-independent variable set, *X*, such as speed limits and geographic elements. Eq. (1) recognizes priority granted in the following order: bus lanes, HOV3+ lanes, HOV2+ lanes, and GP lanes.

The maximum priority occurs when the lane operates at the free flow speed, *ffs*, whereas the minimum priority occurs at the jam speed, S_j. The greater the difference between the average speed, S_{ln}, and the free flow speed, the lower is the speed priority, as expressed below:

$$P_{ln}^{s} = \frac{1}{ffs - S_{ln}}, \text{ for } S_j \le S_{ln} \le ffs \tag{2}$$

The priority relationship between HOV and GP lanes is as follows:

$$\frac{P_{hov}^{s}}{P_{gp}^{s}} = \frac{ffs - S_{gp}}{ffs - S_{hov}} = \frac{AVO_{hov}}{AVO_{gp}} \tag{3}$$

Eq. (3) highlights that larger values of AVO_{hov} provide higher HOV priority with larger values of S_{hov} or moderate the priority of GP lanes with smaller values for S_{gp}, and vice versa. By substituting $R = AVO_{hov}/AVO_{gp}$ in Eq. (3), which illustrates the priority relationship, the equation becomes

$$S_{gp} = R \cdot S_{hov} - ffs(R-1), \text{ or } S_{hov} = \frac{S_{gp} + ffs(R-1)}{R} \tag{4}$$

The *AVO* ratio, *R*, can be obtained via regular HOV surveys. *R* is typically greater than one and is approximately two or three less than the settings for HOV2+ or HOV3+, respectively. In California, for example, where the bus volumes are relatively low, motorcycles and hybrid vehicles are allowed to use HOV lanes without the occupancy constraint, and some HOV-eligible vehicles stay in the GP lanes (Caltrans District 4, 2009; District 7, 2008). In such a case, Eq. (4) is simplified to the following rule of thumb, given a free flow speed of 75 mph:

$$\begin{cases} S_{gp} = 2S_{hov} - 75 & \text{for HOV2+ lanes} \\ S_{gp} = 3S_{hov} - 150 & \text{for HOV3+ lanes} \end{cases} \tag{5}$$

HOV and GP lanes are regarded as well-prioritized if the speeds of both lanes comply with Eq. (4) when $R = r$; the corresponding values are called equilibrium speeds. Otherwise, either HOV or GP lanes are over-prioritized because of their mismatched speeds; this affects their contributions to person movement. The scheme, derived from the concept of vehicle occupancy, is related to lane utilization under the simplified speed (*S*)–density (*K*) relationship: $S_{\#} = \alpha K_{\#} + ffs$ (which is basically Greenshield's equation), as illustrated below:

Rearranging Eq. (3), $(ffs - S_{gp})AVO_{gp} = (ffs - S_{hov})AVO_{hov}$, we get

$$\equiv \left(\frac{S_{gp} - ffs}{\alpha}\right)AVO_{gp} = \left(\frac{S_{hov} - ffs}{\alpha}\right)AVO_{hov} \equiv K_{gp}AVO_{gp} = K_{hov}AVO_{hov} \tag{6}$$

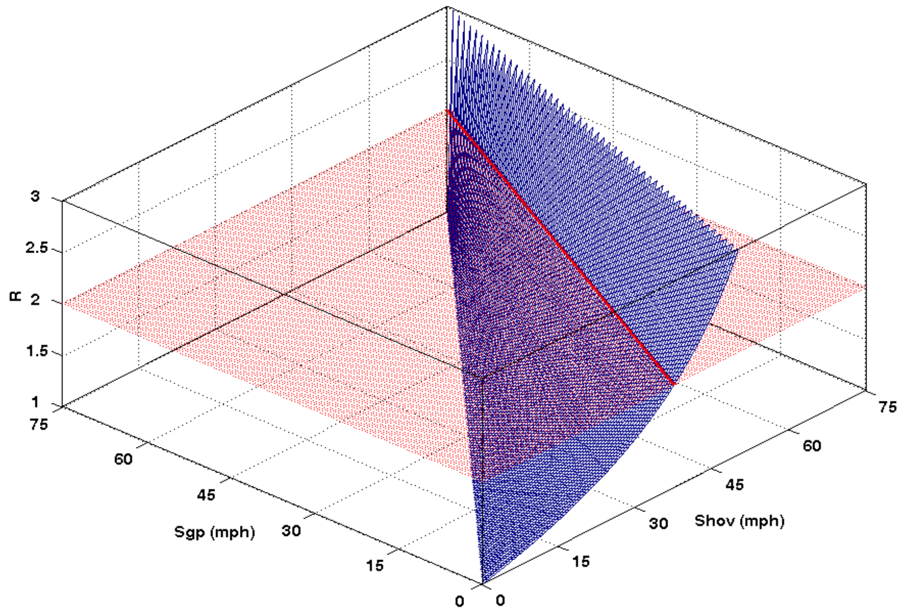
$K_{ln}AVO_{ln}$ measures lane utilization for a certain number of persons over a specific distance; it echoes the core value of HOV lanes, that is, prioritization of person transport over vehicle traffic. In the equilibrium status, the speed difference (ΔS) increases with the *AVO* ratio and the free flow speed, but decreases with the speeds of both lanes, i.e.,

$$\Delta S = S_{hov} - S_{gp} = (R-1)(ffs - S_{hov}) = \left(1 - \frac{1}{R}\right)(ffs - S_{gp}) \tag{7}$$

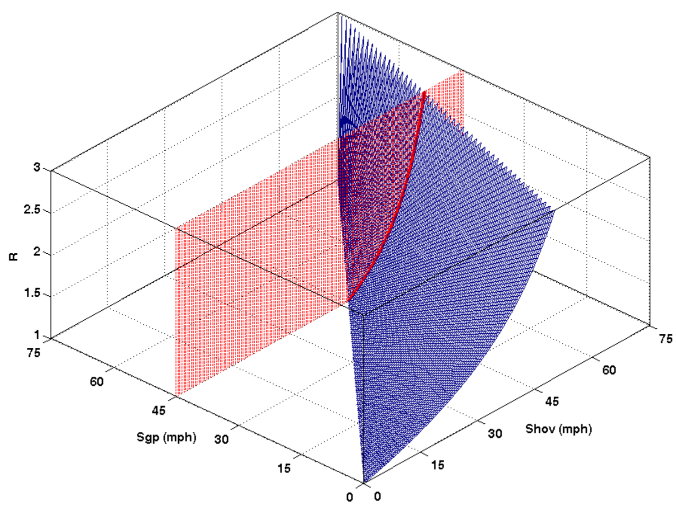
Interaction of S_{hov}, S_{gp}, and R

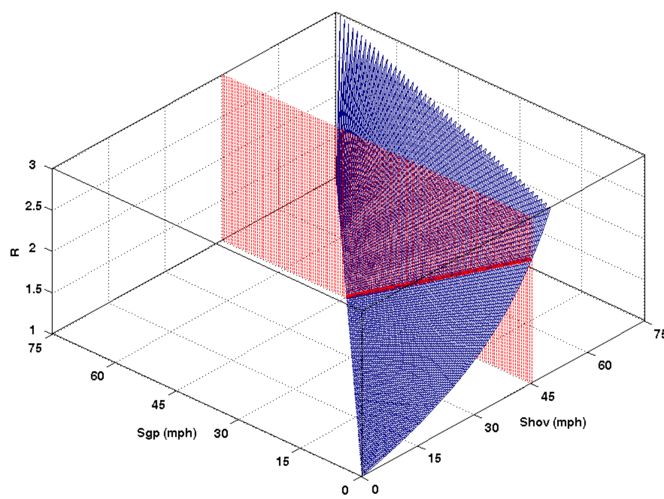
Figure 1 shows Eq. (4) as an equilibrium surface at S_{hov} and S_{gp} from 0 to 75 mph, *R* from 1 to 3, and *ffs* of 75 mph. The surface has the following characteristics:

- S_{hov} is not less than S_{gp} when the HOV and GP lanes reach speed equilibrium.
- Figure 1(a) shapes linear speed equilibrium as the intersection of the plane of *R* = 2 and the equilibrium surface. The left side of the line indicates that either S_{hov} is less than its equilibrium speed due to the over-utilized HOV lanes, or S_{gp} is greater than its equilibrium speed due to the under-utilized GP lanes. The right side denotes the opposite. The equilibrium line, $S_{gp} = 2S_{hov} - 75$, starts at $S_{hov} = 32.5$ and $S_{gp} = 0$, and ends at $S_{hov} = S_{gp} = 75$. The extreme condition of *R* = 1, in which the HOV lane serves equal persons as each GP lane, forms a diagonal equilibrium line with $S_{hov} = S_{gp}$.
- The equilibrium surface skewed to the right signifies that HOV priority increases with *R*, given $S_{gp} = s_{gp}$. As shown in Figure 1(b), the plane of $S_{gp} = 45$ intersects the surface and forms a curvy equilibrium, given by $R = 30/(75 - S_{hov})$ with an increasing slope of $30/(75 - S_{hov})^2$ for which S_{hov} increases at a decreasing rate, proportional to *R*. The curve is a vertical line for the extreme condition of $S_{hov} = 75$.
- The surface skewed to the right also signifies that the priority of the GP lanes decreases with *R*, given $S_{hov} = s_{hov}$. As demonstrated by Figure 1(c), the $S_{hov} = 45$ plane intersects the surface and forms a linear equilibrium given by $R = (-1/30)S_{gp} + 2.5$, which has a negative slope. Axle *R* intersects axle S_{gp} at 75 mph, making a line from the lower-left to the upper-right and a negative slope. The minimum S_{hov} threshold of 45 mph, specified by SAFETEA-LU, corresponds to an S_{gp} of 15 mph for *R* = 2, and an S_{gp} of 0 for *R* > 2.5.



(a) S_{hov} vs. S_{gp}, given R





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(b) S_{hov} vs. R, given S_{gp} (c) S_{gp} vs. R, given S_{hov}

Figure 1 Relationships between HOV Speed, S_{hov}, GP Lane Speed, S_{gp}, and AVO Ratio, R, in Vehicle Occupancy Scheme

Effect of Different Free Flow Speed (*ffs*)

In instances where the free flow speed is not the assumed 75 mph, the equilibrium surface will shift toward the axle of S_{gp} if the new value is less than 75 mph, or toward the axle of S_{hov} if otherwise; Figure 2 exemplifies a free flow speed change from 75 mph to 65 mph. All of the characteristics previously mentioned are consistent, but with different scaling. The equations below illustrate a slower free flow speed, in favor of S_{gp} over S_{hov}, given $R = r$.

From Eq. (4) regarding speed equilibrium, the following equation is obtained:

$$R = \frac{S_{gp1} - ffs_1}{S_{hov1} - ffs_1} = \frac{S_{gp2} - ffs_2}{S_{hov2} - ffs_2} = r \tag{8}$$

Let $ffs_2 = ffs_1 - b > ffs_1$ and $S_{hov1} = S_{hov2} = s_{hov}$. Eq. (8) becomes:

$$\frac{S_{gp1} - ffs_1}{s_{hov} - ffs_1} = \frac{S_{gp2} - \left(ffs_1 - b\right)}{s_{hov} - \left(ffs_1 - b\right)} \Rightarrow S_{gp1} + b\left(\frac{S_{gp1} - s_{hov}}{s_{hov} - ffs_1}\right) = S_{gp2} \tag{9}$$

$$\because S_{gp1} - s_{hov} \le 0 \wedge s_{hov} - ffs_1 \le 0 \Rightarrow b\left(\frac{S_{gp1} - s_{hov}}{s_{hov} - ffs_1}\right) \ge 0 \Rightarrow S_{gp1} \le S_{gp2}.$$

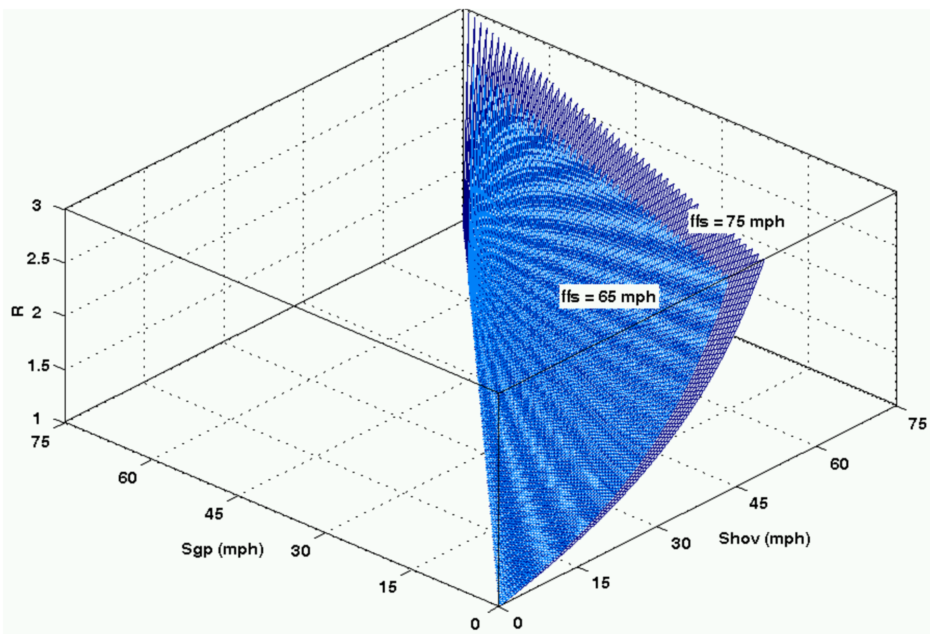


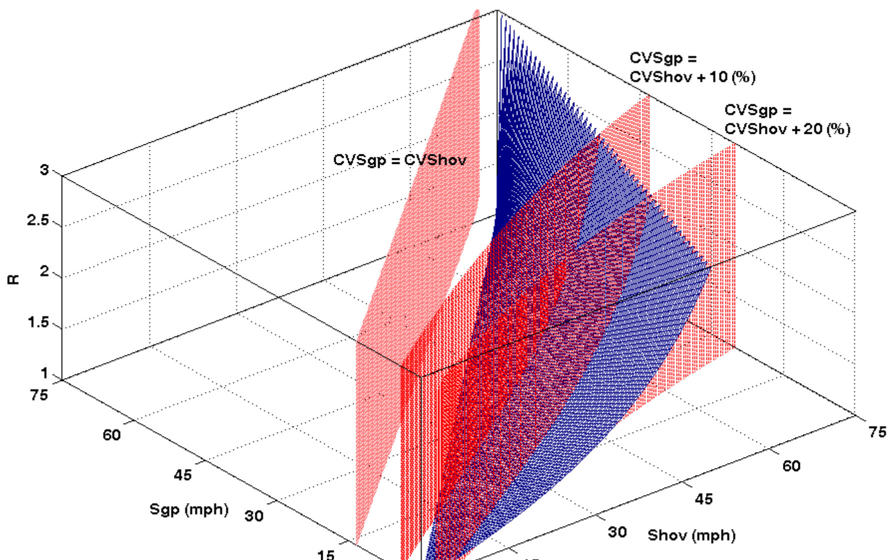
Figure 2 Equilibrium from Free Flow Speed *ffs* in Vehicle Occupancy Scheme

Speed Equilibrium and Speed Dispersion

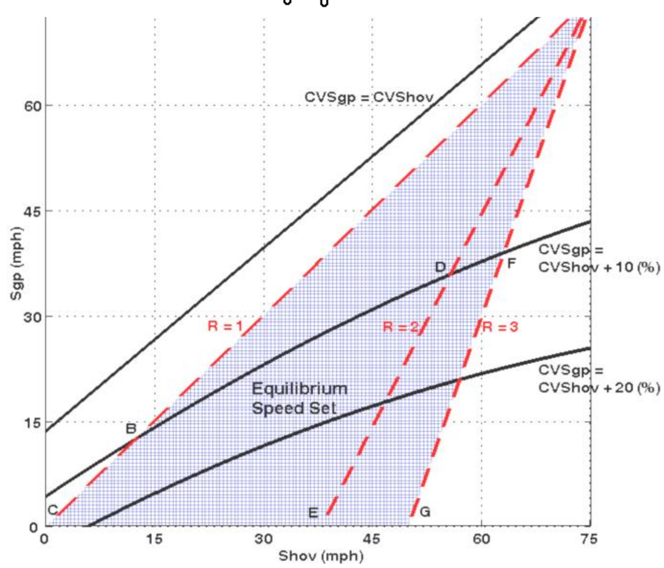
Speed equilibrium under vehicle occupancy is primarily about mobility. For trip reliability, it can be addressed by speed dispersion. Chung and Recker (2010) associated speed with a common measure of speed dispersion: the coefficient of variation of speed (*CVS*); the relationships in Eq. (10) are used to examine the speed dispersion under speed equilibrium with the same settings of S_{hov}, S_{gp}, R, and *ffs*.

$$\begin{cases} CVS_{gp} = 51.601Exp\left(-0.026S_{gp}\right) & \text{for GP lanes} \\ CVS_{hov} = 36.187Exp\left(-0.023S_{hov}\right) & \text{for HOV lanes} \end{cases} \tag{10}$$

Three criteria, $\Delta CVS = CVS_{gp} - CVS_{hov} = 0$, 10, and 20 (%), are depicted in Figure 3(a), with respect to the equilibrium surface. The equilibrium surface not intersecting $CVS_{gp} = CVS_{hov}$ ensures that speed dispersion of the HOV lanes is always less than that of the GP lanes, i.e., the scheme provides not only a faster but a more reliable HOV lane.



(a) 3-D Plot



(b) 2-D Projection

Note: CVS_{gp} and CVS_{hov} are the coefficients of the speed variations in GP and HOV lanes, respectively.

Figure 3 Speed Dispersion and Equilibrium in Vehicle Occupancy Scheme

As shown in Figure 3(b), projection of the surfaces on the $S_{hov}-S_{gp}$ plane reveals that ΔCVS increases as the equilibrium speed set approaches the axle of S_{hov}, or ΔCVS increases with ΔS. A smaller *R* is more likely to result in smaller ΔCVS. For example, $\Delta CVS = 10$ respectively intersects *R* = 1, 2, and 3 at points B, D, and F in the figure. A value of *R* = 1 has the greatest likelihood to produce the inequality, $\Delta CVS < 10$, followed by *R* = 2, and then *R* = 3:

$$P(\Delta CVS < 10)_{R=1} = \frac{\overline{AB}}{\overline{AC}} > P(\Delta CVS < 10)_{R=2} = \frac{\overline{AD}}{\overline{AE}} > P(\Delta CVS < 10)_{R=3} = \frac{\overline{AF}}{\overline{AG}} \quad (11)$$

where $P(*)$ is the likelihood of the given condition. This finding matches the prior analysis; an increase in *R* will prioritize S_{hov} or moderate S_{gp}, resulting in greater values of ΔS and ΔCVS.

SPEED EQUILIBRIUM UNDER TRAVEL TIME SAVING

The second scheme employs a commonly used measure, time saving, to evaluate the lane relationship because transportation professionals usually set a target value for time saving to ensure the competitiveness and effectiveness of an HOV facility. Unlike the existing HOV principle of 1 min saved per mile applicable in limited traffic conditions, the proposed time saving scheme is valid for the range of traffic conditions from near standstill to free flow states. The scheme is defined by the speed relationship between HOV and GP lanes, given that HOV time saving is equal to a pre-specified threshold, i.e.,

$$TS_{hov} = TT_{gp} - TT_{hov} = \frac{60L}{S_{gp}} - \left(\frac{60L}{S_{hov}} + T_{wr}\right) \quad (12)$$

where TS_{hov} is the HOV time saving threshold (approximately 5–10 min, as suggested in the guidelines). TT_{gp} and TT_{hov} are the travel times using GP and HOV lanes, respectively. HOV qualifiers, whether they are fampools or non-fampools, may spend T_{wr} min on additional waiting and routing for carpooling. *L* is the travel length; for instance, *L* is approximately 23.8 miles in southern California (SCAG 2004). The speed equilibrium for the time saving scheme becomes:

$$S_{gp} = \frac{60L \cdot S_{hov}}{60L + (TS_{hov} + T_{wr})S_{hov}}, \text{ or } \; S_{hov} = \frac{60L \cdot S_{gp}}{60L - (TS_{hov} + T_{wr})S_{gp}} \quad (13)$$

The speed difference increases with S_{hov}, S_{gp}, TS_{hov}, and T_{wr}, but decreases with *L*:

$$\Delta S = S_{hov} - S_{gp} = \frac{(TS_{hov} + T_{wr})S_{hov}^2}{60L + (TS_{hov} + T_{wr})S_{hov}} = \frac{(TS_{hov} + T_{wr})S_{gp}^2}{60L - (TS_{hov} + T_{wr})S_{gp}} \quad (14)$$

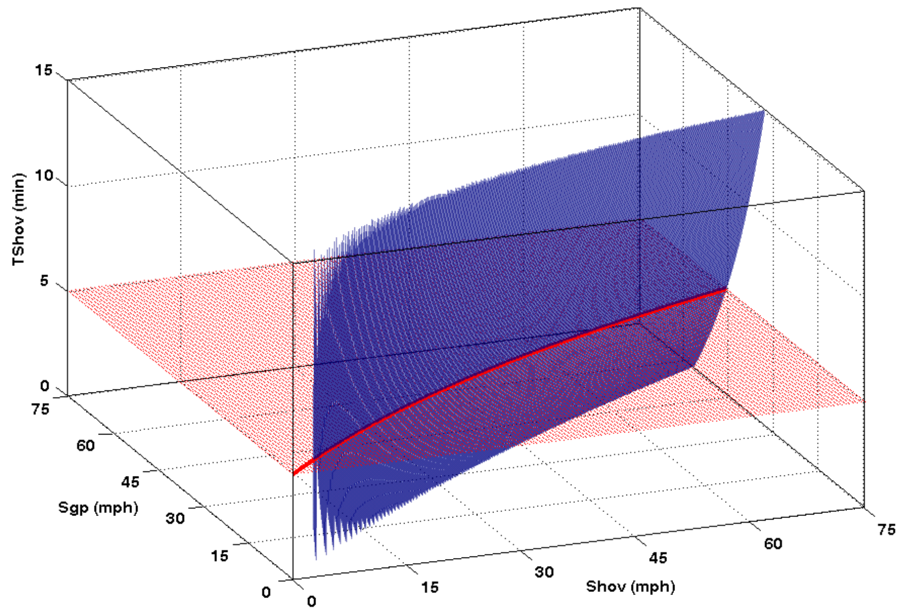
Interaction of S_{hov}, S_{gp}, and TS_{hov}

Figure 4 shows the result of Eq. (13) for L = 20 miles and T_{wr} = 5 min in the boundary of S_{hov} and S_{gp} from 0 to 75 mph, and TS_{hov} from 0 to 15 min. Some characteristics are identified below:

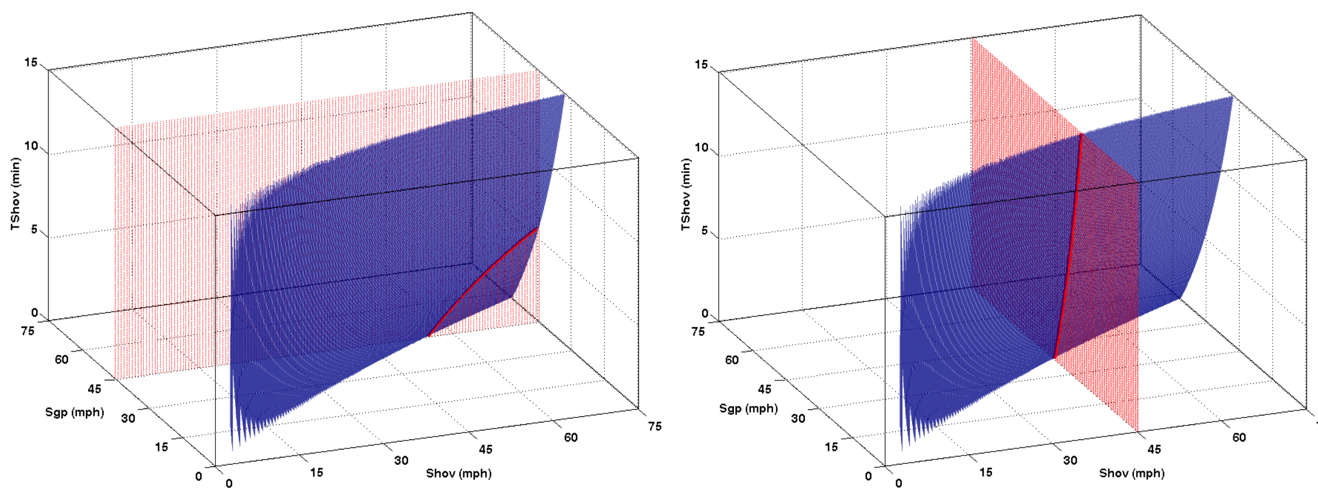
- S_{hov} is greater than S_{gp} when the HOV and GP lanes reach speed equilibrium.
- Given $TS_{hov} = ts$, the equilibrium speed pairs start at $S_{hov} = S_{gp} = 0$, and end at $S_{hov} = 75$ and $S_{gp} = 1200/(ts + 21)$.
- The surface intersecting $TS_{hov} = ts$ forms an equilibrium curve $S_{gp} = 1200S_{hov}/[1200 + (ts + 5)S_{hov}]$ with a decreasing, positive slope given by $\{1200/[1200 + (ts + 5)S_{hov}]\}^2$ which starts at 1. Figure 4(a) demonstrates the plane of $TS_{hov} = 5$ min. In such a case, S_{hov} progressively increases with S_{gp}.
- The surface skewed to the right signifies that HOV expectations increase with TS_{hov}, given $S_{gp} = s_{gp}$, as shown in Figure 4(b). Specifically, the intersection of the surface and the plane of $S_{gp} = s_{gp}$ is an equilibrium curve given by $TS_{hov} = -1200/S_{hov} + \left(1200/s_{gp} - 5\right)$, with a decreasing slope of $1200/S_{hov}^2$, such that S_{hov} progressively increases with TS_{hov}.
- The surface skewed to the right also signifies that expectations of the GP lanes decrease with TS_{hov}, given $S_{hov} = s_{hov}$, as shown in Figure 4(c). The equilibrium surface intersecting the plane where $S_{hov} = s_{hov}$ forms a curve given by $TS_{hov} = 1200/S_{gp} - (1200/s_{hov} + 5)$ that has a decreasing negative slope of $-1200/S_{gp}^2$ and S_{gp} decreases with TS_{hov}. A value of 45 mph for S_{hov} corresponds to values of 38 and 27 mph for S_{gp} in the extreme conditions of TS_{hov} = 0 and 15 min, respectively.

Effect of Different Trip Lengths (L) and Waiting and Routing Time (T_{wr})

In instances of different L or T_{wr} from the exemplary values of 20 miles and 5 min, the new surface will shift toward the axle of S_{hov} for smaller values of L, and will shift toward the axle of T_{wr} for greater values of L, as shown in Figure 5. It is self-explanatory that smaller values of L or greater values of T_{wr} rely on greater values of S_{hov} to accomplish the targeted time saving. All of the characteristics mentioned above are valid, but on a different scale.

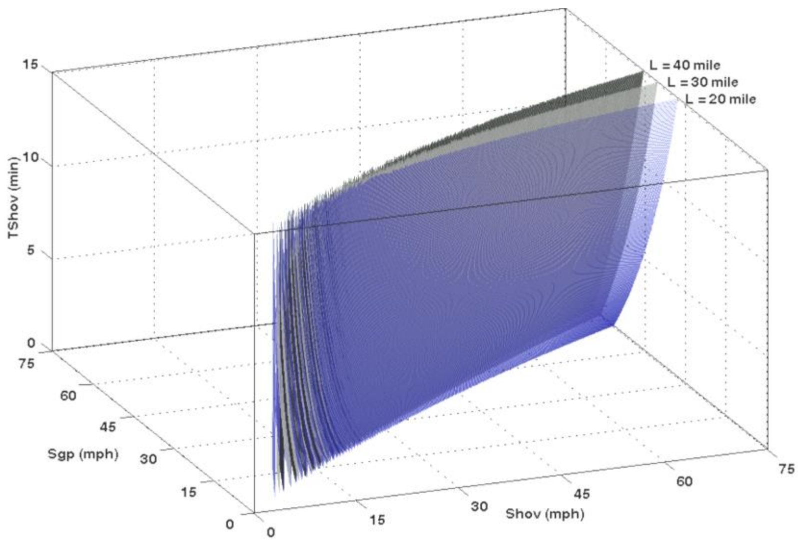


(a) S_{hov} vs. S_{gp}, given TS_{hov}

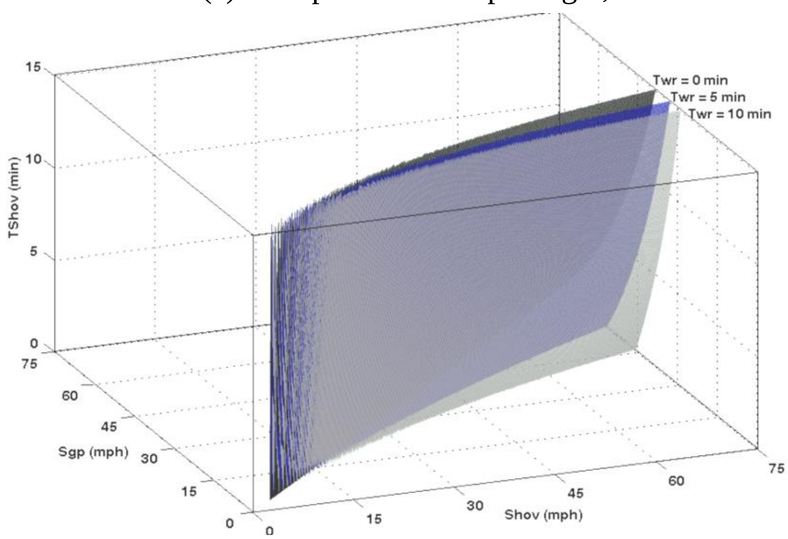


(b) S_{hov} vs. TS_{hov}, given S_{gp} (c) S_{gp} vs. TS_{hov}, given S_{hov}

Figure 4 Relationships between HOV Speed, S_{hov}, GP Lane Speed, S_{gp}, and HOV Time Saving, TS_{hov} for Time Saving Scheme



(a) Comparison of Trip Length, L



(b) Comparison of Waiting and Routing Time, T_{wr}

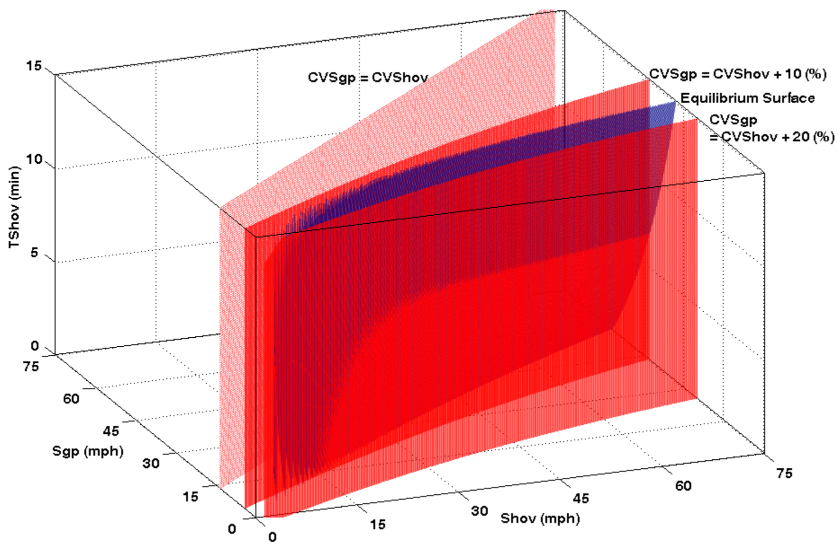
Figure 5 Equilibrium in Time Saving Scheme

Speed Equilibrium and Speed Dispersion

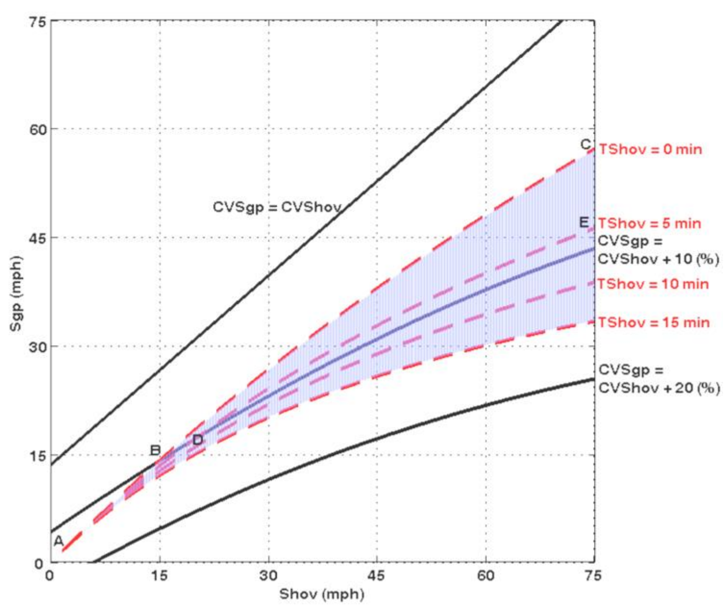
Similar to the vehicle occupancy scheme, the time saving scheme also results in more reliable HOV lanes. Given the identical relationships in Eq. (10) and the criteria for ΔCVS, the equilibrium surface does not intersect $CVS_{gp} = CVS_{hov}$ in Figure 6(a), which ensures that the speed dispersion of the HOV lanes is less than that of the GP lanes. Projection of the surfaces on the $S_{hov} - S_{gp}$ plane repeatedly reveals that ΔCVS increases with ΔS, as shown in Figure 6(b). A smaller value of TS_{hov} is more likely to result in a smaller value for ΔCVS. For example, $\Delta CVS = 10$ intersects TS_{hov} = 0 and

5 at points B and D, respectively, in the figure. TS_{hov} = 0 has the greater likelihood of producing the result, $\Delta CVS < 10$ than TS_{hov}= 5, i.e.,

$$P(\Delta CVS < 10)_{TS_{hov}=0} = \frac{\widehat{L}_{BC}}{\widehat{L}_{AC}} > P(\Delta CVS < 10)_{TS_{hov}=5} = \frac{\widehat{L}_{DE}}{\widehat{L}_{AE}} \quad (15)$$



(a) 3-D Plot



(b) 2-D Projection

Note: CVS_{gp} and CVS_{hov} are the coefficients speed variations in GP and HOV lanes, respectively.

Figure 6 Speed Dispersion and Equilibrium in Time Saving Scheme

Approximation of the Equilibrium Surface

The relationships between any two of the three variables—S_{hov}, S_{gp}, and TS_{hov}—are nonlinear given that the third is fixed. To facilitate the application of the scheme, linear approximation was used for a 20-mile trip. The resulting equation is given by:

$$S_{gp} = \left(0.8 - \frac{TS_{hov} + T_{wr}}{50}\right) S_{hov} \tag{16}$$

Substituting TS_{hov} with 0, 5, 10, and 15 min generates a rule of thumb that states that S_{gp} is proportional to 80% of S_{hov} with a 10% decrease for each 5-min increase in TS_{hov}, i.e.,

$$S_{gp} = \begin{cases} 0.8S_{hov} | TS_{hov} = 0 \\ 0.7S_{hov} | TS_{hov} = 5 \\ 0.6S_{hov} | TS_{hov} = 10 \\ 0.5S_{hov} | TS_{hov} = 15 \end{cases} \text{ if } T_{wr} = 5\,\text{min, or } S_{gp} = \begin{cases} 0.8S_{hov} | TS_{hov} = 5 \\ 0.7S_{hov} | TS_{hov} = 10 \\ 0.6S_{hov} | TS_{hov} = 15 \\ 0.5S_{hov} | TS_{hov} = 20 \end{cases} \text{ if } T_{wr} = 0 \tag{17}$$

Based on Eq. (17), the existing principle of 5- to 10-min saving per trip corresponds to a GP lane speed that is 20% to 40% lower than the HOV lane speed. Such linear approximations, within ± 5 mph from the originals, have a better fit when TS_{hov} is low. As shown in Figure 7, the intersection of the two surfaces projected on the $S_{hov} - S_{gp}$ plane forms parabola $\hat{L}_{ACB}$ at approximately the transition of congested and uncongested states. This indicates the approximations will somewhat have underestimated S_{gp} when traffic is congested, and overestimated S_{gp} when traffic is uncongested.

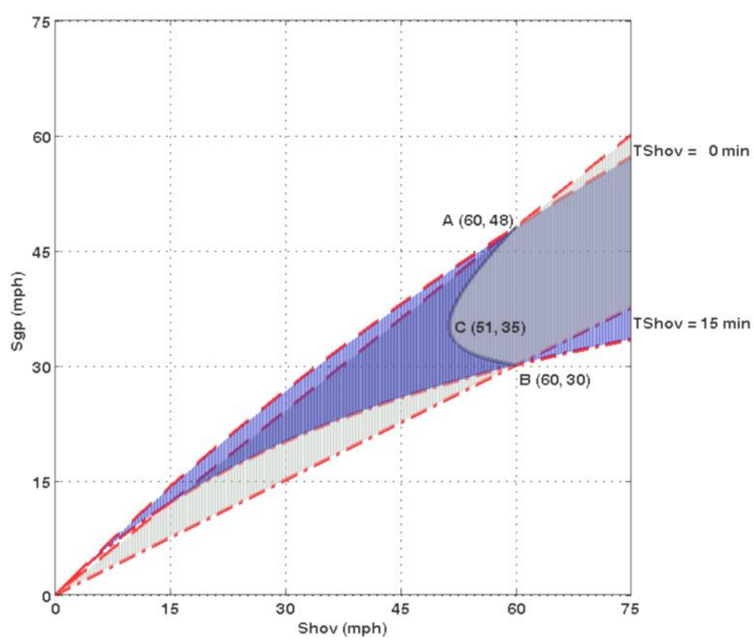


Figure 7 Contrast of Original Curve and Approximated Linear Equilibrium

DISCUSSION

The fundamental distinction behind the two schemes is obvious: the vehicle occupancy scheme, regarded as equity-oriented, prioritizes HOV mobility based on the person movement capacity, whereas the time saving scheme, regarded as policy-oriented, secures HOV incentives based on the time saving set by decision makers. Chung and Recker (2012) also proposed another two schemes that are regarded as utility-oriented. These schemes built upon different aspects highlighting the need for developing prospective tools with respect to the idea of “how much better should HOV lane performance be than GP lanes” to refine the current practice that “HOV lane performance should be better than GP lanes.”

The characteristics of the vehicle occupancy and time saving schemes are compared in Figure 8. Depending on which scheme is used, different results follow:

(1) The equilibrium speed of the vehicle occupancy scheme features varied initial conditions but ends at the free flow speed, whereas that of the time saving scheme starts at the jam speed but ends up in various conditions. In other words, the vehicle occupancy scheme treats HOV and GP lanes similarly during heavy traffic, but the time saving scheme does the same during light traffic.

(2) The speed difference between HOV and GP lanes increases with *R*, but decreases with S_{hov} and S_{gp} in the vehicle occupancy scheme. The speed difference increases with TS_{hov}, S_{hov}, and S_{gp} in the other scheme.

(3) The relationships between any two of the endogenous variables of the vehicle occupancy scheme are linear except for S_{hov} and *R*; the variables of the time saving scheme, instead, are all nonlinear functions.

The two schemes also share some characteristics:

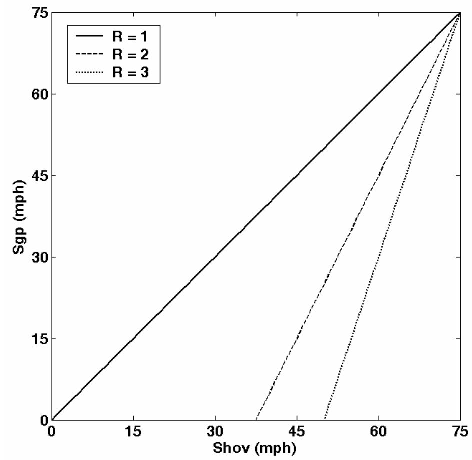
(1) S_{hov} is greater than S_{gp} to ensure HOV lane priority, as reflected in the equilibrium surface skewed to the plane of $S_{gp} = 0$.

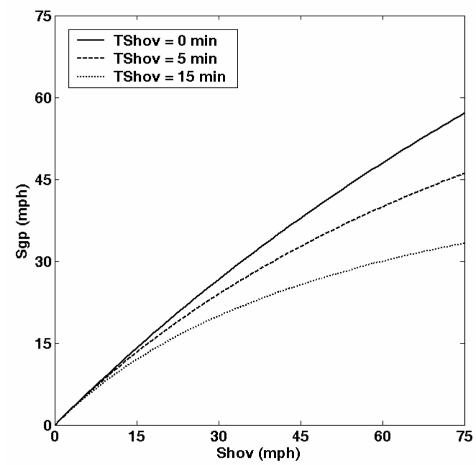
(2) *R* and TS_{hov} both decrease with S_{gp}, but increase with S_{hov}.

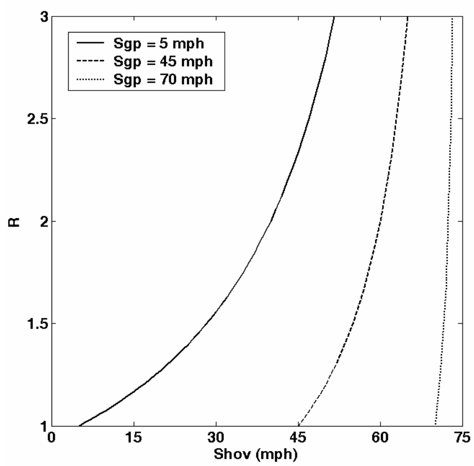
(3) S_{gp} is positively proportional to S_{hov}, for specific values of *R* and TS_{hov}.

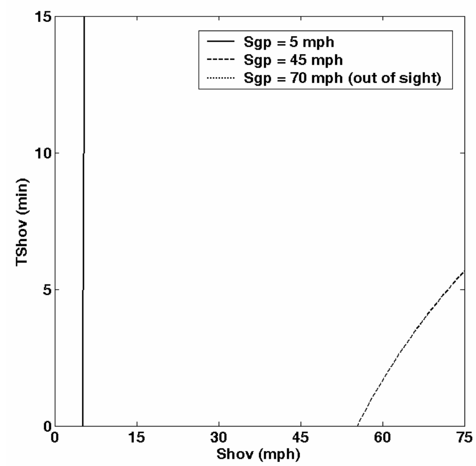
(4) Both schemes ensure more consistent speeds in HOV lanes, relative to GP lanes.

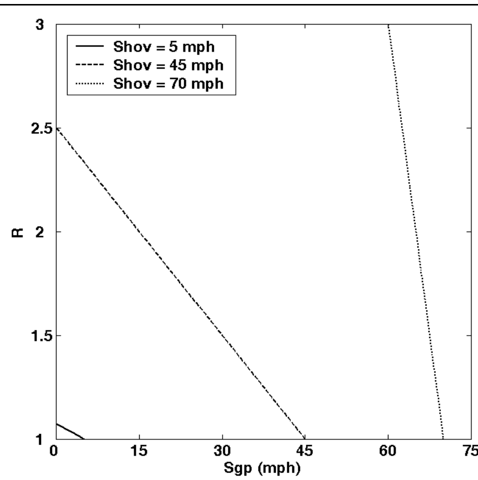
Field data for I-5 and I-405 in Orange County, California, were examined to better understand what empirical traffic data might reveal using the two schemes. The two selected interstate highways, known for heavy traffic during peak hours, have one to two limited accessed HOV2+ lanes, and four to six GP lanes in each direction. Obviously, it would be ideal to comply exactly with the equilibrium surface conditions; however, for practical applications, the equilibrium surface buffers are expanded, turning Eq. (4) into Eq. (18) while using the vehicle occupancy scheme, and turning Eq. (13) into Eq. (19) while using the time saving scheme.

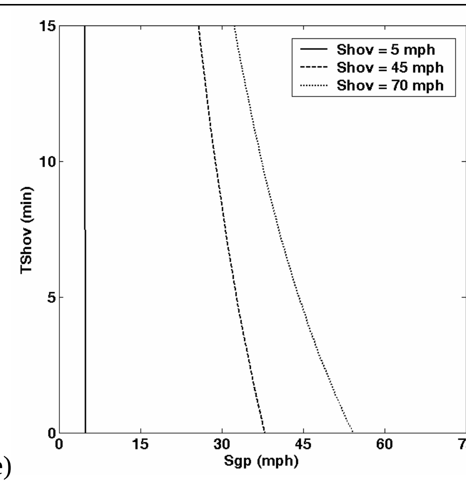
<table>
<tr><th></th><th>Vehicle Occupancy Scheme</th><th>Time Savings Scheme</th></tr>
<tr><td>Mathematical expression</td><td>$S_{hov} = \dfrac{S_{gp} + \gamma(R-1)}{R}$</td><td>$S_{hov} = \dfrac{60L \cdot S_{gp}}{60L - (TS_{hov} + T_{wr})S_{gp}}$</td></tr>
<tr><td>Endogenous variable</td><td>$R,\ S_{hov}, S_{gp}$</td><td>$TS_{hov}, S_{hov}, S_{gp}$</td></tr>
<tr><td>$S_{hov} - S_{gp}$</td><td>

(a)</td><td>

(b)</td></tr>
<tr><td>Vehicle occupancy scheme
$S_{hov} - R$;
Time saving scheme
$S_{hov} - TS_{hov}$</td><td>

(c)</td><td>

(d)</td></tr>
<tr><td>Vehicle occupancy scheme
$S_{gp} - R$;
Time saving scheme
$S_{gp} - TS_{hov}$</td><td>

(e)</td><td>

(f)</td></tr>
</table>

Figure 8 Contrasts of Vehicle Occupancy and Time Saving Schemes

$$S_{hov}^{*} = S_{hov} \pm \beta = \frac{S_{gp} + ffs(R-1)}{R} \pm \beta, \quad \text{for the vehicle occupancy scheme} \qquad (18)$$

$$S_{hov}^{*} = S_{hov} \pm \beta = \frac{60L \cdot S_{gp}}{60L - (TS_{hov} + T_{wr})S_{gp}} \pm \beta, \text{for the time saving scheme} \qquad (19)$$

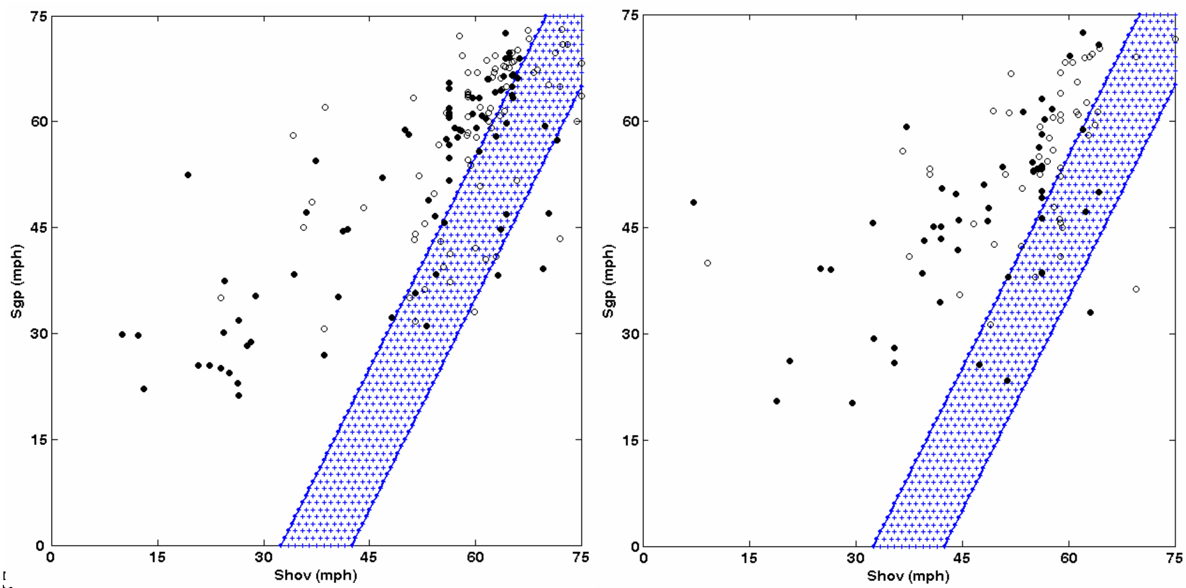
where S_{hov}^{*} is the HOV speed equilibrium boundary with a tolerance of β.

With R = 2, $ffs = 75$, and $\beta = 5$ for Eq. (18), Figure 9 shows a plot of the peak-hour fields, S_{gp} and S_{hov}, with respect to the equilibrium buffer. Of the 80 observations along I-5, 65% to 76% have HOV speeds slower than warranted (i.e., the HOV lane is under-prioritized), and 19% to 30% are within the buffer (well-prioritized). Similarly, along I-405, 73% to 80% of the 51 observations have HOV speed slower than warranted, and 18% to 25% are within the buffer. Only 5% and 2% of the observations for I-5 and I-405, respectively, have HOV speeds higher than warranted (i.e., the HOV lanes are over-prioritized). The results reveal that these HOV lanes are over-utilized in comparison to the GP lanes, indicating that improvement of the HOV lanes is more urgent than that of the GP lanes. Many dots falling beyond the diagonal indicate that the HOV lanes may have slower speeds than the GP lanes. These situations are not uncommon because HOV motorists can become "trapped" in the HOV lanes with limited egress/ingress points as a result of misjudgment, lane overflow, and/or slow vehicles that govern the HOV lanes. This phenomenon was also reported in the Varaiya's research (2007).

Regarding the travel time saving scheme, the same dataset was applied for L = 20, $TS_{hov} = T_{wr} = 5$, and $\beta = 5$ for Eq. (19). Figure 10 shows that of the 86% to 89% of the 80 observations along I-5, five have HOV speeds slower than warranted, and 8% to 11% are within the buffer. Similarly, along I-405, 82% to 92% of the 51 observations have HOV speed slower than warranted, and 4% to 10% are within the buffer. Only 3% to 4% of the observations for I-5 and 4% to 8% for I-405, which is sufficiently low to be regarded as exceptional, have HOV speed higher than warranted. The results for these settings reveal that HOV motorists likely overestimated the travel time saved when using the HOV lanes, and they chose to stay in the HOV lanes without knowing the actual traffic conditions; this phenomenon was also mentioned in other research (SCAG, 2004; Liu et al., 2004).

The speed equilibrium buffer can serve as the fundamental basis of HOV policy adjustments. If most traffic conditions are located beyond the buffer, i.e., the HOV and GP lanes are under-prioritized or over-prioritized, adoption of lane management strategies, such as fewer HOV access points, more strict HOV eligibility requirements, or additional HOV lane(s) could increase HOV speeds. In contrast, pricing and differing strategies could also be used to encourage HOV utilization. The concept of using speed equilibriums is especially useful for both HOV and GP lane speeds greater than a certain level, e.g., 45 or 50 mph. Given that most speed pairs are less the specified levels, lane management alone is not sufficient to improve traffic operations and various alternatives should be considered, such as developing transit, adding new lanes, land management, toll roads (instead of just toll lanes), and so on.

Regarding the limitations of the current HOV guidelines exemplified in the introduction, the first can be solved using the vehicle occupancy scheme, and the second one resolved by plotting the speed pairs in the equilibrium diagram that determines which lane type should be prioritized. It should also be noted that the assessment does not intend to analyze lane choice, but evaluates lane relationships for highway operations. Finally, these two schemes are not for high-occupancy toll (HOT) lanes because the speed relationship is justified by toll costs.



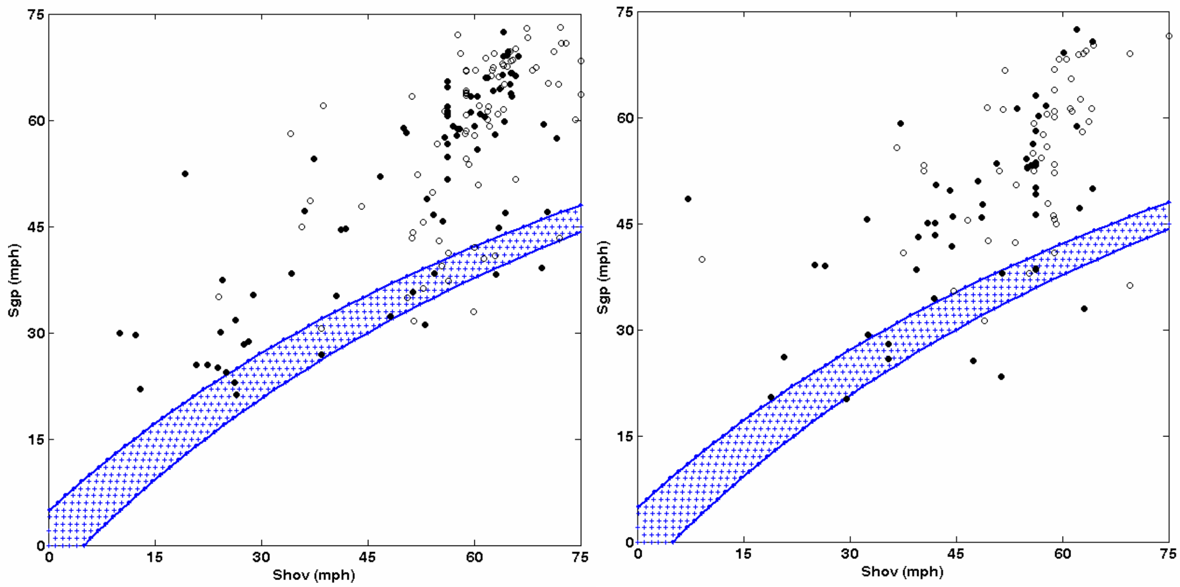
(a) I-5 Northbound (b) I-405 Northbound

Highway	Period	Observed numbers	HOV status		
			Under-prioritized	Well-prioritized	Over-prioritized
I-5 Northbound, Orange County, CA	AM	80	65%	30%	5%
	PM	80	76%	19%	5%
I-405 Northbound, Orange County, CA	AM	51	73%	25%	2%
	PM	51	80%	18%	2%

(c) Summary

Note: The data contains weekday (white dots for 7–8 AM & black dots for 4–5 PM) mean speeds.

Figure 9 Empirical Speed in Vehicle Occupancy Scheme (R = 2)



(a) I-5 Northbound (b) I-405 Northbound

Highway	Period	Observed numbers	Status of the HOV speed		
			Under-prioritized	Well-prioritized	Over-prioritized
I-5 Northbound, Orange County, CA	AM	80	86%	11%	3%
	PM	80	89%	8%	4%
I-405 Northbound, Orange County, CA	AM	51	92%	4%	4%
	PM	51	82%	10%	8%

(c) Summary

Figure 10 Empirical Speed in Time Saving Scheme $(TS_{hov} = 5)$

CONCLUSIONS

By establishing two schemes to achieve speed equilibrium between HOV and GP lanes, this study focused on an issue that is not addressed in the current HOV guidelines: how much greater must HOV speeds be than GP lane speeds as traffic changes from free flow to jam states. Both the vehicle occupancy and time saving schemes ensure that HOV lanes are properly prioritized, relative to the speed dispersion, within different traffic regimes. Rules of thumb were formed for each scheme (Eq. (5) and Eq. (17)) for common traffic situations. The vehicle occupancy scheme that highlights an HOV's contribution to person movement grants additional HOV priority in heavy traffic. The time saving scheme requires extra HOV priority in light traffic to meet the pre-determined time saving estimations. Both schemes could serve as supplements to the existing HOV guidelines and could be easily applied to the evaluation of freeway operations with localized settings for *AVO* ratios or time saving. The schemes are primarily concerned with mobility (time saving) and reliability (speed dispersion). The authors suggest that future research of this topic could develop alternative equilibrium schemes for a single objective, e.g., safety, air emissions, and energy consumption, or for multiple objectives.

ACKNOWLEDGEMENT

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REFERENCES

AASHTO (2004). Guide for High-Occupancy Vehicle Facilities. American Association of State Highway and Transportation Officials, Washington, D.C.

Caltrans (2003). High-Occupancy Vehicle Guidelines, Sacramento, CA.

Caltrans District 4 (2009). Annual HOV Lane Report, Bay Area, CA.

Caltrans District 7 (2008). Annual HOV Report, Los Angeles/Ventura Counties, CA.

Caltrans Performance Measurement System. http://pems.dot.ca.gov. (accessed May 2010)

Chang, M., Wiegmann, J., Smith, A., Bilotto, C. (2008). A Review of HOV Lane Performance and Policy Options in the United States, Federal Highway Administration, Washington D.C.

Chung, C. L., Recker, W. W. (2012) Evaluation of Operational Effects of Joint Managed Lane Policies. *ASCE Journal of Transportation Engineering* 138(7), 882-892.

Chung, C. L., Recker, W.W. (2010). “Characteristics of Speed Dispersion and Its Relationships with the Fundamental Traffic Flow Parameters.” Transportation Research Board 89th Annual Meeting, Washington D.C.

Liu, H.X., Recker, W.W., Chen, A. (2004). “Uncovering the Contribution of Travel Time Reliability to Dynamic Route Choice Using Real-time Loop Data.” Transportation Research Part A 38(6): 435-453.

SCAG (2004). Regional High-Occupancy Vehicle Lane System Performance Study, Final Summary Report. The Southern California Association of Governments.

SAFETEA-LU (2005). Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, Public Law 109–59—AUG. 10, 2005.

TRB (1998). HOV Systems Manual. NCHRP Report 414, Transportation Research Board, Washington, D.C.

Varaiya, P. (2007). Effectiveness of California’s High Occupancy Vehicle (HOV) System. California PATH Report No. UCB-ITS-PRR-2007-5, Berkeley, CA.

WS DOT (1991). Washington State Freeway HOV System Policy: Executive Summary. Washington State Department of Transportation, Olympia, WA.