Operational Performance of High-Occupancy Vehicle (HOV) Facilities:
Comparison of Contiguous and Limited Access HOV Lanes in California

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ABSTRACT

Traffic operational data from High-Occupancy Vehicle (HOV) facilities in California are evaluated in this study. Freeway performance measures are tailored to gauge efficiency and effectiveness of HOV operations and applied to measure the operational performance of HOV facilities in the study sites. The measured operational performance is then compared between HOV and GP lanes and between different types of HOV configurations. Findings from the comparative evaluation show that when compared with GP-lane travels, HOV facilities carry more people-miles with fewer vehicle-miles while offering substantial travel time savings to their users; and, when compared with limited-access, contiguous-access offer greater travel time savings for the sites examined in this study while the levels of utilization by vehicles and people are similar. Statistical tests validate the statistical significance of differences of operational performance. Based on these findings, implications for further improvement of HOV facilities are discussed.
1. INTRODUCTION

High-Occupancy Vehicle (HOV) facilities have been regarded as a cost-effective and environmentally friendly option to enhance travelers’ mobility along congested routes. These facilities offer two kinds of incentives to HOV travelers – savings in travel time, along with a reliable and predictable travel time. Since HOV lanes carry vehicles with a higher number of occupants, they can move significantly more people during congested periods even when the number of vehicles that use the HOV lane may be lower than on the adjoining general purpose lanes. In general, carpoolers, vanpoolers, and bus patrons are the primary beneficiaries of HOV lanes by allowing them to bypass the congested sections.

In California, 1388 lane-miles of HOV lanes have been implemented to counteract growing congestion in major metropolitan areas (1). HOV facilities are an evolving part of freeway infrastructure and induce compounding effects on operational performance of freeways with those facilities. Hence, many studies (2-6) evaluated the effects of HOV lanes on traffic streams in both HOV and its adjacent General Purpose (GP) lanes. These studies suggested that configurations of HOV facilities influence drivers’ maneuvering behavior and, therefore, may result in substantial differences in operational performance. These studies, however, are mostly limited to the contiguous-access non-separated HOV facilities. One comparative study between two different types of HOV configurations has shown that there are significant differences in safety performance of HOV facilities with different configurations (7). Since safety performance can be considered as a negative byproduct of freeway operation, it is conjectured that the configuration of HOV lane may determine the operational performance of that lane in an influential manner.

Although the aforementioned studies unveiled intriguing traffic phenomena on freeways with HOV lanes, they have not yet evaluated or compared operational performance of HOV facilities with different configurations. Kwon and Varaiya (8) examined peak hour traffic data from loop-detector based vehicle detection stations over many months from various types of HOV facilities to evaluate effectiveness of HOV facilities. However, the study did not attempt to compare the operational performance but instead analyzed the data without differentiating them by HOV configurations. A couple of recent studies (9, 10) have evaluated operational performance on the basis of a large set of traffic data and compared operational performance between two different types of HOV facilities – contiguous, non-separated vs. limited, buffer-separated. The present study extends these studies by examining data sets from diverse HOV facilities by applying various measures of operational performance.

The objective of this study is to establish an understanding of the potential effects on operational performances caused by the access control and operational policy of HOV facilities in California. The following section contains descriptions on HOV facilities, data and sites investigated in this study. Section 3 describes measures of freeway operational performance that are tailored to evaluate the performance of HOV facilities. Section 4 presents operating conditions of HOV facilities and Section 5 furnishes comparative outcomes of operational performance between different HOV facilities. The final section discusses implications for effective HOV operation.

2. BACKGROUND

2.1. HOV Configurations

Since the first HOV facility was implemented at the San Francisco-Oakland Bay Bridge toll plaza in California in 1970, two primary configurations for HOV facilities – contiguous, non-separated and limited, buffer-separated – have emerged on California freeways (see Figure 1).
Contiguous, non-separated HOV facilities are often associated with operations on freeways with short duration, relatively high peak-hour traffic volume, and therefore in operation only during peak hours only. The timed transition of HOV activation is equivalent to setting up a virtual partition between the HOV lane and the adjacent left lane that allows only HOV vehicles to enter. The effect is that there are influences on driver lane-changing maneuvers, but there is no physical restriction on the movements. Also, contiguous access HOV lanes may be used when right of way limitations preclude buffer separation of the HOV lane from the mixed-flow traffic. Since the contiguous, non-separated HOV lanes allow vehicles to enter or exit the HOV facility continuously along the freeway, traffic operation in this type of HOV lane is more frequently interrupted by the lane-changing vehicles.

Limited, buffer-separated HOV facilities have designated locations for ingress and egress HOV maneuvers, and are separated from other freeway lanes by buffer zones demarcated by pavement marking. The limited access configuration is designed to facilitate separate operation of traffic flows, typically at relatively high speeds within HOV lanes, and lessens the impact from slower traffic in mixed-flow lanes. Conceptually, the ingress/egress sections serve as transition lanes, or virtual ramps, from the general-purpose lanes into the HOV lane, and vice versa. In this type of HOV facilities, maneuvers in and out of HOV lane tend to concentrate in the vicinity of ingress/egress sections while prohibiting interactions between HOV and GP lanes along separated section.

Built upon the two primary categories of HOV access, there are four types of HOV operations currently in the California Highway System: i) part-time contiguous access; ii) full-time limited access with buffer separation; iii) full-time contiguous access; and iv) part-time limited access with buffer separation.

(a) Limited Access, Buffer-separated

(b) Contiguous Access, Non-separated

Figure 1. HOV Configurations: (a) Limited Access, Buffer-separated; and (b) Contiguous Access, Non-separated
2.2. Site and Data Descriptions
To evaluate the performance of HOV facilities, this paper is based on the use of real-world data to evaluate the performance of HOV facilities in a number of routes listed in Table 1. Geographic locations of these corridors are displayed in Figure 2. The routes for this study were recommended by the California Department of Transportation (Caltrans) Technical Advisory Group for this study based on their familiarity with the HOV facilities in their prospective regions. With potential differences in directional traffic phenomena and geometric attributes, one route comprises only one direction of a freeway segment with the associated ramps and HOV lanes.

![Figure 2 Study Routes](image)

<table>
<thead>
<tr>
<th>HOV Type</th>
<th>County</th>
<th>Route</th>
<th>Direction</th>
<th>Length (Mile)</th>
<th>Operation Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-Time Contiguous-access</td>
<td>Orange</td>
<td>SR-22</td>
<td>Both (E&amp;W)</td>
<td>11</td>
<td>24 Hours, All Days</td>
</tr>
<tr>
<td></td>
<td>Orange</td>
<td>SR-55</td>
<td>North</td>
<td>6</td>
<td>24 Hours, All Days</td>
</tr>
<tr>
<td>Full-time Buffer-separated</td>
<td>LA</td>
<td>I-105</td>
<td>West</td>
<td>14.2</td>
<td>24 Hours, All Days</td>
</tr>
<tr>
<td></td>
<td>LA</td>
<td>I-105</td>
<td>East</td>
<td>15.7</td>
<td>24 Hours, All Days</td>
</tr>
<tr>
<td></td>
<td>LA</td>
<td>I-210</td>
<td>East</td>
<td>14.8</td>
<td>24 Hours, All Days</td>
</tr>
<tr>
<td></td>
<td>LA</td>
<td>I-405</td>
<td>South</td>
<td>9.3</td>
<td>24 Hours, All Days</td>
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</tbody>
</table>
The data for evaluating statewide HOV facilities utilized in this paper is developed mainly based on HOV annual reports (11) and Freeway Performance Measurement System (PeMS) (12). Information on HOV facility data, such as facility information and average number of occupants in both HOV and GP lanes, were taken from HOV reports from various Caltrans Districts (11). To be consistent across districts, occupancy count data from 2008 HOV reports of all districts were used in this study because HOV reports were not available in all districts after 2008.

As for traffic information, the present study takes samples of 5-minute interval from inductive loop detectors in all weekdays from May to October 2009: for part-time operational HOV facilities, only HOV operation hours are included in the analysis and for full-time operational HOV facilities, hours from 5 AM to 9 PM are included in the analysis. It should be noted here that even though the operational hours are different in the selection of data as stated here, our methodology of operational assessment as explained in a later section will selectively filter data samples and allow meaningful comparisons.

Other data sources (e.g., probe vehicles) for traffic information are also available in certain corridors. Data sources of this kind continuously measure traffic speed while vehicles with special equipment are being driven within the real traffic. Hence, the collected data could include more accurate and detailed information than detector data, which are located sparsely along the freeway. However, these probe data (often cited as tach-run data) are available only for selective corridors during limited times (i.e., insufficient coverage and sample size), and therefore are not sufficiently adequate to compute large-scale system-wide performance measures, which is required in the current study. Thus, we chose to use the system-wide PeMS data for the computation and comparison of performance measures.

### 3. PERFORMANCE MEASURES

#### 3.1. Selection of Performance Measures

Since the assessment of traffic conditions is a fundamental component in gauging the effectiveness and efficiency of freeway operations there has been an extensive list of studies regarding performance...
measures concerning freeway operations (13). However, these measures are not necessarily tailored for comparing performance measures between different HOV configurations, which is intended in this study. In this section, we will down-select to a few key performance measures that are most representative and allow system-level comparisons. The selection of measures is based on the following considerations:

1) The use of a large number of performance measures makes it challenging to control some exposure variables.

2) The parameters such as speed, VMT and PMT are basic and representative factors to directly describe performance. These measures can be independently and objectively calculated for all sites and compared for different HOV types.

3) The operational performance of both HOV and GP lanes are intertwined, thus the evaluation should allow the identification of situations when GP traffic conditions have a meaningful impact on HOV operations. For example, as will be explained in a later section, the performance comparison is considered most significant when the GP lanes are operating in a degraded state.

4) Due to the nature of heterogeneous travel patterns across routes, it is important to investigate the HOV operational performance at the system level as well at the route level.

Based on the aforementioned considerations, three more focused, representative, and comparable performance measures are selected for comparative evaluation in this study. They are defined and explained below.

- **Speed differential** (= Speed in HOV Lane – Average Speed in GP Lanes)
  Speed differential is a proxy for travel time savings, and comparable between samples. The speed differential definition chosen for this study is the difference between the speeds in the HOV and the adjacent GP lanes. For example, if traffic in the GP lane is moving faster than that in the HOV lane then the speed differential is negative. If traffic in the HOV lane travels at slower speeds than that in GP lanes, the HOV facilities do not provide travel time savings.

- **VMT ratio** (= (segment length × traffic flow in HOV lane) / {(segment length × traffic flow in HOV lane) + (segment length × average traffic flow in GP lanes)})
  This ratio measures the utilization level of HOV lane by vehicle-miles but is calculated on a relative basis in comparison to the GP lanes. If the ratio is greater than 0.5, it means that the subject HOV lane carries more vehicle-miles than the average GP lane.

- **PMT ratio** (= (segment length × average vehicle occupants in HOV lane × average traffic flow in HOV lane) / {((segment length × average vehicle occupants in HOV lane × average traffic flow in HOV lane) + (segment length × vehicle occupants in GP lanes × average traffic flow in GP lane)})
  This ratio measures the utilization level of HOV lane by person-miles, also on a relative basis in comparison to the GP lanes. If the ratio is greater than 0.5, it means that the subject HOV lane serves more person-miles than the average GP lane.

One of major objectives implementing HOV lanes is to carry more passengers with fewer vehicles. Thus, PMT ratio should be given a high-priority consideration in addition to VMT ratio in terms of evaluating operational performance of HOV facilities. Combining the measures of VMT and PMT, four possibilities are:

i) VMT ratio < 0.5 and PMT ratio < 0.5: HOV lane serves fewer vehicles and people than average GP lane, which implies the potential of *not optimally utilized HOV facilities*. Although in this category, the HOV lane may still meet the minimum requirement by serving more than 800 vph or 1800 persons per hour according to the HOV guidelines (14).

ii) VMT ratio < 0.5 and PMT ratio >= 0.5: HOV lane serves fewer vehicles but move the same or higher numbers of people than an average GP lane.
iii) VMT ratio > 0.5 and PMT ratio < 0.5: HOV lane serves more vehicles but fewer people than average GP lane. This situation is unlikely due to the nature of multiple occupancy requirements in HOV lanes, but it may occur when average occupancy of GP lane traffic is greater than that of HOV lane traffic.

iv) VMT ratio > 0.5 and PMT ratio >= 0.5: HOV lane serves more vehicles and move more people than the average GP lane, which implies the possibility of highly utilized HOV facilities. If an excessive large number of vehicles travel in the HOV lanes, however, it may begin to cause the speed differential to become negative, thus resulting in a deterioration of operations in the HOV lane.

3.2. Conditions for Computing Performance Measures

For comparability, it is important to take congestion into account because different routes may have different HOV operation hours and exhibit different congestion patterns. In addition, since HOV facilities are implemented as a measure for congestion relief, there is an additional incentive to understand the impact of congestion on operational performance of HOV facilities in California. This is further explained with actual congestion data collected from two of our study routes.

Figure 3 shows the contour plots of average speed across GP lanes in time-space dimensions for two different routes, 8 peak hours only for I-880 on the left chart vs. 24 hours of HOV operations for I-210 on the right chart. The horizontal axis is plotted as the HOV operation hours and the vertical axis is the post-mile of the study site. The dash line on Figure 3(a) for I-880 denotes the boundary of morning (5-9 AM) and afternoon (3-7 PM) HOV operation hours. Red color denotes congested conditions while green indicates free-flow conditions. Although the two corridors stretch over a comparable distance, congestion patterns are quite different.

(a) Interstate 880 Northbound, District 4
(b) Interstate 210 Eastbound, District 7

Figure 3. Speed contour plots: (a) Interstate 880 Northbound, Alameda, California; and (b) Interstate 210 Eastbound, Los Angeles, California

Visual inspection of Figure 3(a) shows that the recurrent bottleneck resides near post-mile 17 of I-880 northbound in Alameda during morning and afternoon operation hours. In morning hours, bottleneck activates around 7 AM due to the increase in traffic demand while the congestion exists throughout the HOV afternoon operation hours. On the other hand, as shown in Figure 3 (b), congestion in I-210 Eastbound spans over 13-mile stretch and over 5-hour afternoon peak hours. Based on the calculation of congestion by counting hour-distance samples, I-210 Eastbound is considered more congested. However,
if the congestion is calculated by the percentage of congested samples within the total operational hours, 18.8% of samples from I-880 Northbound are operating below 45 mph versus 16.2% of samples from I-210 Eastbound. Without knowing the operational differences between the corridors, the latter calculation may be interpreted to state that I-880 is more congested. This exercise suggests that the performance measures should control for the conditions of congestion in comparing performance measures between different types of HOV facilities.

To control for the congestion variable for comparative assessment, congestion should be clearly defined. There could be multiple definitions for traffic congestion. For example, the criteria may include vehicle traveling below a certain speed threshold, existence of vehicle queuing, elongated trip time, etc. To define congestion for the analysis, the current study adopts the definition from the Highway Capacity Manual (HCM) (15), in which congestion is defined as the state when the flow reaches the capacity of the segment and thus becomes slow. Speed-flow curves for basic freeway segments presented in HCM (15) show that the flow capacity reaches its maximum around 2,400 passenger-car/hour/lane at around 45 mph. The present study, therefore, adopts an approach to define congestion in the GP lanes when their speeds are below 45 mph. Thus, samples from the congested traffic states characterized by speed below 45 mph in GP lanes will be used to compute performance measures.

Please note that in Section 4.1 below, all data samples from study sites are used to reveal the characteristics of HOV and GP operations in different access types. It is only in later sections that the condition of GP lanes operating below 45 mph is used as a criterion to filter data samples for calculating performance measures.

### 4. OPERATIONAL PERFORMANCE OF HOV FACILITIES

#### 4.1. Speed-Flow Probability Density Plots

Overall operating conditions in HOV and GP lanes are measured with two traffic parameters—flow and speed. Flow is the rate at which vehicles pass a fixed point (vehicles per hour, vph), and speed is the rate of change of a vehicle’s position (miles per hour, mph). To evaluate how the facility is being operated, two-dimensional (speed vs. flow) joint probability histogram is constructed. The procedure is described below:

1. Partition the collected samples into two dimensional cells at increments of 2-mph (speed) and 50-vph (flow).
2. Count the number of samples that belong to each cell.
3. Divide the numbers by total sample size.

The equation below explains how the value for each cell is calculated. The value for each cell represents the percentage of data samples that fall into the corresponding cell, which is represented by the operating condition measured in the corresponding flow and speed.

\[
P_{i,j}(x) = \frac{\sum_{k=1}^{N} I\{v_i \leq x_k < v_{i+1}\} \cdot I\{q_j \leq x_k < q_{j+1}\}}{N}
\]

Where, \(P_{i,j}(x)\): Percent of total samples belong to a cell \((i,j)\),

\(v_i\): \(i^{th}\) interval in speed,

\(q_j\): \(j^{th}\) interval in flow,

\(I\{\}\) : indicator function,

\(N\) : total number of samples
Figure 4 and Figure 5 show probability densities for HOV and GP lanes by four HOV facility types. Probability densities for each facility type are simple aggregations of those for all the routes in each type. The patterns shown in Figures 4 and 5 are well representative of probability densities of the corridors within the corresponding type. Visual inspection of the figures can be summarized below:

1) As can be seen in Figures 4 and 5, operating conditions in HOV lanes indicate higher speed and lower flow than those in GP lanes but the HOV lanes are often found to carry a flow rate higher than 800 vehicles per hour or 1800 person per hour that is specified in the HOV guidelines.

2) In Figures 4 and 5, there exist significant amount of congestion both in HOV and GP lanes that appeared as grey color in low speed regimes. However, more samples from GP lanes are associated with congestion.

3) With a comparison across access types, it is noticeable that speed difference between HOV and GP lanes is higher in contiguous access than limited access. However, this observation may be skewed because samples of contiguous access were collected from mostly peak hours when the HOV is in operation while samples of other types represent all operational hours including peak and non-peak hours. The peak hours of individual routes may vary; therefore these figures are provided to reveal the overall flow-speed patterns and are not meant for direct performance comparison.

4) The third finding above again emphasizes the importance of taking congestion into considerations when computing the performance measures. Hence, only samples collected when the GP lane speed is below 45 mph (marked by red dotted line) were used to compute performance measures in the section below.

Figure 4. Probability density of speed-flow in HOV Lane: (a) Contiguous and full-time, (b) Contiguous and part-time, (c) Limited and full-time and (d) Limited and part-time.
Figure 5. Probability density of speed-flow in GP Lane: (a) Contiguous and full-time, (b) Contiguous and part-time, (c) Limited and full-time and (d) Limited and part-time

4.2. Computation of Select Performance Measures

This section presents the outcomes of computing performance measures that have been selected to represent the comparisons of HOV operations, speed differential, VMT ratio, and PMT ratio, as described in Section 3.1. Outcomes from the data analysis are computed then displayed by using box plots (also known as Box-and-Whisker plot). The plots provide a convenient way of graphically depicting groups of numerical data with five summary statistics: minimum of samples, lower quartile (i.e., 25th percentile), median of samples, upper quartile (i.e., 75th percentile), and maximum of samples. These plots display distribution of samples in a non-parametric fashion. Please note again that the samples used are only from the GP lane speed below 45 mph.

For comparison between different types of HOV configurations, samples are grouped into four different categories by configurations and operation type, as listed in Table 1. The results presented below show that there exist differences in performance measures across groups, even though the magnitude of differences is small.

- **Speed differential**

Figure 6 exhibits speed differential between HOV and GP lanes with box plots. The figure shows that vehicle speeds in HOV lanes is higher than those in GP lanes. This can be seen by noticing the lower bottoms of the boxes are higher than zero for more than 75% of the examined samples in all HOV facility
types. Contiguous access HOV facilities appeared to provide slightly higher speed differential than limited access HOV facilities.

![Figure 6. Speed differential: (a) Contiguous access, (b) Limited access](image)

- **VMT Ratio**

  Box plots in Figure 7 shows that about 75% of VMT ratios (representing relative level of utilization by vehicles to average across GP lane) in all HOV facility types were below 0.5, indicating that the HOV lane serves fewer vehicle-miles traveled than a GP lane. This phenomenon is frequently observed in many HOV facilities, which is one consideration that has supported the conversion of HOV into HOT (High-Occupancy or Toll) facilities in many regions.

![Figure 7. VMT ratio: (a) Contiguous access, (b) Limited access](image)

- **PMT Ratio**

  In the analysis of PMT shown here, both directions of I-80, which is originally included in the list of study sites, are excluded in the charts below because occupancy requirement for both directions of I-80 is 3 or more, which may cause a bias in the calculated results of PMTs. PMT ratios shown in Figure 8 show that about 75% of PMT ratios (representing relative level of utilization by people to average across GP
lane) in all HOV facility types (except contiguous, full-time) were above 0.5, meaning that a HOV lane serves more person-miles traveled than a GP lane.

![PMT ratio: (a) Contiguous access, (b) Limited access](image)

**Figure 8.** PMT ratio: (a) Contiguous access, (b) Limited access

### 4.3. Statistical Tests

To determine whether the differences in the calculated performance measures are significant, statistical tests were performed for the data samples. The two-sample Kolmogorov-Smirnov test is conducted because the tests can compare any pair of distributions shown in Figure 6, 7 and 8.

The Kolmogorov-Smirnov test (K-S test) is a goodness-of-fit test used to examine the statistically significant difference between two probability distributions based on finite samples ([16, 17]). The test is nonparametric in the sense that no assumption is made concerning the distribution underlying the sample data, while it can sensitively measure the differences in both location and shape of the empirical Cumulative Distribution Functions (CDFs) of the two sample groups. The test is applicable to compare each pair of distributions from two different HOV facilities.

To describe the application of K-S test, we can begin by stating the null hypothesis. $F_C(x)$ and $F_L(x)$ is two empirical CDFs, where superscript indicates operation time, full-time and part-time; and subscript indicates HOV configurations, contiguous and limited access. The null and alternative hypotheses:

$$H_0: F_C(x) = F_L(x)$$

**Versus**

$$H_A: F_C(x) \neq F_L(x) \text{ or } F_C(x) > F_L(x) \text{ or } F_C(x) < F_L(x)$$

The test statistic, $D = \max_x |F_C(x) - F_L(x)|$, is derived by taking the maximum absolute difference over the value of $x$ between two empirical CDFs, $F_C(x)$ and $F_L(x)$.

Comparing $D$ against a critical value derived from the confidence level, $\alpha$, and the number of samples from each group, one can determine whether to reject the null hypothesis or not. The “Reject” and “Accept” is determined with respect to the null hypothesis. In other words, the “Reject” in the cell indicates rejecting the null hypothesis $H_0$ and accepting the alternative hypothesis, $H_A$ and “Accept” means that the test accepting the null hypothesis, $H_0$ against the alternative hypothesis, $H_A$.

Table 2 summarizes the results of two-tailed K-S test of each performance measure between any pair of different HOV facilities. Without exception, all the K-S test results lead to the conclusion that $F_C(x)$ is not equal to $F_L(x)$, meaning that the operational performance of HOV facilities vary with the
operational schemes such as operation hours and configurations. These findings confirm that the differences observed in Figures 6, 7 and 8 are statistically significant.

Table 2. Two-tailed hypothesis test at 5% confidence level

<table>
<thead>
<tr>
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<th>Speed Differential</th>
<th>VMT Ratio</th>
<th>PMT Ratio</th>
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<tr>
<td>H₀: Fₜ(x) = Fₗ(x)</td>
<td>Reject</td>
<td>Reject</td>
<td>Reject</td>
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<tr>
<td>Part-time Contiguous vs. Part-time Limited</td>
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<td></td>
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<tr>
<td>H₀: Fₜ(x) = Fₗ(x)</td>
<td>Reject</td>
<td>Reject</td>
<td>Reject</td>
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<tr>
<td>Part-time Contiguous vs. Full-time Limited</td>
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<tr>
<td>H₀: Fₜ(x) = Fₗ(x)</td>
<td>Reject</td>
<td>Reject</td>
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<td>Full-time Contiguous vs. Part-time Limited</td>
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5. CONCLUDING REMARKS

The present paper examined the operational performance of an extensive list of HOV facilities with different operational schemes, configurations and operation hours. Performance of different operational schemes was evaluated by analyzing the collected data from six months of real-world data in a comparative approach. The first comparison was conducted between HOV and GP lanes, and the outcomes are summarized as follows:

1) Travel speed in HOV lanes is generally higher than that in GP lanes.
2) VMT ratio for HOV lanes is generally below 0.5, indicating HOV lanes serve fewer vehicle-miles than GP lanes.
3) PMT ratio for HOV lanes is generally above 0.5, indicating HOV lanes carry more people-miles than GP lanes.

The combination of the above findings imply that the HOV facilities carry more people with fewer vehicles while providing travel time savings when compared with GP lanes.

Another set of comparative analysis has been conducted to evaluate the operational performance of HOV facilities by different types of operational schemes. Please note that the compilation of results is based on the inclusion of study sites that have been selected for this study. They are representative of operational performance in different regions in California but they do not encompass all HOV facilities. Thus, the evaluation results should be considered within the scope of data samples from the selected corridors. The outcomes of the comparative study between different HOV facilities are summarized below:

1) Compared with limited access, contiguous HOV lanes offer higher speed differentials when GP lanes are operating under congested regimes (i.e., below 45 mph).
2) VMT ratios in both types of HOV access are comparable. However, the contiguous access has larger standard deviation, indicating that the VMT ratios across contiguous access vary in greater magnitude.
3) Similarly, the PMT ratios in both types of HOV access are at comparable levels but a bit higher in limited access. Again, the contiguous access has a wider variation.

With regard to operation hours, the outcomes of comparing performance rely only on the observations from one and two routes for limited, part-time and contiguous, full-time, respectively. Although they appeared to be significant, they may be affected by some unobserved conditions inherent to the sites. For more conclusive evidence, therefore, it is necessary to confirm the findings with more samples.

It should be noted that each type of HOV configurations can offer differing advantages. Contiguous-access configuration provides the flexibility for accommodating concentrated demand during peak hours while relaxing the restriction for the remaining hours. On the other hand, limited-access configuration provides a clear separation of flows and isolates roadways users from frequent lane-changing maneuvers except at designated access areas. In addition, at certain freeway junction locations, limited access configurations can also prevent or discourage last-second traffic weaving maneuvers so that traffic flows can be channelized safely.

The findings in the present study show that the HOV facilities in California offer travel advantages to HOV-lane commuters, while strategies to seek operational improvements continue to be pursued. Managed lane concepts that have recently emerged for administering active operation of traffic flows may be one of the options to this end. More in-depth evaluation of empirical data and project experiences from demonstration projects (18) is expected to provide promising improvement plans for HOV-lane operations. The further study in this realm is the topics of further research.
REFERENCE
11. California Department of Transportation (Caltrans) (2008) HOV Annual Reports, District 3, 4, 7 and 12