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Partially limited access control design for special-use freeway lanes

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ABSTRACT

Most special-use freeway lanes, such as High Occupancy Vehicle (HOV) lanes, have traditionally been designed with either limited access or continuous access control from the adjacent general-purposed (GP) lanes. Studies have shown the advantages and disadvantages of each design in terms of safety, mobility, environment, and enforcement, among other factors. With a focus on improving the operational performance of HOV facilities, this paper proposes a new design called partially limited access control where the continuous access is mostly designated along the freeway to achieve higher travel speed while buffers between the HOV lane(s) and the adjacent GP lanes are strategically placed on selected freeway segments to accommodate higher throughput on those segments. The placement of buffers primarily aims to reduce the impact of HOV cross-weave flow on the capacity of GP lanes. In this research paper, a methodology for determining the location and length of buffers in the partially limited access control has been developed. A case study is performed along a 13-mile section of HOV facility on SR-210 E in Southern California, which is coded and evaluated in traffic microsimulation. The results show that the partially limited access control increases the throughput (represented by total vehicle miles traveled or VMT) and decreases the delay (represented by total vehicle hours traveled or VHT) of the freeway as compared with either the limited access or continuous access control. As a result, the overall efficiency (represented by average travel speed calculated as VMT/VHT) of the freeway with partially limited access HOV facility is 21% and 6% higher than that of the freeway with limited access and continuous access HOV facility, respectively, under the baseline traffic demand.

1. Introduction

Special-use freeway lanes, including High-Occupancy Vehicle (HOV) lanes, are an integral part of many freeway systems. Traditionally, HOV lanes have been designed with either limited access or continuous access control (see Fig. 1(a) and (b)). Over the last several years, the performance of limited access and continuous access HOV facilities in terms of safety (Chung et al., 2007; Jang et al., 2008, 2009; Du et al., 2012), mobility (Chang et al., 2008), environment (Boriboonsomsin and Barth, 2006, 2008; Shewmake, 2012), enforcement, etc. have been extensively compared through empirical and simulation studies.

Based on data from the Freeway Performance Measurement System (PeMS) in California, Chen et al. (2005) found that the

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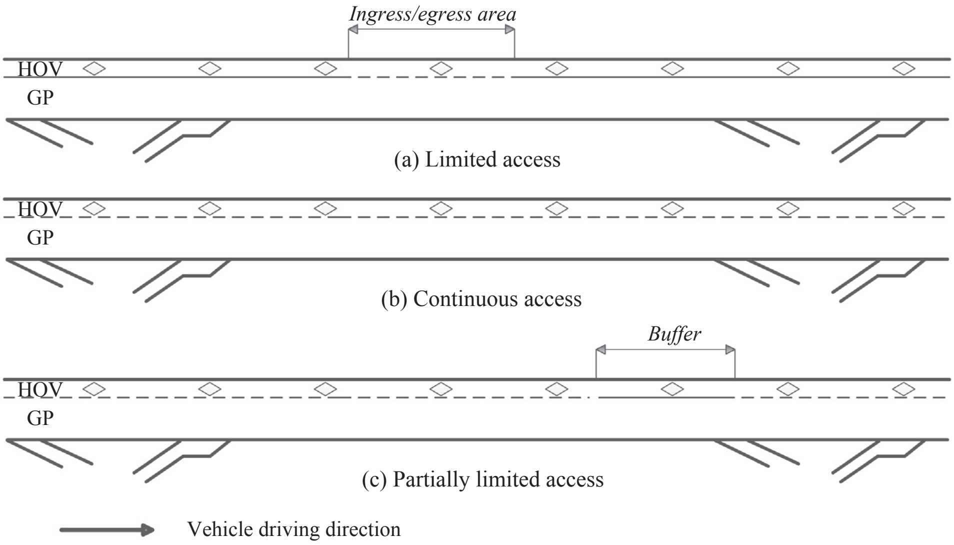


Fig. 1. Different configurations of HOV lanes.

general-purposed (GP) lanes suffer a congestion penalty due to the capacity drop, and the HOV lanes suffer a capacity penalty as the speed in single HOV lanes is governed by the low speed vehicles. On the contrary, Menendez and Daganzo (2007) theoretically showed that HOV lane implementation diminishes the lane changes between the HOV lane and the adjacent GP lane, a phenomenon called the smoothing effect of HOV lane, which was validated using real-world data by Cassidy et al. (2010). Also based on real-world data, Wu et al. (2011) found that the ingress/egress areas of limited access HOV facilities could trigger the formation of bottlenecks in the HOV lanes. A study by Jang et al. (2012) revealed that the continuous access control offers slightly higher utilization of HOV lanes, compared with the limited access control.

However, the continuous access control could suffer from the frictional effect where HOVs in the HOV lane would slow down as the speed differential with the adjacent GP lane increases (Jang and Cassidy, 2012). Wu et al. (2015) found that a freeway segment with limited access control would have higher capacity than that with continuous access control, given that everything else is held equal. Based on high-resolution lane change data collected in the field, it was shown that, compared to continuous access HOV facilities, limited access HOV facilities have higher lane change intensity (over ingress/egress areas), and the HOVs on these facilities have shorter time gaps when they move out of the HOV lane (Du et al., 2013; Qi et al., 2016). According to Boriboonsomsin et al. (2013), limited access HOV facilities are better at regulating traffic flow resulting in higher freeway throughput, while continuous access HOV facilities are more likely to spread out lane changes, which allows traffic to maintain higher travel speed.

These findings imply that an alternative design in geometric configuration of HOV facilities, where the continuous access is generally provided along a freeway to achieve higher travel speed while buffers are strategically placed on selected freeway segments (e.g., recurrent bottlenecks, ramp areas) to accommodate higher throughput on those segments, may result in better overall operational performance than either the limited access or continuous access designs. Therefore, this research investigates the so called *partially limited access* design (see Fig. 1(c)) and evaluate its operational performance compared with the other two access controls.

A major consideration in the design of partially limited access HOV facilities is determining the location and length of buffers that prohibit or discourage lane changes from the HOV lane to the adjacent GP lane, and vice versa. These buffers are designed primarily for reducing the impact of HOV cross-weave flow on the capacity of GP lanes. Liu et al. (2012) analyzed the HOV cross-weave effect downstream of on-ramps to a freeway with a limited access HOV facility using simulation method. The results reveal that the capacity of GP lanes decreases as the HOV cross-weave flow or the number of GP lanes increases. The length of buffer from the gore point of the on-ramp to the starting point of the ingress/egress area has significant influence on the capacity drop. In the design of partially limited access HOV facilities, it is also important to understand the HOV cross-weave effect upstream of off-ramps where mandatory lane changes occur frequently. However, to the best of our knowledge such effect has not been analyzed.

2. Research objectives

The objectives of this research are to: (1) analyze the impact of HOV cross-weave flow on the capacity of GP lanes upstream of off-ramps; (2) develop a methodology for designing partially limited access HOV facilities that also conforms with the existing general guidelines for designing HOV facilities, e.g., (California Department of Transportation, 2003; California Department of Transportation, 2011); and (3) evaluate the operational performance of freeways with partially limited access HOV facilities in comparison with freeways with limited access or continuous access facilities.

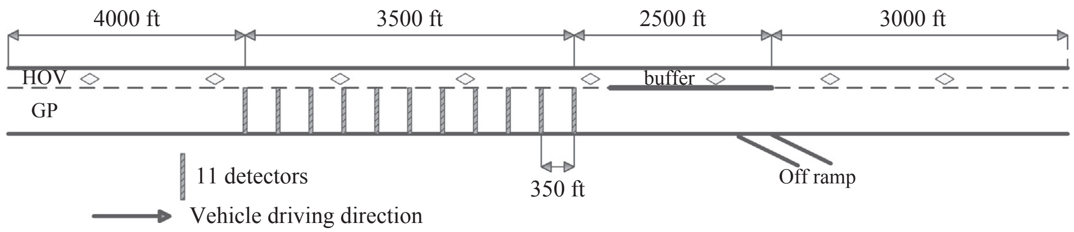


Fig. 2. Simulation test scenario for evaluating HOV cross-weave effect upstream of off-ramps.

3. HOV cross-weave effect upstream of off-ramps

In this section, we present a simulation study to quantify the HOV cross-weave effect upstream of off-ramps in the partially limited access design, which is caused by HOVs' needs in cross-weaving over multiple GP lanes to take an exit ramp. This may result in a negative impact on the capacity of GP lanes upstream of the exit ramp. Simulation test scenarios are first introduced. Then Van-Aerde's curve (Van Aerde, 1995) is applied to estimate the capacity of GP lanes using the Genetic Algorithm (Ma and Abdulhai, 2002). Finally, simulation results are analyzed to quantify the road capacity drops in relation to buffer length, cross-weave flow, and the number of GP lanes.

3.1. Simulation test scenarios

Compared with the limited access design, the continuous access design would likely lead to higher HOV lane utilization due to HOVs having more flexibility in terms of where to get in or out of the HOV lane. But in the upstream area of off-ramps, having too much of that flexibility may result in some HOVs making aggressive and last-minute lane changes (which are too close to the off-ramp) in order to exit the freeway. This will lead to the HOV cross-weave effect which could reduce the throughput of the GP lanes in the area upstream of off-ramps, increase delay, and potentially break down the traffic flow. It would be beneficial to place a buffer immediately upstream of an off-ramp to prevent or at least alleviate such HOV cross-weave effect. Therefore, it is necessary to explore the HOV cross-weave effect on the capacity of GP lanes upstream of off-ramps for aiding the design of buffer length in partially limited access HOV facilities.

We code a simulation network of a generic freeway section in PARAMICS, a high-fidelity traffic microsimulation software tool, where a buffer is placed immediately upstream of an off-ramp up to the gore point of the off-ramp, as shown in Fig. 2. The total length of this simulation network is 13,000 ft or 2.5 mi (4 km). Eleven vehicle detector stations are placed across all the GP lanes starting at the point at 4000 ft through the point at 7500 ft. The distance between two adjacent detectors is 350 ft. The reason for this detector placement plan is that in a normal condition, there are vehicles in the GP lanes wanting to exit the freeway, which could also result in freeway capacity drops near the off-ramp. Traffic volume and speed data are collected by the eleven vehicle detector stations over 15-minute intervals during the simulation period, and then are used for freeway capacity estimation. The values of driving behavior model parameters such as mean reaction time and mean target headway are from the same as the calibrated SR-210 E simulation network presented later in the simulation network calibration and validation section of this paper.

In our simulation test scenarios, only one vehicle type (i.e., passenger car) is used in order to simplify the freeway capacity estimation. Three influential factors are included in the sensitivity analysis of the HOV cross-weave effect upstream of off-ramp as follows:

(1) *HOV cross-weave flow*: 0, 100, 200, 300, 400 and 500 passenger car per hour per lane (pcphpl)
(2) *Number of GP lanes*: 2-lane, 3-lane and 4-lane configurations
(3) *Buffer length*: 0 ft, 1,500 ft, 2,500 ft, and 3,500 ft

The number of HOVs entering the simulation network through the HOV lane is set to be 1,400 pcphpl based on field observations of SR-210 E. The number of vehicles entering the simulation network through the GP lanes varies from 1,200 to 2,400 pcphpl with 200 pcphpl increments. We also assume that the number of vehicles in the GP lanes taking the off-ramp is 150 pcphpl, resulting in traffic congestion upstream of the off-ramp. There is no bottleneck downstream of the off-ramp, leading to the downstream free-flow traffic. In addition, three different simulation seed numbers are used to capture the stochastic variability of simulation results. This means that a total of 216 simulation runs (6 levels of cross-weave flow × 3 number of GP lanes configurations × 4 levels of buffer length × 3 simulation seed numbers = 216) in PARAMICS are conducted.

3.2. Capacity estimation approach

With the data points collected from the eleven vehicle detector stations in the simulation, the Van-Aerde's curve that represents speed-flow diagram is used to estimate the capacity of GP lanes. This method has been found to achieve good performance in freeway capacity estimation (Modi et al., 2014; Li and Laurence, 2015). Also, the same method has been used in the research of HOV cross-weave effect downstream of on-ramps (Liu et al., 2012). The functional forms of the Van-Aerde's curve are illustrated in Eqs. (1) and

(2).

$$d = \frac{1}{c_1 + \frac{c_2}{S_f - S} + c_3 \times S} \tag{1}$$

$$q = d \times S = \frac{S}{c_1 + \frac{c_2}{S_f - S} + c_3 \times S} \tag{2}$$

where d is traffic density (veh/mile); q is traffic volume (pcphpl); S is traffic speed (mph); S_f is free flow speed (mph); c_1 is a constant representing the fixed distance headway (mile); c_2 is a constant representing the first variable headway (mile^2/h); and c_3 is a constant representing the second variable distance headway (1/h). These three constants can be calculated by the following equations:

$$m = \frac{2 \times S_c - S_f}{(S_f - S_c)^2} \tag{3}$$

$$c_2 = \frac{1}{d_j \times \left(m + \frac{1}{S_f}\right)} \tag{4}$$

$$c_1 = m \times c_2 \tag{5}$$

$$c_3 = \frac{-c_1 + \frac{S_c}{q_c} - \frac{c_2}{S_f - S_c}}{S_c} \tag{6}$$

where S_c is speed-at-capacity (mph); q_c is capacity (pcphpl); and d_j is jam density (veh/mile).

In this study, the Genetic Algorithm (GA) is applied to estimate the four parameters. The number of population sizes is 10, the maximum number of iterations is 2000, and the values of probabilities of crossover and mutation operations are 0.8 and 0.005, respectively. Based on the limited speed of freeway and the calibrated fundamental diagram using real-world data as shown in HCM 2010 (High Capacity Manual), the ranges of these four parameters are: $S_f \in [60, 65]$, $S_c \in [45, 55]$, $q_c \in [1800, 2400]$, and $d_j \in [170, 200]$. The function of fitness is based on the calculated errors between simulated data points and estimated data points given by

$$Fitness = \sum_i \left\{ \left(\frac{q_i - \hat{q}_i}{\tilde{q}}\right)^2 + \left(\frac{d_i - \hat{d}_i}{\tilde{d}}\right)^2 \right\} \tag{7}$$

where q_i is simulated flow; $\hat{q}_i$is estimated flow using Eq. (2); $\tilde{q}$ is simulated average flow; d_i is simulated density using the equation of q_i/S_i; S_i is simulated speed; $\hat{d}_i$ is estimated density; and $\tilde{d}$ is simulated average density.

3.3. Simulation results

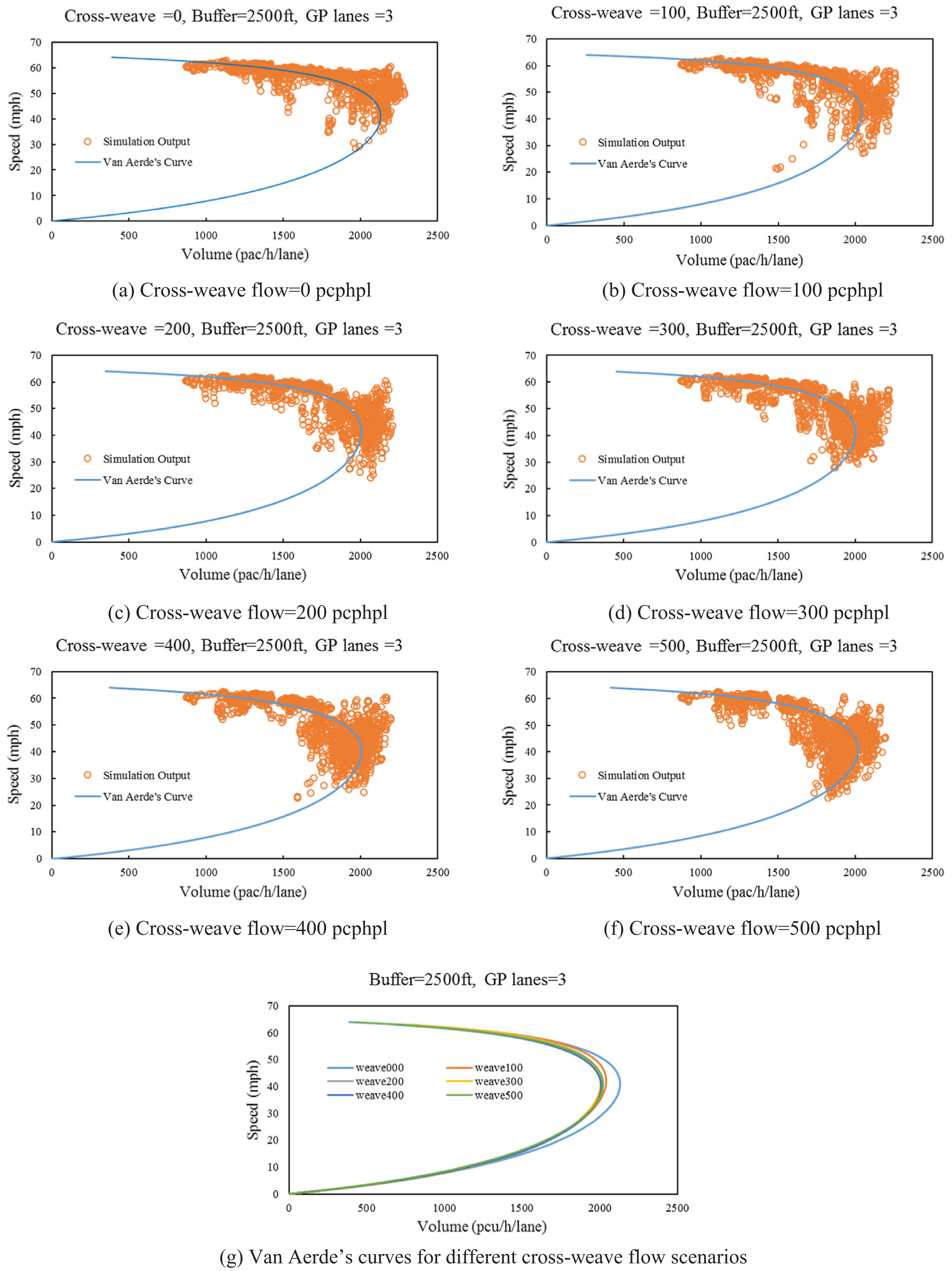
Due to the limited space, we only show the speed-flow diagram results and the fitted Van Aerde's curves for the 3-GPL (three GP lanes) configuration with the buffer length of 2,500 ft, and cross-weave flow ranging from 0 pcphpl to 500 pcphpl (see Fig. 3).

As shown in Fig. 3, due to the HOV cross-weave effect upstream of the off-ramp, the GP lane capacity shows a decreasing trend from 2,150 pcphpl to 2,000 pcphpl with the increase of HOV cross-weave flow from 0 to 500 pcphpl. Fig. 4 presents the capacity values of 3-GPL and 4-GPL scenarios under different levels of HOV cross-weave flow and buffer length. The results reveal that placing a buffer immediately upstream of the off-ramp can help maintain the level of capacity of the GP lanes. For different lengths of buffer, the capacity values for both 3-GPL and 4-GPL scenarios are around 2,020 pcphpl. Table 1 shows the results of a one-way analysis of variance in capacity for 3-GPL with the three different buffer lengths at a level of significance of 0.05. We accept the null hypothesis, with the p-value (0.851) larger than 0.01. For the 4-GPL, the observed value of F is 0.041, with the p-value of 0.96. Thus, there is no statistically significant difference in capacity between the three different buffer lengths.

In summary, with the increase in HOV cross-weave flow, the capacity of GP lanes shows a decreasing trend. And the capacity of GP lanes upstream of the off-ramp fluctuates slightly as the buffer length increases. These results imply that HOV cross-weave flow has a tangible negative effect on the capacity of GP lanes upstream of an off-ramp in the continuous access configuration, and placing a buffer immediately upstream of the off-ramp can help mitigate that effect irrespective of the buffer length.

4. Partially limited access design methodology

Results in the previous section show that HOV cross-weave flow affects the capacity of GP lanes upstream of off-ramps, which implies that an optimal design may be achieved by carefully selecting the location and length of buffers. In this section, design concepts of partially limited access HOV facilities are introduced, taking into account the HOV cross-weave flow effect and per lane weaving distance. Then, the partially limited design methodology is presented using a case study.



(a) Cross-weave flow=0 pcphpl

(b) Cross-weave flow=100 pcphpl

(c) Cross-weave flow=200 pcphpl

(d) Cross-weave flow=300 pcphpl

(e) Cross-weave flow=400 pcphpl

(f) Cross-weave flow=500 pcphpl

(g) Van Aerde's curves for different cross-weave flow scenarios

Fig. 3. Speed-flow diagrams from simulation outputs and fitted Van-Aerde's curves for scenarios with 3 GP lanes and 2500 ft buffer length.

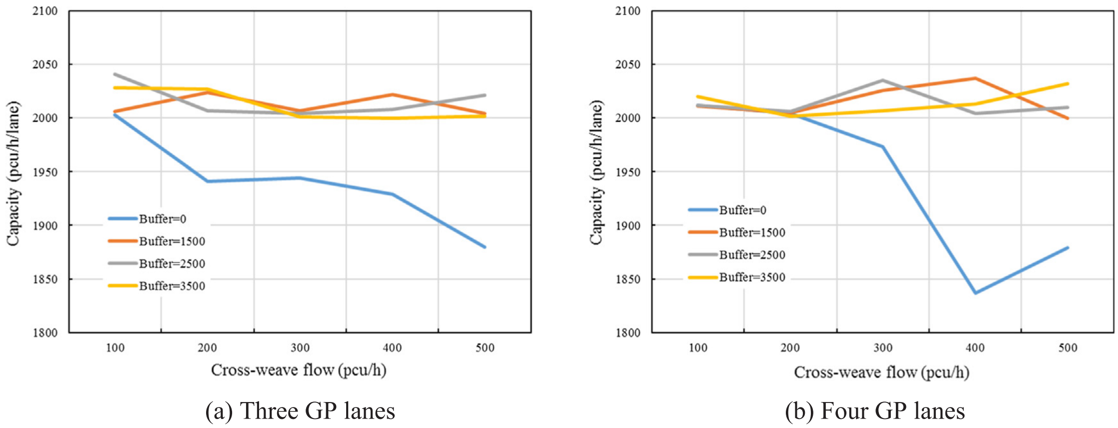


Fig. 4. Freeway capacity as a function of cross-weave flow and buffer length.

Table 1
One-way analysis of variance for 3-GPL with the three different buffer lengths.

Source of variation	Sum of squares	Degrees of freedom	Mean square	Observed *F*	p-value
Between groups	58.5	2	29.27	0.163	0.851
Within groups	2151.2	12	179.27	—	—
Total	2209.7	14	—	—	—

4.1. Partially limited access design concept

Previous studies reveal that: (a) buffer-separated HOV facilities are better at regulating traffic flow, resulting in higher freeway throughput (Wu et al., 2015); and (b) continuous HOV facilities are more likely to spread out lane changes, allowing traffic to maintain higher travel speed (Boriboonsomsin and Barth, 2006, 2008). The partially limited access design aims to take advantage of both HOV access designs by placing buffers at proper locations and selecting the appropriate buffer lengths, with the following specific design objectives: (1) to reduce the negative impact of HOV-related lane changes; (2) to improve HOV lane utilization; and (3) not to violate official HOV design guidelines.

In general, a freeway can be divided into four sections: (1) between off-ramp and on-ramp, (2) downstream of on-ramp, (3) basic segment, and (4) upstream of off-ramp, as shown in Fig. 5. We assume that the on-ramp and off-ramp are far enough from each other so that the weaving effect can be ignored. Each section is then discussed below to assess whether or not a buffer should be placed over.

In the basic segment and the section between off-ramp and on-ramp, there are usually few cross-weave flows that could negatively affect the capacity of GP lanes. For these sections, allowing continuous access to and from the HOV lane would likely result in higher HOV lane utilization, compared with limited access, as HOVs are able to move into the HOV lane without restriction. This is especially true for HOVs traveling in GP lanes that start to get congested. Once those HOVs realize the comparatively higher travel speed in the HOV lane, they can try to move into the HOV lane right away. This will not be achieved with the limited access design as the HOVs must go through the congested traffic in the GP lanes until they reach an ingress/egress zone before they can move into the HOV lane.

For the section downstream of on-ramp, it would also be better to allow continuous access to and from the HOV lane. In mild to

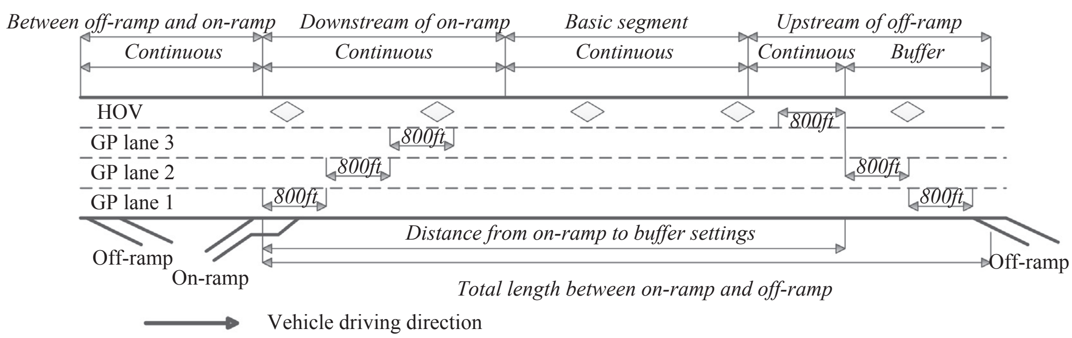


Fig. 5. Partially limited access design for freeway HOV facilities.

moderate traffic, the HOV lane utilization would likely be higher because HOVs that just enter the freeway from the on-ramp can safely make lane changes and merge into the HOV lane in a relatively short time. When the traffic is congested, both simulation and field observations reveal that the continuous access facility does not cause significant HOV cross-weave effect which may reduce the capacity of the GP lanes (Cassidy et al., 2010; Liu et al., 2012). This is because the HOVs that just enter the freeway from the on-ramp can merge into the HOV lane in a flexible and safe manner with the continuous access design. On the other hand, in the limited access design, if the ingress/egress zone is located in the area downstream of the on-ramp too close to the on-ramp, then HOVs that enter the freeway will face a challenge of making consecutive lane changes over multiple GP lanes to get into the HOV lane before they miss the ingress/egress zone.

For the area upstream of off-ramp, HOVs that intend to exit the freeway have to make multiple lane changes to take the exit ramp. These mandatory lane changes make negatively impact on traffic flow in the GP lanes, especially if many of the lane changes are concentrated over a short distance. Therefore, it is beneficial to place a buffer before the off-ramp to disallow or discourage lane changes in the last minute, which are often aggressive and may significantly disrupt traffic flow in the GP lanes. However, the buffer length should be as short as possible to keep a high level of HOV lane utilization. For safety purposes, official HOV design guidelines recommend a minimum weaving distance per lane l_{min} for a lane change. Burgess (2006) pointed out that the weaving distance per lane change is 1000 ft, with a minimum of 500 ft. The California Department of Transportation (2011) suggested that the per lane weaving distance should be larger than 800 ft. Recently, Machumu et al. (2017) investigated the lane choice decision distance for express lanes with consideration of level of service and number of GP lanes. They determined that the minimum distance was 4000 ft for six lane segments (two managed lanes and four GP lanes) with 1000 ft per lane change. In this study, we choose l_{min} = 800 ft.

For a freeway with 3 GP lanes, an HOV in the HOV lane needs to take 2 lane changes *within the boundary of the buffer* in order to take the exit ramp (see Fig. 5). Therefore, the buffer distance should be longer than $l_{min} \times (N_{GP}-1)$ ft, where N_{GP} is the number of GP lanes. On the other hand, an HOV vehicle that just enters the freeway needs to take three lane changes to get into the HOV lane, thus requiring a minimum weaving distance from the on-ramp to the buffer of $l_{min} \times N_{GP}$.

4.2. Partially limited access design methodology

In summary, following steps are taken to design partially limited access HOV lanes based on geometric characteristics of the freeway:

(1) If an on-ramp and the next off-ramp are far enough from each other, a buffer should be placed immediately upstream of the off-ramp. The buffer length can be determined using the following equations:

$$L_{buffer} = l_{min} \times (N_{GP}-1) \quad when\ (L_{tot}-L_{buffer}) \geqslant l_{min} \times N_{GP} \tag{8}$$

$$L_{tot} \geqslant l_{min} \times N_{GP} + L_{buffer} = l_{min} \times N_{GP} + l_{min} \times (N_{GP}-1) = l_{min} \times (2 \times N_{GP}-1) \tag{9}$$

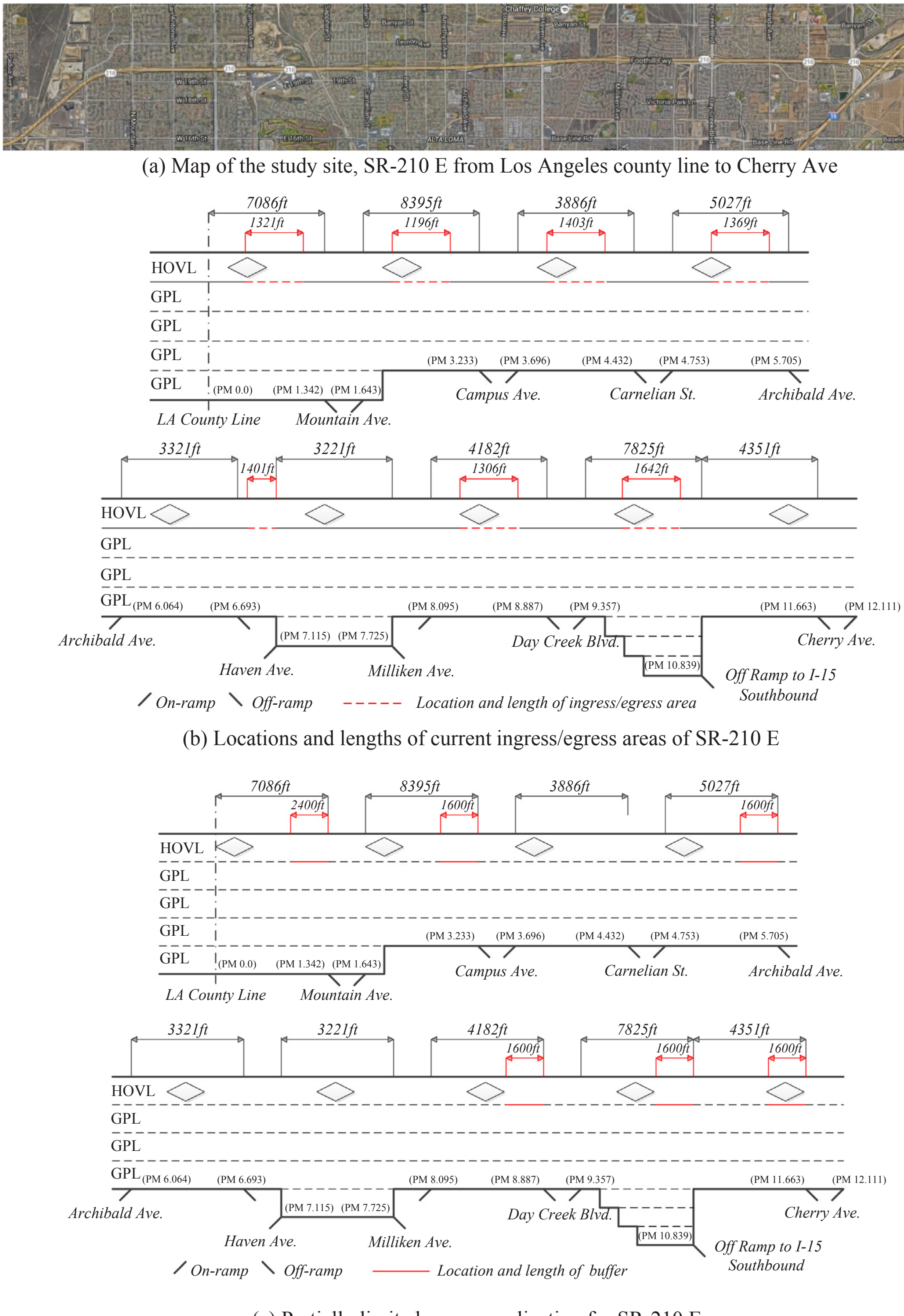
where L_{tot} is the length from on-ramp to the next off-ramp, and $N_{GP} \geq 2$.

(2) If an on-ramp and the next off-ramp are too close to each other, i.e., L_{tot} cannot meet the minimum length required by Eq. (9), continuous access should be provided for that segment due to its operational flexibility for HOVs. If the traffic is congested, HOVs in GP lanes that plan to merge into the HOV lane can keep moving along the GP lanes without making aggressive lane changes to the HOV lane. Also, HOVs that intend to move out of the HOV lane (especially to exit the freeway) can make the lane change at a preferable location when there is gap opening in the adjacent GP lane.

4.3. Partially limited access application

Fig. 6(a) shows a 13-mile (21-km) section of SR-210 E between Los Angeles (LA) County line and I-15 in San Bernardino County, which is used as the study site. The number of lanes on different segments of the study site varies from 4 to 5. Currently, the left-most lane is a full-time HOV lane with limited access design. As shown in Fig. 6(b) and (c), the Post Miles (PM) of each gore point of the on-ramps and off-ramps are used to calculate the distance between adjacent on-ramp and off-ramp pairs. There are 8 pairs of off-/on-ramps with inter-spacing ranging from 3,200 ft to 8,400 ft. In the existing limited access design, there are 7 ingress/egress areas as depicted by the red dashed lines in Fig. 6(b). The length of these ingress/egress areas ranges from about 1,200 ft to about 1,600 ft. Six of the ingress/egress areas are located between on-ramp and the adjacent off-ramp while the other one is located between an off-ramp and the adjacent on-ramp.

Using the developed partially limited access design methodology, the HOV access control on the study site is converted into the partially limited access design, as shown in Fig. 6(c). For example, the number of GP lanes between the on-ramp from Mountain Ave and the off-ramp to Campus Ave is 3. And the distance is 8,395ft, larger than 4,000 ft ($l_{min} \times (2 \times N_{GP}-1)$ = 800 × (2 × 3–1) = 4,000 ft). Therefore, a buffer should be placed before the off-ramp to Campus Ave. Based on Eq. (8), the length of the buffer is 1600 ft ($l_{min} \times (N_{GP}-1)$ = 800 × (3–1) = 1600 ft). In another example, the number of GP lanes between the on-ramp from Haven Ave and the off-ramp to Milliken Ave is 4. And the distance is 3,221 ft, less than 5,600 ft ($l_{min} \times (2 \times N_{GP}-1)$ = 800 × (2 × 4–1) = 5,600 ft). That means the distance is not long enough to place a buffer before the off-ramp to Milliken Ave. In the end, six buffers are placed upstream of off-ramps in this case study. The buffer length varies from 1,600 ft to 2,400 ft due to the different numbers of GP lanes. Three pairs of on-/off-ramps have inter-spacing much less than the minimum required, resulting in the continuous access design for those segments.



(a) Map of the study site, SR-210 E from Los Angeles county line to Cherry Ave

(b) Locations and lengths of current ingress/egress areas of SR-210 E

(c) Partially limited access application for SR-210 E

Fig. 6. Schematic of a case study and a partially limited access application.

5. Simulation-based evaluation of partially limited access HOV facility

Due to the lack of real-world deployment of partially limited access control, we resort to traffic micro-simulation to evaluate the operational performance of partially limited access HOV facility. A simulation network of the same segment of SR-210 E is coded, calibrated and validated with field data, and then used for the evaluation.

5.1. Simulation settings in PARAMICS

There are six vehicle types in the simulation network, namely HOV-passenger car, HOV-light duty truck (LDT), single-occupancy vehicle (SOV)-passenger car, SOV-LDT, medium duty truck (MDT) and heavy duty truck (HDT). Also, we develop two Origin-Destination (OD) matrices in this study; one for HOVs and the other for SOVs. In the HOV OD matrix, passenger cars and LDTs account for 57.43% and 42.57%, respectively. In the SOV OD matrix, the proportions of four vehicle types are 50.66% for passenger car, 37.55% for LDT, 6.43% for MDT and 5.36% for HDT, respectively. Note that the percentages of the different vehicle types are based on the fleet of Riverside County in September 2005 (Boriboonsomsin and Barth, 2008; Boriboonsomsin et al., 2013). The afternoon peak hour (16:30–17:30) is selected as the simulation period, with 45 min added to the beginning as a simulation warm-up time.

5.2. Microscopic traffic simulation model calibration and validation

Network calibration and validation are crucial to simulation studies as drivers in different areas may have different driving behaviors, which results in different traffic characteristics. In this study, we first use the Estimator tool in PARAMICS to estimate the two OD matrices based on flow data measured by loop detectors of the PeMS. Then, the freeway capacity of the study site is calibrated by adjusting global parameters, such as mean target headway and mean driver's reaction time. Lastly, link-level parameters such as link headway factor and link cost factor are fine-tuned to satisfy network calibration criteria (Dowling et al., 2002).

Data from 26 loop detectors (13 detectors in the HOV lane and 13 detectors in the GP lanes) are used to calibrate the simulation network. After completing the network calibration, the final values of the mean target headway and mean driver's reaction time for this study site are both 0.95. The link cost factor for HOV lane is 0.8 while the value for GP lanes is 1.0. The signpost distance and signpost range values which govern the decision point for lane changing in PARAMICS is set to 2,460 ft (about 750 m) and 3.3 ft (about 1 m), respectively. The simulated data of traffic flow and speed are compared with the real-world data, as shown in Fig. 7. The results show that the simulated flow and speed data are very close to the observed flow and speed data.

Table 2 summarizes the network calibration results in comparison with the targets suggested by Dowling et al. (2002). The results confirm that the simulated traffic has been satisfactorily calibrated to replicate the actual traffic in the real world. The GEH statistic (Oliver, 1962) in Table 2 is calculated using the following equation:

$$\mathrm{GEH} = \sqrt{2 \times (q_s - q_o)^2 / (q_s + q_o)} \tag{10}$$

where q_s is simulated hourly flow and q_o is observed flow.

The suggested method for validating a calibrated simulation network is to compare the simulation results against the fundamental traffic flow relationships (Dowling et al., 2002). Fig. 8 shows the speed versus flow diagram based on the data points from the calibrated simulation network. It follows the expected fundamental diagram and closely matches the diagram based on real-world observation. This validates the simulation network.

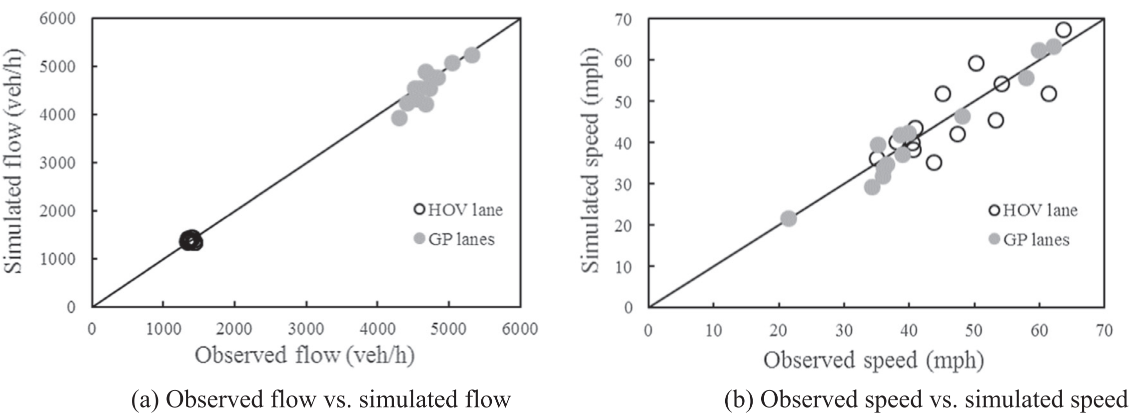


Fig. 7. Results of micro traffic simulation model compared with real-world data.

Table 2
Summary of calibration targets and results.

Criteria and measures	Acceptability targets	Calibration results
Hourly flows: simulated versus observed		
Individual link flows		
Within 100 veh, for flow < 700 veh	> 85% of all cases	Not applicable
Within 15%, for 700 veh < flow < 2700 veh	> 85% of all cases	100% of 13 cases
Within 400 veh, for flow > 2700 veh	> 85% of all cases	92% of 13 cases
Total Link flows-within 5%	All accepting links	1.8%
GEH statistics-individual link flow (GEH < 5)	> 85% of all cases	88% of 26 cases
GEH statistics-total link flows (GEH < 4)	All accepting links	2.5
Visual audits		
Individual link speeds		
Visually acceptable speed-flow relationship	To analyst's satisfaction	Satisfied
Bottlenecks		
Visually acceptable queuing	To analyst's satisfaction	Satisfied

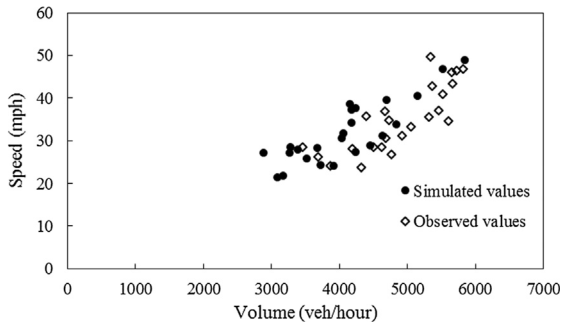
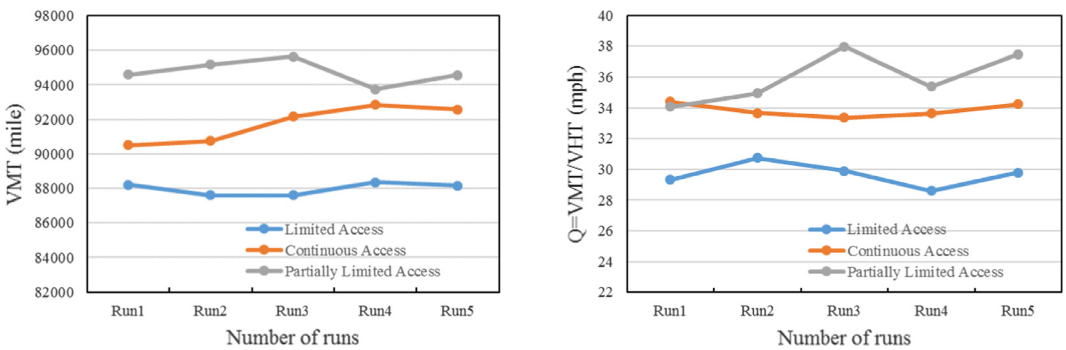


Fig. 8. Model validation of the freeway capacity.

5.3. Operational performance of partially limited access HOV facility

Based on the calibrated and validated simulation network (with limited access control), we code additional simulation networks with the other two HOV lane access controls (i.e., continuous access and partially limited access). Five simulation runs with different simulation seed numbers are made to reduce the variations in the simulation outputs caused by the stochastic nature of traffic microsimulation. Operational performance of the three HOV lane controls to be analyzed include vehicle miles travel (VMT), vehicle hours traveled (VHT), and operational efficiency or Q (= VMT/VHT), as shown in Fig. 9. Q can also be regarded as the average travel speed on the network.

According to Fig. 9, due to the short ingress/egress zones and thus high lane change intensity (to be presented in a later section), the limited access HOV lane design has the lowest value of VMT (87,985 veh-miles) and Q (29.6 mph). For the continuous access design, HOVs can merge into or out of the HOV lane freely, resulting in better performance in terms of VMT and Q. Due to the mitigation of HOV cross-weave effect on the capacity of GP lanes, the partially limited access design shows the best operational performance, with the values around 94,745 veh-miles for VMT and 35.9 mph for Q.



(a) VMT for different simulation runs (b) Q for different simulation runs

Fig. 9. Simulation results of the three different HOV lane configurations.

Table 3
Operational Performance of Different HOV Lane Controls.

Performance indicators	Limited access	Continuous access	Partially limited access
VMT (mile)	87985.4	91774.8 (4%)	94745.3 (8%)
VHT (hour)	2967.7	2711.26 (−9%)	2638.0 (−11%)
Q = VMT/VHT (mph)	29.6	33.8 (14%)	35.9 (21%)

Note: The percent values in parentheses are in comparison with the existing limited access control which is set as the baseline.

Table 3 summarizes the average operational performance of different HOV lane access controls. As shown in the table, the facility with partially limited access control improves the average travel speed by 21%, compared with that with the limited access control. In addition, the partially limited access control scenario shows the largest average VMT (representing throughput) and the smallest average VHT (representing delay) among the three HOV lane access controls.

5.4. Lane change features of partially limited access HOV facility

In this study, lane change features of the three different HOV facilities are also analyzed between the on-ramp from Mountain Ave and the off-ramp to Campus Ave. Using the simulation network, we record the lane-changing position of each vehicle from the HOV lane to the adjacent GP lane, and vice versa. The cumulative counts of lane changes for the three HOV access types are then calculated, and plotted in Fig. 10.

As can be seen in Fig. 10(a), in the case of limited access, the lane changes are highly concentrated over the short ingress/egress area (Location 3,300–4,100 ft). In the case of continuous access, lane changes are spread out. Some of them occur much in advance (before Location 3,000 ft), while others may delay significantly (after Location 6,000 ft). The lane changes close to the exit ramp can disrupt the mainline flow. On the other hand, the partially limited access addresses the drawbacks of the other two access types. It allows lane changes over a longer distance, thus avoiding intensive lane changes at a specific location. This eliminates those lane changes too close to the exit ramp. For the cumulative number of lane changes into HOV lane in Fig. 10(b), the partially limited access shows the largest number of lane changes from the adjacent GP lane into the HOV lane, leading to the highest HOV lane utilization. On the other hand, buffers placed upstream of off-ramps in the partially limited access HOV facility can help spread the spatial distribution of lane changes and reduce the last-minute lane changes, as compared with the other two access controls. This may result in a better operational performance.

5.5. Sensitivity analysis of buffer length

Sensitivity analysis is conducted for the proposed partially limited access design methodology to quantify the impact of buffer length l_{min}. The value of l_{min} ranges from 50 ft to 1000 ft. The operational performances are calculated based on the simulation results, as shown in Table 4.

As can be seen in Table 4, for the partially limited access control, the average travel speed increases with moderate value of l_{min} and later decreases with large l_{min}. The results of l_{min} = 600 ft show the best operational performance in terms of average travel speed (Q = 36.70 mile/h). When l_{min} is greater than 600 ft, HOV vehicles need to get out HOV lane early before off-ramps, resulting in low HOV lane utilization. When l_{min} is less than 600 ft, the compound effect due to HOV cross weave and capacity drop at off-ramps may lead to serious congestion on GP lanes.

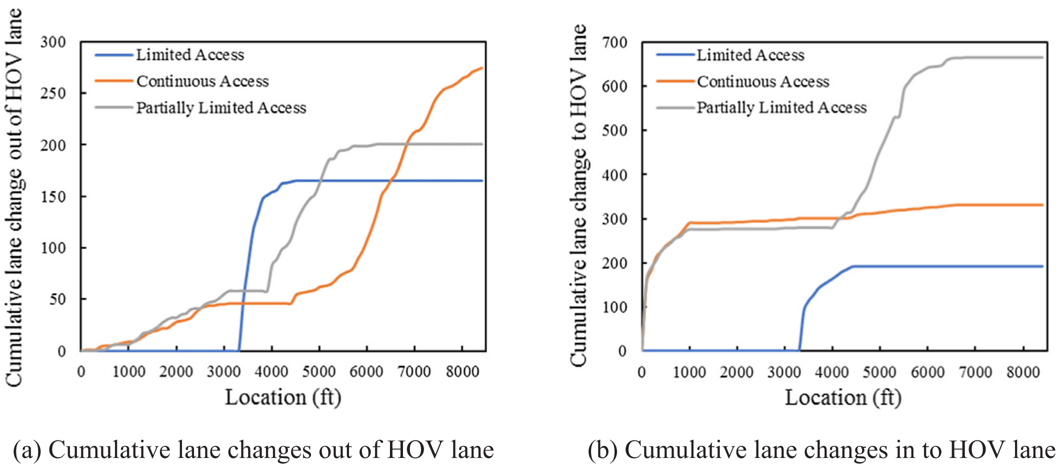


Fig. 10. Cumulative lane change between HOV lane and the adjacent GP lane.

Table 4
Operational performance of different l_{min}.

Performance indicators	l_{min} = 50 ft	l_{min} = 200 ft	l_{min} = 400 ft	l_{min} = 600 ft	l_{min} = 800 ft	l_{min} = 1000 ft
VMT (mile)	80,011	86,333	90,951	93,759	94,745	90,447
VHT (hour)	3799	3038	2722	2555	2638	2841
Q = VMT/VHT	21.06	28.42	33.42	36.70	35.92	31.84

6. Conclusions

This paper presented a novel design of HOV access control for improving the operational performance of the HOV facilities. The proposed partially limited access design aimed to provide continuous access along the majority of HOV facilities to achieve higher travel speed and strategically place buffers on selected segments to mitigate intensive weaving maneuvers (thus accommodating higher throughput on those segments). In the development of the design, the HOV cross-weave effect upstream of off-ramps was first analyzed. Then, a method for determining the location and length of buffers in the partially limited access control was developed and applied to a study site on SR-210 E in Southern California. Finally, the operational performance of the proposed design was compared with the performances of limited access and continuous access designs based on the well-calibrated simulation network of SR-210 E, as well as the lane change features. Sensitivity analysis was conducted to quantify the impact of different buffer lengths.

The results revealed that HOV cross-weave flow had tangible effect on the capacity of GP lanes upstream of off-ramps. Three influential factors, i.e., HOV cross-weave flow, number of GP lanes, and length of buffer were quantitatively analyzed. It was found that placing a buffer (with appropriate length) before an off-ramp could reduce the HOV cross-weave effect, keeping the capacity of GP lanes at a high level.

A methodology for designing partially limited access control for HOV facilities was developed based on the following criteria: (1) to reduce HOV cross-weave effect; (2) to improve HOV lane utilization; and (3) not to violate existing HOV design guidelines. A freeway segment with a pair of on-ramp and off-ramp was divided into four portions, including between off-ramp and on-ramp, downstream of on-ramp, basic segment, and upstream of off-ramp. For partially limited access HOV lane, buffers should be placed upstream of off-ramps as long as the buffer length could satisfy other requirements of existing HOV design guidelines.

The traffic microsimulation results for the case study of SR-210 E showed that the partially limited access control increased the throughput and decreased the delay of the freeway as compared with the limited access and continuous access controls. As a result, the overall network efficiency of the freeway with partially limited access HOV facility was 21% and 6% higher than that of the freeway with limited access and continuous access HOV facility, respectively. For the sensitivity analysis, the simulation results of l_{min} = 600 ft showed the best operational performances in terms of average traveling speed (36.70 mph).

It should be noted that this study is based mostly on simulation, and an evaluation of the operational performances of a freeway with partially limited access HOV facility in real world is still needed. As part of the future work, other performance indexes such as safety and environmental sustainability of the partially limited access design should also be evaluated in comparison with the two prevailing designs. Also, the weaving distance per lane should be further investigated with the consideration of many site-specific factors, such as level of service and number of GP lanes.

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