ANALYSIS ON OPERATIONAL INTERACTIONS BETWEEN FREEWAY MANAGED LANES AND PARALLEL GENERAL PURPOSE LANES

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ABSTRACT

Roadway agencies face growing challenges to expand freeway capacity. Under consideration of rising construction costs, right-of-way limitations, and environmental constraints, transportation agencies are seeking solutions to efficiently manage the demand on existing freeway facilities and to provide options for travelers. The concept of managed lanes (MLs) is an increasingly popular countermeasure that aims to make the most efficient use of freeway facilities, by restricting access to one or more lanes to certain vehicle classes on a facility that is parallel to existing general purpose (GP) lanes. With different strategies for separating ML and GP lanes, this study examines the interaction between GP lanes and ML operations. It scrutinizes this effect as a function of different separation types, the number of MLs, and operational ML strategies including high-occupancy toll (HOT) and high-occupancy vehicle (HOV) lanes. Four freeway sites were selected to explore this effect. The research shows that for HOT facilities, the separation type had the most significant impact on explaining the frictional effect intensity, as paint-separated ML facilities are readily impacted by congestion in the adjacent GP lanes. For HOV facilities, the frictional effect is observed by adopting a stochastic capacity estimation approach to estimate the capacity distribution function for both GP lanes and HOV lanes. It is determined that GP lanes have a stochastic dominance over HOV lanes under any breakdown probability. The results make the case that ML operations should not be evaluated independent of adjacent GP lanes, which have implications for proposed analytical approaches, but also for simulation-based analyses.

KEYWORDS: High-Occupancy Toll (HOT), High-Occupancy Vehicle (HOV), Managed Lanes, Capacity, Freeway Operations, Frictional Effect.

INTRODUCTION

The focus of current highway system analyses has shifted from infrastructure expansion to better managing existing facilities for improved sustainability and efficiency. The concept of Managed Lanes has been gaining more and more popularity and being adopted nationwide. Managed Lanes (MLs), as defined by the Federal Highway Administration (FHWA), are *"Highway facilities or a set of lanes in which operational strategies are implemented and managed (in real time) in response to changing conditions" (1)*. MLs include a wide range of operational and design practices including high-occupancy vehicle (HOV) lanes, express lanes or high-occupancy toll (HOT) lanes, and exclusive-use lanes such as truck-only toll (TOT) lanes, etc. *(2)*. In recent years, a significant amount of literature has discussed the planning, implementation and monitoring issues of MLs *(3-8)*. However, only limited sources have focused on the operational assessment of MLs, and in particular, knowledge of the interaction between MLs and adjacent General Purpose (GP) lanes is limited. Understanding the operations of MLs and their interaction with GP lanes is important to analyze the impact of MLs on the overall highway capacity and quality-of-service from a Highway Capacity Manual (HCM, *9*) perspective. Based on operational data collected under NCHRP project 3-96, Analysis of Managed Lanes on Freeway Facilities, this paper explores the interaction between two parallel ML and GP lane groups. The analysis includes four different freeway locations with various geometric design and operational strategies. Results are discussed in the context of traditional freeway performance principles following HCM theory.

BACKGROUND AND LITERATURE

Managed lanes encompass a series of operational strategies to efficiently manage the traffic demand by altering pricing, vehicle eligibility and access control. In the *Managed Lane Handbook (2)*, ML facilities are defined as a "freeway within freeway" where a set of lanes are physically separated from GP lanes within a freeway cross section to allow a certain degree of operational flexibility over time in response to changing traffic conditions. The NCHRP 3-96 project focuses on the development of an analytical methodology to evaluate the operations on two particular types of MLs: HOV and HOT lanes. As part of this effort, the interactions between the two parallel facilities are studied from empirical evaluation of sensor-based performance measurements. This paper focuses on the interaction of ML and GP lanes and in particular the factors that may impact the performance of the ML due to congestion on parallel GP lanes. Some important operating characteristics of existing ML facilities that may affect the intensity of this interaction are reviewed as follows:

Operational Strategy

HOV lanes are by far the best documented among all the ML facilities in terms of design, implementation, and performance monitoring *(5)*. The development of HOV facilities in the United States has evolved over 30 years. An HOV pooled fund study initiated by FHWA in 2002 continuously assembles information on existing HOV facilities in the United States, which currently identifies 345 HOV facilities in operation across the U.S. *(10)*. The main intent of implementing HOV lanes is to improve person-throughput rather than vehicle-throughput on congested freeway corridors. Accessing an HOV facility often requires two or more persons

(HOV 2+) per vehicle. Some agencies require three or more occupants per vehicle to assure reliable travel conditions in those lanes.

In locations where HOV lanes are underutilized, a conversion to HOT lanes is considered an effective way to increase the overall throughput by providing single-occupancy vehicles (SOV) or low-occupancy vehicles (LOVs) the ability to choose the MLs as an alternative to the GP lanes. Pricing constitutes a core element of this practice. SOVs are allowed to use the HOT lanes by paying a toll in exchange for travel time savings or improved trip reliability. The toll is either dynamically-changed based on real-time traffic conditions or scheduled by time of day. There are ten HOT facilities in operation to date *(11)*, including I-10 and US 290 in Houston, Texas, I-394 MnPass in Minneapolis, Minnesota, I-95 in Miami, Florida, I-15 in San Diego, California, SR 91 in Orange County, California, SR 167 in Seattle, Washington, I-25 in Denver, Colorado, and I-15 in Salt Lake City, Utah. Tolling policy may be customized for different facilities to achieve their specific objectives, whether it is to reduce emissions, to collect revenue, or to increase overall throughput. This will greatly affect how the users respond to the pricing. However, in general HOT lanes are operated as a reliability control valve for the overall system. When the GP lane is experiencing congestion, some SOV drivers will opt to pay to use the HOT lane in exchange for travel time savings. As those SOVs divert to the HOT lane, the level of GP lane congestion is expected to decrease as a result of the drop in demand. This will theoretically improve the overall throughput and operations of both freeway facilities.

Separation Type

Most concurrent-flow MLs are separated from GP lanes by painted stripe or narrow buffer (at least 2 feet or 0.6m wide). Because of this proximity of GP and ML traffic, increasing congestion levels on GP lanes are hypothesized to have an adverse effect on ML operations, well before the ML demand reaches breakdown levels. The reason for this frictional effect is that drivers in the MLs can readily observe the traffic on the adjacent lanes, and feel uncomfortable passing congested GP traffic at a high speed differential without adequate barrier separation. While the effect of narrow lanes and freeway shoulders are documented to result in a reduction in free-flow speed according to HCM theory (*9*), this ML-GP frictional effect has not been well documented in analysis practice to date. Nonetheless, in order to fully utilize the capacity of the ML facility and avoid this potential friction effect, many 2-lane or reversible ML facilities use concrete barrier separation. Some other facilities use soft barriers (plastic pylon), while others still rely on striping only for separation. Intuitively, a wider and more permanent separation between the GP lanes and MLs is hypothesized to reduce the interaction between the two parallel facilities.

Number of Lanes

Considering the construction and operation cost, most ML facilities in the United States are one-lane facilities, which means that they have a single ML in each direction. Two-lane ML facilities exist in several states including California, Northern Virginia, Minnesota, Florida, Texas, and Washington. It is hypothesized that the number of lanes within the ML facility is expected to affect its performance. For single ML facilities, a few slow-moving vehicles may quickly impact the general operations, much like they would on a two-lane highway. On contrary, multi-lane ML facilities allow opportunities for passing, and the impact of slow-moving vehicles is expected to have less of such an effect, at least until higher flow levels are reached.

RESEARCH OBJECTIVES

The goal of this research is to quantitatively explore the interaction between parallel GP and ML facilities by examining two different types of facilities: HOV and HOT lanes. To identify the operational interaction between MLs and parallel GP lanes, it is necessary to employ suitable methodologies on the basis of different operational strategies and geometric designs. Specific objectives of the research include:

1. Examining the HOT lane demand management strategy and its ability to control ML operations;
2. Evaluating and comparing the frictional effects of congested GP lanes on adjacent HOT facilities as a function of separation type;
3. Comparing the operations of single-lane and two-lane HOT facilities; and
4. Distinguishing interaction effects between HOT and HOV facilities, including the implementation of an approach to examine the stochastic dominance of GP lane capacity over adjacent HOV capacity.

To achieve these research objectives, sensor data were collected from three HOT lane sites and one HOV site. This study focuses on the analysis of multi-lane cases (2+ MLs), but also incorporated a single lane HOT facility case for comparison.

STUDY FACILITIES AND SITES

The database for NCHRP 3-96 consists of nine HOV/HOT facilities in different regions of the country. The data collection sites encompass a combination of multiple configurations in terms of separation type, access points, number of lanes, operational strategies, etc. This study chose four locations from the database to analyze the interaction between GP lanes and MLs. The four sites are labeled as Site A, B, C and D, which differ in separation types, number of lanes and operational strategies. The details on each site are given below.

Site A

Site A data were collected from the I-394 MnPass HOT Lane System in Minneapolis, Minnesota. SOVs who want to use the HOT lane will be charged a toll upon entry. The toll rate is changed in real time according to the congestion level in the MnPASS lanes. This 11-mile corridor is operating in the east/west direction and is serving traffic between downtown Minneapolis and the western suburbs. The whole facility is divided into two parts: a buffer-separated single HOT lane in the east and west directions of Hwy 100 (eastbound operating 6 a.m. to 10 a.m., and westbound operating 2 p.m. to 7 p.m.), and a reversible two-lane section east of Hwy 100 to downtown Minneapolis (Operating eastbound from 6 a.m. to 1 p.m. and westbound from 2 p.m. to 5 a.m.). Site A is located on the reversible 2-lane HOT lane portion, where a concrete barrier separates the HOT lanes from the GP lanes. The configuration of Site A is shown in Figure 1(a). The speed limit of I-394 MnPass is 55 mph, with lane width of 12 ft. The inner shoulder width is 8 ft.

Site B

Site B data were collected from the SR 91 Express Lane system in Orange County, California. The SR 91 Express Lane project is the very first HOT lane project in the nation that adopted the congestion pricing concept. The four-lane toll road operates in the median of an eight-lane freeway, with two MLs each dedicated permanently to eastbound and westbound traffic. The express lanes are separated from the GP lanes by soft barrier (plastic pylons and double yellow line marking), as shown in Figure 1(b). The tolling policy in this corridor has evolved since its opening to traffic in 1995. Starting in 2003, HOV3+ occupancy vehicles were eligible to use the express lane free of charge, except during afternoon peak period (4:00 P.M. and 6:00 P.M.) in the eastbound direction. During that peak time, HOV3+ occupancy vehicles need to pay 50% of the posted toll. All other vehicles (1 or 2 occupancy vehicles) need to pay the amount posted on the sign. It is reported that users of the SR 91 express lanes save on average 12-13 minutes of travel time *(12)* compared to GP traffic over the ten-mile facility. The SR 91 has a speed limit of 70 mph, with an average lane width of 12 ft. The inner shoulder width is 8 ft.

Site C

Site C data were also collected from I-394 MnPass HOT system as Site A. The difference is that Site C is located in the buffer-separated single-lane HOT section, where a two-foot buffer (double solid white line) separates the single HOT lane from the adjacent GP lanes. The configuration of Site C is shown in Figure 1(c).

Site D

After the SR 91 express lane from site B ends in the eastbound direction, it continues operating as a dual-lane HOV facility running parallel to the GP lanes with a double yellow line separation (buffer). Site D data was collected from a location in that section as shown in Figure 1 (d).

Since the interaction between MLs and GP lanes of basic freeway segment is the concern of this study, it is imperative to select locations where the weaving effects due to presence of on- and off-ramp, access points to the MLs, etc is limited. Therefore, the locations for frictional effect analysis were selected to be at least 1500 ft away from any on- or off- ramps in accordance with Highway Capacity Manual definitions *(9)*. The four selected sites allow the comparison of two-lane priced HOT facilities with different separation types (Site A vs. B), the comparison of a two-lane and a single-lane HOT segment along the same facility (Site A vs. C), and the comparison between a two-lane HOT and a two-lane HOV-only section along the same facility (Site B vs. D).

METHODOLOGY

Historical sensor data for the four sites illustrated in Figure 1 were obtained from the Performance Measurement System (PeMS) sponsored by California Department of Transportation (Caltrans) and the Minnesota Department of Transportation (MNDOT). Data were recorded for each lane in 5-min intervals over the duration of the sampling period. The sampling periods ranged from 5 to 24 hours per day depending on the operating hours of the MLs. One month of data were obtained at Site B and D (September, 2009), and four months of data were obtained for Site A and C (May to August, 2009). The sensor data include 5-min lane-by-lane traffic counts and speed. All the data were carefully reviewed in detail for erroneous detector readings. And the data sample sizes for Site A, B, C and D are 2448, 3360, 2448, and 3347, separately.

The purpose of this analysis is to identify if a degraded performance on GP lanes adversely affects the performance of the adjacent MLs. The approach evaluates ML speed-flow observations that are paired with either congested or uncongested GP lane conditions. The HOT lane data is separated into two categories based on GP lane speed:

- GP speed > 40 mph
- GP speed ≤ 40 mph

The threshold chosen for this analysis is 40 mph because the speed for HOT lane is typically above 60 mph (96 km/h) and a GP lane speed of 40 mph (64 km/h) results in a significant speed differential perceived by HOT lane users. It was also validated by examining the time series plots of four sites, where 40 mph is the general speed bar at which the recurrent congestion on GP lanes begin to accumulate. It is hypothesized that if the ML speed drops to a significantly lower level relative to the free-flow speed and before reaching its own capacity then a frictional effect is demonstrated, attributable to adjacent GP congestion.

Three of the four sites (A, B, and C) are HOT lane facilities, and this study particularly examined their HOT lane demand management effectiveness through a pricing component (Objective 1). Tolling dynamically manages the demand on HOT lanes to prevent breakdown in the ML and assure toll-paying drivers a high degree of travel-time reliability. Therefore, HOT lanes are expected to seldom experience breakdown no matter how congested the adjacent GP lanes are, provided that the demand management strategy is effective, and provided that any frictional effects from congested GP lanes are mitigated by facility design (barrier separation).

It is expected that different separation types would impact the intensity of the frictional effect (Objective 2). For example, soft barrier and buffer separation may have a more severe friction impact due to the proximity between GP lanes and MLs. On the contrary, a concrete barrier separated facility would have less such impact, because the more permanent separation between lanes provides added comfort to ML drivers. The effect of barrier separation on the interaction between ML and GP lanes is explored by comparing sites A and B.

Next, the test sites include two locations along a HOT facility with varying number of lanes (Sites A and C). It is hypothesized that the operations on a single-lane ML facility are significantly different from a two-lane site, as the impact of slow-moving vehicles on a single-lane facility will impede overall performance at lower flow rates than at a two-lane location (Objective 3).

Finally, HOV facilities are expected to exhibit different traffic operational characteristics than HOT facilities, because demand is not dynamically managed by a tolling component (Objective 4). Consequently, HOV lanes are expected to more readily experience breakdown concurrent with the GP lanes as entering demands are not controlled through pricing. The difference between HOV and HOT operations are explored in a comparison of sites B and D. The demand volume that causes the breakdown in the real traffic flow scenarios and the flow rate that a breakdown depends on, vary from day to day and from one location to another *(13)*. Therefore, breakdown volume is considered to be a random variable and it is plausible to be estimated using a stochastic approach. It is hypothesized that GP lane capacity exhibits a dominant effect on the HOV's capacity, which explains the frictional effect between the two lane groups. A breakdown is defined as the average speed falling below a certain threshold, and the observed throughput volume dropping below the capacity to the congested portion of the speed-flow curve.

Estimating Stochastic Dominance

To investigate how the HOV's traffic is stochastically dominated by the GP lanes' traffic, a stochastic capacity estimation approach is applied. In this approach, the capacity distribution function is based on the analogy to the statistics of lifetime data analysis, which serves to describe the statistical properties of human life duration. This approach was first proposed to be used in capacity analysis by Minderhoud *et al. (14)*. Later, Geistefeldt *(15)* further modified some basic assumptions of this method specific to application for freeway operations. The breakdown events can be detected using time series analysis containing both traffic volume and speed. Using a constant speed threshold value determined from the time series speed plot and justified by the speed flow diagram, if the speed falls below the threshold value in the next interval *i+1*, and lasts for more than 15 minutes (3 intervals), the traffic volume in interval *i* is regarded as causing a breakdown. For the stochastic capacity estimation, not only the intervals that cause breakdown but also the intervals that are not followed by a breakdown deliver valuable information on the capacity. The latter type of the data is called "censored data".

The capacity estimation involves both non-parametric and parametric methods. The non-parametric approach to estimate the survival function is the Product Limit Method (PLM) *(16)*, in which the capacity distribution function $F_c(q)$ can be estimated by:

$$F_c(q) = 1 - \prod_{i:q_i \le q} \frac{k_i - d_i}{k_i}, \qquad i \in \{B\} \tag{1}$$

where: q = flow rate (veh/h/ln)

q_i = flow rate in interval i (veh/h/ln)

k_i = number of intervals with a flow rate of $q \ge q_i$

d_i = number of breakdowns at a flow rate of q_i

{B} = set of breakdown intervals.

The relationship in Equation 1 is calculated over all observed data $q_i \le q$ that were followed by a breakdown. The distribution function will only reach 1 when the maximum observed volume is an uncensored data sample. Otherwise, it will terminate at a value of $F_c(q) < 1$. For parametric estimation, the parameters are pre-determined based on statistic techniques to find a distribution that best fits PLM curve. Typically, a Weibull distribution is chosen over other distribution functions such as Gamma and Normal distribution. The Weibull distribution function is expressed as:

$$F(x) = 1 - e^{-(\frac{x}{\beta})^{\alpha}} \qquad \text{for } x \ge 0 \tag{2}$$

where: α = shape parameter

β = scale parameter

The maximum log-likelihood method used to calibrate the parameters of the Weibull distribution is given as:

$$LL = \sum_{i=1}^{n} \{\delta_i \cdot \ln[f_c(q_i)] + (1 - \delta_i) \cdot \ln[1 - F_c(q_i)]\} \tag{3}$$

where: $f_c(q_i)$ = statistical density function of the capacity *c*

$F_c(q_i)$ = cumulative distribution function of the capacity *c*

n = number of intervals

δ_i =1, if interval i contains an uncensored value; = 0, if interval i contains a censored value

RESULTS

Effectiveness of HOT Demand Management

Two 2-lane HOT lane locations with different separation types are illustrated in Figure 1 and marked as Site A and B. To evaluate the effectiveness of the HOT demand management strategies, Figure 2 illustrates a representative time series plot of speed and volume for two data samples collected on June 17, 2009 at Site A, and on September 3, 2009 at Site B. For Site A, since the HOT lane system is only operating from 6:00 A.M. to 10:00 A.M., only the morning period data is shown in the figure. Intuitively, the strongest interaction would be observed between the HOT lane (s) and the most adjacent GP lane, therefore, only the sensor data for the most adjacent GP lane (left-most) is used for analysis. The period of GP lane breakdown is easily identifiable from Figure 2 (a) and (b), where a sudden speed drop below 60 mph is observed from the two cases. For example, for Site B, before 2:15 P.M., the average speed across the GP lane is relatively high, maintaining at 70 mph. However, at 2:15 P.M., it is experiencing a sharp speed drop to below 50 mph, and generally remains below that threshold until 7:10 P.M., after which speeds recover to the pre-congestion stage. During that congested period, the speed of the dual HOT lanes is maintained at non-breakdown levels, although a slight speed drop to around 55 mph in average is observed. By looking at the corresponding time series volume plot, it is easy to identify that as the GP lanes are experiencing traffic breakdown, more people opt to pay to use the HOT lane to avoid the congestion. However, tolling is playing a key role during that period to dynamically manage the demand, so the HOT lanes can help alleviate part of GP lane traffic by directing those paid customers to use the "express road". The same story holds true for Site A (Figure 2 (a)).

It is worth mentioning that, although Site C is operating as a single HOT lane case, the tolling is functioning just as effective as the two-lane cases as illustrated in Figure 3. However, we do observe a more severe speed drop to around 45 mph at 8:00 A.M., hypothetically, which may be due to the frictional effect imposed from the GP lanes.

Different states have been using different tolling strategies on their HOT lane facilities and the performance of an HOT lane system ties directly to the tolling strategy. Comparing tolling strategies has been a difficult problem due to missing pieces of information critical to HOT lane operations. However, the essence of tolling is to effectiveness improve the overall throughput by diverting certain volume of the approaching traffic into the HOT lanes. In a macroscopic level of examining the tolling effect, the findings presented in this section can be served as a reference for the practitioners to further conduct price elasticity analysis and examine how users respond to the tolling on different sensitivity levels.

Effect of HOT Separation Type

To better observe the frictional effect, speed-flow diagrams are plotted using the data collected in the entire sampling period. Figure 4 shows the speed-flow diagrams at the two dual HOT lane locations (Site A and B). In comparison, Following the HCM basic freeway methodology *(9)*, a reference line for the density at capacity of 45 passenger cars per mile per lane (pc/mi/ln) is added to all the diagrams. Because tolling adjusts the demand in the HOT lanes, it is expected that HOT lanes maintain stable flow conditions, and that breakdown conditions are prevented. This is validated from the field data collected, where only the stable portion of the speed-flow curve are observed for the MLs.

In the speed-flow diagram, ML speed-flow data is paired with the GP lane speed. The ML data points are color-coded respective to whether they are measured while GP lane speed was below a certain threshold (40 mph in this study). The purpose is to identify if a degraded performance on the GP lane exhibits an adverse effect on the parallel MLs. If the ML data indicates a reduction in speed before reaching theoretical capacity when the GP speed is less than 40 mph, then the congestion on GP lane may have a frictional effect on the ML operation. Figure 4 (a) explores the frictional effect for the concrete-barrier separated ML facility. It is observed from the figure that the green triangles (GP speed < 40mph) are distributed in a manner comparable to the red-colored stars for GP speeds greater than 40mph. A simple t-test between the two HOT lane speed data sets was conducted under the volume range of 600 to 1300 vphpl, which corresponds to the observed ML volume range where GP lanes are congested. The t-test indicates that the speed difference between the two data sets are statistically insignificant (t=0.85, P=0.19) at the 95% confidence interval. This suggests that at this location the HOT lane speeds are not significantly affected by the GP lane congestion. When applying the same principle to Figure 4 (b) for the soft-barrier separated location, a frictional effect is more apparent. Under the same volume conditions, the green low-GP-speed triangles generally represent lower speeds than the red high-GP-speed stars. The t-test shows that the two speed data sets are significantly different (t=3.94, P=0.00). When the GP lane speed is less than 40 mph, the corresponding HOT lane speed drops to 50% even when the theoretical capacity has not been reached. It is also noted that HOT lane capacity at this site may be between 1650 vphpl and 1800 vphpl. However, it is premature to make the conclusion before more analysis can be done using longer periods of data.

Figure 5 plots the corresponding speed-flow relationship for the single-lane buffer-separated facility (Site C), and once again, the frictional effect can be observed clearly and is more intensive than the barrier-separated cases. It is observed in Figure 5 that, under the same volume, the green triangles (GP speed < 40mph) correspond to a lower ML speed than the red stars. It is confirmed that the two speed data sets are significantly different (t=15.2, P=0.00) at the 95% confidence interval. Consequently, when the GP lane experiences congestion, the HOT lane is affected as well, even though it does not reach its capacity.

It can be concluded from this empirical data that separation type appears to impact the interaction between GP and MLs. The buffer-separated HOT location (Site C) appears to have more interaction between GP lanes and MLs, although this finding may be confounded by a difference between one-lane and two-lane ML facilities explored below. A soft barrier separation (e.g. Site B) appears to have a less significant friction effect than the buffer-separated facilities. The concrete barrier separated site exhibits the least interaction between the two lane groups (e.g. Site A). As hypothesized, it appears that the presence of a barrier imposes more isolation for HOT lanes, making drivers more comfortable, and correspondingly reducing the friction effect. A concrete barrier appears to further reduce friction compared to a soft-barrier separation. Following the t-test theory of comparing the two speed data sets of HOT lanes under the volume range of 600 to 1300 vphpl, the average speed difference between the two speed data sets are 0.3 mph, 2.2 mph and 5.6 mph for Site A, B and C. These are important indicators to further quantify the frictional effect to fit in the context of a HCM methodology framework.

Contrasting Single-Lane and Two-Lane HOT facilities

A comparison between the two-lane sites shown in Figure 4 and the single-lane ML facility in Figure 5 indicates that the speed-flow relationship for the single-lane ML drops more rapidly. Further, the speed-flow relationships for all three ML sites seem to drop more rapidly than what the HCM method would predict (*9*). This hypothesis is confirmed by using linear regression to estimate the slope of the HOT lane speed-flow data for Sites A, B and C as marked by the black lines in Figure 4 and Figure 5. The resulting slopes of the regression lines are -0.0046, -0.0042, and -0.0080, respectively. Correspondingly, the slope of the observed single-lane site is approximately twice as steep as the two-lane locations. This finding is as hypothesized for single-lane ML facilities, where the impact of a few slow-moving vehicles more quickly impacts the general operations. In the context of this discussion it is further important to emphasize that GP basic freeway segments in the HCM2010 have a constant speed (zero slope) up to a flow rate of 1200 passenger cars per hour per lane. The ML data therefore suggest a speed drop of 0.4 to 0.8 mph for every 100-vehicle increase in flow rate. At the HCM2010 breakpoint, this corresponds to an observed difference in speed of 4.8 to 9.6mph.

Evaluating HOV Capacity

Figure 6 shows the time series plot of speed and flow using a representative data sample of Site D on September 03, 2009. It is noted that the HOV lane speed and flow pattern appear to closely trail operations in the GP lanes. When the GP lane is experiencing a speed drop, the HOV lane is also operating at a lower speed. This finding is important in comparison to the HOT operations shown in Figure 2 and Figure 3, where the demand management in the HOT lanes assured satisfactory operations in the MLs, despite breakdown conditions in the GP lanes.

The apparent interaction between HOV and GP lanes in Figure 6 are not necessarily attributable to a frictional effect of GP on HOV lanes, in that the HOV lanes may themselves be in a breakdown state. By examining the speed-flow curve of the HOV site in Figure 7 (a), it is easy to identify that HOV lane operations also exhibit periods in the unstable portion of the speed-flow curve. Therefore, the drop of speed in HOV lane cannot be classified as having a frictional effect from GP lane, rather it is due to the breakdown state it is experiencing itself.

From the time series plot of speed in Figure 6 and speed-flow curve in Figure 7 (a), it is easy to identify the stable state and congested state for both HOV and GP lanes using 50 mph and 60 mph as speed thresholds, separately. Therefore, we use these two thresholds to identify the breakdown state for HOV and GP lanes, respectively. To further justify these speed thresholds, Van Aerde's steady-state car-following model is used for the calibration of the speed-flow diagram as shown in Figure 7 (b) *(17)*. It is noted that 50 mph and 60 mph are the critical speed for the dual HOV and the adjacent GP lane, separately. The operational parameters derived from the Van Aerde's model are shown in Table 1.

Using the stochastic capacity analysis approach introduced above, the capacity distribution of both HOV and GP lanes can be determined. The capacity distribution curve (shown in Figure 8) can provide information about the probability of a freeway location being in breakdown state at the observed flow for both HOV and GP lanes.

Table 2 shows the fitted Weibull distribution result. It is noted that when the observed volume reaches 1540 vphpl for HOV and 2310 vphpl for adjacent GP lane, then there is a 15% probability that the location would breakdown, separately. The capacity distribution estimation for both HOV and GP also indicates that GP lane's capacity is always stochastically dominating over the HOV's capacity. For comparison, the theoretical capacity of a GP basic freeway segment with a free-flow speed of 65mph is 2350 vphpl.

DISCUSSION

The concept of MLs has been adopted widely nationwide as an effective countermeasure against freeway congestion. A lot of research has been done to examine how MLs can improve the overall throughput and alleviate congestion from transportation policy and roadway design perspective. However, few efforts have been performed to investigate the interaction between GP lanes and MLs from an operational standpoint. This analysis suggests that the intensity of this interaction can vary as a function of separation type, ML operational strategy, and the number of lanes.

This paper specifically investigated the frictional effect between GP lanes and MLs on four basic freeway segments as defined by the HCM, and analyzed how the intensity varied due to different design and operational strategies. For HOT facilities, tolling is playing a key role to dynamically manage the demand and avoid the HOT lanes from reaching breakdown. By examining the speed-flow diagram from selected location, it is concluded that the most significant characteristic that affects the friction intensity is the separation type. Buffer-separated HOT facilities appear to have more interaction between GP lanes and MLs than those separated by barriers. Due to an observable friction effect, a congested GP lane would have an adverse effect on the adjacent HOT lanes, even when the HOT lanes themselves are operating below capacity. The ranking is followed by soft barrier, where the frictional effect is less significant than the buffer-separated facilities. Concrete barrier separated sites appear to have the least interaction between the two lane groups. This suggests that facility design and specifically the type of separation impacts sustainable operations on the MLs.

For HOV facilities, a similar frictional effect is confirmed by adopting a stochastic capacity estimation approach to estimate the capacity distribution function for both GP lanes and HOV lanes. It is determined that GP lanes have a stochastic dominance over HOV lanes under any breakdown probability.

The results of this research are important as analysts are developing methods to better estimate the operational performance of ML facilities. The findings of this paper suggest that depending on the separation type and other facility characteristics, a managed lane facility should not be evaluated in isolation, since its operational performance can be impacted by congestion on adjacent GP lanes. This is important in the consideration for an analytical procedure for ML evaluation in a Highway Capacity Context under NCHRP 3-96. This is also a milestone for developing new speed-flow relationships for MLs, where the frictional effect can be identified as an adjustment factor when evaluating the speed-flow diagram for a specific site. However, it is also important for simulation-based evaluation of ML facilities, which oftentimes do not capture the interaction of parallel (but separate) GP and ML facilities.

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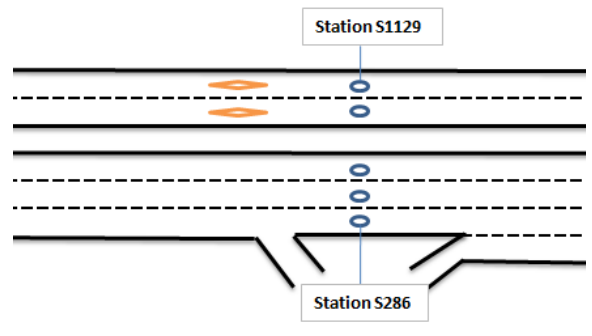
List of Tables and Figures

TABLE 1 Operational Parameters Estimated Using Van Aerde's Model

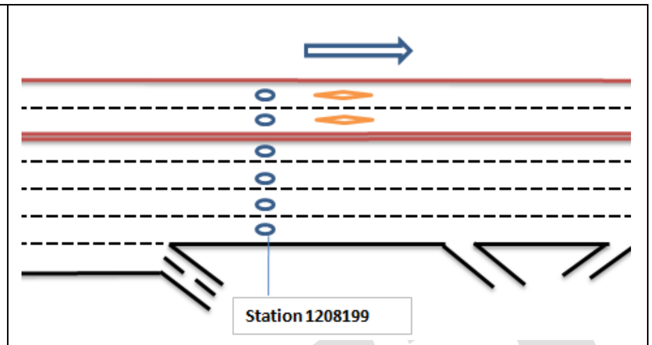
Lane Type	Free Flow Speed (mph)	Critical Speed (mph)	Jam Density (veh/mile)	Capacity (vphpl)
Dual HOV	60.2	49.5	155.9	1550
Adjacent GP	66.8	59.6	145.6	2051

TABLE 2 Stochastic Capacity Estimation using Weibull Distribution Function

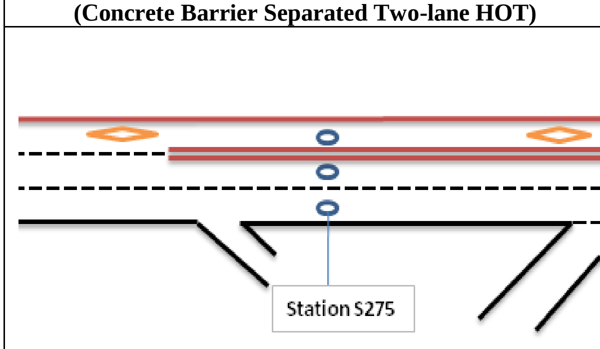
Lane Type	α	β	Capacity (vphpl)@ 15% Breakdown Probability
Dual HOV	7.55	1950	1540
Adjacent GP	17.68	2565	2310



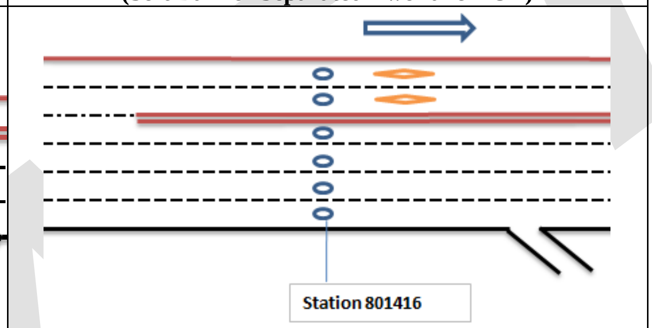
(a) Site A: I-394 EB @ Penn Avenue
(Concrete Barrier Separated Two-lane HOT)



(b) Site B: SR 91 EB @ W of Gypsum
(Soft Barrier Separated Two-lane HOT)

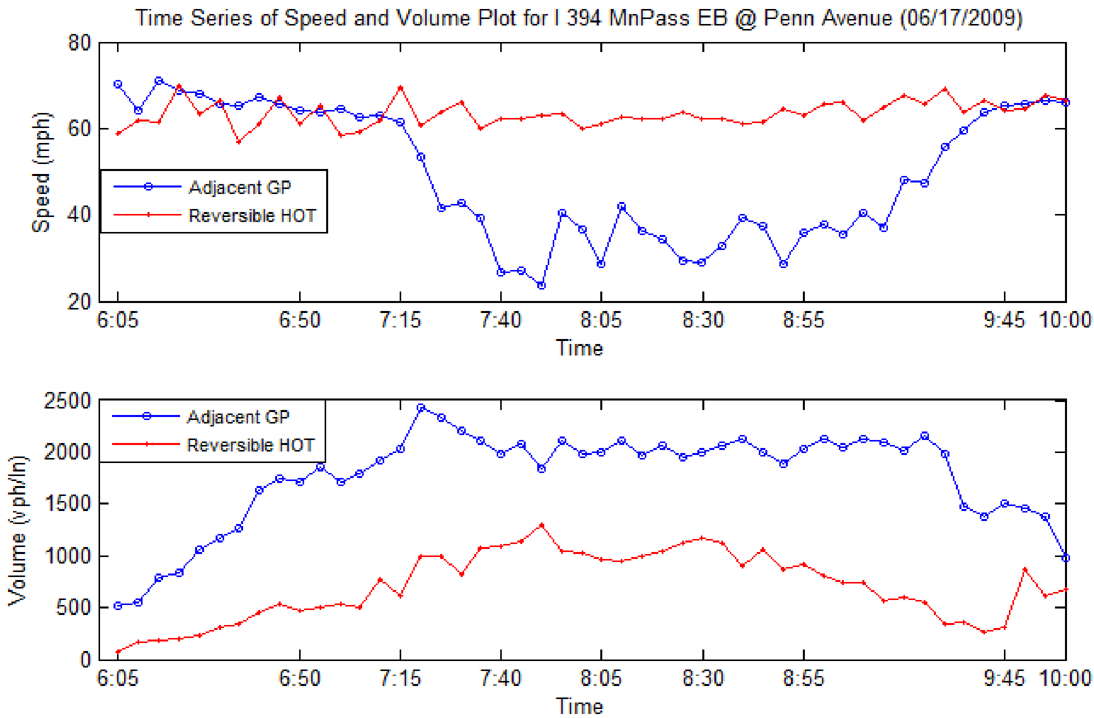


(c) Site C: I-394 EB @ General Mills
(Buffer Separated Single-lane HOT)

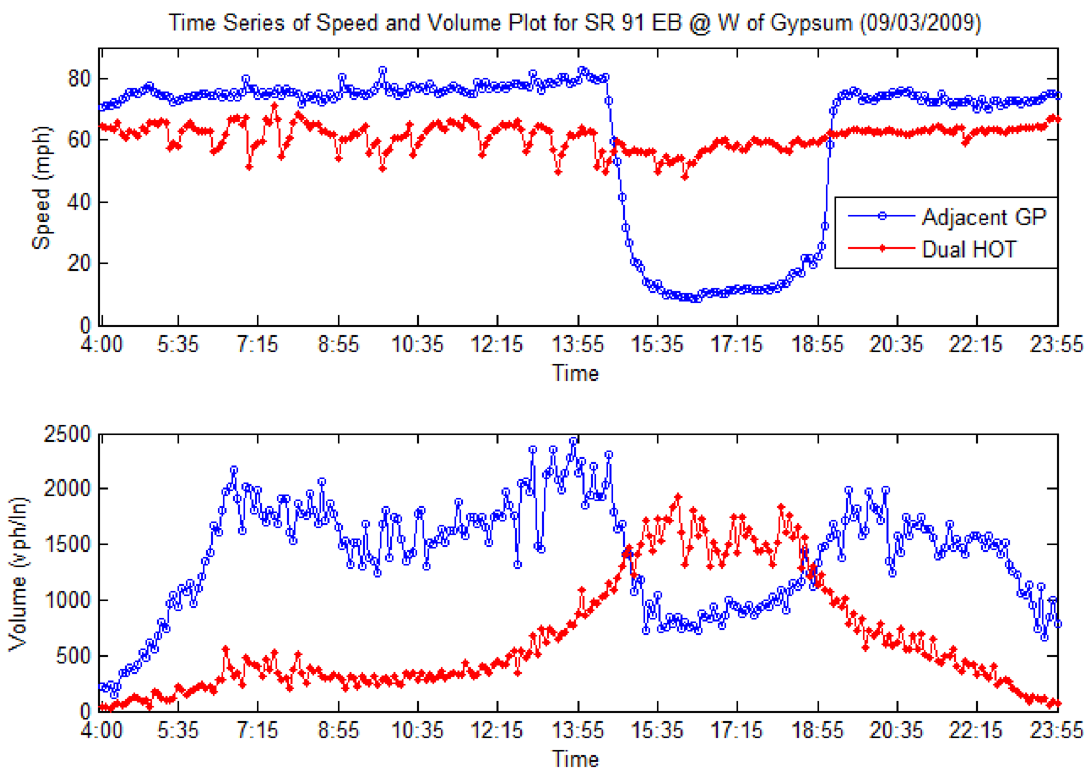


(d) Site D: SR 91 EB @ W of Green
(Buffer Separated Two-lane HOV)

FIGURE 1 Schematics of site configurations (not to scale).



(a) Time Series of Speed and Flow Plot for Site A



(b) Time Series of Speed and Flow Plot for Site B

FIGURE 2 Time series of speed and flow plots for Site A and B.

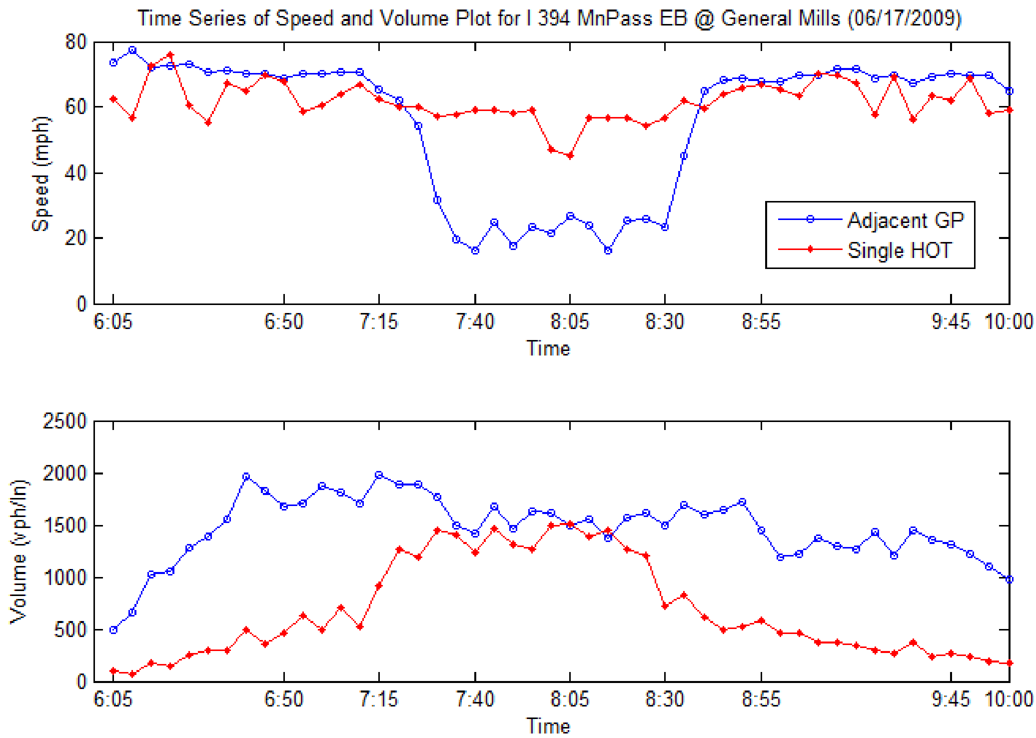
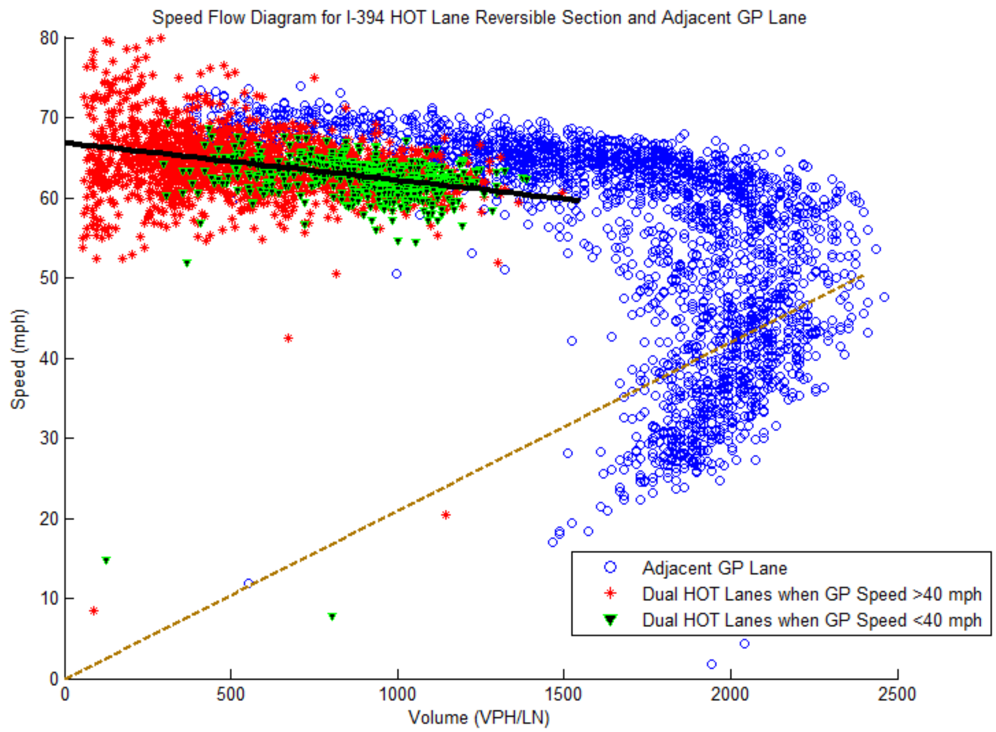
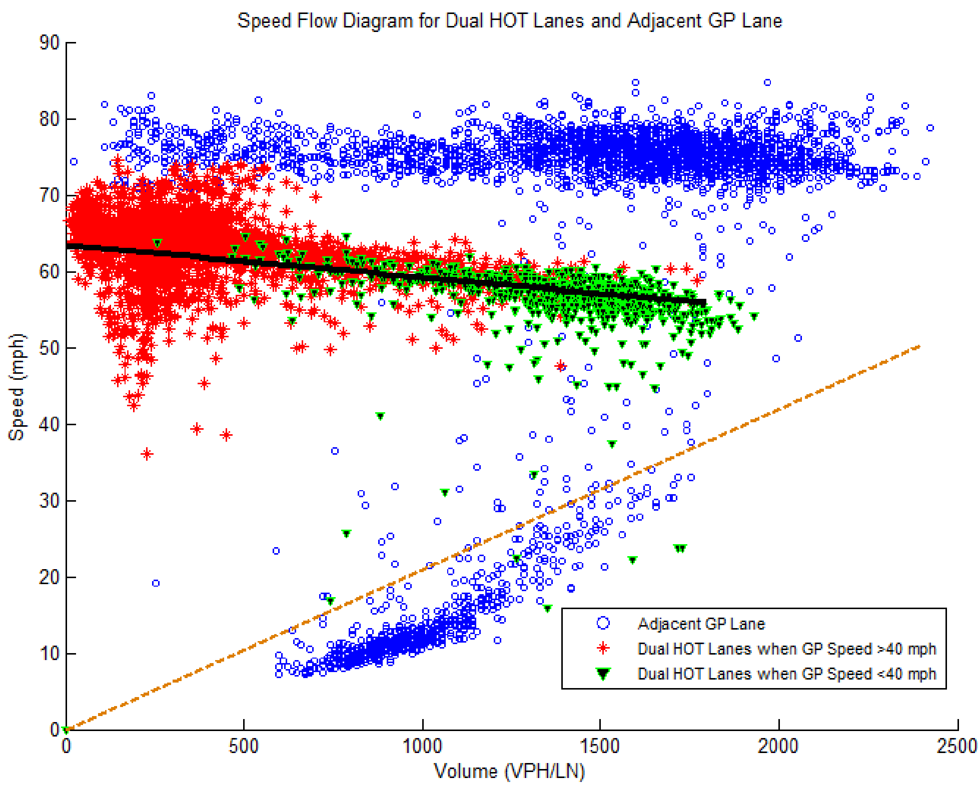


FIGURE 3 Time series of speed and flow plots for Site C.



(a) Speed-Flow Diagram for Site A (Concrete Barrier Separated)



(b) Speed-Flow Diagram for Site B (Soft Barrier Separated)

FIGURE 4 Speed-flow diagram for Site A and B.

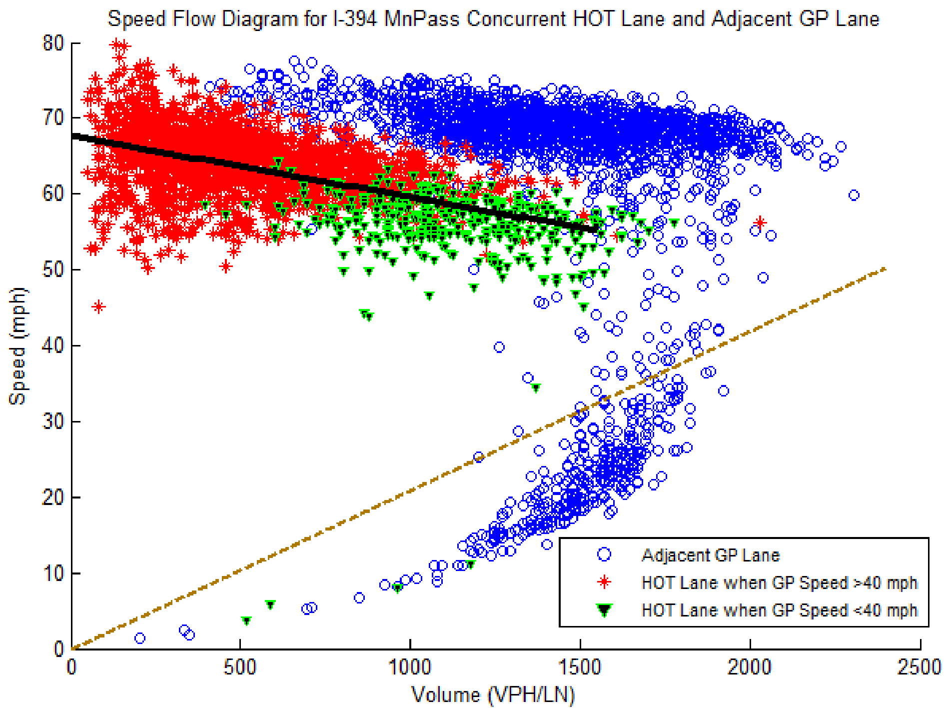


FIGURE 5 Speed-flow diagram for Site C.

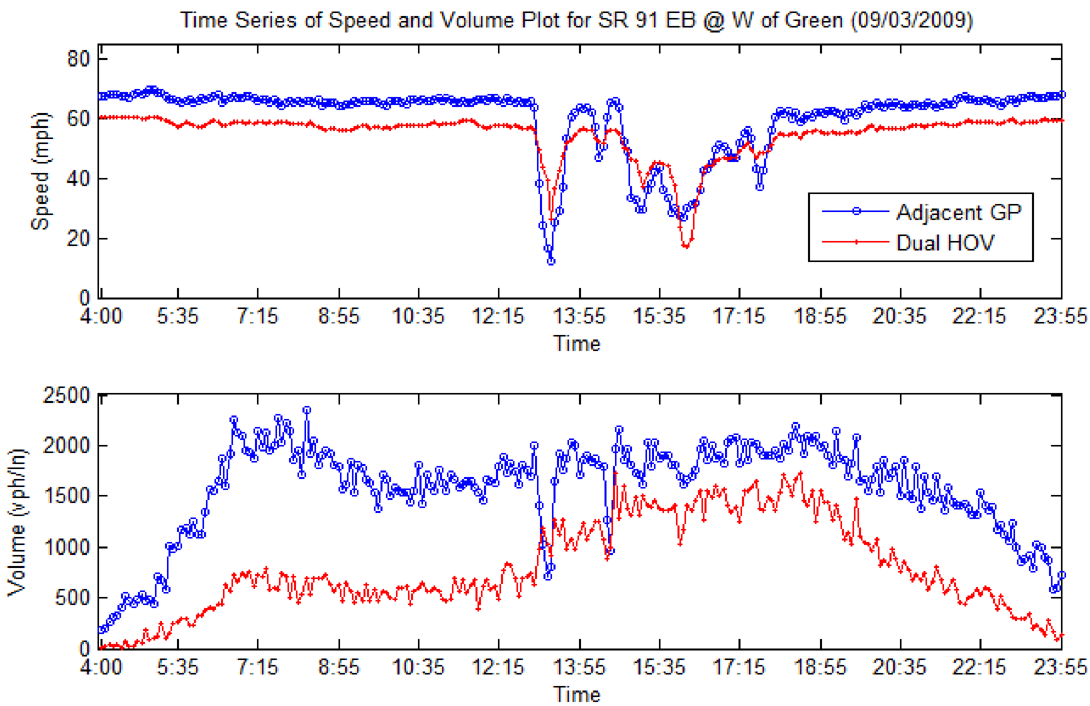
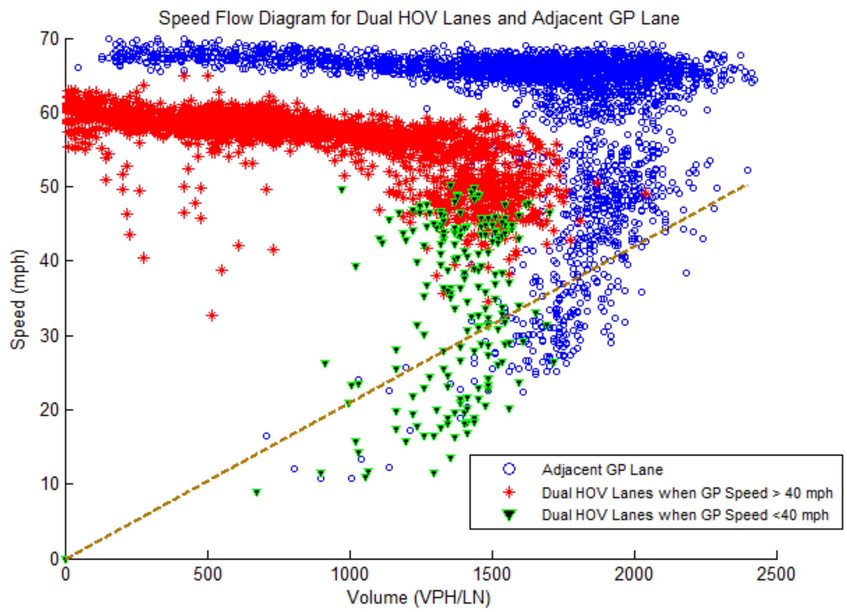
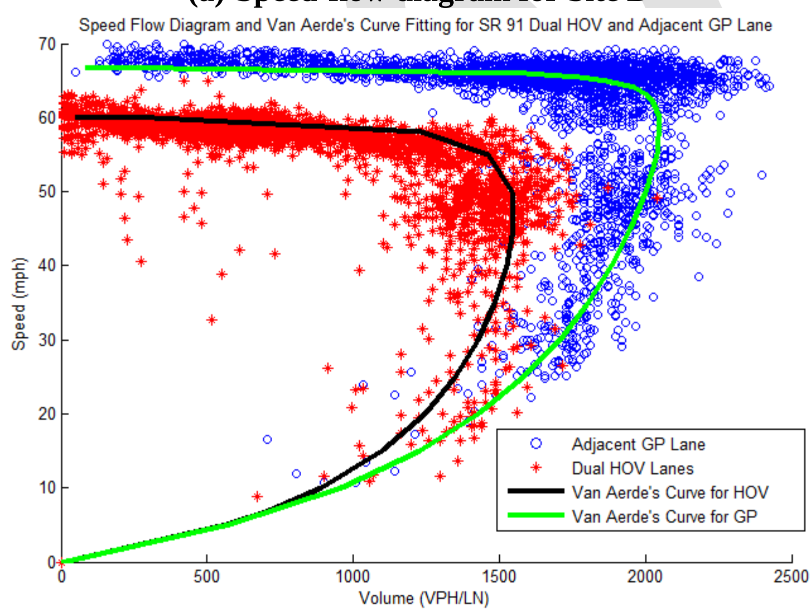


FIGURE 6 Time series of speed and flow plot for Site D.



(a) Speed-flow diagram for Site D



(b) Speed-flow diagram and Van Aerde's Curve Fitting for Site D

FIGURE 7 Speed-flow diagram for Site D.

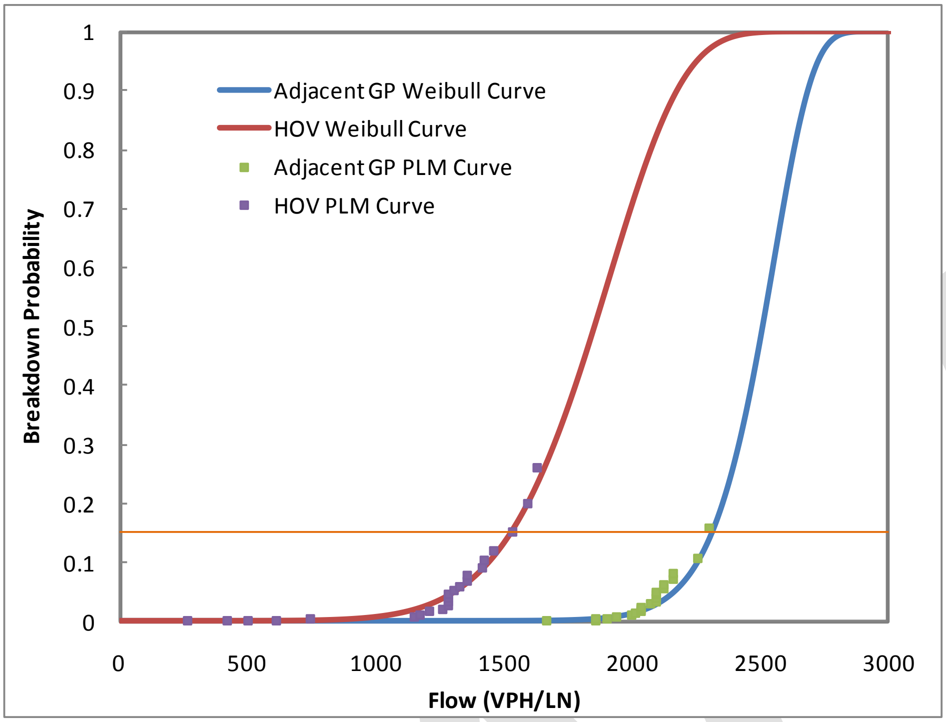


FIGURE 8 Estimated capacity distribution functions for Site D using PLM and Weibull Method.