An Analytical Framework for Managed Lane Facility Performance Evaluation

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ABSTRACT

Managed Lane (ML) system has been considered as a very effective countermeasure against freeway congestion in the recent decades. With limited work has been documented for analytical evaluating ML facilities, transportation agencies often rely heavily on time-consuming and cost-ineffective simulation experiments for ML performance analysis. This paper presents the methodological framework for analyzing the freeway performance consisting of General Purpose Lane (GPL) and ML facilities in a Highway Capacity Manual (HCM) context. The method incorporates new features for performance assessment accounting for the unique attributes of ML facilities. The cross-weave effect, which describes the ML cross-weaving traffic impact on the GPL segment, was quantitatively modeled. A CRF is developed to account for this feature. It allows for an appropriate integration of this phenomenon into the ML methodology developed under the research project NCHRP 03-96. The frictional effect, which is a result of speed reduction in the ML traffic due to congestion in the adjacent GPLs is appropriately modeled and incorporated into a new set of speed-flow curves. A macroscopic simulation is also developed incorporating the frictional effect to demonstrate the uniqueness of traffic evolution on single-lane ML facilities. The developed methodological framework presents an important, new approach for the performance analysis of ML-enabled freeway segments, which is valuable in providing guidance for analysts in evaluating freeway segments in the presence of concurrent GPL and ML in an HCM context.

KEYWORDS: Managed Lane, Framework, Frictional Effect, Cross-Weave Effect, and Cell Transmission Model

1. INTRODUTION

According to the 2011 Urban Mobility Report *(1)*, roadway congestion cost a total of 101 billion dollars and induced a total delay of 4.8 billion hours in the U.S. in 2010, with approximately 60% of the congestion occurring on freeways. More and more strategies have been implemented to mitigate congestion by utilizing cutting-edge information technologies to proactively control and manage traffic system operations. Among them, Managed Lanes (MLs) are considered one of the most effective countermeasures against traffic congestion. MLs provide an innovative control mode for managing traffic in response to real time traffic condition changes, without adding any physical capacity on the existing infrastructure. They allow the allocation of an appropriate portion of existing freeway facility capacities to special categories of roadway users. The restriction imposed onto user groups often includes the number of occupants, types of vehicles, and tolling *(2)*. Some of the prevailing ML operational and design practices are High-Occupancy Vehicles (HOV), High-Occupancy Toll (HOT), Truck-Only Tolling (TOT), or Express Tolling. While there are more and more ML facilities in operation nationwide, the operational guidance for ML is minimal, especially in terms of the methodology or modeling technique to quantify the performance of MLs as well as appropriately model its interaction with the adjacent General Purpose Lanes (GPLs).

The National Cooperative Highway Research Program (NCHRP) project 03-96, *Analysis of Managed Lanes on Freeway Facilities*, was geared at developing an analytical framework to evaluate the performance of ML facilities along with parallel GPLs. This framework is consistent with the Highway Capacity Manual (HCM) to provide a more standardized basis for analyzing and quantifying ML facility performance under diverse traffic conditions. This paper is based on the research developed in the NCHRP 03-96 project to elaborate the analytical framework and methodology for modeling ML facilities.

2. BACKGROUND AND RESEARCH OBJECTIVES

2.1 Background

The current 2010 HCM *(3)* classifies freeway facilities into three different types: basic freeway segment, merge and diverge segment, and weaving segment. The current facility analysis principle initially establishes the input data requirements, then adjusts demands (if necessary), and computes the operational performance of each individual segment according to the updated methodologies for each different segment type. Capacities can then be adjusted to emulate the effects of adverse weather or work zones, before computing segment demand to capacity ratios (d/c). If no segment is at d/c>1.0, the methodology then aggregates the facility performance based on individual segment operations. If any segment operates at d/c>1.0, an entirely different procedure is applied to estimate the effects of congestion based on shockwave theory.

2.2 Research Objectives

The major goal of this research is to develop a methodological framework for analyzing freeway facilities with ML and GPLs operating and interacting simultaneously. The framework acknowledges that the compositional and behavioral characteristics of the ML traffic stream are quite different from those for the GPLs in terms of traffic volume, free-flow speed, capacity, vehicle type, etc. The framework further confirms that there are certain levels of interactions between these two lane groups, especially for those facilities which do not have physical (barrier) separations, either en route or at access points, between them. The dichotomy of design and behavioral attributes therefore requires an updated analytical framework fitting within the HCM methodology to accommodate both ML and GPL facilities, while retaining the impact of interactions between the two. Specific objectives of this research include:

1. Developing a methodological framework for analyzing freeway facilities with the presence of parallel MLs and GPLs;

2. Building a Capacity Reduction Factor (CRF)/ Capacity Adjustment Factor (CAF) to account for the capacity reduction impacts of the cross-weaving ML traffic on one or more GPL segments; and

3. Quantifying the frictional effect imposed onto the MLs into the speed-flow models due to the congestion on GPLs, and developing a simulation model incorporating the frictional effect to model traffic evolution dynamics on freeway facilities with ML component.

To precisely reflect ML facility traffic operational attributes, field data were collected to quantify the cross-weaving effect as well as the frictional effect.

3. METHODOLOGY

3.1 Methodological Framework

The methodological flow chart that incorporates ML facilities is depicted in Figure 1. A major difference between the existing HCM and proposed methodologies is the introduction of the new lane group concept (parallel GPL and ML lane groups), which affects the definition of facility geometry in Step 1. Further, with the introduction of MLs, time-varying demand volumes needed are likely to be more challenging to estimate. In Step 3, capacity estimation for the GPL segments is not initially affected by the introduction of MLs. However, several new ML-specific segment types and associated segment capacities will need to be defined and calibrated. Next, segment capacities are adjusted for work zones and weather effects (step 4a) as in the current HCM. The existing methods for estimating the capacity reduction in the HCM 2010 are adopted. When adjusting the segment capacity, one unique segment, ML Access Segment, needs to be treated with special care. This segment often exists in ML facilities with intermittent access. The segment itself is treated as weaving segment using HCM Chapter 12 to compute its impact. However, for the segments between an GPL on-ramp and the ML Access Segment, or between the ML Access Segment and an GPL off-ramp, the cross-weaving module needs to be invoked to estimate the capacity reduction effects (if any) on the GPLs due to the cross-weaving flows. The cross-weave effect, associated with the ML Access Segment, will be introduced at length in the next section.

Within each cell of the time-space unit, d/c ratio needs to be calculated for both lane groups. Depending on the prevailing congestion levels, either under-saturated or oversaturated performance modules are executed. It is assumed that the oversaturated methodology for GPLs (Step 6b) will remain unchanged. For under-saturated operations (Step 6a), performance measures are estimated for each segment, under consideration of traffic demands and appropriate adjustments to segment capacity. Note that for the ML group, the methodology is limited to the under-saturated conditions. It is assumed in this method that the operations of congested ML facilities are beyond the scope of the current HCM method, and will be reserved for a simulation-based analysis if necessary *(4)*.

The fact that ML performance is affected by GPL traffic requires the GPL analysis to be done prior to the ML analysis. When the GPLs operate at densities above the specified threshold, the friction-based speed prediction model should be invoked. When the GPLs operate below the specified threshold, the non-friction-based speed prediction model needs to be invoked. The frictional effect module will be discussed in detail as follows.

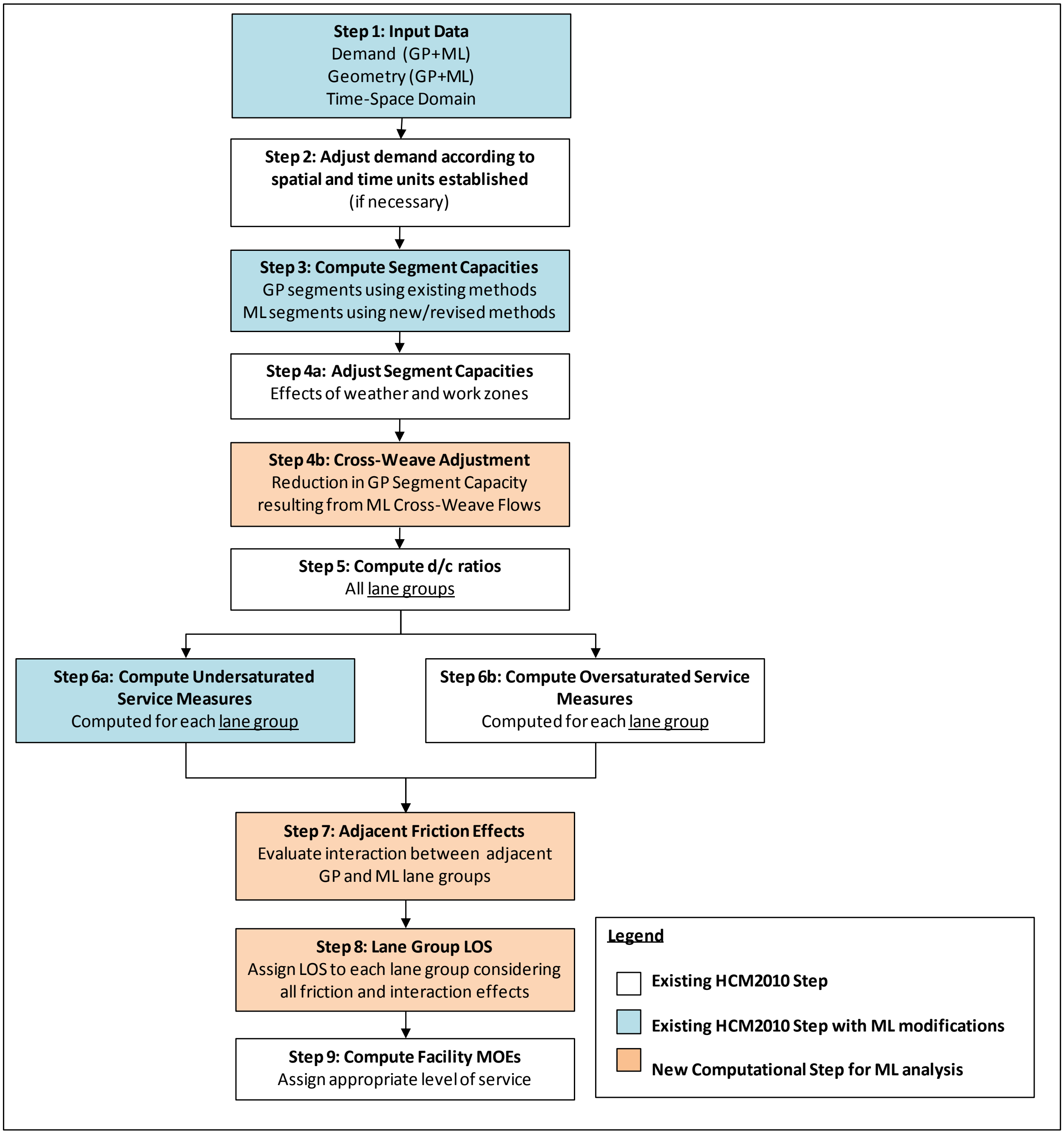


FIGURE 1: Methodological Flow Chart Incorporating MLs

Upon the completion of the frictional effect adjustments, the LOS assignment for each segment within each 15-min time interval is performed. Finally, facility MOEs are estimated as before, with the caveat that additional MOEs specific to MLs or the relative comparison of the MLs and GPLs is needed. Aggregations of MOEs over the entire time-space domain of the analysis would be performed for each separate lane group. Cumulative travel time and average speed, weighted by both length of segments and number of lanes in segments, would be calculated and compared between the two lane groups.

3.2 Cross-Weave Effect Adjustment

ML access points are potential bottlenecks for an ML facility due to the interaction between ML and GPLs. ML access point design therefore plays a critical role in determining operational performance of freeway facilities. As illustrated in Figure 2, there are three principal types of ML access configurations in practice.

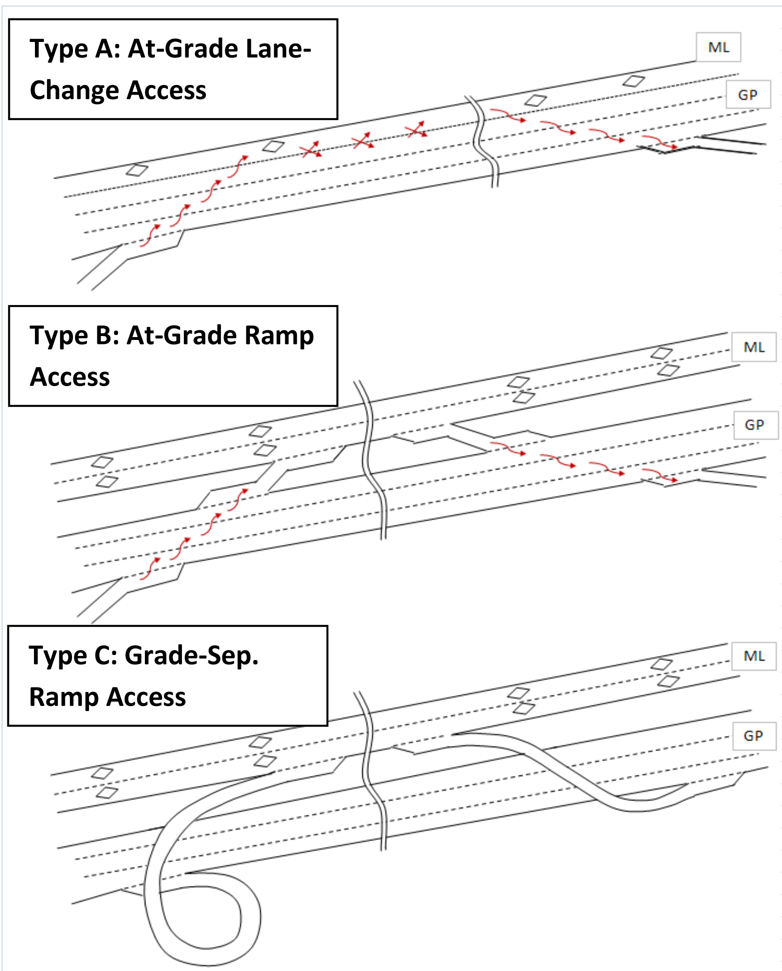


FIGURE 2: Typology of ML Access Point Designs

The spatial extent of the *Access-Point Influence Area* (APIA) for Type C is already defined in HCM ramp junction methodologies. For Types A and B access points, the intensity and impact of the *cross-weaving (CW) flows* between a GPL ramp and the ML Access Segment need to be analyzed. Figure 3 illustrates this concept for a concurrent single ML next to three GPLs with buffer separation. In this case, on-ramp vehicles desiring to enter the ML must complete all three lane-change maneuvers (not counting the merge from the acceleration lane), resulting in a cross-weave friction on the GPL traffic. It is found from previous research *(5)* that most drivers attempt to complete lane change maneuvers as early as possible, resulting in lower operating speed and capacity on the GPLs prior to the ML Access Segment. The overall cross-weave intensity can be estimated based on the number of lane change maneuvers, minimum and maximum available distances to complete all lane changes ($L_{CW\text{-}Min}$ and $L_{CW\text{-}Max}$), as well as the cross-weave demand.

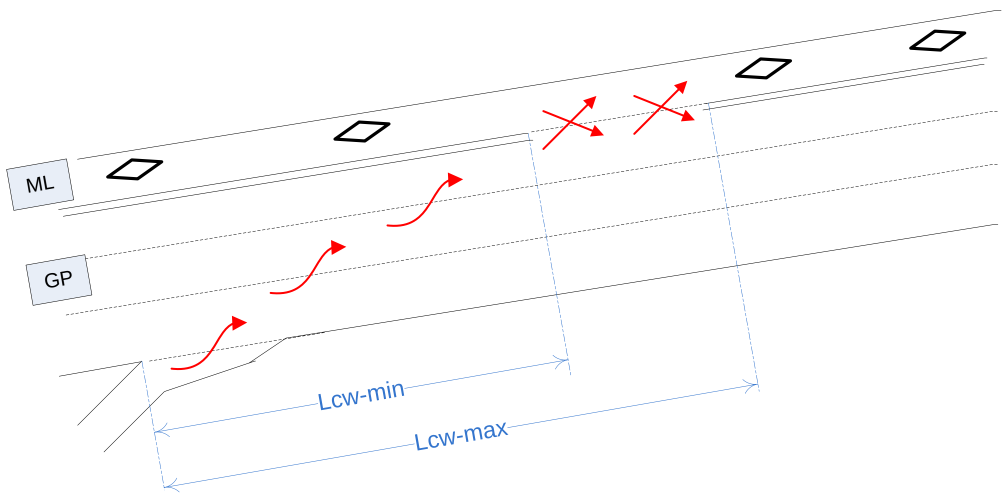
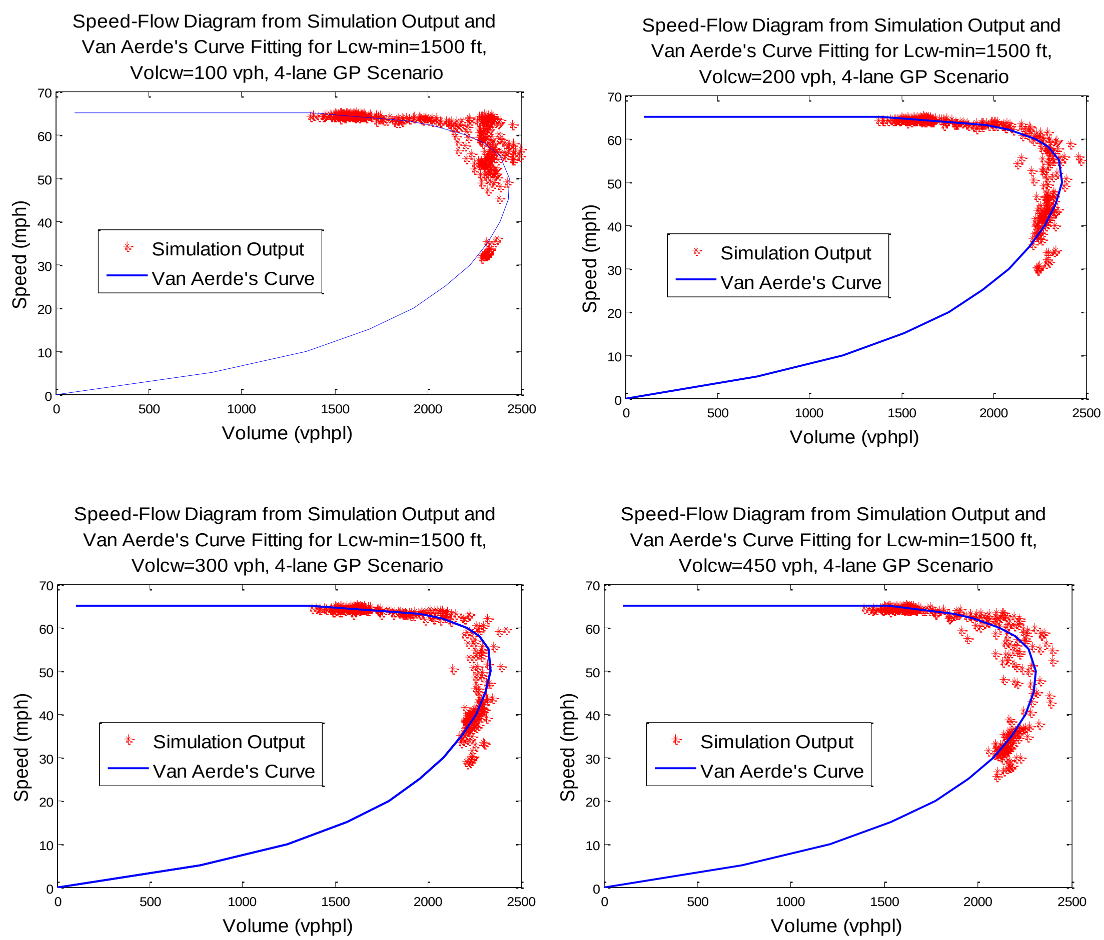


FIGURE 3: Defining Dimensions of APIA through Minimum and Maximum Cross-Weave Lengths

Methodologically, the cross-weave friction may result in a reduction in GPL capacity and operating speeds, similar to the way a weaving segment with significant weaving traffic has a lower capacity than a basic freeway segment. Due to the technical difficulties in estimating this capacity reduction in the field, a calibrated micro-simulation model was developed to estimate this effect. Field measurements of this effect are very complicated, because the Lcw-max distance can cover up to one-mile or even longer freeway segments, along which point roadside (human observer) or overhead (surveillance cameras) observations are not very sufficient. A video dataset was collected at one ML access point along IH 635 in Dallas, Texas. It was used to calibrate the simulation model developed in

VISSIM. Through the well-calibrated simulation model, various scenarios with different number of GPLs, cross-weave demand, Lcw-min length can be tested.

For each simulation scenario, an analytical approach proposed by Van-Aerde is used to calibrate the speed-flow relationship from the simulation data. Van Aerde's steady-state speed-flow model is a multivariate estimation procedure that provides better fits than other single-regime models *(6)*. The capacity estimated is independent of the speed or density threshold between congested and non-congested states, which is needed in two-regime traffic flow models. Due to the length constraints, the speed-flow diagram results are only partially shown in Figure 4, for the 4-lane GPL scenarios with Lcw-min=1,500 ft, and cross-weave volumes ranging from 100 vph to 600 vph. Within each cross-weave setting, the GPL mainline demand changes from 1,600 vphpl to 2,400 vphpl, such that a set of complete data points can be collected from the simulation.



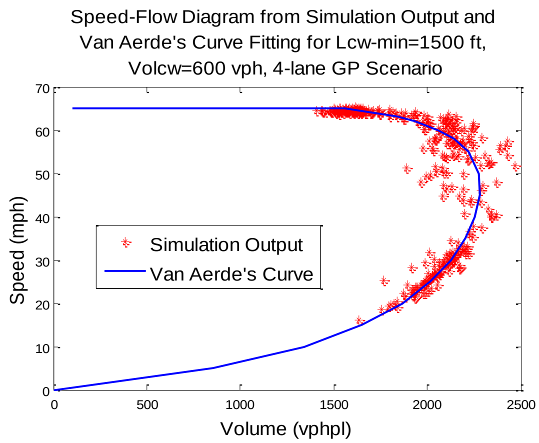


FIGURE 4: Speed-Flow Diagrams from Simulation Output and Van Aerde's Curve Fitting for 4-lane GPL Scenarios

This *capacity reducing effect* is reflected through a set of Capacity Reduction Factors (CRF) or conversely the HCM Capacity Adjustment Factors (CAF). A CRF is expressed as a function of the base capacity C_{base} and the cross-weave capacity C_{cw}. The CRF and CAF can be estimated as follows:

$$CRF = \frac{C_{base} - C_{cw}}{C_{base}}, \quad CAF = 1 - CRF$$

Based on intensive VISSIM simulation result, the CRF is estimated as a function of the number of GPLs, cross-weave flows, and length of $L_{CW\text{-}Min}$.

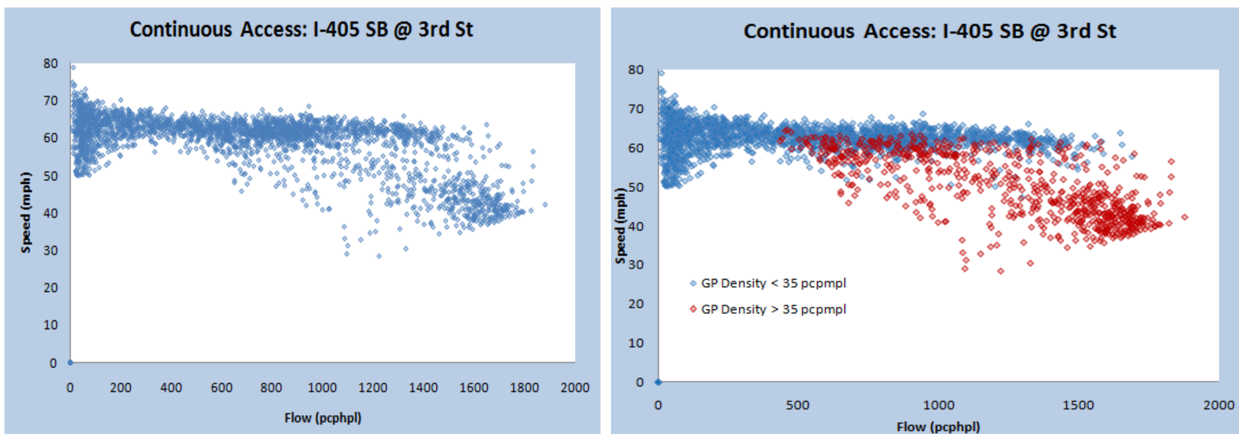
$$CRF(\%) = -8.957 + 2.52 \times \ln(CW) - 0.001453 \times L_{cw-min} + 0.2967 \times (No.of\ GP\ Lanes)$$

where CW is the cross-weave flow measured in pcph, $L_{CW\text{-}Min}$ is the length from the ramp gore to the beginning of ML Access Segment measured in ft, and number of GPLs ranging from 2 to 4.

3.3 Frictional Effect Adjustment

3.3.1 Frictional Effect Formulation

Congested GPLs have an adverse effect on the adjacent MLs. This effect is referred to as "*Frictional Effect*" in this paper and was observed from several studies *(7, 8 and 9)*. The frictional effect becomes more obvious and stronger on facilities with minimal physical separation such as continuous access and/or buffer-separated ML facilities. Figure 5 illustrates this effect for a Continuous Access facility. In Figure 5a, all of the speed-flow data are shown. There is a wide spread in the data from a flow of 600 pcphpl to 1700 pcphpl. This trend is atypical for what is usually seen in the GPL speed-flow curves, which normally show little variance in speed between conditions of equal flows. When the data are segregated based on the quality of operations in the GPLs as shown in Figure 5b, the reason for the dispersion of speed can be ascertained. A density of 35 pcpmpl is used as a threshold for the degraded performance of GPL facilities. This particular threshold was selected as it serves as the transition point from LOS D to LOS E in HCM 2010. During time periods when the GPL has a density greater than 35 pcpmpl, lower speeds can be observed on the ML. The lack of continuity of the curve can be seen as breakdown appears to occur at different levels of flow depending on the GPL's performance.



(a) All ML Data Points (b) Paired ML Data Points by GPL Density
FIGURE 5: Continuous Access Facility at I-405 SB @ 3rd St, King County, Washington

To incorporate the frictional effect into the analytical framework, formulation of speed-flow curves for different types of ML facilities (based on physical separation) is developed. Sensor data were collected at different ML sites across the country for all the facility types. For details, please refer to the study by Thomson *et al. (10)*. Figure 6 shows the speed-flow curve family for the single-lane buffer-separated ML facility based on a total of 17,683 data points collected. It should be noted that for each FFS (free flow speed), there are two sets of curves to represent friction and non-friction scenarios, separately. That is because the performance of the buffer-separated facility is dependent on not only the characteristics of the ML but also the performance of the adjacent GPLs. The frictional curve, therefore, is produced showing the speed-flow relationship during GPL congestion. The friction curves terminate at a density of 45 pcpmpl, consistent with the methodology used in HCM 2010. The range of observed data for the non-friction curves never reached such high density levels, which could be probably attributable to a low likelihood of observing non-friction cases in combination with high flow rates. As a result, the terminal density of the non-friction curves is 30 pcpmpl.

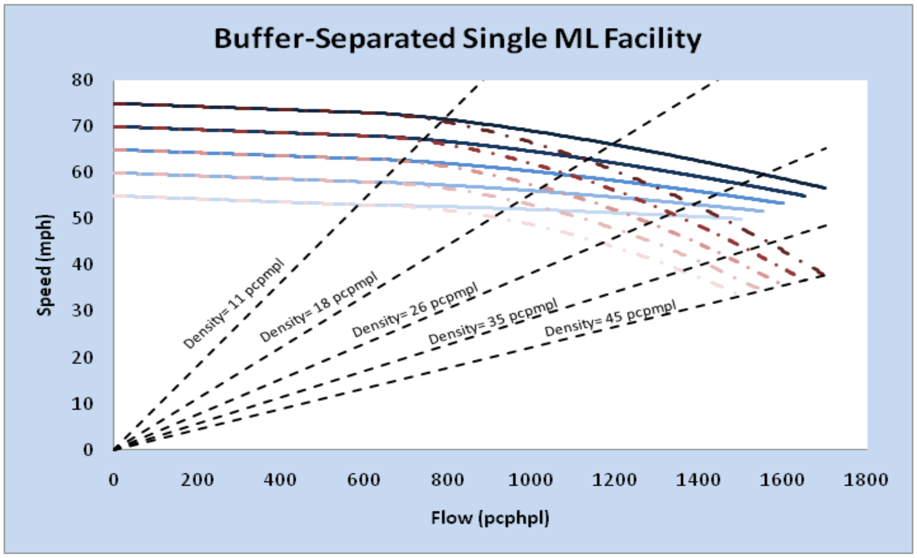


FIGURE 6: The Speed-flow Curve Family for Buffer-separated Single ML Facility

3.3.2 Simulation Model and Case Study Incorporating Frictional Effect

A simulation model is developed to incorporate frictional effect for modeling traffic flow dynamics on freeway facilities with MLs. The underlying traffic flow model used in the simulation is the Cell Transmission Model (CTM) due to its analytical simplicity and ability to reproduce congestion wave propagation dynamics *(11)*. In CTM, freeway is divided into homogeneous cells and the length of each cell is determined such that all vehicles in one cell will flow into the downstream cell in one time step under free-flow conditions *(12)*. However, when queue is formed, the simulation will be based on a recursion where the number of vehicles (cell occupancy) in each cell at time *t+1* equals its occupancy at time *t*, plus the inflow and minus the outflow. The following expression therefore stands:

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t)$$

where $n_i(t+1)$ is the number of vehicles in cell *i* at time *t+1*. $y_i(t)$ is the inflow of cell *i* at time t. $y_{i+1}(t)$ is the outflow of cell *i*, which is also the inflow of downstream cell *i+1*.

In each cell, CTM assumes a piecewise linear relationship between flow and density. The flow advancing equation can be correspondingly derived as:

$$y_i(t) = \min\{n_{i-1}(t), Q_i(t), \delta \cdot [N_i(t) - n_i(t)]\}$$

where $n_{i-1}(t)$ is the number of vehicles in cell i-1 at time t; $Q_i(t)$ is the maximum number of vehicles that can flow into cell *i* in one time step (capacity); $N_i(t)$ is the maximum occupancy of cell i. $\delta = w/v$.

The CTM is applied here to model the one-way traffic on the ML freeway segment. A cell representation of the freeway segment of interest is shown in Figure 7. The freeway segment, exploited as a single unidirectional link in this study, is homogeneous. This segment is simulating the SR 167 HOT lane system in Seattle, Washington, where a single ML is separated from two GPLs by a double white line buffer.

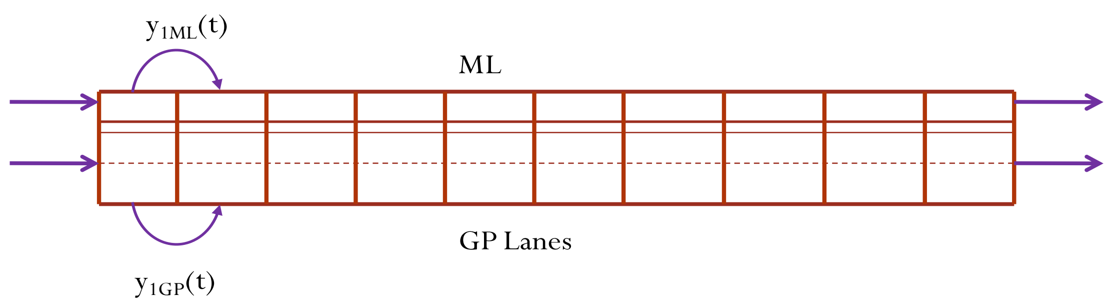


FIGURE 7: Cell Representation of Single-Lane ML Facility

Under the HCM context, the parameters for the flow-density relationship characterizing the link can be calibrated. The determination of the capacity and jam density for the GPLs and buffer-separated ML is based on the calibrated curves provided in HCM 2010 and NCHRP 03-96 research project. At the SR 167 HOT lane corridor, the FFS is determined to be 65 mph for the freeway link. On the GPLs, the capacity is determined as 2300 pcphpl, and the jam density is approximately 165 pcpmpl. Based on the assumed triangular shape of flow-density relationship, the backward wave speed is 17 mph. For the ML, when no frictional effect is present, the capacity can reach up to 2000 pcphpl, and the jam density is about 160 pcpmpl. The backward wave speed is therefore about 15 mph. However, when frictional effect exists, the capacity reduces to 1600 pcphpl, and the jam density is only around 125 pcpmpl. The corresponding backward wave speed is 16 mph.

The total length of the freeway segment analyzed in this study is 6.5 mile. The free-flow travel time is then 0.1 hour. The traffic advancing logic on the GPLs follows equations above. While for ML, the flow advancing to next cell will also be determined by its neighboring GPL cell condition. If the neighboring GPL cell is under congested condition (>35 pcpmpl), then the inflow to the next ML cell will use the set of parameters for the "friction" state. Accordingly, if the neighboring GPL cell is in the uncongested scenario, then the flow advancing to the next cell will adopt the parameters of the "non-friction state".

With the developed model, a numerical study is performed to observe the inflow patterns within the simulated freeway segment. For a simulation period of 100 time steps (1 hour period), the GPL volume that enters into the segment is changed from 2000 to 2800 pcphpl with a 200 pcphpl increment for every 20 time steps (0.2 hour). The ML volume that is trying to enter the segment is set as 1800 pcphpl constant for the entire period. Figure 8 shows the contour plot of traffic evolution (cell inflow) of the freeway segment for ML and GPLs, separately in both spatial and temporal dimensions. It is noted that the traffic will fill up the entire segment by the end of 10 time steps (0.1 hour) which is consistent with the assumption of the FFS = 65 mph. With the increase of the traffic flow trying to enter the GPLs, the GPLs are getting congested. After the 40^{th} time step where the GPL inflow (2400 pcphpl) exceeds its capacity (2300 pcphpl), the GPL cells are unable to provide enough space for accommodating all the incoming vehicles. Therefore, for the rest of the simulation period, the largest flow that each cell could take is constrained to 23 pc/time step. For the ML cell, since it is affected by the status of the GPL, it is noted that although the inflow into the ML is constant, the actual flow passed on to each cell indeed varies. Beginning at the 40^{th} time step, the adjacent GPL cell was detected to have a density higher than 35 pcpmpl, and it thus imposed a frictional effect onto the ML. Correspondingly, the ML cell was shifted to the "friction state", where its cell capacity and maximum occupancy were decreased. The maximum inflow that it could take in for each cell is constrained to 16 pc/time step.

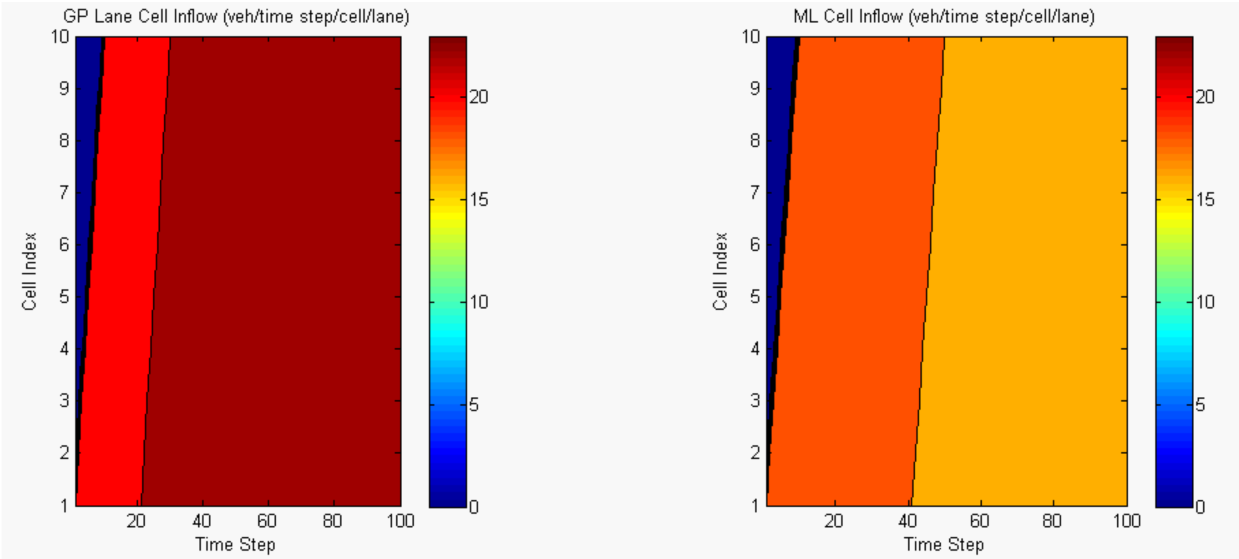


FIGURE 8: Temporal-Spatial Traffic Evolution for the Numerical Study using the Developed Model

4. CONCLUSION

With the increasing concerns over environmental impacts and sustainable transportation system development, transportation agencies are seeking for solutions for congestion mitigation other than the traditional roadway expansion. ML systems are considered a very effective approach to optimize the utilization of freeway capacities. In the absence of a methodology for analytical evaluating ML facilities in the HCM, analysts typically reply on time-consuming and cost-ineffective simulation experiments. This paper presents the methodological framework for analyzing the freeway performance consisting of GPL and ML facilities in an HCM context. The method incorporates new features for performance assessment accounting for the unique attributes of ML facilities. The cross-weave effect, which describes the ML cross-weaving traffic impact on the GPL segment, was quantitatively modeled. A CRF is developed to account for this feature. It allows for an appropriate integration of this phenomenon into the ML methodology developed under the research project NCHRP 03-96. The frictional effect, which is a result of speed reduction in the ML traffic due to congestion in the adjacent GPLs is appropriately modeled and incorporated into a new set of speed-flow curves.

The developed methodological framework presents an important, new approach for the performance analysis of ML-enabled freeway segments, which have been widely adopted nationwide. In the HCM context, the method allows users to calibrate/adjust freeway segment capacity based on input traffic condition and geometry information, which can be quite challenging in a simulation environment. It is also capable of evaluating alternative ML configurations and traffic patterns via taking into account a variety of key factors, such as incidents, or work zones.

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