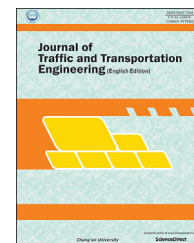


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## Original Research Paper

# Macroscopic and microscopic analyses of managed lanes on freeway facilities in South Florida



Soheil Sajjadi <sup>a,\*</sup>, Alexandra Kondyli <sup>b</sup>

<sup>a</sup> Planung Transport Verkehr (PTV) Group, Portland, OR 97225, USA

<sup>b</sup> Department of Civil, Environmental and Architectural Engineering, The University of Kansas, Lawrence, KS 66045, USA

### HIGHLIGHTS

- Speed-flow models and key freeway segments performance measures such as pre-breakdown capacity, queue discharge flow, percent drop in capacity after the breakdown, and free flow speed were surveyed from two sites in South Florida representing one-lane and two-lane managed lane facilities.
- Two microsimulation models were developed, calibrated, and validated utilizing South Florida managed lanes traffic data.
- The built-in VISSIM car-following model of Wiedemann 99 was calibrated effectively to demonstrate key performance measures such as pre-breakdown capacity, queue discharge flow, and free flow speed.

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### ABSTRACT

As congestion grows in metropolitan areas, agencies tend to utilize managed lanes on their freeway systems. Managed lanes have several forms and names, such as high-occupancy vehicle (HOV) lanes, high-occupancy toll (HOT) lanes, express lanes, and bus-only lanes. Although managed lanes have received significant attention as they increased the overall throughput and improved mobility without adding more lanes, little has been known about their operational capabilities. In addition, calibrating managed lane facilities can be challenging as they do not necessarily follow the same behavior with general purpose freeway lanes.

This paper presents an operational analysis of two HOT lane segments located in South Florida. The sites are one-lane and two-lane segments separated by flexible pylons (FPs). The paper includes a macroscopic capacity analysis, and a microscopic calibration of the two sites using VISSIM microsimulation. The research findings assist in determining the capacity and speed-flow relationship of these segments, and also provide guidance for microsimulation model calibration for practitioners.

The results of the study indicate that the percent drop in capacity for the one-lane FP site is 7.6% while the flow did not substantially change after the breakdown in the two-lane FP site. The research findings also include guidelines for simulating the breakdown events and calibrating one-lane and two-lane managed lane facilities in VISSIM microsimulation software. The Wiedemann car-following parameters (CC0 = 3.9 ft, CC1 = 1.9 s, CC2 = 26.25 ft, CC4 = -0.35, and CC5 = 0.35) provided the best fit for the one-lane FP site, while the

\* Corresponding author. Tel.: +1 503 297 2556.

E-mail addresses: [soheil.sajjadi@ptvgroup.com](mailto:soheil.sajjadi@ptvgroup.com) (S. Sajjadi), [akondyli@ku.edu](mailto:akondyli@ku.edu) (A. Kondyli).

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combination (CC0 = 4.92 ft, CC1 = 1.9 s, CC2 = 39.37 ft, CC4 = -0.7, and CC5 = 0.7) parameters is recommended for the two-lane FP site.

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## 1. Introduction and motivation

As congestion grows in metropolitan areas, agencies tend to utilize managed lanes on their freeway systems. The roadway capacities increasing requires substantial amount of funding but public funding is limited. Built mostly on private sector funding, managed lanes (MLs) could increase existing roadway capacities and alleviate congestion in overly populated areas. Federal Highway Administration (FHWA) emphasizes that the managed lanes concept or definition varies from agency to agency. In some agencies, managed lanes are referred to high-occupancy toll (HOT) roads which are facilities that combine pricing and vehicle eligibility to traverse at free flow speed (FFS) even in the oversaturated conditions. Other agencies use a broader definition which may include high-occupancy vehicle (HOV) lanes, priced lanes, and special use lanes such as express, bus-only, or truck-only lanes. The FHWA defines managed lanes as “highway facilities or a set of lanes in which operational strategies are implemented and managed (in real time) in response to changing conditions” (Obenberger, 2004).

Although managed lanes have drawn the attention of transportation engineers as they increase the overall throughput, little has been known about the capacities of these segments. Managed lanes are not designed to break-down, therefore, capacities as a function of the flow break-down are difficult to be obtained. In addition, from a microscopic perspective, calibrating microsimulation models of managed lanes can be challenging, since the car-following logic on these facilities may be different from that on general purpose lanes.

The motivation of this paper is to provide insight on the managed lanes traffic operations performance and speed-flow

characteristics of one-lane and two-lane managed lane segments with flexible pylon (FP) separators in South Florida. Also, the paper seeks to investigate the microsimulation modeling capabilities of VISSIM simulation software in terms of modeling and calibrating accurately managed lane facilities. Fig. 1 demonstrates an example of the flexible pylons on the roadway.

## 2. Objectives

The main objectives of this paper include:

- (1) Analyze one-lane and two-lane managed lanes (HOT) segments with FP separators and report managed lane traffic key operations performance measures that correspond to pre-breakdown flow rate, post-breakdown flow rate, and FFS.
- (2) Compare speed-flow curves obtained from the field data with the Highway Capacity Manual (HCM) models (Transportation Research Board, 2016), and develop new curves that correspond to the specific sites.
- (3) Propose key microsimulation car-following calibration parameters in VISSIM (PTV Group, 2016a) for capacity determination based on the Objective (1) findings.

The following sections describe past research on speed-flow models for managed lane facilities as well as simulation calibration efforts using VISSIM. Next, the methodology undertaken in this study is briefly discussed and followed with the results of the macroscopic and the microscopic analysis. Research conclusions and future steps are presented at the end.



Fig. 1 – Flexible pylons on FP1 site merge area (Google, 2016).

### 3. Literature review

Chang et al. (2008) developed a compendium of existing HOV lane facilities in the United States. The document which is published by FHWA includes comprehensive information of the MLs in the United States. Guin et al. (2008) analyzed reduction in capacities of HOV lanes on highly congested I-85 HOV lanes in Atlanta, GA. The research team assessed the relative performance of the HOV lane to the adjacent general purpose (GP) lanes. The result demonstrated that the managed lane capacity depends on the GP lanes congestion level. The research used data from a corridor that covered about 10 miles of the I-85 freeway near Atlanta, GA. The data collection site had a buffer separated HOV lane and the data were collected between October 2006 and February 2007. The breakdown of the HOV lane occurred at around 1500 vph at a speed of 40 mph and critical density of about 37 vpm. The study of Kwon and Varaiya (2008) investigated effectiveness of California's 1171 mile HOV system using peak-hour traffic data from more than 700 loop detector stations over many months. The conclusions of the paper indicated that 81% of HOV detectors flow below 1400 veh/h/l in which means that HOV lanes are underutilized.

The recent National Cooperative Highway Research Program (NCHRP) 03–96 research project was aimed at developing guidelines for performance evaluation of the MLs on freeways (Wang et al., 2012). The researchers emphasized that the MLs performance measures vary greatly from site to site. The basic ML segments were categorized in five categories based on their separation type characteristics of continuous access, Buffer 1, Buffer 2, Barrier 1, and Barrier 2. The continuous access is referred to single lane concurrent ML facilities, in which accesses between the ML and general purpose (GP) lanes are allowed at any point, entrance and exit to the ML lane are unrestricted. The Buffer 1 ML segment type refers to single concurrent lane ML facilities with intermittent access and segment type. Buffer 2 is like Buffer 1 but with multiple MLs. Barrier 1 type refers to single lane barrier separated MLs, and Barrier 2 refers to barrier separated facilities with multiple lanes. It should be noted that, FP sites were not considered in this research. The authors also considered friction effect with the GP lanes and suggested that the speed at capacity would drop considerably for the continuous access and Buffer 1 ML segment types. The researchers utilized ten data collection sites on five basic defined ML segment types, and reported operational performance as well as traffic flow characteristics for each ML segment type. All Barrier 1 and Barrier 2 sites had concrete barriers and were in California, Washington, and Minnesota. The study resulted in the development of speed-flow models for managed lanes that are included in the HCM (TRB, 2016). Although this study was comprehensive in terms of the number and location of data collection sites, the data obtained do not necessarily reflect capacities, but rather, maximum observed flows, and therefore, there is no guidance on what the capacities of the managed lane facilities are. The project provided key operational performance measures such as capacity, speed at capacity of ML categories (categorized by separation type)

for FFS ranging from 55 mph to 75 mph. The continuous access ML segment type showed capacity from 1600 to 1800 pc/h/ln with speed at capacity ranging from 35.6 to 40 mph (friction) and 53.3 to 60 mph (non-friction). The Buffer 1 site demonstrated capacity from 1500 to 1700 pc/h/ln with speed ranging from 36.7 to 40 mph (friction) and from 50.0 to 56.7 (non-friction). The Buffer 2 site demonstrated capacity from 1650 to 1850 pc/h/ln with speed at capacity from 36.7 to 41.1 mph. The operational analysis of Barrier 1 site depicted observed capacity from 1550 to 1750 pc/h/ln with speed 51.8 to 71.8 mph while the capacity for the Barrier 2 sites ranging from 1900 to 2100 pc/h/ln and the speed ranging from 42.2 to 46.7 mph.

Schroeder et al. (2012) proposed a deterministic approach to analyze managed lane facilities in context of HCM. Liu et al. (2012a) quantified cross-weave impact on reduction of capacity for freeway facilities with managed lanes. In another study, Liu et al. (2012b) proposed an analytical framework for managed lane facility performance evaluation. In a recent study, Aghdashi et al. (2015) introduced general speed-flow models for basic freeway segment in undersaturated flow conditions. Qi et al. (2016) conducted statistical analyses on lane-changing maneuvers using a unique set of aerial photo data before and after a conversion of HOV lane to characterize lane-changing behavior.

From the microsimulation level analysis perspective, limited research focused on calibrating managed lane facilities has been conducted thus far. Zhang et al. (2009) developed an external module using VISSIM component object module (COM) interface to provide additional flexibility to satisfy specific toll pricing strategies (PTV Group, 2016b). The study offered a simulation model using the Washington State Route 167 HOT lane project, which can be applied to analyze other HOT lane operations.

VISSIM microsimulation model utilizes the Wiedemann 99 model (Wiedemann, 1974) for modeling car-following on freeway facilities. This model has four modes of free, approaching, following and danger. The car-following model has ten user-defined parameters as CC parameters numbered from 0 to 9:

- CC0 is standstill distance. The distance between two consecutive vehicles at the stop position. This parameter impacts jam density considerably.
- CC1 is the time headway between two consecutive vehicles expressed in time.
- CC2 defines the distance variation in the oscillation condition expressed in feet.
- CC3 determines the threshold which following vehicle enters the following condition.
- CC4 and CC5 control the vehicle speed oscillation when the vehicle enters the following mode.
- CC6 represents influence of distance on speed oscillation the following process.
- CC7 is the actual acceleration during the oscillation process.
- CC8 defines the desired acceleration when starting from the standstill situation.
- CC9 represents acceleration at 50 mph limited by maximum acceleration curves.

Bloomberg and Dale (2000) summarized the findings of a comprehensive traffic operations analysis with two simulation models of VISSIM and CORSIM. The authors suggested both tools could be applied confidently for modeling congested networks in the microsimulation level analysis.

Dowling et al. (2004) developed a guideline for applying traffic microsimulation software using different platforms. The guideline provided a comprehensive reference to conduct different aspects of microsimulation analysis such as project scoping, data collection, model development, error checking and different algorithms for calibration. Park and Qi (2004) evaluated three microsimulation models of VISSIM, PARAMICS, and CORSIM. The research study indicated that all three models have pros and cons for simulating various types of traffic studies but they all provide acceptable results.

Menneni (2008) offered a generalized calibration methodology which would be applicable for different analysis levels. The authors presented disaggregated data-based calibration using vehicle trajectory data and aggregate data-based calibration methodology using fundamental traffic stream parameters. They also offered a simplified calibration method for practitioners. The method suggested that CC0, CC1, CC2, CC4, and CC5 have the highest impact on the simulated capacity, and highlighted that the magnitude of the CC1 impact on the capacity is larger than the rest. The authors also offered detailed sensitivity analysis of car-following parameters on simulated capacity.

Williams et al. (2010) used VISSIM to analyze, calibrate, and validate microsimulation models of managed lanes weaving and access points. They used genetic algorithm to calibrate their model.

Chou and Miller-Hooks (2011) studied the potential benefits of traffic diversion in incident management for freeway operations of concurrent flow rate facilities. The authors used capabilities of component object module (COM) interface of the software to assess managed lanes operations performance measures in different incident scenarios.

There are multiple other protocols and guidelines in the literature on how to calibrate microsimulation models against field data such as the Oregon Department of Transportation Protocol (2011), the Washington Department of Transportation (Schilperoort et al., 2014), and Virginia Department of Transportation (Park and Won, 2006); however, guidelines for calibrating managed lane segments specifically, are missing from the literature.

## 4. Methodology

This section presents the research methodology in data collection, operational analysis methodologies, and the development of the microsimulation models.

### 4.1. Data collection site

Since one of the goals of this research is to define the capacity at managed lane segments, the data collection focused on managed lane merge locations, as these locations can be characterized as bottlenecks where breakdowns occur as the demand exceeds the available capacity. Two sites were selected on I-95 freeway in South Florida (Florida Department of Transportation). Data such as traffic counts and speeds at 15-min increments were available for upstream and downstream of the merge through the remote traffic microwave sensors (RTMS). These data were used for calculating the free flow speed (FFS), identifying the breakdown event, corresponding the pre-breakdown and the post-breakdown (discharge) flow rates.

FPS are used in South Florida for the separation between MLs and GP Lanes. Since a direct correspondence with the barrier type designation introduced in HCM (TRB, 2016) is not possible, for the purposes of this research, the authors assume that the FP separation type constitutes a new separation type, which is denoted as FP1 and FP2 for separated facilities with one-lane and two-lane, respectively. Table 1 demonstrates the data collection site properties.

Data collection sites are shown in Fig. 2. In Fig. 2, the end of the merge areas, and approximate detector locations are located with blue arrows.

Two months of data were considered for the data collection. Data in the days with inclement weather, incidents, work zone construction, and special events were removed from each data set. Also, only the data of midweek days (Tuesday, Wednesday, and Thursday) were considered for further analysis. The remaining number of data points was 1585 in 15-min observation for the one-lane site, and 2119 in 15-min observation for the two-lane site.

### 4.2. Macroscopic freeway operations analysis

This research followed the HCM (TRB, 2016) methodology for surveying key freeway facility performance measures of the FFS, the breakdown event and recovery, the pre-breakdown flow rate, and the queue discharge flow rate. The FFS was calculated as average speed during low-volume observations (i.e., volume is less than 600 vph) as this is also defined in the HCM. The breakdown event was defined as a sudden speed drop at least 25% below the FFS, which is sustained for at least 15 min, and the recovery was defined to occur when prevailing speed is within 10% of the FFS for at least 15 min. Based on the breakdown event, the HCM (TRB, 2016) defines capacity as the pre-breakdown flow rate, which occurs immediately prior to the breakdown event. The queue discharge flow rate was defined as the average flow rate during oversaturated conditions (i.e., during the time

**Table 1 – Data collection site properties.**

Data collection site	Interchange/state mile post	Station index	Number of lanes/direction	Latitude	Longitude	Distance from merge area (m)
FP1	NW 151st. St./11.66	690912	1/SB	25.823950	-80.206251	~457.2
FP2	US 195/5.63	690431	2/NB	25.912380	-80.210382	~97.5

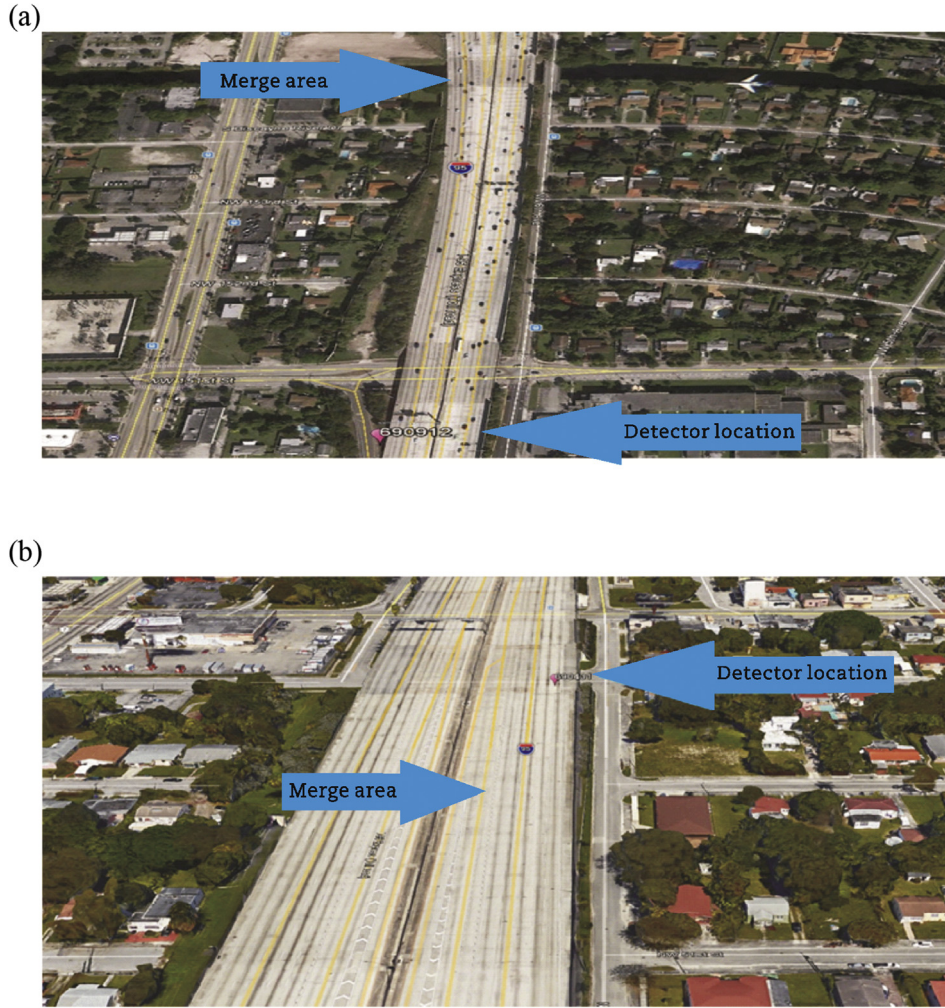


Fig. 2 – Data collection sites (Google, 2016). (a) FP1. (b) FP2.

interval following breakdown and prior to recovery). At all merge segments, capacity was measured at the downstream detectors.

Next, speed-flow curves were developed for the two sites, and these were compared with the managed lane speed-flow models provided in the HCM (TRB, 2016). According to the HCM, both speeds and capacities at managed lanes are functions of their separation from the general purpose lanes, and the number of managed lanes. The general analytical form of the speed-flow relationship is given in the following equations.

$$S_{ML} = S_1 \quad v_p \leq BP \quad (1)$$

$$S_{ML} = S_1 - S_2 - I_c S_3 \quad BP < v_p \leq c_{adj} \quad (2)$$

$$S_1 = FFS_{adj} - A_1 \min(v_p, BP) \quad (3)$$

$$S_2 = \frac{S_{1,BP} - \frac{c_{adj}}{K_c^{nf}}}{(c_{adj} - BP)^{A_2}} (v_p - BP)^{A_2} \quad (4)$$

$$A_2 = A_2^{55} + \lambda_{A_2} (FFS_{adj} - 55) \quad (5)$$

$$S_3 = \frac{\frac{c_{adj}}{K_c^{nf}} - \frac{c_{adj}}{K_c^f}}{(c_{adj} - BP)^2} (v_p - BP)^2 \quad (6)$$

where  $S_{ML}$  is space mean speed of basic managed lane segment (mi/h),  $S_1$  is speed with linear portion of speed-flow curve (mi/h),  $S_2$  is speed drop within the curvilinear portion of the speed-flow curve (mi/h),  $S_3$  is additional speed drop (mi/h) within curvilinear portion of speed-flow curve when density of adjacent general purpose lane is more than 35 pc/mi/ln (21.8 pc/km/ln),  $I_c$  is indicator variable equal to 1 when densities are greater than 35 pc/mi/ln in the adjacent general purpose lane, or when segment type is Buffer 2, Barrier 1 or Barrier 2, and zero otherwise,  $BP$  is breakpoint in speed-flow curve,  $v_p$  is 15-min average flow rate (pc/h/ln),  $A_1$  is speed reduction per unit of flow rate in the linear section of the speed-flow curve (mi/h),  $A_2$  is speed reduction per unit of flow rate in the curvilinear section of the speed-flow curve (mi/h),  $S_{1,BP}$  is speed at the breakpoint of the speed-flow curve, calculated from Eq. (1) by setting  $v_p$  to  $BP$  (mi/h),  $K_c^{nf}$  is density at capacity, without the frictional effect of the adjacent general purpose lane,  $K_c^f$  is density at capacity, with the frictional effect of the adjacent general purpose lane,  $\lambda_{A_2}$  is

**Table 2 – Speed-flow estimation parameters based on HCM (TRB, 2016).**

Segment type	$BP_{75}$	$\lambda_{BP}$	$c_{75}$	$\lambda_c$	$A_2^{55}$	$\lambda_{A_2}$	$A_1$	$K_c^{nf}$	$K_c^f$
Continuous access	500	0	1800	10	2.5	0.00	0.0000	30	45
Buffer 1	600	0	1700	10	1.4	0.00	0.0033	30	42
Buffer 2	500	10	1850	10	1.5	0.02	0.0000	45	NA
Barrier 1	800	0	1750	10	1.4	0.00	0.0040	35	NA
Barrier 2	700	20	2100	10	1.3	0.02	0.0000	45	NA

rate of change in  $A_2$  per unit increase in FFS,  $A_2^{55}$  is calibration factor for a FFS of 55 mi/h.

$$BP = [BP_{75} + \lambda_{BP}(75 - FFS_{adj})] \cdot CAF^2 \quad (7)$$

$$c_{adj} = CAF \cdot [c_{75} - \lambda_c(75 - FFS_{adj})] \quad (8)$$

where  $BP_{75}$  is breakpoint for FFS = 75 mi/h (~120 km/h) as demonstrated in Table 2,  $\lambda_{BP}$  is rate of increase in breakpoint per unit decrease in FFS (Table 2),  $FFS_{adj}$  is adjusted free flow speed (mi/h), CAF is capacity adjustment factor (assumed 1 here),  $c_{adj}$  is adjusted basic managed lane segment capacity (pc/h/ln),  $c_{75}$  is managed lane capacity for FFS = 75 mi/h (~120 km/h) as demonstrated in Table 2,  $\lambda_c$  is rate of change in capacity per unit change in FFS (Table 2).

The remaining variables shown in Eqs. (4)–(8) are provided in Table 2.

To convert the 15-min volumes to 15-min analysis flow rates, the equation from the HCM was used ( $v_p = V/PHF \cdot f_{hv}$ ). In this equation, the peak-hour factor (PHF) was calculated for the two study sites based on the available data. For the heavy vehicle adjustment factor ( $f_{hv}$ ) level terrain and 6% heavy vehicles were assumed, based on the Florida Department of Transportation (FDOT) proposed values (FDOT, 2013).

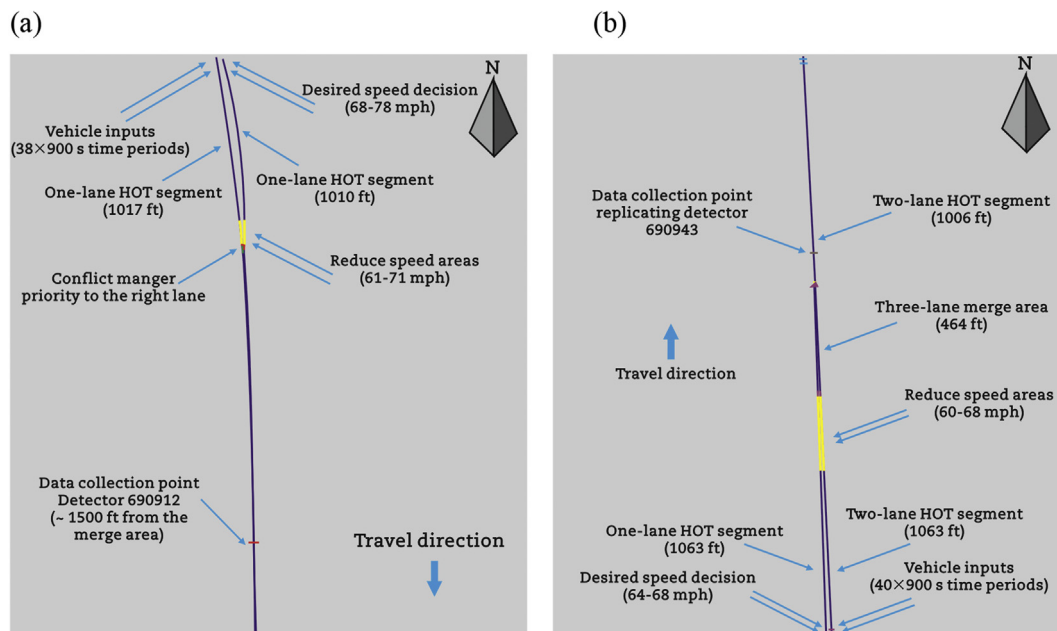
Given that the FP separation type in the study sites is not described by any of the available separation types in the HCM,

it was decided to evaluate all ML curves proposed in the HCM, except from the continuous access types. New model parameters were finally fitted to this specific separation type.

#### 4.3. Microsimulation models development

The VISSIM microsimulation software was selected to model the two data collection sites in this research. The exact geometry information was obtained using the Google Earth (Google, 2016). The desired speed decisions were modeled as uniform distribution within 5% range of the field measured FFS. It was assumed that vehicles would incur approximately 10% drop in speed approaching each merge and the effect was modeled using reduced speed areas before the merge areas. Fig. 3 demonstrates FP1 and FP2 microsimulation models. Note that both facilities depicted in Fig. 3 are just the managed lanes and general purpose lanes have not been modeled. In Fig. 3(a), two one-lane HOT lanes merge together and form another one-lane HOT lane. In Fig. 3(b), a two-lane HOT lane merged with one-lane HOT lane.

The hourly demand in both models was entered so that the full speed-flow spectrum could be observed. The default value of 6% heavy vehicle was considered for this study, as this is the percentage that FDOT recommends (FDOT, 2013). The demand was modeled from 0 vph in the starting time periods and increased incrementally (100 vph in FP1 model, and 120 vph in FP2 model) until the breakdown occurred by exceeding the available capacity. The FP1 model included two single managed lanes merging and equal demand distribution was assumed between the two lanes. The FP2 model included one-lane managed lane merging with a two-lane managed lane segment. Since detailed lane-by-lane field data were not available, a 33.5%/66.5% share was assumed. The maximum imposed demand reached 3000 veh/h/ln in the 29th time period (27,000 simulation seconds) for the FP1 model. In the FP2 model, the imposed



**Fig. 3 – Microsimulation models. (a) FP1 south bound. (b) FP2 north bound.**

demand reached 5480 veh/h (2740 veh/h/ln) in 38th time period (33,300 simulation seconds). A minimum of three time periods were considered as the cool down period to make sure that all potential queues are cleared. Similar to the field data, pre-breakdown flow rate and queue discharge flow were measured using the definitions in HCM and methods described in the previous sections.

In this study, it is assumed that the car-following logic on managed lanes in VISSIM follows the freeway facilities car-following model (Wiedemann 99). Key car-following parameters of CC0, CC1, CC2, CC4, and CC5 which were known to be the most effective parameters in the flow rate calibration, were selected (Menneni, 2008). Also, the values of CC parameters were selected from this study as well. The final calibration values of these five parameters are shown in Table 3.

The combination of the scenarios resulted in a total of 90 scenarios (3 × 5 × 3 × 2 = 90). Each microsimulation model with the same seed number was ran 90 times incorporating respective CC parameters. The car-following parameters were incorporated into the models utilizing VISSIM component object model (COM) interface. The script containing intra-loops was written in Visual Basic for Application (VBA) language. The downstream segment, the bottleneck, and the upstream segment car-following parameters were modified in each simulation run, which could keep the random seed constant. All other parameters were kept at their default values. The data were collected in 15-min intervals to match the field observations and the calculated performance measures of the HCM.

## 5. Results

This section of the paper summarizes the macroscopic operational analysis of the one-lane and two-lane managed lanes from the field data as well as the finding of the microsimulation calibration efforts.

### 5.1. Macroscopic freeway operations analysis

The pre-breakdown flow and queue discharge flow in both sites were calculated based on the new HCM (TRB, 2016) definition which also considered the stochastic nature of such measurements. Table 4 presents each of such observation as well as basic statistical parameters.

The estimated free flow speed for FP1 site was 73 mph, and for FP2 site was 66 mph. Similar to the general purpose lanes, the average discharge flow rate is less than the pre-breakdown capacities. The percent drop in the post-breakdown flow

**Table 4 – Pre-breakdown and post-breakdown measurements from field observations.**

No.	Pre-breakdown				Queue discharge			
	Flow (veh/h/ln)		Flow (pc/h/ln)		Flow (veh/h/ln)		Flow (pc/h/ln)	
	FP1	FP2	FP1	FP2	FP1	FP2	FP1	FP2
1	1644	1352	1834	1558	1466	1624	1636	1871
2	1428	1380	1593	1590	1460	1706	1629	1966
3	1692	1808	1888	2083	1578	1336	1761	1539
4	1696	1908	1892	2198	1613	1388	1800	1599
5	1649	1524	1790	1756	1452	1580	1620	1820
6	1708	1584	1906	1825	1572	1655	1754	1907
7	1632	1664	1821	1917	1473	976	1643	1125
8	1688	1288	1647	1484	1501	1288	1674	1484
9	1604	1484	1790	1710	1575	1425	1757	1642
10	1624	1324	1700	1525	1640		1830	
11	1592	1880	1776	2166	1545		1724	
12	1552	1256	1928	1447	1500		1674	
13	1588	1212	1772	1396	1320		1473	
14	1676	1260	1870	1452	1377		1536	
15	1608	1484	1852	1710	1464		1634	
16	1212	1288	1352	1484	1270		1417	
17	1616	1532	1803	1765	1357		1514	
18	1136		1268		1197		1336	
19	1560		1785		1286		1435	
20	1284		1433		917		1024	
21	1560		1741		1491		1663	
22	1632		1758		1614		1801	
23	1596		1781		1560		1741	
Avg.	1564	1484	1745	1710	1445	1442	1612	1661
St. Dev.	154	223	172	257	165	230	185	265
Min	1136	1212	1268	1396	917	976	1024	1125
Max	1708	1908	1906	2198	1640	1706	1830	1966

compared to the pre-breakdown flow was 7.6% in one-lane managed lane segment and 0.2% in the two-lane managed lane segment.

During this part of the analysis, the speed-flow curves based on the HCM (TRB, 2016) were developed and contrasted against the collected field data. Note that the HCM curves represent undersaturated conditions only, whereas the field data cover undersaturated and oversaturated conditions. Fig. 4 presents the speed-flow curves for the one-lane and two-lane managed lane segments.

The HCM-based curves for the one-lane ML segment fit relatively well to the field observations (Fig. 4). The data from the models are best described when considering the Buffer 1 separation type and ignoring frictional effects. Also, the two-lane data are not appropriately described by the HCM curves. It appears that the breakpoints on the HCM curves are at lower flow rates than what the data dictate. This may be because the detector is located very close to the merge area. However, further investigation is required to explain why this happens.

Given that the HCM curves do not represent accurately traffic conditions at managed lanes with flexible pylons, a new set of models that fit the uncongested regime was developed. The new curves are similar in format with the HCM curves as described in Eqs. (1)–(8). The curves were developed specifically for the flexible pylons separation. Observations under queue discharge flow were removed from the analysis, as

**Table 3 – Selected Wiedemann car-following parameters.**

Parameter	Value 1	Value 2	Value 3	Value 4	Value 5
	(default)				
CC0 (ft)	4.92	3.90	5.90		
CC1 (s)	0.9	0.8	1.3	1.5	1.9
CC2 (ft)	13.12	26.25	39.37		
CC4	-0.35	-0.70			
CC5	0.35	0.70			

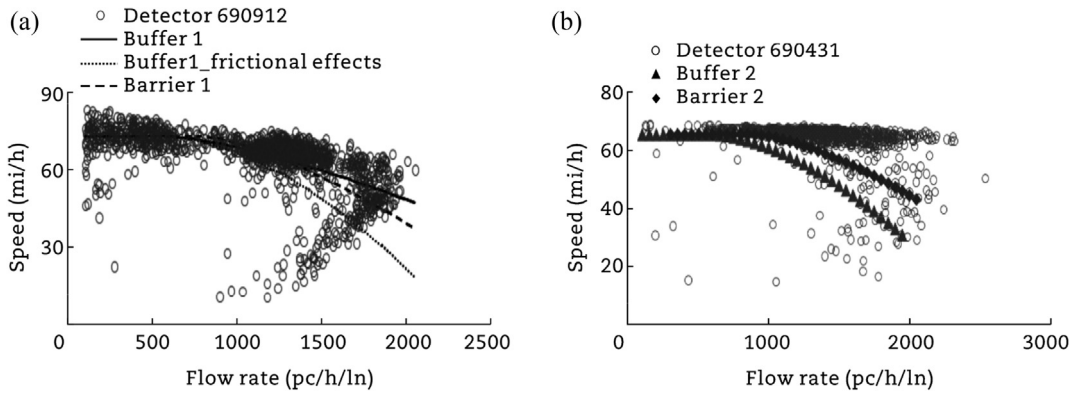


Fig. 4 – Speed-flow curves based on the HCM analysis and field data. (a) FP1 site. (b) FP2 site.

these points correspond to the congested conditions. The final model parameters which minimize the mean square error (MSE) are presented in Table 5.

Fig. 5 depicts the new speed-flow curves that provide the best fit to the two sites that were analyzed in this study. For comparison purposes, the curves that correspond to the remaining types of managed lane separation according to the HCM are also illustrated.

5.2. Simulation of breakdown event and car-following for managed lanes

The microsimulation models were intended to replicate the pre-breakdown as well as the post-breakdown conditions. The analysis results demonstrated that not all the scenarios replicate the traffic stream conditions at both sites. Some scenarios provided a good match with the field data in one site but failed in the other site. Since the freeway breakdown event is stochastic in nature, the observations in Table 4 are expected.

Table 5 – Speed-flow estimation parameters for flexible pylons separation.

Segment	BP <sub>75</sub>	λ <sub>BP</sub>	c <sub>75</sub>	λ <sub>c</sub>	A <sub>2</sub> <sup>55</sup>	λ <sub>A<sub>2</sub></sub>	A <sub>1</sub>	K <sub>c</sub> <sup>nf</sup>	K <sub>c</sub> <sup>f</sup>	MSE
FP1	750	0	1770	10	1.3	0.00	0.0026	30	NA	18.5
FP2	1150	20	1800	-5	1.1	0.02	0.0040	29	NA	7.4

In FP1 microsimulation model, 25 scenarios replicated both pre-breakdown and post-breakdown conditions. The simple Euclidian Distance formula was used to assess the scenarios appropriateness quantitatively (Table 6). Also, scenarios, in which the pre-breakdown flow rate was considerably lower than queue discharge flow rate, were removed from the selection. The legitimate scenarios, even with high Euclidian Distances were also included in Table 6 as a guideline for practitioners to calibrate their simulation model based on their field data. The Euclidian distance (ED) as special case of round mean square error (n = 1) is used to assess the goodness of fit for this study.

$$ED = \sqrt{(x_i - y_i)^2} \tag{9}$$

where x<sub>i</sub> is simulation result and y<sub>i</sub> is field measurement.

$$\text{Sum Euclidean distance} = ED_{\text{prebreakdown flow}} + ED_{\text{queue discharge flow}} \tag{10}$$

Eqs. (9) and (10) have been used in Tables 6 and 7. The average capacities in Table 4 were used to measure the Euclidian Distance in Tables 6 and 7. The average pre-breakdown capacity for FP1 site was 1745 pc/h/ln and for FP2 site was 1710 pc/h/ln. The average post-breakdown capacity for FP1 site was 1612 pc/h/ln and for FP2 site was 1661 pc/h/ln.

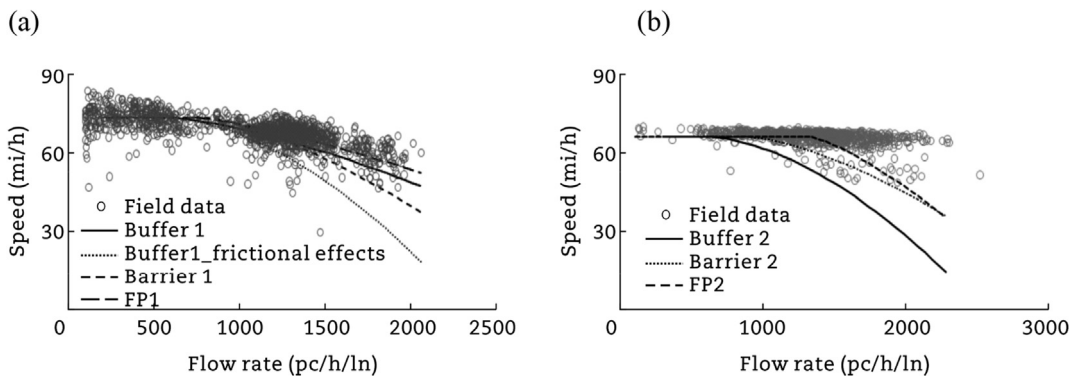


Fig. 5 – Uncongested regime speed-flow curves. (a) FP1 site. (b) FP2 site.



**Table 6 – FP1 microsimulation calibration results.**

Scenario no.	Pre-breakdown			Post-breakdown			Sum Euclidian distance
	Flow (veh/h/ln)	Flow (pc/h/ln)	Euclidian distance	Flow (veh/h/ln)	Flow (pc/h/ln)	Euclidian distance	
57	1576	1816	18	1523	1755	78	96
27	1504	1733	54	1511	1741	66	120
58	1483	1709	75	1527	1759	82	157
26	1500	1728	58	1565	1803	120	178
21	1632	1880	74	1587	1829	142	216
22	1716	1977	158	1582	1823	137	295
28	1761	2029	203	1538	1772	93	296
23	1688	1945	130	1622	1869	177	307
29	1935	2229	377	1561	1799	116	493
56	2188	2521	630	1519	1750	74	704
17	1788	2060	230	1982	2284	537	767
4	2412	2779	854	1958	2256	513	1367

**Table 7 – FP2 microsimulation calibration result.**

Scenario no.	Pre-breakdown			Post-breakdown			Sum Euclidian distance
	Flow (veh/h/ln)	Flow (pc/h/ln)	Euclidian distance	Flow (veh/h/ln)	Flow (pc/h/ln)	Euclidian distance	
30	1518	1694	34	1390	1551	52	86
55	1392	1553	92	1440	1607	2	94
57	1378	1538	106	1458	1627	16	122

Similarly in the FP2 microsimulation model, scenarios were ranked based on their combined Euclidian Distance from the measured pre-breakdown flow and queue discharge flow. After removing scenarios, in which the pre-breakdown flow rate was considerably lower than queue discharge flow rate, the scenarios in Table 7 were selected.

Scenario 57 (CC0 = 3.9 ft, CC1 = 1.9 s, CC2 = 26.25 ft, CC4 = -0.35, and CC5 = 0.35) is recommended for the FP1 site (while it still provides a good fit for the FP2 site as well). Scenario 30 (CC0 = 4.92 ft, CC1 = 1.9 s, CC2 = 39.37 ft, CC4 = -0.7, and CC5 = 0.7) is recommended for the FP2 site as they had the minimum error in terms of Euclidian Distance. Based on the calibration results, it can be concluded that one-lane and two-lane managed lane facilities have different operations and car-following behaviors, and therefore, require different calibration effort. As the freeway breakdown event is stochastic in nature, other scenarios represented in Tables 6 and 7 may become useful in calibrating other sites as well.

## 6. Conclusions

This paper focuses on analyzing the operational efficiency of two managed lane facilities in South Florida (Miami area), and providing calibration guidelines for those facilities in VISSIM. The study sites are separated from the general purpose lanes with FPs, and to-date little is known about the impact of this separation type on traffic operations. The research findings suggest that the capacity (i.e., pre-breakdown flow) at both one-lane and two-lane segments is approximately 1700 pc/h/ln, whereas the queue discharge

flow is approximately 1600 pc/h/ln. The findings also indicate that the current managed lanes method in the HCM is limited, as it does not address efficiently the speed-flow relationships at the study segments. As such, new models and associated parameters that pertain to the flexible pylon separation were estimated for one-lane and two-lane managed lane segments. Lastly, the percent drop in capacity for the FP1 site was 7.6% while the flow did not substantially change after the breakdown in the FP2 site.

The research findings also include guidelines for breakdown event simulating, one-lane and two-lane managed lane facilities calibrating in VISSIM microsimulation package, and the appropriate parameters selecting for the car-following model. The Wiedemann car-following parameters (CC0 = 3.9 ft, CC1 = 1.9 s, CC2 = 26.25 ft, CC4 = -0.35, and CC5 = 0.35) provided the best fit for the FP1 site, while the combination (CC0 = 4.92 ft, CC1 = 1.9 s, CC2 = 39.37 ft, CC4 = -0.7, and CC5 = 0.7) is recommended for the FP2 site.

Given that the samples of the data collection were not many (only two data sites) for this separation type, it is recommended to analyze additional sites and verify the estimated capacity values and the speed-flow model parameters. Future research can also look at varying lane change model parameters of Wiedemann driver behavior model.

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**Dr. Soheil Sajjadi** received his PhD from North Carolina State University and was a postdoctoral researcher at Florida Atlantic University. Dr. Sajjadi is an associate engineer at PTV Group. He has been the lead trainer of the PTV Group in the North America and has conducted multiple workshops in more than 20 public and private agencies in the U.S. He has also been involved in multiple research projects, which have led to more than 20 journal papers, peer-reviewed conference proceedings, and research reports. His research interests are in traffic flow theory, optimization, driver behavior, multi-resolution modeling, traffic operations, and intelligent transportation systems.



**Dr. Alexandra Kondyli** is an assistant professor in the Department of Civil, Environmental and Architectural Engineering at the University of Kansas. She received her PhD in Transportation Engineering from the University of Florida, where she also worked as a postdoctoral researcher. Dr. Kondyli has authored and co-authored more than 50 journal publications, presentations, and research reports. Her research interests include traffic engineering operations, traffic flow theory, driver behavior, microsimulation, and highway capacity.