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Weaving Analysis, Evaluation and Refinement

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16. ABSTRACT

Weaving sections are common design elements on freeway facilities such as near ramps and freeway to-freeway connectors. When the traffic demands exceed the capacity at weaving areas congestion may occur, which affects the operation of the entire freeway section. Traffic operational problems also may exist at weaving areas even when traffic demands are less than capacity because of the complexity of vehicle interactions, resulting in poor level of service (LOS) and potential safety problems. Existing procedures for the design and analysis of freeway weaving sections have several shortcomings, and their practical application often produces inconsistent results.

This report describes the work performed under PATH Task Order 6304. The objective of the study was to evaluate the existing weaving analysis procedures to determine under which conditions the "best available" tools are most effective. The HCM2000, Leisch and Level D methods were evaluated using field data from 36 weaving sections for a total of 189 data points of speeds and volumes. A weaving performance matrix was developed to assist in determining which method to be used for a given mix of design and operational characteristics in a weaving section.

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EXECUTIVE SUMMARY

Objectives and Methodology

Several methods exist for the design and analysis of freeway weaving sections. However, the existing procedures have several shortcomings, and their practical application often produces inconsistent results. This is mostly due to the lack of empirical data on weaving operations. Most of the existing methods are based on limited data that are not representative of the entire range of the geometric characteristics and traffic patterns in weaving areas, especially for California conditions. The systematic evaluation of existing weaving methods and the development of an improved analysis method have been recognized as high priority research needs.

The objectives of this research project are a) evaluation of the existing weaving analysis procedures to determine under which design and operating conditions the "best available" tools are most effective, and b) development of an improved procedure either by modification of existing approaches or a new method as appropriate.

We reviewed the literature on existing weaving analysis methodologies. We selected the Highway Capacity Manual 2000 (HCM2000), Leisch and Level D methods for evaluation with field data from real-world weaving sections. We assembled a database of 36 real-world weaving sections from California and the rest of the country for a total of 189 data points of operating conditions (traffic volumes and speeds). The analysis of the results identified the strengths and limitations of each method in determining the performance of a freeway weaving section for a range of operating conditions. Additional analyses were performed by applying the selected analysis methods to synthetic datasets for the design and operating conditions that field data were not available. A total of 339 datasets were created. The analysis of the results focused on the consistency of the predictions from each analysis method.

The research team also developed a new weaving analysis model based on empirical study of bottleneck activations in two California freeway weaving sections. A theory was formulated for mandatory lane changing (i.e., lane changes required of a desired origin-destination pattern) based on the empirical findings. The theory was used to enhance an existing simulation model of car-following and lane changing. The model successfully reproduces field operating conditions in weaving sections.

Recommendations

We developed a performance matrix for each weaving analysis method to serve as a guide for Caltrans staff when choosing the "best" analysis method for the weaving section under study. Each cell of the matrix represents a distinct design and operating condition. There are a total of 144 cells for typical weaving sections of two, three, four and five lanes wide. Based on the comparison of the model prediction with field and synthetic data, we show on each cell the performance of the particular method as good (or "green light"), or partially good or often inconsistent (or "yellow light") or poor (or "red light") for a particular design and operating condition.

The proposed performance matrix for each analysis method (HCM2000, Leisch and Level D) is included in Appendix C of the report. Also, included in the Appendix is a single weaving analysis performance matrix that shows the recommended methodology for each design and operating condition. These matrices will be continually updated should more field data and/or results from the methods' applications become available. It is envisioned that the proposed performance matrices will be incorporated in the Caltrans Highway Design Manual.

The new weaving analysis model was coded into an executable standalone computer program written in *MATLAB* for use by Caltrans engineers for analysis and design of weaving sections. The inputs of the program include the weaving section's geometrics, free-flow speed, and traffic demands by vehicles' origin-destination. The software outputs include total delays as well as delay for each O-D pair, and plots of cumulative vehicle count curves that display discharge flows and average speeds. The model is documented in detail in Appendix D.

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CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Weaving sections are common design elements on freeway facilities such as near ramps and freeway-to-freeway connectors. When the traffic demands exceed the capacity at weaving areas congestion may occur, which affects the operation of the entire freeway section. Traffic operational problems also may exist at weaving areas even when traffic demands are less than capacity because of the complexity of vehicle interactions, resulting in poor level of service (LOS) and potential safety problems.

Efforts to develop procedures for the design and analysis of freeway weaving sections begun in the 50's. However, the existing procedures have several shortcomings, and their practical application often produces inconsistent results. This is mostly due to the lack of empirical data on weaving operations. Most of the existing methods are based on limited data that are not representative of the entire range of the geometric configurations and traffic volumes and patterns in weaving areas, especially for California conditions. The systematic evaluation of existing weaving methods and the development of an improved analysis method have been recognized as high priority research needs.

1.2 Objectives of the Study

The objectives of this research project are a) evaluation of the existing weaving analysis procedures to determine under which design and operating conditions the "best available" tools are most effective, and b) development of an improved procedure either by modification of existing approaches or a new method as appropriate. The tasks performed and the end products for each research objective are briefly described below.

1.2.1 Evaluation of the Existing Methods

We reviewed existing weaving analysis procedures. Next, we assembled existing data on real-world weaving sections from several sources. We applied the existing methods to the field data and analyzed the results. Based on the evaluation of the results we developed recommendations regarding the use of existing methods for design and analysis of weaving sections.

The end product of this research effort are guidelines documenting under what conditions which of the "best available" weaving analysis tools are most effective, and how and under what conditions these tools can be properly applied. The guidelines are in the form of weaving analysis performance matrices, which describe the operating conditions under which each analysis method is most effective. It is envisioned that the proposed guidelines will be incorporated in the Caltrans Highway Design Manual (Chapter 500--Section 504.7) [1].

1.2.2 Development of a New Weaving Analysis Procedure

The research first investigated what triggered the bottleneck activations in two California freeway weaving sections, SR-55N and SR22W in Orange County, and I-210W and Lake Avenue in Pasadena. Both sites are recurrent bottlenecks during the rush, and investigations revealed that changes in the spatial patterns of vehicular lane-changes, especially among freeway-to-ramp (F-R) maneuvers, caused variations in bottleneck discharge flow. It was also found that the spatial distributions of these lane changes, in turn, were dictated by the traffic conditions in the auxiliary lane (i.e., the lane connecting the off-ramp to the upstream on-ramp). Reductions in on-ramp flows increased the attractiveness of the auxiliary lane, thus motivating F-R drivers to perform their maneuvers nearer the onramp. Conversely, increases in on-ramp flows motivated F-R drivers to perform their maneuvers over a wider stretch of the weaving section.

Next, a theory was formulated for *mandatory* lane changing (i.e., lane changes required of a desired origin-destination pattern) based on the empirical findings. The theory was used to enhance an existing simulation model of car-following and lane changing. With this new theory, the driver's decision to attempt a lane change is determined by the vehicle's distance from the downstream end of the weaving section's diverge area, the number of lanes to be crossed in reaching the desired destination, and the difference in densities between the driver's target lane and her current one. The model successfully reproduces the observed mechanisms of bottleneck activation and discharge flows in weaving sections.

The model was developed into an executable standalone computer program written in *MATLAB* to be used by Caltrans engineers for analysis and design of weaving sections. The inputs of the program include the weaving section's geometrics (e.g., length of the weaving section of interest, number of lanes), free-flow speed, and traffic demands by vehicles' origin-destination. The software outputs include total delays as well as delay for each O-D pair, and plots of cumulative vehicle count curves that display discharge flows and average speeds.

1.3 Organization of the Report

This document is the final report for the study. Chapter 2 reviews existing methods for the analysis of freeway weaving sections. The study methodology and the approach for developing the weaving analysis performance matrix are described in Chapter 3. Chapter 4 describes the development of the study database. The application of the existing methods to the field data and the analysis of the results are presented in Chapter 5. Chapter 6 summarizes the study findings and recommendations. The proposed guidelines in the form of weaving analysis performance matrix for each method are included in Appendix C. Appendix D includes the research report[1] documenting in detail the new weaving analysis procedure and software.

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[1] Lee, J.H., and M.C. Cassidy, "An Empirical and Theoretical Study of Freeway Weave Bottlenecks," PATH Research Report UCB-ITS-PRR-2009-13, February 2009.

CHAPTER 2

LITERATURE REVIEW

Efforts to develop procedures for the design and analysis of freeway weaving sections begun in the 1950's. Table 2.1 provides an overview of existing analysis procedures; of those methods, the Leisch Method and the Moskowitz and Newman (Level D Method) are included in the Caltrans Highway Design Manual (shown as shaded cells in Table 2.1).

Table 2.1 Existing Procedures for the Analysis of Freeway Weaving Sections [2]

Model	Basic Type	Address Capacity?	Address LOS?	MOE	Comments
HCM 1965 (Normann) 1965	Macroscopic, Equivalent Non-Weaving Vehicles	Not directly.	Yes	Approx. Speed	Based on very sparse data. Quality of Flow used to map into LOS.
Hess 1963	Macroscopic, Lane Distribution	Yes Freeway Capacity Controls	Yes	Merge, Diverge, and Freeway Volume	Regression-based model, focuses on lane 1 of the freeway and the ramp, general LOS criteria based on flow rates
Moskowitz & Newman (Level D method) 1963	Microscopic, Lane Distribution and Lane-Changing by Cell	Yes Freeway Capacity Controls	Yes	Merge, Diverge, Weaving, and Freeway Volume	Focus on high-volume cell among freeway lane 1 and auxiliary lane, general LOS criteria based upon flow rates
Polytechnic Method 1973-1980	Macroscopic, Regression Based, Speed Prediction	Not directly.	Yes	Average Speed of Weaving and Non-Weaving Vehicles	Iterative approach. Introduced weaving section configuration and type of operation into the analysis process.
Leisch 1983	Macroscopic, Equivalent Non-Weaving Vehicles	Not directly.	Yes	Average Speed	A re-calibration of the HCM 1965 Leisch/Normann work. Nomographs used.
JHK method 1984	Macroscopic, Regression-Based, Speed Prediction	Not directly.	Yes	Average Speed of Weaving and Non-Weaving Vehicles	Introduced a different "density" concept tied to weaving intensity, introduced basic model form still used in HCM 2000.
1985 HCM Roess et al	Macroscopic	Not directly.	Yes	Average Speed of Weaving & Non-Weaving Vehicles	Developed as a merger of the earlier Polytechnic and JHK models. The JHK model form was stratified to consider configuration and type of operation.
Fazio 1985	Macroscopic, Regression-Based	Not directly.	Yes	Average Speed of Weaving and Non-Weaving Vehicles	Added lane-changing parameter to Reilly-type model, eliminating the need for different configuration types to be considered.
ITS UC Berkeley 1988-1995	Microscopic, Lane-distribution Lane-changing by Cell	Yes, Based on max flows and max lane-changing per Cell	Yes	Density	A modern look at the Level D method including major weaving sections. Lane distribution modeled for each component flow of the weaving section.
HCM 2000 Roess et al	Macroscopic	Yes	Yes	Density	Addition of density model and capacity predictions to 1985 HCM methodology.
Lertworawanic & Elefteriadou 2001-2002	Microscopic, Gap Acceptance	Yes	No	N/A	Capacity model based upon gap acceptance and linear programming optimization

The first formal procedure for analysis of weaving sections appeared in the 1965 edition of HCM [3], based on research conducted by O.K. Normann [4]. It was intended to cover both simple and multiple weaving areas, one-sided and two-sided weaving areas. The basic model in the 1965 HCM is shown in Figure 2.1. It graphically depicts a relationship between weaving length, total weaving volume, and Quality of Service. The latter is an operational measure that is later mapped into the HCM Level of Service (LOS) definitions. Associated with the five defined qualities of flow (I – V from best to worst) and intermediate points was a weaving equivalence factor, k.

The k-factor essentially converted the total volume in the weaving section to an equivalent non-weaving volume using the following equation:

$$N = \frac{v_{o1} + v_{o2} + v_{w1} + k\,v_{w2}}{SV} = \frac{v + (k-1)\,v_{w2}}{SV}$$

where:

N	=	number of lanes in the weaving section,
$v_{o1,o2}$	=	larger and smaller non-weaving volume respectively, veh/h,
$v_{w1,w2}$	=	larger and smaller weaving volume respectively, veh/h,
k	=	weaving equivalence factor,
SV	=	service volume per lane, veh/h (volume for specified quality of flow, max value: 2,000 veh/h/lane)

The k-factor is drawn from Figure 1 using the weaving length and the total weaving volume, $v_{w1}+v_{w2}$. Its value ranged from 1.0 for Quality of Flow I to 3.0 at Quality of Flow III and above. The value of k=1 also provides a boundary for "out of the realm of weaving," i.e., the point at which length is sufficient for the section to operate as isolated merge and diverge points with a basic freeway section in between. There was no empirical evidence regarding these boundary k-values. The value of 1.0 was logical, given that this was the boundary beyond which weaving operations were equivalent to basic freeway operations. The maximum value of 3.0 was based on the assumption that a weaving vehicle would need a gap of approximately 3 vehicle-lengths to successfully execute a weaving maneuver. Intermediate values of the k-factor were developed using interpolation process without empirical data.

The 1965 HCM method was widely used and brought some national consistency to the analysis and design of weaving areas. The methodology covered a wide range of situations and configurations in which weaving could exist. However, the method was based on very limited few field data.

The 1965 HCM Chapter on ramp junctions contains another procedure for analysis of ramp-weaving configurations, i.e., one lane ramps followed by off-ramp with a continuous auxiliary lane. It was recommended that a procedure developed by Hess [5] will be used to analyze ramp junctions for LOS A to C (free-flow conditions), and the methodology developed in California by Moskowitz & Newman [6] when the LOS is D or E (heavy traffic conditions).

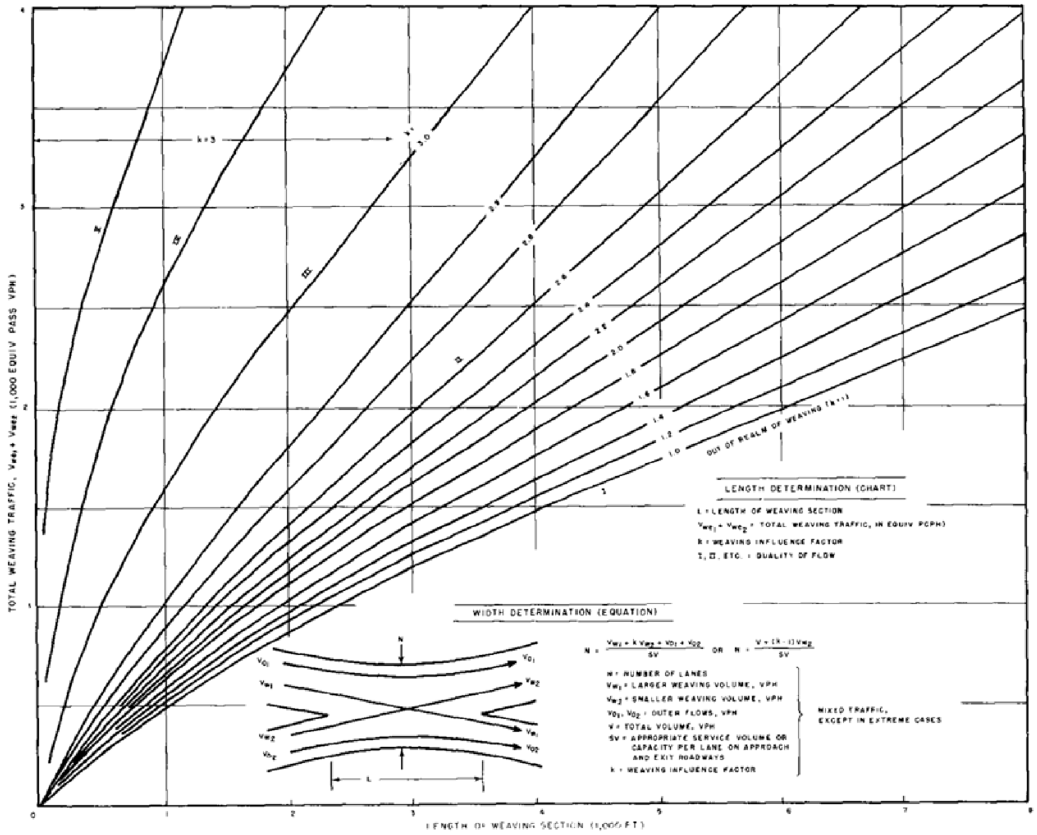


Figure 2.1 Weaving Chart--1965 HCM

(Source: Highway Capacity Manual, 2nd Edition, Special Report 87, Highway Research Board, Washington DC, 1965, pg 166)

2.1 The Level D Method

The Level D method was developed in California by Moskowitz & Newman to analyze weaving sections under heavy traffic conditions (LOS is D or E) [6]. The method applied to weaving sections with one lane ramps followed by off-ramp with a continuous auxiliary lane. The method was included in the ramp junctions Chapter of the 1965 HCM.

Figure 2.2 illustrates the Level D method. It shows, for various weaving lengths, percentages of on-ramp and off-ramp traffic remaining in the auxiliary lane and the right-most through lane at 500 ft intervals through the weaving section. This was augmented by a Table that provides the proportion of the freeway through traffic remaining in outer through lane in the weaving section (Table 2.2). Table 2.2 only applies to traffic not involved in a ramp movement within 4,000 ft.

The analyst estimates the traffic volumes in the right most through lane and the auxiliary lane at 500 ft intervals using the values in Figure 2.2 and Table 2.2. These values are compared against the lane capacities in the weaving section. The method identifies the segment and lane of the weaving section with the highest volume (and highest amount of lane-changing activity).

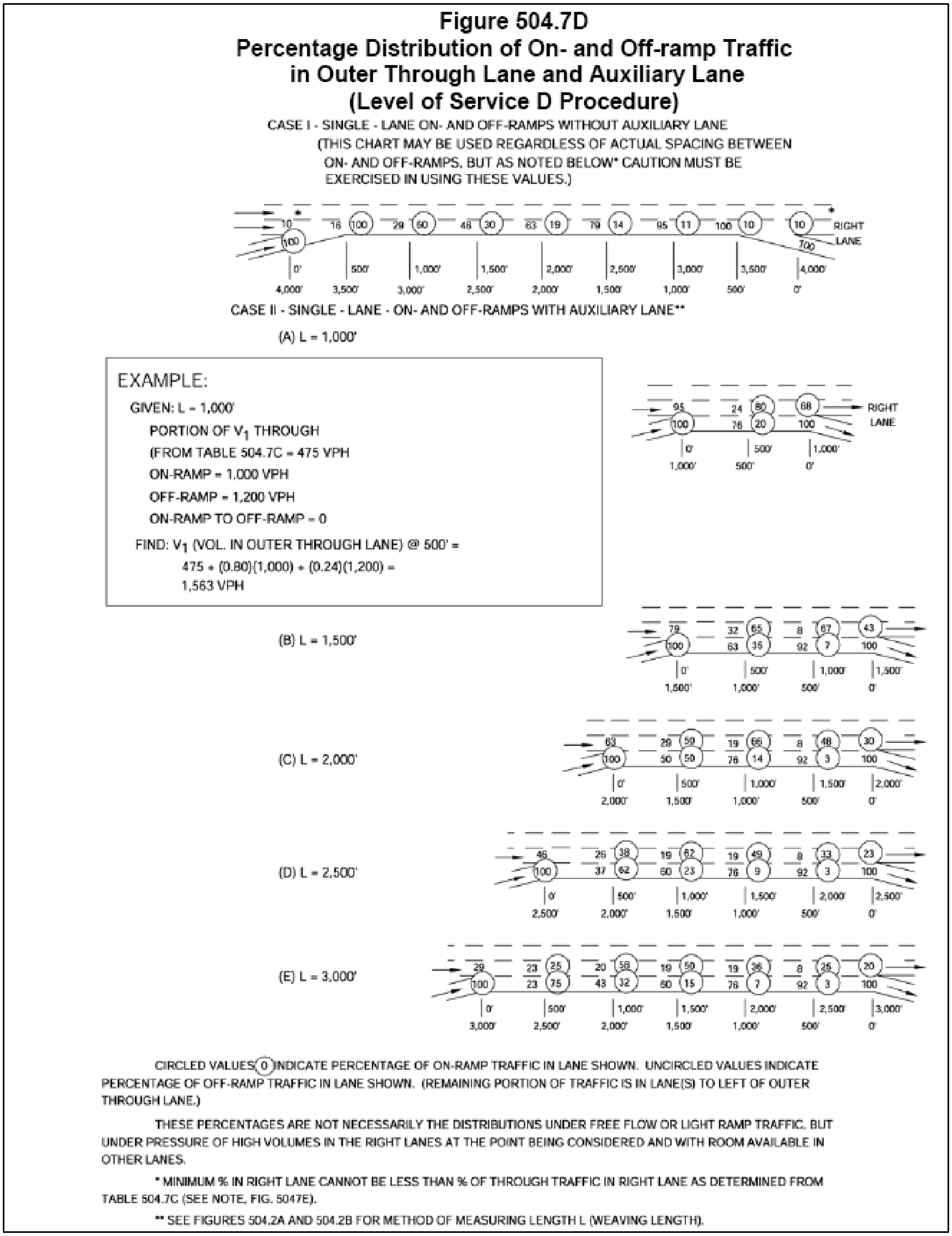


Figure 2.2 Level D Method: Distribution of on- and off-Ramp Traffic in Lane 1 and Auxiliary Lane
(Source: Caltrans, Highway Design Manual, and Highway Capacity Manual, 2nd Edition, Special Report 87, Highway Research Board, Washington DC, 1965).

Table 2.2 Level D Method: Proportion of Through Traffic Remaining in Outer Through Lane
(Source: Caltrans Design Manual, and Highway Capacity Manual, 2nd Edition, Special Report 87, Highway Research Board, Washington DC, 1965.)

TOTAL VOLUME OF THROUGH TRAFFIC, ONE DIRECTION (vph)	APPROXIMATE PERCENTAGE OF THROUGH(1) TRAFFIC REMAINING IN THE OUTER THROUGH LANE IN THE VICINITY OF RAMP TERMINALS AT LEVEL OF SERVICE D.		
	8-LANE(2) FREEWAY	6-LANE(3) FREEWAY	4-LANE(4) FREEWAY
6500 and over	10	-	-
6000 - 6499	10	-	-
5500 - 5999	10	-	-
5000 - 5499	9	-	-
4500 - 4999	9	18	-
4000 - 4499	8	14	-
3500 - 3999	8	10	-
3000 - 3499	8	6	40
2500 - 2999	8	6	35
2000 - 2499	8	6	30
1500 - 1999	8	6	25
Up to 1499	8	6	20

Notes:

(1) Traffic not involved in a ramp movement within 4,000 feet in either direction.

(2) 4 lanes one-way.

(3) 3 lanes one-way.

(4) 2 lanes one-way.

The Level D method was extended for other types of weaving sections in a series of studies conducted at the Institute for Transportation Studies (ITS) at the University of California at Berkeley, in cooperation with Caltrans [7,8,9]. The overall capacity and level of service in a weaving area was most heavily influenced by the flow and lane-changing activity of critical cells (a particular lane at a particular distance from the entry gore area) within the section. Thus, the most effective models should predict the activity in the critical cell(s) of the section, and from that, make overall predictions of section capacity and level of service. The recommended procedures consist of the following steps (Lanes were numbered 1 through n starting with the right-most lane of the weaving section):

1. Predict the proportion (and then the flow rate) of ramp-to-freeway (RF) traffic in lanes 1 and 2 at various distances from the entry gore area.
2. Predict the proportion (and then the flow rate) of freeway-to-ramp (FR) traffic in lanes 1 and 2 at various distances from the entry gore area.
3. Predict the proportion (and then the flow rate) of freeway-to-freeway (FF) traffic in the right-most through at various distances from the entry gore area.
4. Determine the flow rates in the critical cell(s) of the weaving section.
5. Determine the density or lane-changing rate of the critical cell(s); establish capacity and LOS

2.2 The Leisch Method

This method was developed by J. Leisch based on data from 48 weaving sections around the country [10,11]. The method used concepts similar to the 1965 HCM and a nomograph approach. Two sets of nomographs were created: one for one-sided weaving sections, and the other for two-sided weaving areas. A sample of the Leisch nomographs for one-sided weaving sections is shown in Figure 2.3.

In calibrating his nomographs, Leisch retained some key elements of the 1965 HCM weaving chart. The primary relationship is still between the length of the weaving section and the total weaving volume, except that LOS curves replace Quality of Flow curves. The weaving intensity factor (k) continues to range between 1.0 and 3.0 for one-sided weaving sections. Solution of the nomographs results in determination of either the LOS of a weaving section with known design characteristics, or the number of lanes needed to obtain a specified LOS. The method also produces estimates of the average speeds of all vehicles and the weaving vehicles. The method accounts for the difference in operational characteristics between lane-balanced and unbalanced weaving sections. Lane balanced sections have one more lane going away, such as an optional lane at exit; i.e., one weaving movement is not required to change lanes.

The advantage of the Leisch method is that it is relatively easy to apply, and could be manipulated to produce design and/or operational analysis results. However the development and calibration of nomographs was mostly based on experience and judgment with very limited field data.

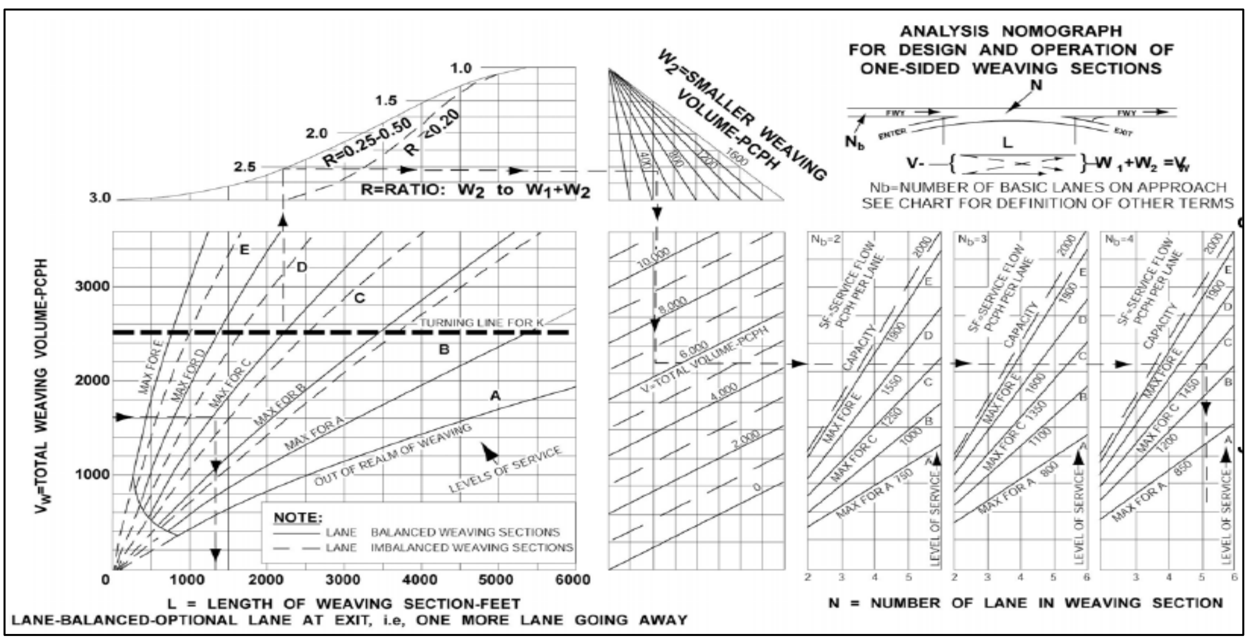


Figure 2.3 Leisch Method: Nomograph for One-Sided Weaving Sections
(Source: Leisch, J., Completion of Procedures for Analysis and Design of Traffic Weaving Areas, Final Report, Vols 1 and 2, Federal Highway Administration, Washington DC, 1983.)

2.3 The HCM2000 Method

The origin of the HCM2000 method is the weaving analysis method developed by the Polytechnic Institute of New York (*PINY method*) [12,13]. This method is based on the same field data as the Leisch method, but it explicitly recognizes the geometric configuration of the weaving section, depending on the minimum number of lane changes required by the weaving vehicles.

Table 2.3 summarizes the PINY method. The LOS is defined based on the speeds of weaving and non-weaving vehicles. Freeway weaving sections are classified into three configurations, depending on the minimum number of lane changes required by weaving vehicles (Figure 2.4).

Type A: each weaving vehicle must make one lane-change (ramp weaves)

Type B: major weaving configurations requiring one lane change for the one weaving movement and none for the other weaving movement

Type C: major weaving configurations requiring two or more lane changes for one weaving movement and none for the other weaving movement

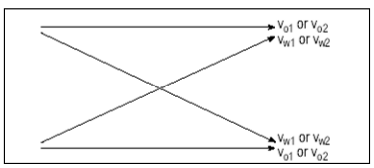


EXHIBIT 24-5. DETERMINING CONFIGURATION TYPE

Number of Lane Changes Required by Movement v_{w1}	Number of Lane Changes Required by Movement v_{w2}: 0	1	≥ 2
0	Type B	Type B	Type C
1	Type B	Type A	N/A
≥ 2	Type C	N/A	N/A

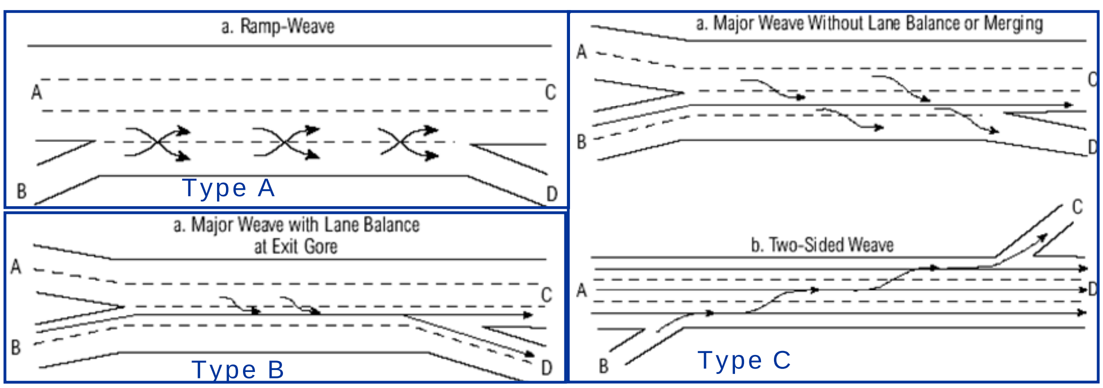


Figure 2.4 Configurations of Freeway Weaving Sections (1985/2000 HCM)
(Source; Highway Capacity Manual, 2000, Transportation Research Board, Washington DC, 2000.)

The concept of constrained vs. unconstrained operations was also introduced. Constrained operations occur when the geometry of the section constrains weaving vehicles from using certain freeway lanes. Under constrained operations weaving vehicles occupy a smaller proportion of the roadway than they would without the constraint of geometry; non-weaving vehicles occupy more space, and the difference between non-weaving and weaving vehicle speeds increases.

The PINY methodology was complex, because of the inter-relationships of values of S_w, S_{nw}, N_w, and N_{nw}. A solution is started by assuming a high value of S_w (e.g., 55 mph) and iterating through the process until the resulting S_{nw} agrees with the starting assumption. The type of operation (constrained or unconstrained) is determined by comparing N_w to N_w (max). The logic of the equations is not intuitively obvious, and many users had difficulty implementing the procedures when they were published.

Table 2.3 The PINY Weaving Analysis Method

Weaving Type	Equation
	Maximum Number of Weaving Lanes, N_w (max)
A	N_w (max) = 2.0
B	Log N_w (max) = 0.741+0.480 log R
C	Log N_w (max) = 0.896+0.186 log R – 0.402 log L_H
	Speed Relationship Between S_w and S_{nw}
A	log S_w = 0.142+0.692 log S_{nw} + 0.313 log L_H
B	S_w = 15.031+ 0.819 S_{nw} – 23.527 VR **
C	S_w = 2.309 + 0.871 S_{nw} + 4.579 VR **
	Portion of Total Lanes Used by Weaving Vehicles, N_w/N
A	log N_w/N = 0.340 + 0.571 log VR – 0.438 log S_w + 0.234 log L_H **
B	N_w/N = 0.761-0.011 L_H – 0.005 (S_{nw} – S_w)
C	N_w/N = 0.085+0.703 VR + (234.763/L) – 0.018 (S_{nw} – S_w)
	Speed – Flow Relationship for Non-Weaving Vehicles
A	
B	V_{nw} = 1500 N_{nw} – 50.0 S_{nw} + 1900
C	

*** Secondary equations only applying when the section is unconstrained, i.e., $N_w < N_w$ (max)*

Notes: 1. All volumes expressed as equivalent passenger cars/hour (pch) under ideal conditions
S_w, S_{nw} = average speed of weaving, non-weaving traffic, mph
V_w, V_{nw} = weaving and non-weaving volume (pch)
N_w = number of lanes used by weaving vehicles under unconstrained operation;
N = Number of lanes in weaving section
VR = ratio of weaving volume to total volume;
R = ratio of smaller weaving volume to total weaving volume.
L = length of weaving section, ft; (L_H = length of weaving section, hundreds of ft.)

The JHK Methodology[14]: This method was developed as part of a research effort sponsored by FHWA to evaluate the accuracy of the PINY and Leisch methodologies against field data. often produced significantly different results. The algorithms were developed based upon the "density" within the weaving section, which was calculated by dividing the ratio of weaving to total volume by the length of the section. The procedures developed were universally applied to all weaving sections, regardless of configuration or type of operation. The procedure consists of two equations to predict the average speeds of weaving and non-weaving vehicles:

$$S_{w,nw} = S_{\min} + \frac{S_{\max} - S_{\min}}{1 + \left[\frac{a(1+VR)^b (v/N)^c}{L^d} \right]} \tag{2-1}$$

where all variables are as previously defined. S_{max} and S_{min} are the maximum and minimum speeds expected for weaving or non-weaving vehicles as appropriate.

The 1985 HCM method: This is a modification of the JHK method to incorporate the concepts of weaving configuration and constrained vs. unconstrained operation [15, 16]. This was accomplished by calibrating the constants (a, b, c, d) in Equation (2-1) for the three different weaving configurations

(A, B, and C), for unconstrained and constrained operations, and for weaving and non-weaving speeds. The result was 12 different equations, all in the form Equation (2-1).

Several concerns have been expressed by transportation researchers and professionals regarding the HCM1985 method because a) it could not provide capacity estimates; b) it uses rather complex equations for estimating weaving and non-weaving vehicle speeds to determine LOS, and the logic of these formulae is not readily apparent, and d) often inappropriately reflects impacts created by changes in geometric configuration of the weaving areas.

Another weaving operations study (NCHRP 3-55) [17] was undertaken as part of the research for the 2000 edition of HCM. The study relied heavily on simulation, due to the high cost of data collection. The study did not produce a satisfactory procedure to replace the existing HCM85 weaving analysis methodology. It yielded a number of trends that were judged to be counter-intuitive, e.g., it proposed that the operation of weaving areas was not influenced by length of the section.

The HCM2000 methodology [18] is a *judgmental* modification of the previous methods to provide improved consistency among the freeway-related methodologies in the HCM. These modifications included a) recalibration of the constants (a, b, c, d) to reflect further changes in other freeway analysis related chapters of the Manual, and b) determination of LOS based upon the density in the weaving section eliminating the practice of assigning separate levels of service to weaving and non-weaving vehicles.

The HCM2000 methodology first calculates the speeds of weaving and non-weaving vehicles as follows:

$$S_{w,nw} = S_{\min} + \frac{S_{\max} - S_{\min}}{1 + W_{w,nw}}$$

$$W_{w,nw} = \frac{a\,(1+VR)^b\,(v/N)^c}{L^d}$$

where:	S_w	=	average speed of weaving vehicles, mph
	S_{nw}	=	average speed of non-weaving vehicles, mph
	S_{min}	=	minimum average speed for weaving section, mph
	S_{max}	=	maximum average speed for weaving section, mph
	W_w	=	weaving intensity factor for weaving vehicles
	W_{nw}	=	weaving intensity factor for non-weaving vehicles
	VR	=	volume ratio; ratio of weaving flow rate to total flow rate
	v	=	total demand flow rate under equivalent ideal conditions, pc/h
	N	=	number of lanes in the weaving section
	L	=	length of the weaving section, ft
	a-d	=	constants of calibration

In the HCM2000, the minimum average speed for all weaving sections (S_{min}) is set at 15 mph. The maximum average speed (S_{max}) is defined as FFS+5, where FFS is the freeway free-flow speed. The additional 5 mph corrects for the shape of the algorithm, which tends to under-predict higher speeds. With these assumptions, the equations for the speed of weaving and non-weaving vehicles become:

$$S_{n,nw} = 15 + \frac{FFS - 10}{1 + W_{w,nw}}$$

The calibration constants (a, b, c, d) are given below (Table 2.4):

Table 2.4 Constants for Computing Weaving Intensity factors (HCM2000, Exhibit 24-6)

General Form

$$W = \frac{a(1+VR)^b \left(\frac{v}{N}\right)^c}{L^d}$$

	Constants for Weaving Speed, S_w				Constants for Nonweaving Speed, S_{nw}			
	a	b	c	d	a	b	c	d
Type A Configuration								
Unconstrained	0.15	2.2	0.97	0.80	0.0035	4.0	1.3	0.75
Constrained	0.35	2.2	0.97	0.80	0.0020	4.0	1.3	0.75
Type B Configuration								
Unconstrained	0.08	2.2	0.70	0.50	0.0020	6.0	1.0	0.50
Constrained	0.15	2.2	0.70	0.50	0.0010	6.0	1.0	0.50
Type C Configuration								
Unconstrained	0.08	2.3	0.80	0.60	0.0020	6.0	1.1	0.60
Constrained	0.14	2.3	0.80	0.60	0.0010	6.0	1.1	0.60

The HCM2000 methodology then converts the component speeds to an average flow weighted speed for all vehicles. Next, the density for the section is computed from the average speed and flow rate. The LOS is determined from the computed density value based on the following table (Table 2.5):

Table 2.5 LOS Criteria for Freeway Weaving Sections (HCM2000, Exhibit 24-2)

LOS	Density (pc/mi/ln)	
	Freeway Weaving Segment	Multilane and Collector-Distributor Weaving Segments
A	≤ 10.0	≤ 12.0
B	> 10.0–20.0	> 12.0–24.0
C	> 20.0–28.0	> 24.0–32.0
D	> 28.0–35.0	> 32.0–36.0
E	> 35.0–43.0	> 36.0–40.0
F	> 43.0	> 40.0

The capacity of a weaving section is established as the minimum of three values:

1. The total flow rate that results in a density of 43 pc/mi/ln, assumed to result in breakdown
2. The total flow rate that results in a weaving flow rate equal to the maximum allowable value (2,800 pc/h for Type A sections; 4,000 pc/h for Type B sections; 3,500 pc/h for Type C sections).
3. The total flow rate equal to the basic freeway capacity of all lanes in the weaving section.

The application of the HCM2000 methodology consists of the following steps:

1. Input: geometric data, traffic volumes per movement, free flow speed of freeway segment
2. Volume adjustment: peak-hour factor, heavy vehicles, driver population
3. Compute flow rates
4. Establish weaving segment configuration type
5. Compute unconstrained weaving and non-weaving speed
6. Check for constrained-flow operation
    - If constrained, compute constrained weaving and non-weaving speeds
    - Otherwise, use the unconstrained parameter
7. Compute average space mean speed within weaving segment
8. Compute density within the weaving segment
9. Determine LOS

2.4 Other Methods

Fazio model: This is a modification of the JHK model. It includes a variable to account for the lane-changing activity in the weaving section [19]. Insertion of such a variable allowed for development of speed-prediction equations (one for weaving speed, one for non-weaving speed) without reference to weaving section configuration categories. The proposed model was based on limited data and assumed an entering lane-distribution pattern for weaving vehicles. It was also assumed that all weaving vehicles left the section on the lane closest to their weaving maneuver.

Penn State model: This methodology for estimating the capacity of ramp-weave and major weave sections is based upon linear optimization and gap acceptance modeling [20]. The methodology defines the sum of weaving section capacity as the sum of two components: a) the capacity of weaving lanes and b) the capacity of non-weaving lanes (all other lanes), assumed to be equivalent to the basic freeway capacity per HCM 2000. The maximum values of each weaving flow rate are based upon gap acceptance modeling of the necessary lane-changing maneuvers made by the weaving vehicles. The study had to assume the values of gap acceptance parameters and the validation data base was relatively sparse, and not microscopically detailed.

Simulation Studies: Several studies have been undertaken using simulation to evaluate the operation of existing weaving sections and to evaluate alternative designs [21]. Most of these studies focused on developing procedures for successfully simulating weaving operations, and evaluating the effectiveness of existing simulation models to simulate weaving sections.

NCHRP 3-75 Study: The objective of this national study is to develop a new procedure for analysis of weaving sections to be included in the 2010 edition of the HCM [2]. The procedures is based on field data on weaving operations collected at 14 sites throughout the country. The new procedure has been included in the 2010 edition of HCM which expected to be available in late 2010.

2.5 Measuring the Weaving Section Length

The measurement of weaving section length according to the HCM2000 is shown in Figure 2.5. The length is measured from a point at the merge gore where the right edge of the freeway shoulder lane and the left edge of the merging lane(s) are 2 ft apart to a point at the diverge gore where the two edges are 12 ft apart. This definition was originally introduced in the 1965 HCM [3], and it also the same for the Leisch method [11] and the Level D method as described in Chapter 8 of the 1965 HCM [3]. This definition appears that is based on the ramp geometry between loops of a cloverleaf interchange, where the exit loop generally diverted at a sharper angle than the entry loop merged.

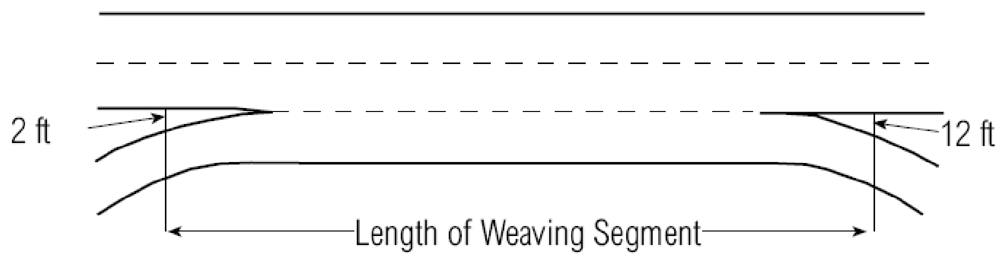


Figure 2.5 Measuring the Weaving Section Length (HCM2000 Exhibit 13-11)

The Caltrans Highway Design Manual defines the length from a point at the merge gore where the right edge of the freeway shoulder lane and the left edge of the merging lane(s) are 6 ft apart to the diverge gore where the two edges meet [1].

In the recently completed NCHRP 3-75 project [2], several ways of measuring weaving length were considered, and the selected ones are shown in Figure 2.6 below:

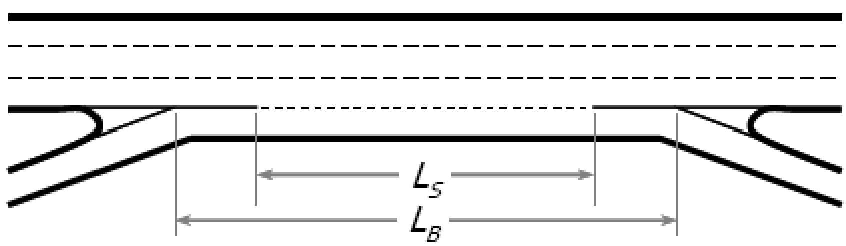


Figure 2.6 NCHRP 3-75 Measurement of Weaving Section Length ([2])

L_s = the distance between the end points of any barrier markings (solid white lines) that prohibit or discourage lane-changing (ft)

L_B= the distance between points in the gore areas where the left edge of the ramp traveled way and the right edge of the freeway traveled way meet (ft)

Field observations indicate that L_B defines the length used for lane-changing, but the use of *Ls* improved the statistical fit of models to the field data, and will be used in the 2010 HCM. In the 3-75 database it was found that *Ls* = 77% of L_B , which can be used as a default value when the details of striping are not known.

In the test sites included in our study, the weaving length was measured as the distance between points in the gore areas where the left edge of the ramp traveled way and the right edge of the freeway traveled way meet (ft).

CHAPTER 3

METHODOLOGY

Currently, the Caltrans Highway Design Manual includes two methodologies for determining the capacity and/or Level of Service of weaving sections: the Level D method and the Leisch method. Although the HCM2000 method is not officially recommended for use, it is often applied to check whether other analysis results are reasonable.

To determine how well each of the above methods predicts operations at weaving sections, for each study site the analysis results of the three methods were compared to the actual operating conditions that correspond to each data set. The results were then further analyzed to determine which of three existing methods predicts best the operating characteristics of a weaving section under certain geometric and operational conditions.

3.1 Weaving Methods Performance Matrix

The weaving analysis performance matrix was created to serve as a guide for Caltrans design engineers when choosing the "best" weaving analysis method for the weaving section under study, based on comparisons with field data. A method that works well for a given geometric/operational mix will be given a "green light", a satisfactory method a "yellow light" and poor one a "red light".

Table 3.1 shows the proposed weaving analysis performance matrix. A performance matrix will be developed for each analysis method.

Table 3.1 Proposed Weaving Analysis Performance Matrix

No. of Lanes in Weaving Section, N =	**2**											
Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy												
Non-Weaving: Heavy Weaving: Mid to Low												
Non-Weaving: Mid to Low Weaving: Heavy												
Non-Weaving: Mid to Low Weaving: Mid to Low												

No. of Lanes in Weaving Section, N =	**3**											
Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy												
Non-Weaving: Heavy Weaving: Mid to Low												
Non-Weaving: Mid to Low Weaving: Heavy												
Non-Weaving: Mid to Low Weaving: Mid to Low												

No. of Lanes in Weaving Section, N =	**4**											
Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy												
Non-Weaving: Heavy Weaving: Mid to Low												
Non-Weaving: Mid to Low Weaving: Heavy												
Non-Weaving: Mid to Low Weaving: Mid to Low												

No. of Lanes in Weaving Section, N =	**5**											
Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy												
Non-Weaving: Heavy Weaving: Mid to Low												
Non-Weaving: Mid to Low Weaving: Heavy												
Non-Weaving: Mid to Low Weaving: Mid to Low												

Each cell represents a distinct design and operating condition. For a given number of lanes in the weaving section, the matrix has 48 cells; operational characteristics are reported by row while geometric characteristics are reported by column. There are a total of 192 possible cells for typical weaving sections of two, three, four and five lanes wide. Shaded cells indicate infeasible conditions. For example, it is not possible to have a two lane weaving section with more than one on- or off-ramps. Therefore, the proposed matrix includes a total of 144 cells.

The following sections describe the classification of design and operational conditions for developing the performance matrix.

3.2 Weaving Section Classification

3.2.1 Geometric Characteristics

The weaving sections geometric characteristics include the total number of lanes in the weaving section, the number of auxiliary lanes, and the length of weaving section. First, we consider the total number of lanes in the weaving section: two, three, four, or five lanes wide. Next, for a given number of lanes, we consider the presence and number of auxiliary lanes:

1. *<u>No</u> Auxiliary Lane, single lane on- & off-ramps*

2. *<u>With</u> Auxiliary Lane, single -lane on & off-ramps (Type A, HCM 2000):* These are weaving sections consisting of two-lane on or off-ramps in which each weaving movement is required to make one lane change. These are also called ramp weaves.

3. *<u>Balanced</u>, >1 lane on- & off-ramps (Type B):* These are weaving sections consisting of two-lane on or off-ramps in which one weaving movement is not required to make a lane change, and the other weaving movement is required to make one lane change. It also includes balanced sections, i.e., weaving sections with an optional lane at exit, i.e., "one more lane going away. Note balanced sections include weaving sections with a single lane on- or off-ramp (Figure 3.1).

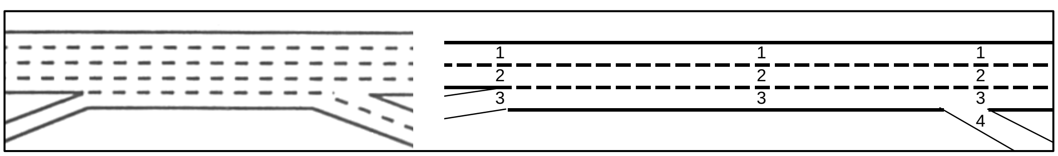


Figure 3.1 Typical Balanced (HCM2000 Type B) Weaving Sections

4. *<u>Unbalanced</u>, >1-lane on-& off-ramps (Type C):* These are weaving sections consisting of two-lane on or off-ramps in which one weaving movement is required to make two lane changes, and the other weaving movement is not required to make a lane change. It also includes unbalanced sections, i.e., weaving sections without an optional lane at exit (Figure 3.2)

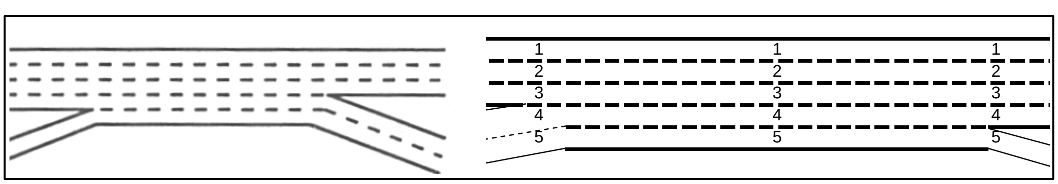


Figure 3.2 Typical Unbalanced (HCM2000 Type C) Weaving Sections

Under each of these groups, a weaving section can further be classified according to its length as short, medium or generous, as follows:

1. Short Weave Length (<1,000 ft)
2. Medium Weave Length (1,000- 2,500 ft)
3. Generous Weave Length (>2,500 ft)

These thresholds were assumed to be reasonable in that weaving sections in each group would exhibit similar traffic behavior given certain traffic volumes.

3.2.2 Operational Conditions

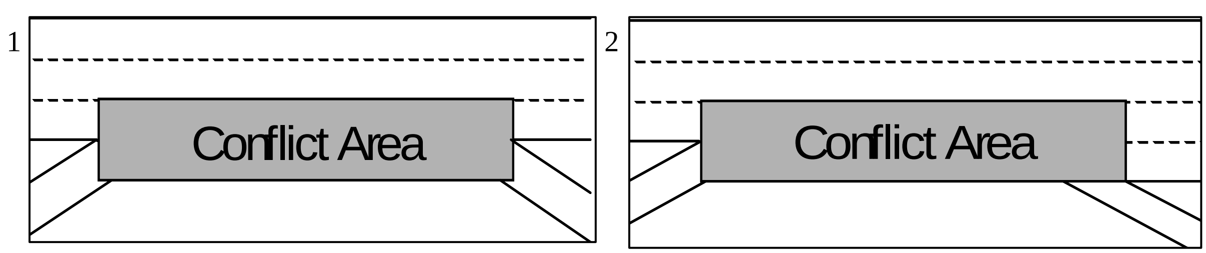
The operational conditions are grouped based on the total weaving and non-weaving traffic volumes in the weaving section as follows:

1. Non-Weaving Volumes: Heavy, Weaving Volumes: Heavy
2. Non-Weaving Volumes: Heavy, Weaving Volumes: Mid to Low
3. Non-Weaving Volumes: Mid to Low, Weaving Volumes: Heavy
4. Non-Weaving Volumes: Mid to Low, Weaving Volumes: Mid to Low

The non-weaving volume includes all traffic traveling through a weaving section (freeway-to-freeway) and from the on-ramp to off-ramp. The weaving volume consists of the on-ramp to freeway volume and the volume from the freeway to the off-ramp. It was determined that volumes could be grouped in this way because it does not appear that performance estimates from the existing analysis methods would differ if, for instance, one weaving section had high on-ramp to freeway volumes and another had high freeway to off-ramp volumes. The analysis methods do not recognize the difference between these two groups of traffic, and two scenarios would yield the same analysis results.

The non-weaving and weaving volumes are classified as "heavy" or "mid to low" based on the number of lanes in the "conflict area" of the weaving section. The term conflict area is used to indicate the travel lanes where most of the turbulence occurs due to merging and diverging traffic. Most turbulence occurs in the lanes adjacent to the on- and off-ramps, and as a result the conflict area is defined as follows, based on "A Proposed Analytical Technique for the Design and Analysis of Major Freeway Weaving Sections" [7]:

1. (Conflict Area 1) The area of the weaving section extending from the right-most auxiliary lane to the lane directly to the left of the diverge gore, or
2. (Conflict Area 2) The area of the weaving section extending from the right-most auxiliary lane to the lane directly to the left of the merge gore.



Whichever of the above descriptions encompasses more lanes of the weaving area will govern as the conflict area. The lanes in the conflict area are those "reserved" for weaving volumes, and the remaining lanes of the weaving section are those “reserved” for non-weaving volumes. The table below indicates the criteria by which weaving and non-weaving volumes are classified as “heavy” or “mid to low”.

Volume (vph)	(A) N – [# lanes in conflict area]	“Heavy” Criteria	“Mid to Low” Criteria
Non-weaving	1 lane	Heavy = >1,800;	Mid to Low < 1,800
	2 lanes	Heavy = >3,600;	Mid to Low < 3,600
	3 lanes	Heavy = >5,400;	Mid to Low < 5,400
	4 lanes	Heavy = >7,200;	Mid to Low < 7,200

Volume (vph)	(B) # lanes in conflict area	“Heavy” Criteria	“Mid to Low” Criteria
All weaving	1	Heavy = >1,000;	Mid to Low < 1,000
	2	Heavy = >2,000;	Mid to Low < 2,000
	3	Heavy = >3,000;	Mid to Low < 3,000

(A) + (B) = N (number of lanes in weaving section)

For instance, for the second “conflict area” figure, there are two lanes in the conflict area and (4-2) = two lanes designated for non-weaving traffic.

The thresholds for “heavy” and “mid to low” traffic for non-weaving volumes were determined by assuming that a freeway lane is operating at or near capacity if volumes are 1,800 vehicles per hour (vph) or greater. The thresholds for “heavy” and “mid to low” traffic for weaving volumes were determined by assuming that a freeway on- or off-ramp lane is operating at or near capacity if volumes are 1,000 vph or greater.

CHAPTER 4

THE STUDY DATABASE

The evaluation of the existing methodologies for the analysis of weaving sections should be based on empirical data representing a wide range of conditions. This Chapter describes the development of the study database. We will select the test sites to be used in the project from the above database that are most typical of California conditions and represent a range of design and traffic characteristics.

4.1 Data Sources

The following data sources were identified from previous studies at UC Berkeley, Caltrans staff, other UC Berkeley studies and contacts with researchers and practitioners:

- California Weaving Studies Database [7]: As it was mentioned in the literature review, a series of studies were undertaken by the Institute of Transportation Studies at University of California, Berkeley to develop new weaving analysis procedures for major weaving sections. Data from eight weaving sections were collected and analyzed.
- The California Ramp Weaving Studies Database [22]: Caltrans collected data in the early 90's on about 20 weaving sites consisting of a one lane on-ramp followed by a single lane off-ramp with a continuous auxiliary lane.
- The NGSIM Data [23]: Detailed data on vehicle trajectories were collected on two California weaving sites as part of the Next Generation Simulation (NGSIM) program.
- The NCHRP 3-75 Database [2]: This data were collected as part of a national project to develop a new weaving analysis procedure for the next edition of the Highway Capacity Manual (HCM 2010).
- The Caltrans District 5 Database [24]: Caltrans District 5 staff provided to the research team data on weaving sections mostly along US-101 in Santa Barbara.

Each of the databases identified are described below:

4.1.1 California Studies —Major Weaving Sections

Table 4.1 shows the eight test sites where data were collected as part of the University of California weaving studies in the early 90s. The schematics for each site are shown in Appendix A. The data were collected using video and processed to obtain volumes per traffic movement, speeds of weaving and non-weaving vehicles and lane distribution of component flows.

All the sites are major weaving sections with more than one on or off-ramps, typical of urban freeway weaving sites. The I-10EB_LA was excluded from the database because it is six lane wide, and the proposed matrix considers up to five lanes. The rest of the sites are all five lanes, except the SR-92WB site which is three lanes wide.

The data were reviewed for accuracy and coded into the study database for further analysis. There are a total of seven test sites and 27 data points of volume/speed conditions.

Table 4.1 California Weaving Studies--Major Weaving Sections

Site	Location	N	L (ft)	C	V (vph)	VR	S (mph)
US-101SB	**Los Angeles**	5	792	A	5909	0.29	53.5
		5	792	A	5534	0.32	54.9
		5	792	A	6463	0.29	60.4
I-805NB	**San Diego**	5	1371	B	7197	0.22	60.9
		5	1371	B	6663	0.23	60.9
		5	1371	B	6903	0.25	61.2
		5	1371	B	6909	0.23	56.9
I-10WB_LA	**Los Angeles**	5	1690	B	7751	0.31	58.0
		5	1690	B	5986	0.31	62.9
		5	1690	B	5941	0.32	62.1
		5	1690	B	5832	0.33	62.3
		5	1690	B	6427	0.33	60.5
I-10WB_SB	**San Bernardino**	5	1989	B	4020	0.25	59.0
		5	1989	B	3822	0.25	60.2
		5	1989	B	4612	0.25	65.6
SR-92WB	**San Mateo**	3	1400	B	3221	0.43	52.1
		3	1400	B	2760	0.41	53.6
		3	1400	B	3035	0.35	59.7
		3	1400	B	4033	0.33	57.6
I-10EB_LA	**Los Angeles**	6	1437	C	4622	0.37	53.0
		6	1437	C	4389	0.40	51.9
		6	1437	C	5800	0.34	57.4
		6	1437	C	6411	0.34	57.0
		6	1437	C	10102	0.37	45.7
US-101NB	**Los Angeles**	5	787	C	9684	0.43	49.2
		5	787	C	9202	0.38	49.0
I-280SB	**San Jose**	5	1347	C	5665	0.30	67.8
		5	1347	C	5130	0.32	67.1
		5	1347	C	4720	0.31	62.7
		5	1347	C	4997	0.31	65.9
		5	1347	C	7092	0.27	64.2
		5	1347	C	7391	0.28	61.4

N: Number of lanes in the weaving section
L: length of the weaving section (ft)
C: Weaving section configuration per HCM2000
V: Total volume in the weaving section (vph)
VR: Ratio of weaving volume to total volume
S: Average speed in the weaving section (mph)

4.1.2 California Studies —Ramp Weaves

Caltrans staff collected data on weaving sections in the early 90's using video recordings, as part of a study to evaluate the accuracy of the Level D methods. All the data were collected on urban freeways with a one lane on- and off-ramp connected with an auxiliary lane (Type A per HCM2000). A total of 20 weaving sections.

Most of the data in each study site consisted of 5 minute volumes per movement. Speeds of weaving and weaving vehicles were extracted for seven sites. Following review of the data we selected the weaving sections where performance measures (speeds) were available. Table 4.2 shows the selected test sites from the Caltrans ramp weaves study.

Note that all weaving sections are five lanes wide typical of urban freeways in Southern California. Also, at the time of the data collection there was a 55 mph posted speed limit on all locations. The final ramp weaves database consists of seven sites and 28 data points of volumes and speeds

Table 4.2 California Weaving Studies—Ramp Weaves

Site	Location	N	L	V (pcph)	VR	S (mph)
I-5SB	San Diego	5	1255	5868	0.21	55.0
		5	1255	6132	0.21	54.6
		5	1255	6240	0.20	54.6
		5	1255	6156	0.16	54.7
		5	1255	5940	0.17	54.8
		5	1255	6192	0.16	54.8
SR-60EB	Los Angeles	5	1100	9240	0.08	57.6
		5	1100	8784	0.09	56.6
		5	1100	8568	0.09	59.5
		5	1100	5400	0.08	60.7
		5	1100	5388	0.10	61.9
		5	1100	5052	0.11	60.3
SR-91WB	Los Angeles	5	1895	5448	0.13	58.7
		5	1895	5124	0.12	57.1
		5	1895	5592	0.11	53.6
I-10WB	Los Angeles	5	777	4428	0.17	56.9
		5	777	4524	0.15	58.0
		5	777	4800	0.16	57.1
SR-91EB	Los Angeles	5	845	6612	0.13	59.0
		5	845	6084	0.14	58.4
		5	845	6396	0.10	58.6
US-101NB	Los Angeles	5	808	6600	0.23	50.2
		5	808	6744	0.19	51.6
		5	808	6636	0.18	55.2
I-110SB	Los Angeles	5	610	7716	0.07	54.8
		5	610	7488	0.07	54.0
		5	610	7440	0.09	53.8

N: Number of lanes in the weaving section
L: length of the weaving section (ft)
V: Total volume in the weaving section (passenger cars/hr)
VR: Ratio of weaving volume to total volume
S: Average speed in the weaving section (mph)

4.1.3 The NGSIM Data Sets

Detailed data on weaving sections have been collected as part of the of NGSIM sponsored by FHWA. The NGSIM database consists of vehicle trajectories and aggregate loop detector data from two freeway sites in California: I-80EB in San Francisco Bay area and US-101NB in Los Angeles. The objective of the data collection is to obtain highly detailed data to study vehicle interactions in car-following and lane changing. A total of 11, 779 vehicle trajectories are available. The format is vehicle ID, lane and position at 0.1 sec intervals.

The I-80EB site is part of the Berkeley Highway Laboratory (BHL). The site is Type B weaving section per HCM2000 with a length of 1,650 ft; there are six freeway lanes entering the weaving section and five freeway lanes leaving it. Lane 1 is an HOV lane. Data on freeway operations are collected from multiple video cameras located on top of a 300 ft building adjacent to the freeway, and loop detectors placed approximately at 0.3 mile intervals on each freeway lane. The video data are processed through a machine vision system that tracks each vehicle as travels through the section and produces vehicle trajectories.

The US-101NB has five through lanes with a continuous auxiliary lane (Type A weaving section). The data include 45 minutes of vehicle trajectories in transition (7:50 to 8;05 am) and congestion (8:05 – 8:35 am).

4.1.4 The NCHRP 3-75 Database

The data base for NCHRP Project 3-75 consists of 14 sites in four different regions of the country. The data on traffic volumes and speeds were collected using video recordings. The data from the two California sites (I-80EB in Emeryville and US-101NB in Los Angeles) were provided by the NGSIM program (described in Section 4.1.3).

Table 4.3 shows the basic characteristics of the test sites, and Appendix B includes the schematics of each test site. A total of 157 5-minute data periods exist, which are also configured as 52 15-minute data periods. Most of the weaving sections are Type B per HCM2000 with five lanes.

Following review of the sites and the data provided, the following sites were excluded from the study database (shown as shaded cells in Table 4.3):

> *Site #3 I-270WB*: This is essentially a one-lane connector plus an auxiliary lane, with a speed of 35 mph. It is not a typical freeway weaving site.
>
> *Site #4 Los Angeles US-101NB (NGSIM 2):* This is a six lane weaving section. The evaluation of existing methods for developing the performance matrix includes weaving sections with up to five lanes.
>
> *Site #6 I-95NB*: This is a two sided weaving section. The scope of the study includes only one sided weaving section.

The final NCHRP data sets included in the study database consist of 11 sites with 113 data points of volumes and speeds.

Table 4.3 The NCHRP 3-75 Database [2]

Site	Location	Type	Length (ft)	# Lanes (N)	Data Periods
1	Emeryville, CA I-80 EB (NGSIM1)	B	1,605	6*	6
2	Portland, OR I-405 EB	B	650	4	6
3	Ohio I-270 WB	A	540	2	24
4	Los Angeles, CA US-101 NB (NGSIM2)	A	698	6	9
5	Miami, FL I-95 SB	B	1,120	5	7
6	Miami, FL I-95 NB	C	1,380	4	12
7	Baltimore, MD MD-100 EB	A	465	3	12
8	Baltimore, MD MD-100 EB	B	1,085	3	12
9	Phoenix, AZ SR 202 EB	B	2,110	5*	12
10	Phoenix, AZ SR 101 EB	C	2,235	5	12
11	Phoenix, AZ SR 101 WB	B	2,010	4	12
12	Portland, OR SR 217 SB	B	2,820	3	12
13	Portland, OR I-5 SB	B	1,565	4	12
14	Portland, OR I-5 SB	B	2,060	5	12

** Includes an HOV lane*

Excluded from the study database

Type: Weaving section configuration per HCM2000
L: length of the weaving section (ft)
N: Number of lanes in the weaving section
Data Periods: Number of 5 minute data periods available

4.1.5 Caltrans District 5 Data

Caltrans District 5 provided data on freeway weaving sections mostly along US-101 in Santa Barbara. The data include geometrics and traffic volumes. Speed data are not available. Most of the sites are three lanes wide and do not include auxiliary lanes. Table 4.4 shows basic information of the District 5 datasets. There are a total of 11test sites with 22 data points.

Table 4.4 Caltrans District 5 Database

Site	HCM Type	N	N_b	L	V (pcph)	VR
US-101SB_SB_1	A	3	2	2379	3242	0.61
		3	2	2379	2451	0.66
US-101SB_SB_4	A	4	3	1181	5093	0.32
		4	3	1181	5658	0.28
US-101NB_SB_1		3	3	3199	5617	0.32
		3	3	3199	6091	0.31
US-101NB_SB_2		3	3	3084	4957	0.16
		3	3	3084	5376	0.15
US-101NB_SB_3		3	3	3986	5136	0.26
		3	3	3986	5094	0.29
US-101NB_SB_4		3	3	3773	3134	0.46
		3	3	3773	3867	0.39
US-101SB_SB_2		2	2	3199	3422	0.31
		2	2	3199	3412	0.44
US-101SB_SB_3		3	3	3281	4852	0.27
		3	3	3281	5809	0.28
US-101SB_SB_5		3	3	1558	5243	0.38
		3	3	1558	5102	0.40
US-101SB_SB_6		3	3	3445	4623	0.43
		3	3	3445	4426	0.44
US-101SB_SB_7		3	3	1312	3958	0.24
		3	3	1312	3665	0.25

N: Number of lanes in the weaving section
Nb: Number of approaching freeway lanes
L: length of the weaving section (ft)
V: Total volume in the weaving section (passenger cars/hr)
VR: Ratio of weaving volume to total volume

4.2 The Study Database

The final database consists of 36 test sites and a total of 189 data points. Table 4.5 shows the available datasets per geometric characteristics (number of lanes and configuration), and Table 4.6 shows a mapping of the data available to the cells in the weaving performance matrix.

Table 4.5 The Study Database: Geometric Characteristics

CONFIGURATION	Number of Lanes in the Weaving Section			
	N=2	**N=3**	**N=4**	**N=5**
NO AUXILIARY LANE	*US-101SB_SB2*	*US-101SB_SB3* *US-101SB_SB4* *US-101SB_SB5* *US-101SB_SB6* *US-101SB_SB7* *US-101NB_SB1* *US-101NB_SB2* *US-101NB_SB3*		
RAMP WEAVE **HCM TYPE A**		**MD-100EB_A** *US-101SB_SB1*	*US-101SB_SB4*	***US-101SB*** SR-91EB SR-91WB I-110EB US-101NB I-10WB SR-60EB I-5SB
MAJOR WEAVE **BALANCED** **HCM TYPE B**		**MD-100EB_B** ***SR-92WB*** **SR-217SB**	**I-405EB** **SR-101WB** **I-5SB_A**	**I-80EB** **I-95SB** **SR-202EB** **I-5SB_B** ***I-805NB*** ***I-10WB_SB*** ***I-10WB_LA***
MAJOR WEAVE **UNBALANCED** **HCM TYPE C**				***US-101NB*** **SR-101EB** ***I-280SB***

XXX: NCHRP/NGSIM Data ***XXX: California Major Weaving Sites Data***
XXX: California Ramp Weaves Data
XXX: Caltrans District 5 Data

Table 4.6 Mapping the Datasets to the Performance Matrix

No. of Lanes in Weaving Section, N = 2

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy			*US-101SB_SB2 (2)*									
Non-Weaving: Heavy Weaving: Mid to Low												
Non-Weaving: Mid to Low Weaving: Heavy												
Non-Weaving: Mid to Low Weaving: Mid to Low												

No. of Lanes in Weaving Section, N = 3

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy			*US-101SB_SB3 (1)* *US-101NB_SB1 (2)* *US-101NB_SB3 (2)*									
Non-Weaving: Heavy Weaving: Mid to Low			*US-101NB_SB2 (2)*	**MD-100EB_A(10)**				***SR-92WB (3)*** **MD-100EB_B(11)**	**SR-217SB (12)**			
Non-Weaving: Mid to Low Weaving: Heavy		*US-101SB_SB5 (2)*	*US-101SB_SB4 (2)* *US-101SB_SB3 (1)* *US-101SB_SB6 (2)*									
Non-Weaving: Mid to Low Weaving: Mid to Low		*US-101SB_SB7 (2)*		**MD-100EB_A(2)**	*US-101SB_SB1 (2)*			***SR-92WB (1)*** **MD-100EB_B(1)**				

No. of Lanes in Weaving Section, N = 4

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy								**I-5SB_A (2)** **SR-101WB (7)**				
Non-Weaving: Heavy Weaving: Mid to Low					*US-101SB_SB4 (1)*		**I-405 EB (3)**	**I-5SB_A (5)** **SR-101WB (3)** **SR-202EB (12)**				
Non-Weaving: Mid to Low Weaving: Heavy								**I-5SB_A (3)**				
Non-Weaving: Mid to Low Weaving: Mid to Low					*US-101SB_SB4 (1)*		**I-405 EB (3)**	**I-5SB_A (2)** **SR-101WB (2)**				

No. of Lanes in Weaving Section, N = 5

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy								**I-80EB (5)**		***US-101NB (2)***		
Non-Weaving: Heavy Weaving: Mid to Low				***US-101SB (2)*** SR-91EB (2) I-110SB (3) US-101NB (1)	SR-60EB (3)			***I-805NB (1)*** **I-95SB (6)**			***I-280SB (3)*** **SR-101EB (5)**	
Non-Weaving: Mid to Low Weaving: Heavy								***I-10WB_LA (3)*** **I-5SB_B (1)** **I-80EB (1)**				
Non-Weaving: Mid to Low Weaving: Mid to Low				***US-101SB (1)*** SR-91EB (1) I-10WB (3) US-101NB (2)	SR-60EB (3) SR-91WB (3) I-5SB (6)			***I-805NB (3)*** ***I-10WB_LA (2)*** ***I-10 WB_SB (3)*** **I-5SB_B (9)** **I-95SB (1)**			***I-280SB (3)*** **SR-101EB (7)**	

XXX: NCHRP/NGSIM Data ***XXX: California Major Weaving Sites Data*** XXX: California Ramp Weaves Data *XXX: Caltrans District 5 Data*

CHAPTER 5

EVALUATION OF EXISTING METHODS

The existing weaving analysis tools were applied to the all the datasets shown in Table 4.6. The predictions from each method were compared to the field measurements within a site and across all sites to determine the strengths and limitations of each analysis tool. The following sections show sample results from the extensive analyses performed.

5.1 Application of Existing Methods to Field Data

Figure 5.1 shows a comparison of the field measured vs. HCM200 predicted weaving speeds by configuration of the weaving section. The data are from the California major weaving sites. It can be seen that HCM2000 under-predicts the weaving speeds in all the sites, especially for Type A (ramp weaves) sections. HCM2000 predictions are close to the field values for Type B weaving sections. In terms of overall average speeds in the weaving section, the mean speed difference between field and HCM2000 estimates are 25% for Type A, 2% for Type B and 10% for Type C weaving section configurations respectively.

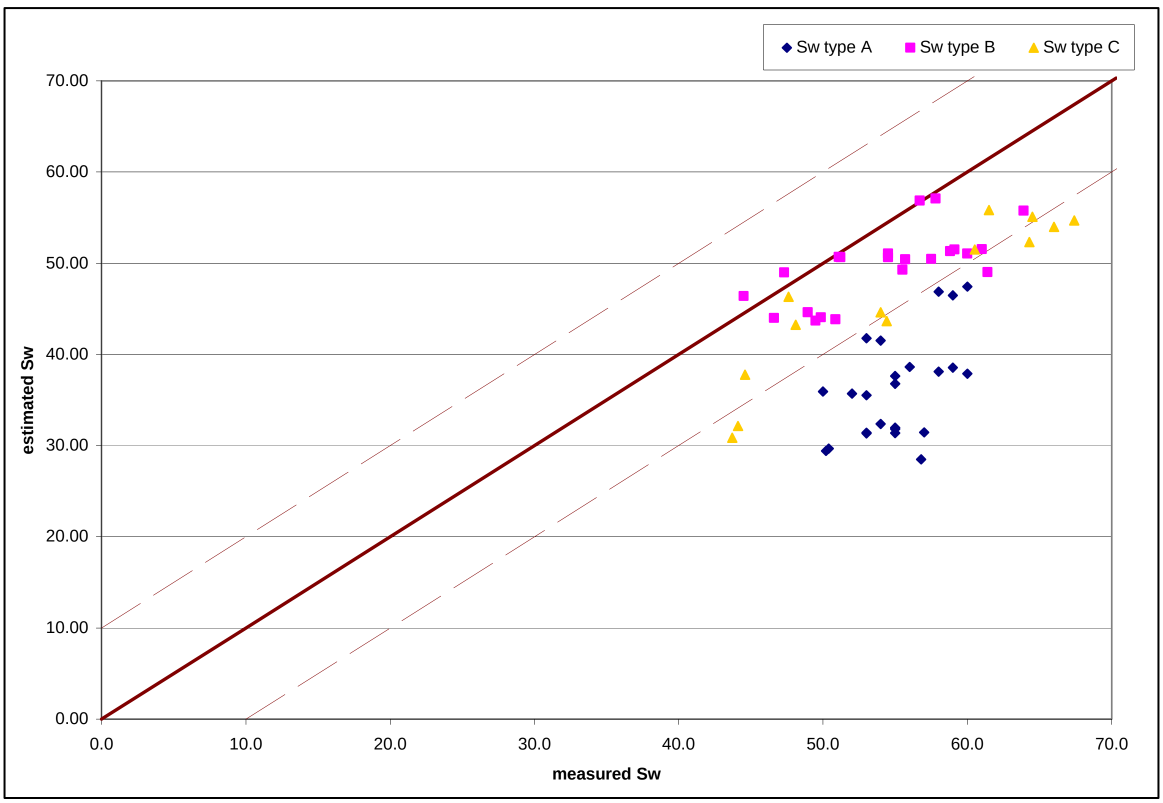


Figure 5.1 Measured vs. HCM2000 Predicted Weaving Speed

Comparisons with the NCHRP datasets show that both HCM2000 and Leisch methods predict a LOS in the weaving area different than the field in about 40 % of the test cases. The Level D method predicts that approximately 50% of the weaving data sets will "fail" (Level of Service D or worse); field data indicate that LOS D or worse occurs in 23% of the cases.

5.2 Santa Barbara Data Sets

The Caltrans District 5 datasets do not have field measured speeds for comparison with the model predictions. Therefore, we compared the predictions of the methods with the same data. Figure 5.2 shows the difference in LOS predicted by Level D vs. HCM2000 and Leisch methods for each dataset. It can be seen that Level D and Leisch methods are in agreement in 16 of the cases, i.e., in 73% of the cases Level D and Leisch predict the same LOS. Only in six datasets (27%) the two methods vary by one LOS designation. However, the differences are greater in the case of Level D vs. HCM2000. The two methods predict different LOS in 14 out of 22 datasets (64%); four datasets have a difference in traffic performance by two LOS designations.

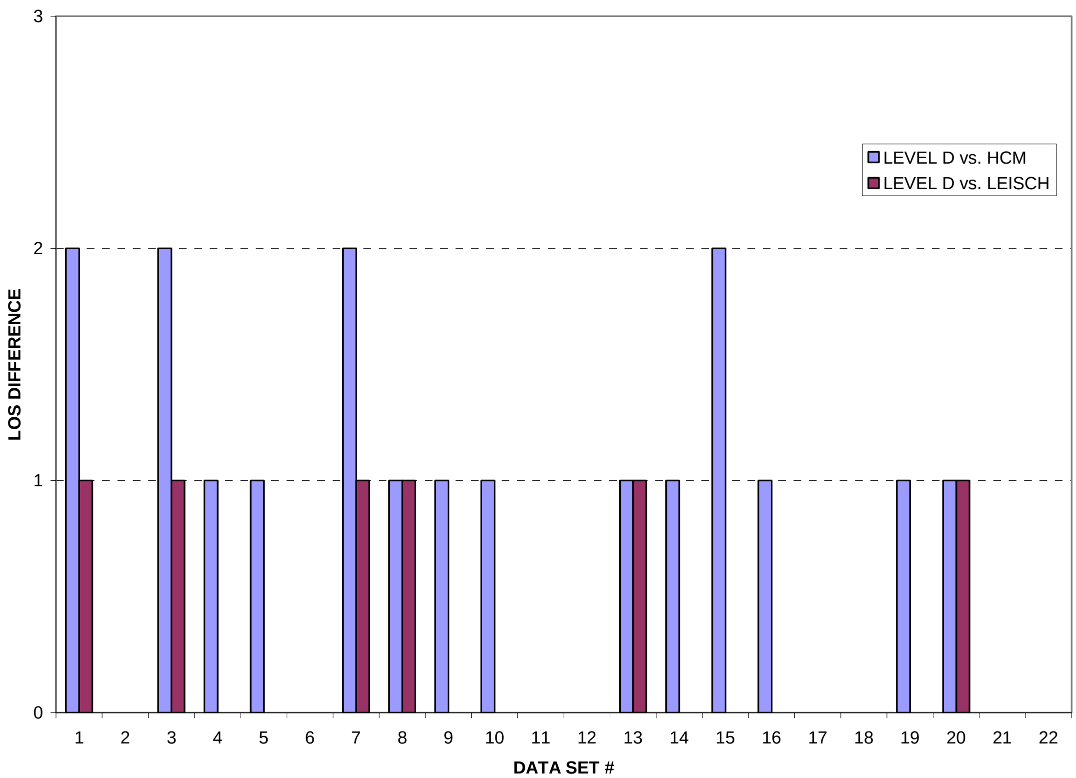


Figure 5.2 Comparison of Weaving Analysis Methods—Caltrans District 5 Data

5.3 Synthetic Data Sets

It can be seen from Table 4.6 that significant gaps in field data exist. Despite the efforts of the research team and the project advisory committee it was not possible to obtain additional real-world data sets. Therefore, we had to develop synthetic data sets representing operating conditions lacking field data. Table 5.1 shows the scenarios for which synthetic data were created. There are a total of 113 scenarios. Under each scenario, three synthetic datasets were created for a total of 339 datasets. For example, under scenario 20 (A three lane weaving section Type A with medium length and heavy non-weaving and weaving volumes), we generated three datasets for the given configuration and total volumes by assuming: i) balanced weaving volumes, ii) unbalanced weaving volumes with high on-ramp to freeway volume and low freeway to off-ramp volume, and iii) unbalanced weaving volumes with low on-ramp to freeway volume and high freeway to off-ramp volume.

Table 5.1 Synthetic Data Sets

No. of Lanes in Weaving Section, N = 2

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	98	102	*US-101SB_SB2 (2)*									
Non-Weaving: Heavy Weaving: Mid to Low	99	103	106									
Non-Weaving: Mid to Low Weaving: Heavy	100	104	107									
Non-Weaving: Mid to Low Weaving: Mid to Low	101	105	108									

No. of Lanes in Weaving Section, N = 3

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	78	2	*US-101SB_SB3 (1)* *US-101NB_SB1 (2)* *US-101NB_SB3 (2)*	18	20	23	39	43	45			
Non-Weaving: Heavy Weaving: Mid to Low	79	46	*US-101NB_SB2 (2)*	**MD-100EB_A(10)**	21	24	40	***SR-92WB (3)*** **MD-100EB_B(11)**	**SR-217SB (12)**			
Non-Weaving: Mid to Low Weaving: Heavy	80	*US-101SB_SB5 (2)*	*US-101SB_SB4 (2)* *US-101SB_SB3 (1)* *US-101SB_SB6 (2)*	19	22	25	41	44	47			
Non-Weaving: Mid to Low Weaving: Mid to Low	81	*US-101SB_SB7 (2)*	1	**MD-100EB_A(2)**	*US-101SB_SB1 (2)*	26	42	***SR-92WB (1)*** **MD-100EB_B(1)**	48			

No. of Lanes in Weaving Section, N = 4

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	82	12	86	27	14	31	16	**I-5SB_A (2)** **SR-101WB (7)**	49	59	63	67
Non-Weaving: Heavy Weaving: Mid to Low	83	109	87	28	*US-101SB_SB4 (1)*	32	**I-405 EB (3)**	**I-5SB_A (5)** **SR-101WB (3)** **SR-202EB (12)**	50	60	64	68
Non-Weaving: Mid to Low Weaving: Heavy	84	13	88	29	15	33	17	**I-5SB_A (3)**	51	61	65	69
Non-Weaving: Mid to Low Weaving: Mid to Low	85	110	89	30	*US-101SB_SB4 (1)*	34	**I-405 EB (3)**	**I-5SB_A (2)** **SR-101WB (2)**	52	62	66	70

No. of Lanes in Weaving Section, N = 5

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000- 2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	90	3	94	4	6	35	53	**I-80EB (5)**	55	***US-101NB (2)***	8	74
Non-Weaving: Heavy Weaving: Mid to Low	91	10	95	***US-101SB (2)*** SR-91EB (2) I-110SB (3) US-101NB (1)	SR-60EB (3)	36	112	***I-805NB (1)*** **I-95SB (6)**	56	71	***I-280SB (3)*** **SR-101EB (5)**	75
Non-Weaving: Mid to Low Weaving: Heavy	92	111	96	5	7	37	54	***I-10WB_LA (3)*** **I-5SB_B (1)** **I-80EB (1)**	57	72	9	76
Non-Weaving: Mid to Low Weaving: Mid to Low	93	11	97	***US-101SB (1)*** SR-91EB (1) I-10WB (3) US-101NB (2)	SR-60EB (3) SR-91WB (3) I-5SB (6)	38	113	***I-805NB (3)*** ***I-10WB_LA (2)*** ***I-10 WB_SB (3)*** **I-5SB_B (9)** **I-95SB (1)**	58	73	***I-280SB (3)*** **SR-101EB (7)**	77

XXX: NCHRP/NGSIM Data ***XXX: California Major Weaving Sites Data*** XXX: California Ramp Weaves Data *XXX: Caltrans District 5 Data* XX **Synthetic Data**

Since there are no field data available for comparison with each method's predictions, emphasis is placed on comparing the methods' results with the same input data, similar to the analysis performed for the Caltrans District 5 datasets.

Figure 5.3 shows the difference between the predicted LOS from HCM2000 and Leisch methods for each dataset. The value of (-1) in the Figure means that HCM2000 predicts better performance by one LOS than the Leisch method. It can be seen that Leisch in general predicts worse Level of Service than HCM2000. HCM2000 predicts worse performance by two LOS designations for short Type A weaving sections (ramp weaves) with heavy volumes.

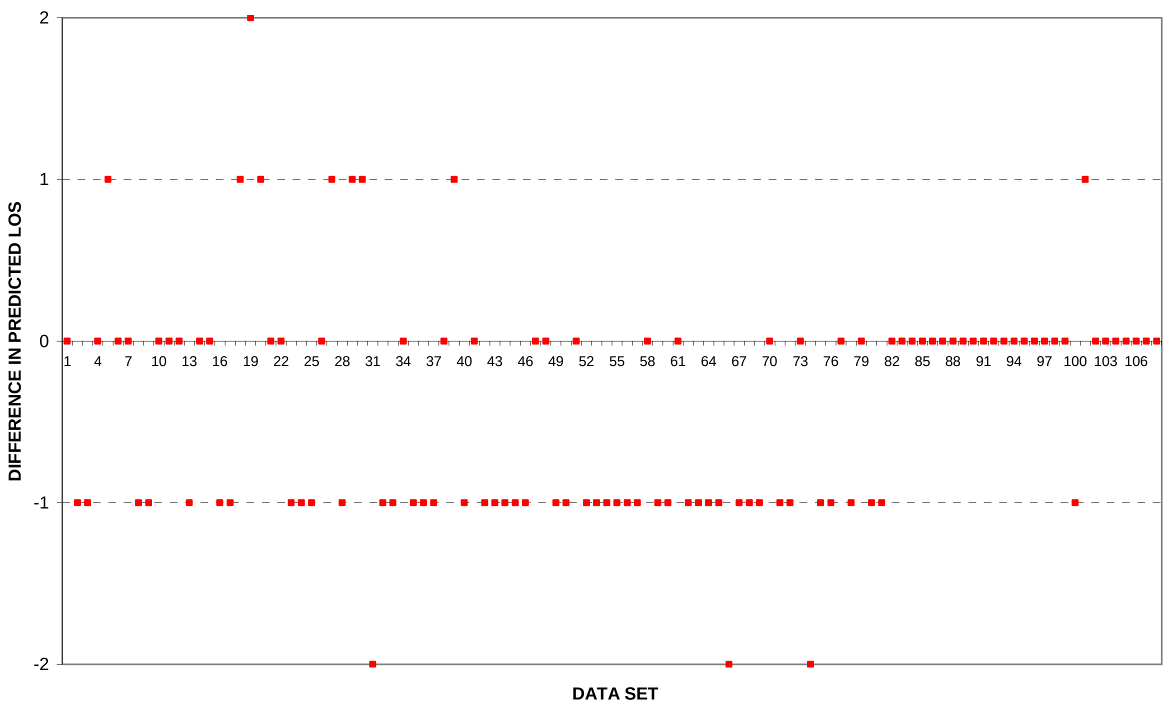


Figure 5.3 Comparison of Leisch vs. HCM2000—Synthetic Data Sets

Comparisons of Level D method with the Leisch and HCM2000 methods shows similar patterns as in the case of Santa Barbara data sets, but there are significant variations among different cases. The results are summarized in Table 5.2 in the same scenario groupings as in Table 5.1. It can be seen that Level D predicts different LOS than HCM2000 and Leisch methods in the cases of ramp weaves with auxiliary lanes. Note that scenarios with multiple on and off-ramps are not included because they cannot be analyzed with the Level D method.

Table 5.2 Differences in LOS Prediction --Synthetic Data Sets

SCENARIOS *				Level D vs. HCM	Level D vs. Leisch
N=2	98	102			
No Auxiliary Lane	99	103	106		
	100	104	107	**0**	**0**
	101	105	108		
N=3	78	2			
No Auxiliary Lane	79	46		**0**	**0**
	80				
	81		1		
N=4	82	12	86		
No Auxiliary Lane	83	109	87	**0**	**0**
	84	13	88		
	85	110	89		
N=5	90	3	94		
No Auxiliary Lane	91	10	95	**0**	**0**
	92	111	96		
	93	11	97		
N=3	18	20	23		
Auxiliary Lane		21	24	**3**	**0**
	19	22	25		
			26		
N=4	27	14	31		
Auxiliary Lane	28		32	**2**	**3**
	29	15	33		
	30		34		
N=5	4	6	35		
Auxiliary Lane			36	**2**	**2**
	5	7	37		
			38		

**Data Sets with multiple on/off ramps not included.*
Level D method not designed for multiple on/off ramps

CHAPTER 6
CONCLUSIONS

6.1 Summary of the Study Findings

The objectives of the study were to a) evaluate the existing weaving analysis procedures to determine under which conditions the "best available" tools are most effective, and b) develop a new weaving analysis method. The end product of the study is an analysis performance matrix that gives guidance on which of the existing analysis methods should be applied for a particular weaving section under study. A new simulation model was also developed to predict the performance of weaving areas.

The HCM2000, Leisch and Level D methods were evaluated using field data from 36 real-world weaving sections for a total of 189 data points of speed and volumes. The analysis of the results identified the strengths and limitations of each method in determining the performance of a freeway weaving section for a range of operating conditions.

Additional analyses were performed by applying the selected analysis methods to synthetic datasets for the geometric and operating conditions that field data were not available. A total of 339 datasets were created. The analysis of the results focused on the consistency of the predictions from each analysis method.

6.2 Recommendations

The proposed weaving analysis performance matrix for each method are shown in Appendix C. The performance matrix is based on the comparison between observed (when available) and predicted conditions from each method. For those operating conditions that field data were not available, the recommended indicators of performance ("good", "inconsistent", "and poor") are based on the comparison of the results from the different method. Also, shown are cells with synthetic data (indicated by X), cells with limited data (indicated XX, typically one real-world data set), and cells with multiple field data sets (indicated by XXX). The performance matrix for each method is also submitted as an Excel spreadsheet and it can be readily updated should more data and analyses become available.

Note that the existing methods appear to have the same performance on several design and operating conditions. In such situations, Caltrans engineers should follow existing guidance as in the Caltans Design Manual, i.e., apply the Leisch method and check operating conditions with Level D method if applicable, because of the complexity in the HCM2000 method relative to the other methods.

6.3 Future Research

The following research activities are suggested towards improving the design and analysis methods for freeway weaving sections:

a) *Update and refinement of the proposed performance matrices*: Several cells in the proposed performance matrix for each method are lacking field data on traffic performance. There is a need to obtain additional data and update these matrices.

b) *Weaving section capacity:* The existing methods do not directly provide estimates of the capacity of the weaving section. There is a need to evaluate the accuracy of the methods regarding capacity prediction, by selecting weaving sites that are bottlenecks and comparing predicted and observed queue discharge flows.

c) *Evaluation of New HCM Weaving Analysis Method:* A new weaving analysis method has been developed as part of the NCHRP study and has been adopted for the next edition of the HCM in late 2010. This method is simpler to use than the existing HCM2000 method because it does not have separate procedures per each weaving configuration and constrained vs. unconstrained operation. This method should be evaluated using the same data used in this study to determine if it an appropriate analysis tool to be used by Caltrans staff.

d) *Evaluation and Refinement of the Weaving Software Tool:* a simulation model was developed in this study to analyze weaving sections based on field data from two weaving bottlenecks. This tool can be potentially used on several freeway operations analyses (e.g., auxiliary lane lengths, ramp metering) provided that accurately represents real-world operating conditions. There is a need for systematic model testing with field data and refinement in order to be a practical analysis tool by Caltrans staff.

e) REFERENCES

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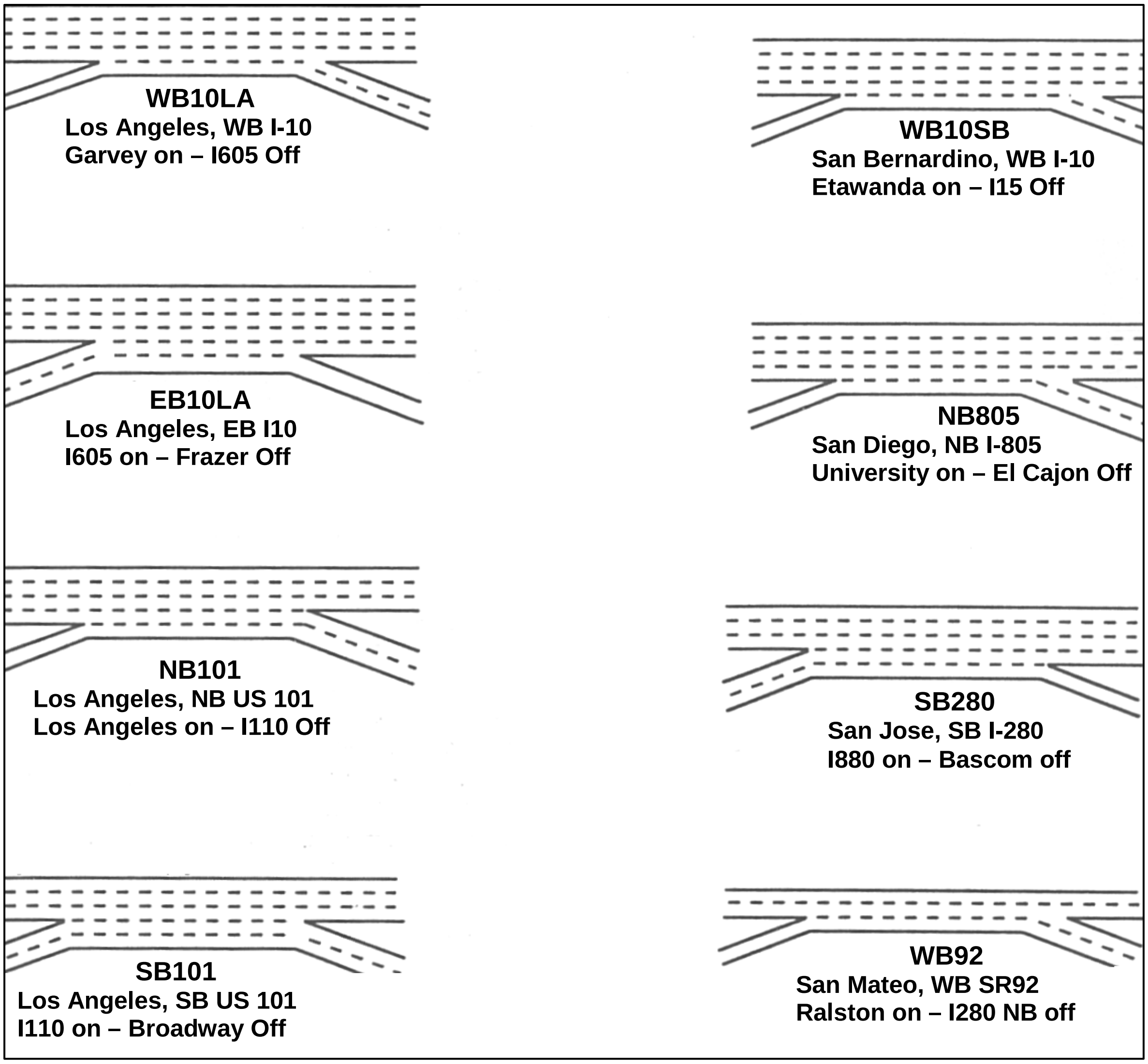
APPENDIX A: CALIFORNIA STUDIES-MAJOR WEAVING SECTIONS



APPENDIX B: NCHRP 3-75 TEST SITES

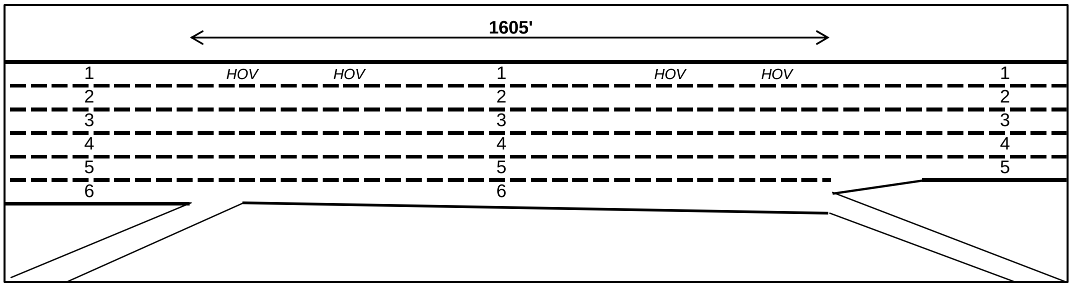


Figure B1. Site 1: I-80EB; Powell St to Ashby Avenue, Emeryville, CA

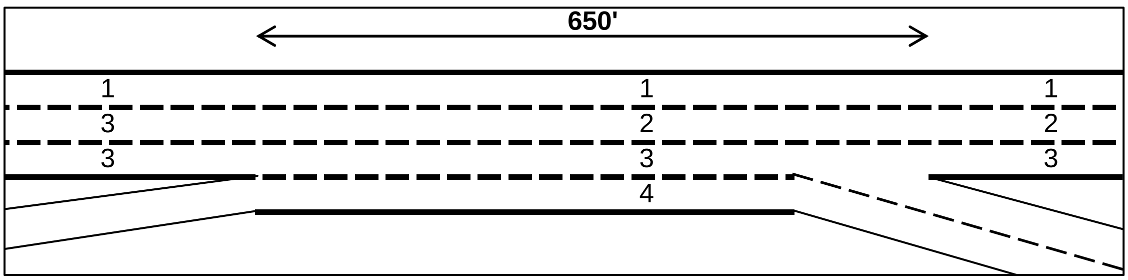


Figure B2. Site 2: I-405EB; 6th Avenue to 12th Avenue, Portland, OR

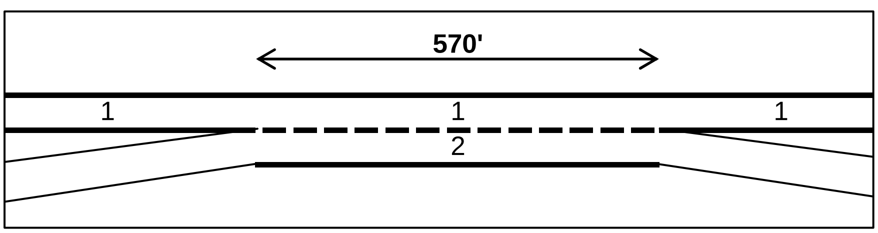


Figure B3. Site 3: I-270WB; I-270 & US23, Franklin Co, OH

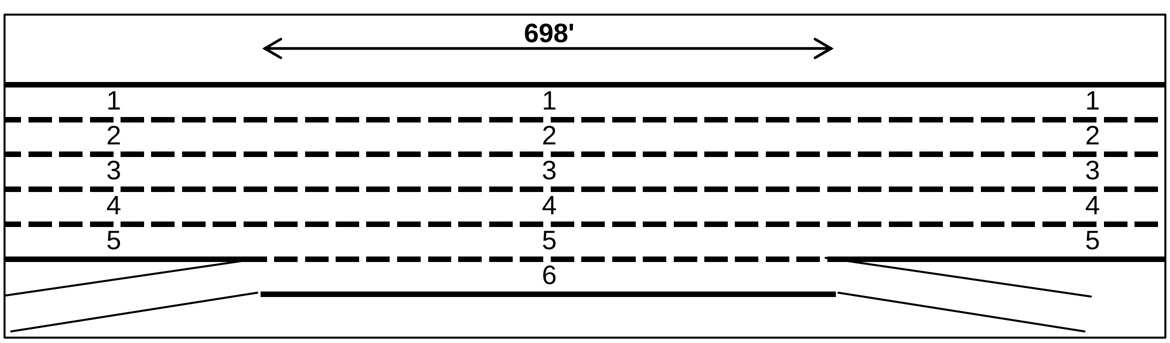


Figure B4. Site 4: US-101NB; Ventura Blvd to Cahuenga Blvd, Los Angeles, CA

APPENDIX B: NCHRP 3-75 TEST SITES (Cont.)

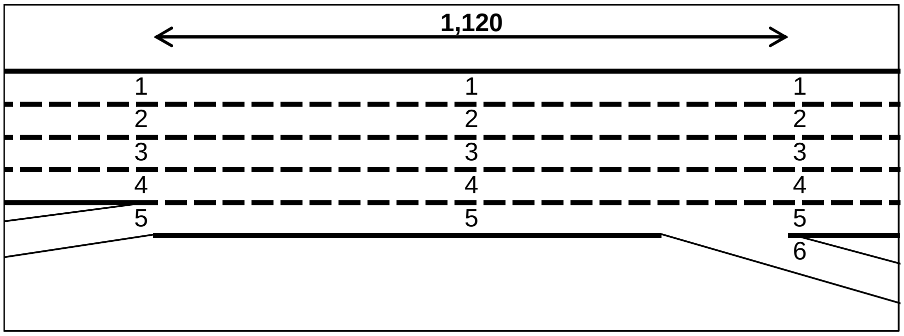


Figure B5. Site 5: I-95SB; NW 135th St to N. Miami Blvd., Miami, FL

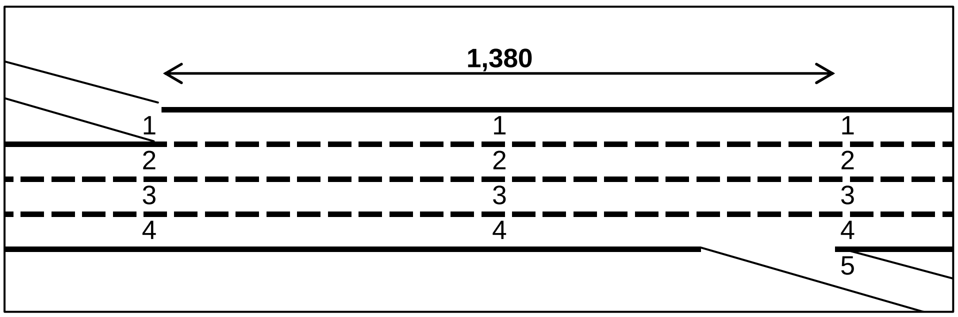


Figure B6. Site 6: I-95NB; SE 8th St to SE 1st St., Miami, FL

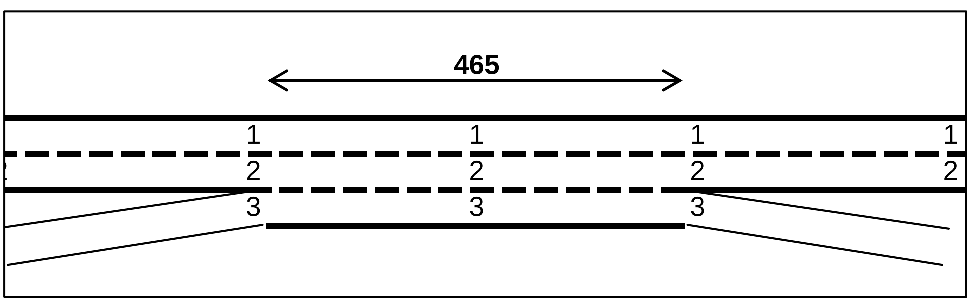


Figure B7. Site 7: MD-100EB; I-95SB to I-95NB, Baltimore, MD

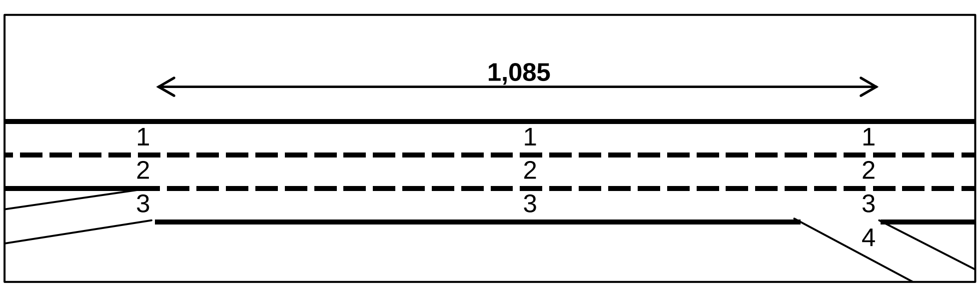


Figure B8. Site 8: MD-100EB; I-95NB to US Rte 1, SB, Baltimore, MD

APPENDIX B: NCHRP 3-75 TEST SITES (Cont.)

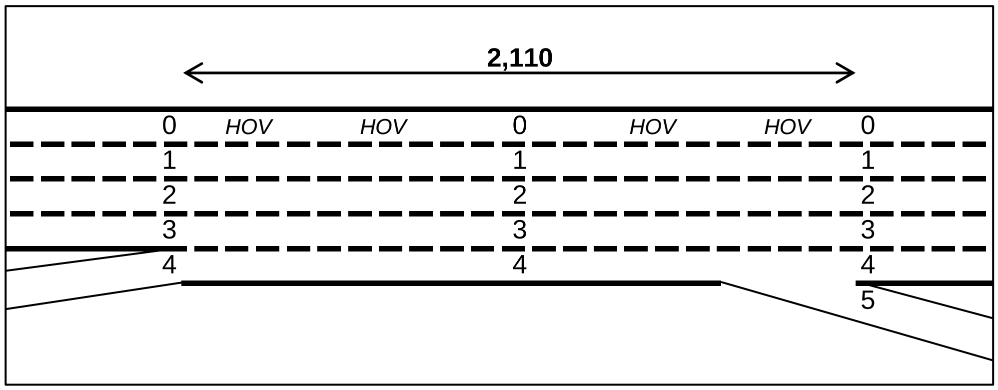


Figure B9. Site 9: SR202 EB; 32nd St to 40th St, Phoenix, AZ

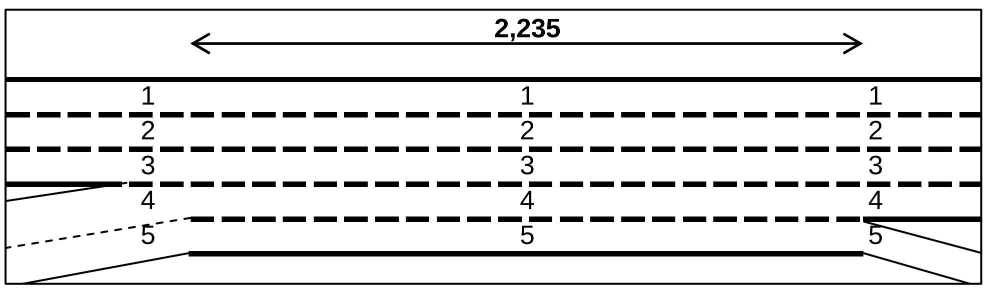


Figure B10. Site 10: SR201 EB; SR 51 to Tatum Blvd, Phoenix, AZ

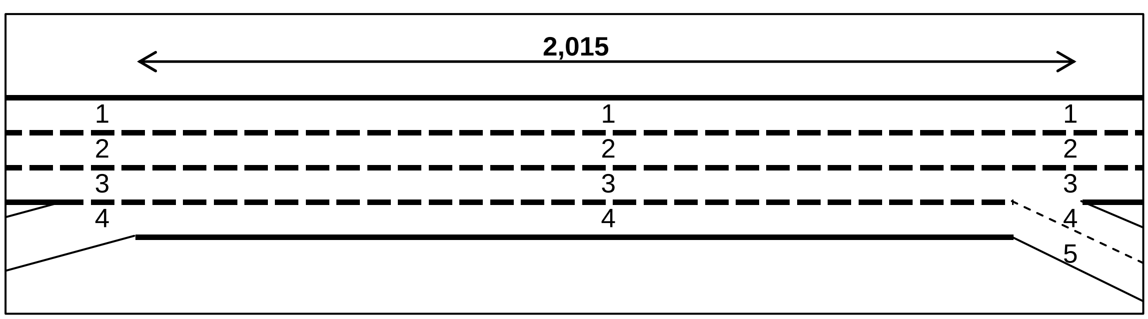


Figure B11. Site 11: SR101 WB; Tatum Blvd to SR 51, Phoenix, AZ

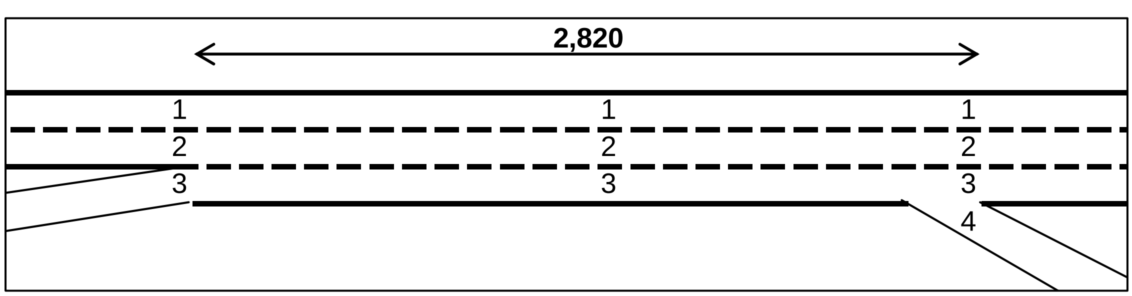


Figure B12. Site 12: SR217SB; SW Pacific Hwy to SW 72nd Ave, Portland, OR

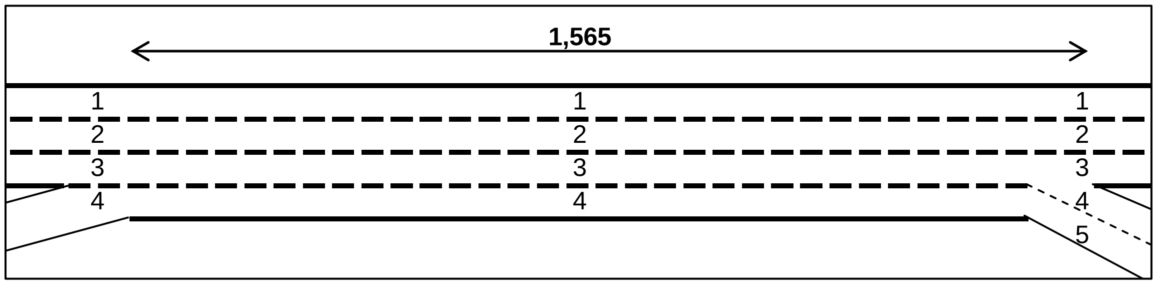


Figure B13. Site 13: I-5SB; SW Nyberg Rd to I-205, Portland, OR

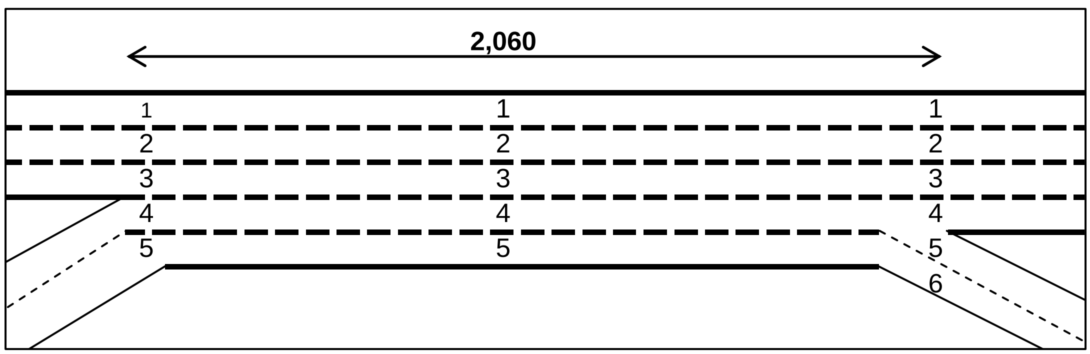


Figure B14. Site 14: I-5SB; SR-217 to Upper Boones Ferry Rd, Portland, OR

APPENDIX C
WEAVING ANALYSIS PERFORMANCE MATRIX

C1. HCM2000 Method

C2. Leisch Method

C3. Level D Method

C4. Weaving Analysis Performance Matrix – Recommended Methodology

APPENDIX C

C1. Weaving Analysis Performance Matrix—HCM2000 Method

Weaving Analysis Performance Matrix

Methodology: **HCM2000**

No. of Lanes in Weaving Section, N = 2

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	XX									
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X									
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X									
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X									

No. of Lanes in Weaving Section, N = 3

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	XXX	X	X	X	X	X	X			
Non-Weaving: Heavy Weaving: Mid to Low	X	X	XX	XX	X	X	X	XXX	XX			
Non-Weaving: Mid to Low Weaving: Heavy	X	XX	XXX	X	X	X	X	X	X			
Non-Weaving: Mid to Low Weaving: Mid to Low	X	XX	X	XX	XX	X	X	XXX	X			

No. of Lanes in Weaving Section, N = 4

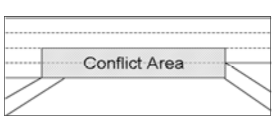
Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	X	X	X	X		XXX	X	X	X	X
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X	X	XX	X	XX	XXX	X	X	X	X
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X	X	X	X	X	XX	X	X	X	X
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X	X	XX	X	XX	XXX	X	X	X	X

No. of Lanes in Weaving Section, N = 5

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	X	X	X	X	X	XX	X	XX	X	X
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X	XXX	XX	X	X	XXX	X	X	XXX	X
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X	X	X	X	X	XXX	X	X	X	X
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X	XXX	XXX	X	X	XXX	X	X	XXX	X

LEGEND: Methodology's prediction of performance

= Poor, inconsistent results
= Fair; sometimes inconsistent results
= Good and consistent results



X Synthetic Data
XX Limited Data
XXX Multiple Data Sets

Notes

* All weaving sections considered are single side, right side configurations (i.e. does not include left side or two sided configurations)

Non-weaving Vols in vph: **N – [# lanes in conflict area] =

1 lane:	Heavy = >1,800; Mid to Low < 1,800
2 lanes:	Heavy = >3,600; Mid to Low < 3,600
3 lanes:	Heavy = >5,400; Mid to Low < 5,400
4 lanes:	Heavy = >7,200; Mid to Low < 7,200

Weaving Vols in vph: **[# lanes in conflict area] =

1 lane:	Heavy = >1,000; Mid to Low < 1,000
2 lanes:	Heavy = >2,000; Mid to Low < 2,000
3 lanes:	Heavy = >3,000; Mid to Low < 3,000

APPENDIX C

C2. Weaving Analysis Performance Matrix—Leisch Method

Weaving Analysis Performance Matrix

Methodology: **LEISCH**

No. of Lanes in Weaving Section, N = 2

Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	XX									
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X									
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X									
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X									

No. of Lanes in Weaving Section, N = 3

Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	XXX	X	X	X	X	X	X			
Non-Weaving: Heavy Weaving: Mid to Low	X	X	XX	XX	X	X	X	XXX	XX			
Non-Weaving: Mid to Low Weaving: Heavy	X	XX	XXX	X	X	X	X	X	X			
Non-Weaving: Mid to Low Weaving: Mid to Low	X	XX	X	XX	XX	X	X	XXX	X			

No. of Lanes in Weaving Section, N = 4

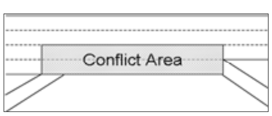
Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	X	X	X	X	X	XXX	X	X	X	X
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X	X	XX	X	XX	XXX	X	X	X	X
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X	X	X	X	X	XX	X	X	X	X
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X	X	XX	X	XX	XXX	X	X	X	X

No. of Lanes in Weaving Section, N = 5

Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	X	X	X	X	X	XX	X	XX	X	X
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X	XXX	XX	X	X	XXX	X	X	XXX	X
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X	X	X	X	X	XXX	X	X	X	X
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X	XXX	XXX	X	X	XXX	X	X	XXX	X

LEGEND: Methodology's prediction of performance

= Poor, inconsistent results
= Fair; sometimes inconsistent results
= Good and consistent results



X Synthetic Data
XX Limited Data
XXX Multiple Data Sets

Notes

* All weaving sections considered are single side, right side configurations (i.e. does not include left side or two sided configurations)

Non-weaving Vols in vph: **N – [# lanes in conflict area] =

1 lane:	Heavy = >1,800; Mid to Low < 1,800
2 lanes:	Heavy = >3,600; Mid to Low < 3,600
3 lanes:	Heavy = >5,400; Mid to Low < 5,400
4 lanes:	Heavy = >7,200; Mid to Low < 7,200

Weaving Vols in vph: **[# lanes in conflict area] =

1 lane:	Heavy = >1,000; Mid to Low < 1,000
2 lanes:	Heavy = >2,000; Mid to Low < 2,000
3 lanes:	Heavy = >3,000; Mid to Low < 3,000

APPENDIX C

C3. Weaving Analysis Performance Matrix—Level D Method

Weaving Analysis Performance Matrix

Methodology: LEVEL D

No. of Lanes in Weaving Section, N = 2

Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	XX									
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X									
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X									
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X									

No. of Lanes in Weaving Section, N = 3

Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	XXX	X	X	X						
Non-Weaving: Heavy Weaving: Mid to Low	X	X	XX	XX	X	X						
Non-Weaving: Mid to Low Weaving: Heavy	X	XX	XXX	X	X	X						
Non-Weaving: Mid to Low Weaving: Mid to Low	X	XX	X	XX	XX	X						

No. of Lanes in Weaving Section, N = 4

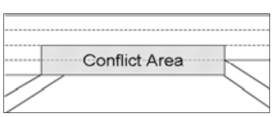
Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	X	X	X	X						
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X	X	XX	X						
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X	X	X	X						
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X	X	XX	X						

No. of Lanes in Weaving Section, N = 5

Configuration* --->	**No Auxiliary Lane, 1-lane on & off ramps**			**With Aux. Lane, 1-lane on/off ramps (Type A)**			**Balanced >1-lane on & off ramps (Type B)**			**Unbalanced >1-lane on & off ramps (Type C)**		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	X	X	X	X	X	X						
Non-Weaving: Heavy Weaving: Mid to Low	X	X	X	XXX	XX	X						
Non-Weaving: Mid to Low Weaving: Heavy	X	X	X	X	X	X						
Non-Weaving: Mid to Low Weaving: Mid to Low	X	X	X	XXX	XXX	X						

LEGEND: Methodology's prediction of performance

= Poor, inconsistent results
= Fair; sometimes inconsistent results
= Good and consistent results



METHOD NOT DESIGNED FOR MULTIPLE ON/OFF RAMPS

X Synthetic Data
XX Limited Data
XXX Multiple Data Sets

Notes

* All weave sections considered are single side, right side configurations (i.e. does not include left side or two sided configurations)

Non-weaving Vols in vph: **N – [# lanes in conflict area] =
1 lane: Heavy = >1,800; Mid to Low < 1,800
2 lanes: Heavy = >3,600; Mid to Low < 3,600
3 lanes: Heavy = >5,400; Mid to Low < 5,400
4 lanes: Heavy = >7,200; Mid to Low < 7,200

Weaving Vols in vph: **[# lanes in conflict area] =
1 lane: Heavy = >1,000; Mid to Low < 1,000
2 lanes: Heavy = >2,000; Mid to Low < 2,000
3 lanes: Heavy = >3,000; Mid to Low < 3,000

C4. Weaving Analysis Performance Matrix—Recommended Methodology

Weaving Analysis Performance Matrix

Recommended Methodology

No. of Lanes in Weaving Section, N = 2

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**									
Non-Weaving: Heavy Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**									
Non-Weaving: Mid to Low Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**									
Non-Weaving: Mid to Low Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**									

No. of Lanes in Weaving Section, N = 3

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**LEISCH LEVEL D**	**LEISCH LEVEL D**	**LEISCH LEVEL D**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**			
Non-Weaving: Heavy Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000**			
Non-Weaving: Mid to Low Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**			
Non-Weaving: Mid to Low Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**			

No. of Lanes in Weaving Section, N = 4

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**LEISCH LEVEL D**	**LEISCH LEVEL D**	**LEISCH LEVEL D**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**
Non-Weaving: Heavy Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**
Non-Weaving: Mid to Low Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**
Non-Weaving: Mid to Low Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000**	**HCM2000**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**

No. of Lanes in Weaving Section, N = 5

Configuration* --->	No Auxiliary Lane, 1-lane on & off ramps			With Aux. Lane, 1-lane on/off ramps (Type A)			Balanced >1-lane on & off ramps (Type B)			Unbalanced >1-lane on & off ramps (Type C)		
Operational Conditions(vols) **	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')	Short Weave Length (<1000')	Medium Weave Length (1000-2500')	Generous Weave Length (>2500')
Non-Weaving: Heavy Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**LEISCH LEVEL D**	**LEISCH LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**
Non-Weaving: Heavy Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**LEISCH LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**
Non-Weaving: Mid to Low Weaving: Heavy	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**LEISCH LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**
Non-Weaving: Mid to Low Weaving: Mid to Low	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH/ LEVEL D**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000**	**HCM2000 LEISCH**	**HCM2000 LEISCH**	**HCM2000 LEISCH**

APPENDIX D

Lee, J.H., and M.C. Cassidy,
"AN EMPIRICAL AND THEORETICAL STUDY OF FREEWAY WEAVE BOTTLENECKS"
PATH Research Report UCB-ITS-PRR-2009-13
February, 2009.

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

An Empirical and Theoretical Study of Freeway Weave Bottlenecks

Joon ho Lee, Michael J. Cassidy

California PATH Research Report
UCB-ITS-PRR-2009-13

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Part I: An Empirical and Theoretical Study

of

Freeway Weave Bottlenecks

by

Joon ho Lee

and

Professor Michael J. Cassidy

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ABSTRACT

The present research performed an empirical and theoretical analysis on what triggers bottleneck activations and discharge flow changes in weaving sections. Investigations revealed that changes in the spatial distributions of mandatory lane changes, especially for Freeway-to-Ramp (F-R) maneuvers, led to variations in bottleneck discharge flows. When the F-R maneuvers were concentrated near on-ramp, they became more disruptive, resulting in bottleneck activations with reductions in discharge flows. Findings further indicate that the spatial distributions of these lane changes, in turn, were dictated by the traffic conditions in the auxiliary lane. On-ramp flow reductions increased the attractiveness of the auxiliary lanes, thus motivating F-R drivers to perform their maneuvers nearer the on-ramp, and vice versa. A micro-simulation model was developed based on the observed lane-changing behaviors, and it successfully reproduced the observed mechanisms of weaving bottleneck flows.

Keywords: Weaving, Weaving sections, Simulation, Discrete choice modeling

EXECUTIVE SUMMARY

Though there have been numerous studies of freeway weaving sections (i.e., segments in which an on-ramp is followed by an off-ramp), there remains a significant lack of empirical and theoretical understanding of the traffic behavior that causes weaving sections to become bottlenecks with varying discharge flows. The present research entails empirical analysis and theoretical modeling of what triggered the bottleneck activations and discharge flow changes in two freeway weaving sections. Both sites were recurrent bottlenecks during the rush, and investigations revealed that changes in the spatial patterns of vehicular lane-changes, especially among Freeway-to-Ramp (F-R) maneuvers, caused variations in bottleneck discharge flow. When the F-R maneuvers were concentrated near a weaving section's on-ramp, they became more disruptive, resulting in bottleneck activations with diminished discharge flows. Findings further indicated that the spatial distributions of these lane changes, in turn, were dictated by the traffic conditions in the auxiliary lane (i.e., the lane connecting the off-ramp to the upstream on-ramp). Reductions in on-ramp flows increased the attractiveness of the auxiliary lane, thus motivating F-R drivers to perform their maneuvers nearer the on-ramp. Conversely, increases in on-ramp flows motivated F-R drivers to perform their maneuvers over a wider stretch of the weaving section.

Based on these empirical findings, the study formulated a theory for *mandatory* lane changing (i.e., lane changes required of a desired Origin-Destination pattern); and used this theory to enhance an existing microsimulation model of car-following and lane

changing. With this new theory, the driver's decision to attempt a lane change is determined by the vehicle's distance from the downstream end of the weaving section's diverge area, the number of lanes to be crossed in reaching the desired destination, and the difference in densities between the driver's target lane and her current one. The model reproduces the observed mechanisms of bottleneck activation and discharge flow changes in weaving sections. These empirical findings, together with the outcomes of simulation, point to two key features of driver behavior in weaving sections: i) traffic conditions (especially densities) in an auxiliary lane influence drivers' decisions regarding where to perform mandatory lane changes; and ii) the spatial distributions of lane changes determine weave bottleneck discharge flows.

The model was developed into an executable standalone program in MATLAB so that it can help users, especially Caltrans employees, to analyze the traffic characteristics of weaving bottlenecks and design weaving sections. The inputs of the program include traffic demands by vehicles' Origin-Destination and geometric configurations (e.g., length of the weaving section of interest, number of lanes, free-flow speed, and etcetera) The program generates simulation results including total delays as well as delay for each OD maneuver. Further, it plots oblique cumulative vehicle count curves that display discharge flows and average speeds. The simulation program is based on the empirical findings of the present study, and therefore it is only applicable to weaving sections with connected (full) auxiliary lanes. Applications of the program to acceleration or deceleration auxiliary lanes are not recommended.

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CHAPTER 1. INTRODUCTION

Freeway weaving sections form where an on-ramp is followed closely by an off-ramp, such that vehicles' merging and diverging maneuvers co-exist; see, for example, figure 1. There are two types of vehicle's lane-changing maneuvers in weaving sections: (i) mandatory lane changes needed to achieve a particular O-D movement; and (ii) optional lane changes that drivers might perform to improve their travel speeds. Vehicular conflicts that arise due to these lane-changing maneuvers, particularly between weaving (F-R & R-F; see figure 1) and non-weaving (F-F & R-R) traffic streams, can cause weaving areas to become active bottlenecks and their discharge flows to diminish. The discharge flows from a weaving bottleneck are defined here as the sum of the freeway and off-ramp outflows.

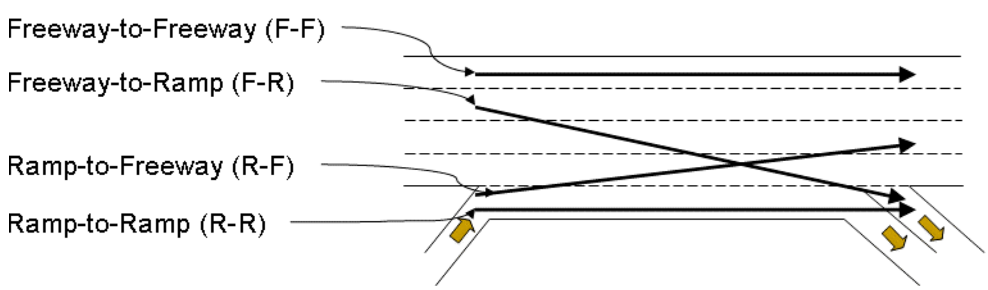


Figure 1. Origin-Destination (O-D) maneuvers in a weaving section

1.1. Problem Overview

Research on freeway weaving section design and analysis has a long history. It is one that is characterized by a near-constant stream of proposed models, most of which attempt to predict vehicle travel speeds within weaving sections. However, using vehicle speeds as a weaving section's performance metric has a number of limitations (e.g., speeds are unreliable for assessing capacity and cannot be used to assess the system-wide delays that arises upstream of weaving sections). In light of these drawbacks, there have been several more recent attempts to estimate weaving section capacity. However, most of these studies did not verify that their measurements were from active weaving bottlenecks (and therefore could not verify that their measured flows were bottlenecks' capacity); and did not examine the mechanisms (i.e., lane changes) that affect weaving section capacity. The present research explores freeway weaving from a microscopic perspective in an attempt to understand and model the mechanisms that trigger weave bottlenecks, and that dictate changes in their discharge flows.

1.2. Research Objectives

The objectives of this research are (i) to empirically study the traffic details that cause freeway weaving sections to become active bottlenecks and that trigger changes in discharge flows; and (ii) to advance existing theories to capture these details, and to test the advancements with real data.

1.3. Report Outline

Chapter 2 of this report summarizes previous efforts to develop mathematical tools for analyzing freeway weaving sections and/or to develop weaving models. Chapter 3 describes the two freeway weaving sites used for the present study and the empirical findings from these sites. Chapter 4 describes a theoretical model formulated to reproduce empirical findings at both study sites; and the tests of this theory against real data. Finally, Chapter 5 presents a summary, future research plans, and concluding remarks.

CHAPTER 2. LITERATURE REVIEW

Numerous studies have been conducted on freeway weaving sections, and most of these have been efforts to improve procedures in the Highway Capacity Manual. Many of these have produced models for predicting vehicle travel speeds within weaving sections. Curiously, a good many studies claimed to have developed models of weaving capacity, yet there seem to be only two studies to have examined weaving sections that were active bottlenecks. In spite of these efforts, the models were typically found to be inconsistent and unreliable, and thus the literature traces a long series of attempts to develop improved models.

Section 2.1 describes and critiques the speed-prediction models that have shaped much of the current thinking on weaving analyses. Models of weaving area capacity are briefly discussed in section 2.2. Section 2.3 summarizes previous empirical efforts to understand traffic in weaving sections that actually were bottlenecks. Section 2.4 describes the models of driver lane-changing behavior that will be adapted for the present work.

2.1. Speed Prediction Models

Descriptions of speed prediction models are given below. This is followed with a critique.

A methodology for weaving design and analysis was first presented in the 1950 Highway Capacity Manual (HCM). It predicted flows and speeds within freeway weaving sections, and the results were illustrated in a graphic form. The model was based on field observations at six sites near Washington D.C. The researchers reported (seemingly as an aside) that reductions in speed and discharge flows occurred whenever traffic density (the number of vehicles per distance) in the weaving section exceeded a critical value.

An update to the above procedure was furnished in a nomographic form in the next version of the HCM (1965). In the newer version, speeds depend on the length and width of the weaving section. The 1965 HCM also reported that a weaving section became congested when the sum of F-R and R-F flows exceeded the capacity of the two rightmost lanes, but this insight was not captured by the model

In 1975, Pignataro, et al. (1975) developed the PINY (Polytechnic Institute of New York) method. It involved the use of a nomograph to separately predict speeds of weaving and of non-weaving vehicles for a given number of lanes, weaving section length, volumes of weaving and of non-weaving vehicles.

In 1979, Leisch proposed an extension of the nomograph procedure of the 1965 HCM. Like the PINY method, the Leisch extension predicted speeds of weaving vehicles as a function of the weaving section length, the number of lanes, and weaving volume. However, unlike PINY method, the Leisch procedure did not estimate the speeds of non-weaving vehicles.

Users reportedly found nomograph procedures difficult to apply, and the two weaving procedures (PINY and Leisch) often yielded very different predictions. Thus, a modified procedure was developed by JHK and Associates. This model consists of regression-based equations used to predict the average travel speeds of weaving and of non-weaving vehicles. The 1985 HCM included a revised version of this JHK method.

Fazio and Rouphail (1986) examined three of the above-cited weaving procedures (Leisch, JHK, and 1985 HCM), and proposed a new speed-prediction regression-based technique (Fazio Method). Inputs to the model include the weaving area's geometry and the total number of lane-changing maneuvers required by F-R and by R-F drivers operating within the section.

Cassidy, et al. (1989) enhanced an existing microscopic computer model (INTRAS[1]) and calibrated its parameters using video data from eight weaving sections in California. The researchers tested this model, along with six existing methods (1965 HCM, Leisch, PINY, JHK, 1985 HCM, and Fazio) against real data. They found that the average speeds predicted by INTRAS were closer to the field data than those predicted by the analytical methods, concluding that microsimulation is a useful tool for analyzing weaving segments. They also found that:

- congestion at freeway weaving sections was often triggered by queue formation in a single lane:

[1] Fazio, J., Rouphail, N. (1990)

- vehicle speeds were insensitive to weaving section geometry over the range of values in the data set; and thus
- average vehicle travel speed may not be an ideal measure of effectiveness for weaving sections.

Further research in Cassidy and May (1991) confirmed that the operation of weaving sections is influenced largely by what occurs in individual lanes. The researchers proposed an analytical procedure for estimating capacity and speed in weaving sections. The procedure predicts how F-R and R-F vehicles are distributed at any locations along the two rightmost lanes (the auxiliary lane and its adjacent lane). These estimates generate estimation of total outflows. The researchers tested this analytical procedure with extensive simulation modeling using INTRAS.

Additional empirical study by Cassidy, et al. (1993) revealed some important considerations:

- the F-R and R-F movements creates very high flows at points near the on-ramp within the auxiliary lane,
- the highest proportion of lane-changing activity occurs near these points as well.

Finally, the 2000 HCM estimated the speed of weaving and of non-weaving streams, using the method of the earlier edition (1985 HCM). It also included a series of new tables that provide capacity estimates for various weaving section geometries.

Even setting aside the insensitivity of speeds to flows (as noted in Cassidy, et al. (1989)), the time spent traveling in a weaving section (even at low speeds) can be trivial when compared with the large delays that may occur if the weaving section becomes a bottleneck and generates a queue that grows long upstream. Thus the primary objective in weaving analysis should be to determine whether a weaving section becomes a bottleneck; and the bottleneck's capacity (maximum queue discharge flows) should be the metric of interest.

2.2. Capacity Prediction Models

In light of the above, there have been several more recent attempts to estimate the capacity of freeway weaving sections.[2] Some of these tested microsimulation models such as INTRAS, FORSIM, and INTEGRATION (e.g., Stewart et al. 1996; Vermijis 1998; Rakha and Zhang 2004). Others focused on gap-acceptance with linear optimization models (e.g., Lertworawanich and Elefteriadou 2002, 2003, 2004), or regression models (e.g., Cassidy et al. 1989; Kwon et al. 1999, 2000; HCM 2000). These efforts led to the recommendations concerning the use of existing models, or to modifications of these models, to estimate weaving section capacity.

[2] The capacity of a weaving segment is claimed by some to be any combination of flows that causes the density to reach the LOS E/F boundary condition of 43 pc/mi/ln (passenger car per mile per lane) for freeways or 40 pc/mi/ln for multilane highways. (2000 HCM)

Researchers sought to estimate parameters in their models using real traffic data. They did not, however, verify that their empirical measurements were from active bottlenecks[3]. As such, the outflows measured in these studies may not have actually reflected weaving area capacity. Moreover, there were no attempts to use real data to explore the traffic details that trigger bottleneck activation; or the mechanisms that cause bottleneck discharge flows to change with varying O-D flows. These models therefore may not reliably predict system-wide queuing and vehicle delays induced by weaving bottlenecks over the course of a rush.

2.3. Empirical Observations of Weaving Bottlenecks

Though most of the previous studies failed to capture traffic details regarding weaving bottlenecks, there were two empirical studies that serve as exceptions. E. Kwon (1999) collected real data from six freeway weaving sections. The study did not verify that the sites were active bottlenecks. It did, however, report an interesting phenomenon: as weaving flows increase, F-R vehicles tend to perform their lane-changing maneuvers closer to the merge. Similar observations were made in the present study, where it was found that this lane-changing behavior influences both the activation of weaving bottlenecks, and their discharge flows.

R.L. Bertini (2004) used loop detector data to study a freeway weaving bottleneck with a metered on-ramp. The report noted that the activation of the weaving bottleneck was

[3] The term active denotes that a queue forms upstream while freely flowing traffic persists downstream

accompanied by discharge flow reductions. Bertini observed surges in on-ramp and off-ramp flows prior to the bottleneck activation, and conjectured that the bottleneck was triggered by vehicular conflicts between merging and diverging traffic.

Bertini further observed (on three different days) that reductions in on-ramp flow consistently coincided with bottleneck activations, and speculated that these reductions in ramp flows were constrained by queues on the freeway. Interestingly though, the on-ramp flows were only around 200 vph immediately prior to the bottleneck activations. This suggests that the on-ramp reductions were caused by reductions in demands, not by queues on the freeway. The recurrent pattern (reductions in ramp flows coinciding with bottleneck activations) implies that the reductions in ramp flows may be a causal factor of weaving bottlenecks; and this is consistent with findings from the present study.

2.4. Car-following Models with Optional Lane Changes

The present research approaches weaving from a microscopic perspective. To model microscopic traffic details on weaving sections, theories of driver lane-changing behavior developed by Laval (2006) and Menendez (2006) were adapted. Unlike other simulation models, these are parsimonious (they have a small number of parameters that can be readily observed in real traffic data.).

Laval formulated a multilane kinematic wave model with a hybrid structure; i.e., the model is macroscopic but lane changes are treated microscopically. According to this model, lane-changing maneuvers can create voids in traffic streams, and these voids can travel forward and reduce bottleneck discharge flows. This model was not developed for weaving sections. Rather, it considers freeway sections away from diverges, where the main incentive for drivers to change lanes is to increase their speeds. Under dense traffic conditions, a lane-changing vehicle can behave as a moving-bottleneck in its destination lane while it accelerates to the speed prevailing in that lane. This disturbance can trigger lane changes among other vehicles. Findings of the present study indicate that similar lane-changing phenomena occur in weaving sections.

Laval's model was a starting point for work by Menendez who developed a microscopic car-following model with lane changes (detailed descriptions of this model are presented in the appendix.). The car-following component of the Menendez's model has three parameters calibrated to data based on three physical principles: vehicles' mechanical limitations (vehicles are constrained by their maximum acceleration and deceleration rates); safety (vehicles must be able to make a full stop at any time without crashing into vehicles in front); and driver comfort (vehicles are also limited by comfort constraints based on a simple linear car-following model (CF(L)) in Daganzo, 2004.). The model is discrete in time, but continuous in space. All drivers make decisions simultaneously. Additionally, there are two types of lane changes in the model:

i) optional lane changes generated by speed differences between two adjacent lanes

ii) mandatory lane changes generated by the activation of part-time High Occupancy Vehicle (HOV) lanes, or by the desire to enter/exit the freeway.

The Menendez model was tested at an on-ramp merge, a lane-drop bottleneck, and a freeway section with an HOV lane. The model consistently reproduced real-world phenomena including discharge flow reductions at merge bottlenecks; the generation of oscillations created by a lane-drop bottleneck; and discharge flow reductions due to lane changes induced by the activation of a part-time HOV lane.

However, the Menendez model was not designed for weaving sections, and it describes only simplified mandatory lane-changing maneuvers; i.e., the model specifies that mandatory lane changes should be performed within a certain area (*a lane-changing cone*) of freeway sections, and the shape of this area is fixed regardless of traffic conditions (see section 4.1 for details). As a result, it cannot reproduce some of the findings of the present study, which will be shown momentarily. Therefore, the mandatory lane-changing component in Menendez's model will be enhanced and extended to capture these weaving phenomena.

CHAPTER 3. EMPIRICAL FINDINGS

This chapter describes the empirical study of two freeway weaving sites. The findings indicate that a high concentration of F-R maneuvers near the on-ramp triggered bottlenecks; and that discharge flow reductions occurred immediately thereafter. Bottleneck discharge flows subsequently varied in response to the F-R vehicles' lane-changing patterns; i.e., discharge flows increased (diminished) as F-R maneuvers occurred further from (closer to) the merge. Findings further indicate that these F-R lane changes, in turn, were influenced by the conditions in the auxiliary lane; i.e., F-R maneuvers migrated further from (closer to) the on-ramp as density in the auxiliary lane increased (decreased). The evidence follows. Section 3.1 presents empirical findings from the first study site. Section 3.2 shows that these findings were reproducible at a second study site. Section 3.3 summarizes the empirical findings from both sites.

3.1. *Site 1: SR-55N, Santa Ana, CA*

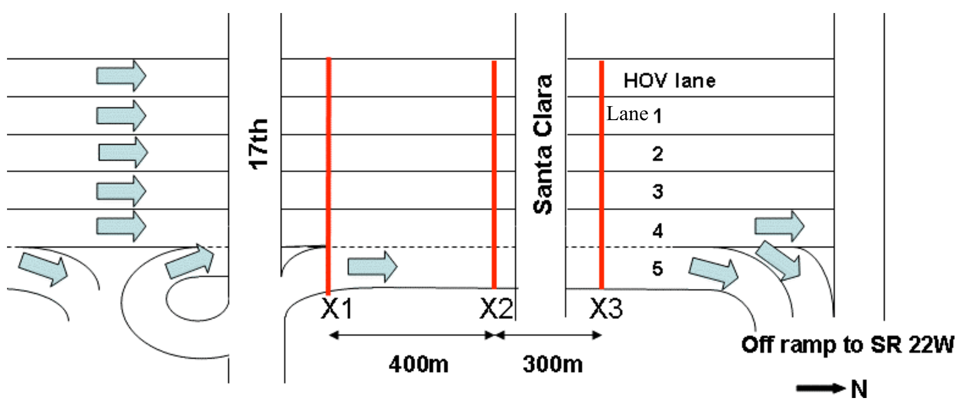


Figure 2. Study site, SR-55N

The first weaving study site, a stretch of northbound SR 55 in Santa Ana, California, is shown in figure 2. There are two on-ramps from 17th street. These ramps are not metered, and were not queued during the three observation days (May, 16, 2005; May, 17, 2005; and August, 9, 2005). The median lane is reserved for HOVs. No vehicles entered or exited that lane within the segment labeled X1 and X3; the HOV lane was separated from the other general-purpose lanes over this length by means of solid painted stripes. There are in total 6 lanes, including the HOV lane. Those labeled 4 and 5 in the figure provide access to the off-ramp connector to State Route (SR) 22 west. There are two over-crossings (Santa Clara Ave. and 17th street), which offer suitable vantage points for videotaping traffic within the weave section. Multiple video cameras were installed on these over-crossings and detailed traffic data were extracted from the afternoon rush periods on the three observed days.

3.1.1. Details of Bottleneck Activation and Discharge Flow Reductions

Vehicle counts were measured at the locations labeled X1, X2, and X3, and cumulative count curves of these were constructed on an oblique coordinate system (O-curves), as shown in figure 3[4]. The slopes of the O-curves are the excess flows over a background flow, which is 9100 vph in the present case: high (low) slopes indicate high (low) flows. Moreover, the curves were constructed in such ways that superimposed curves indicate free flow traffic, and separated curves indicate delays between the measurement locations: the wider the separations, the longer the delays (see Cassidy and Windover,

[4] Since vehicles in the HOV lane were freely flowing and not affecting vehicles in other lanes, the former were not used for constructing the O-curves.

1995). All three curves in figure 3 were superimposed until 16:51 hrs, indicating that traffic was initially freely flowing. The curve at X1 started to diverge at this time from the curve at X2, indicating that delays and queuing arose between X1 and X2; i.e., the weaving segment became an active bottleneck at about 16:51 hrs. Note that the location of the bottleneck (between X1 and X2) indicates that the slow-down in the weaving section was not trigged by a queue spill-over from anywhere downstream, including the off-ramp.

Figure 3 also shows that the bottleneck's activation was accompanied by discharge flow reductions; flows dropped from 9865 vph to 8465 vph, a 14 percent reduction. Detailed analysis shown momentarily indicates that this diminished discharge flows (at 16:51 hrs) resulted from the concentration of disruptive F-R maneuvers near the on-ramp. To unveil this mechanism, the discharge flows in individual lanes 3, 4, and 5 are examined next.

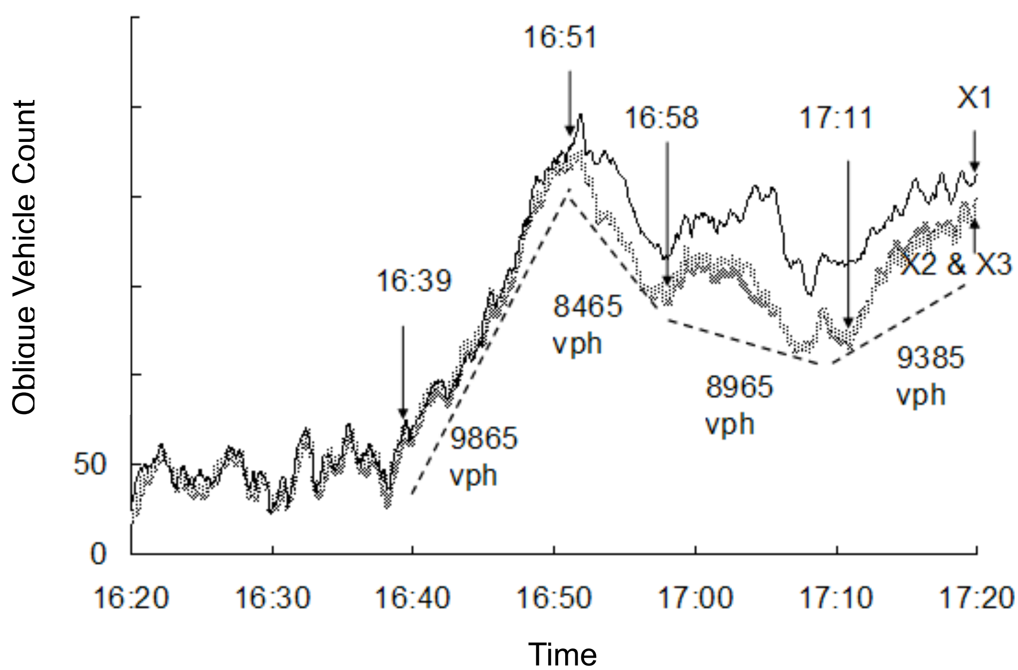


Figure 3. Oblique count curves at X1, X2, and X3, SR-55 N

3.1.2. Individual Lane Discharge Flows

Figure 4 shows separate O-curves for lanes 3, 4, and 5 that were measured at X2 during the period surrounding the bottleneck activation. The discharge flow reduction was first observed in lane 4 at 16:51:10; then in lane 5 at 16:51:22; and eventually in lane 3 at 16:51:46. Also note that after the initial flow reduction in lane 4, there was a short period (period (iii)) with a higher discharge rate (the cause of this increase will be presented in a moment.). For now, note the four periods characterized by distinct discharge flow in lane 4 (where the events began); these are labeled (i) ~ (iv) in figure 4. To understand the mechanism of these changes in discharge flows (reductions in the periods (ii) and (iv) plus increases in the period (iii)), vehicle trajectories in lane 4 are examined next.

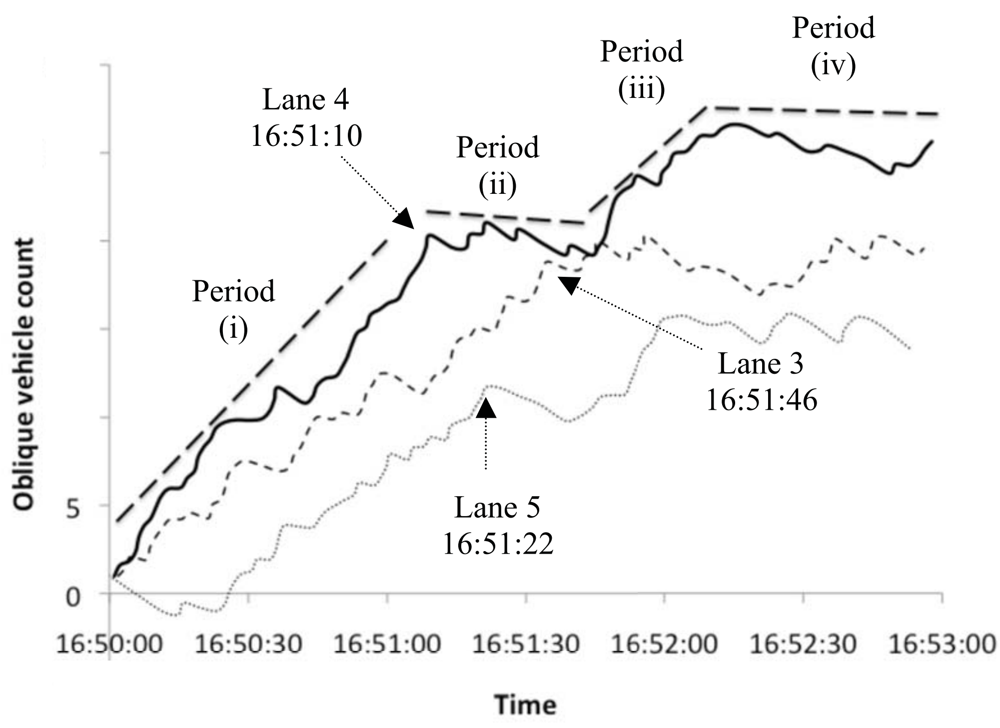


Figure 4. Discharge flows in individual lanes at X2, lanes 3, 4 and 5, SR-55N

3.1.3. Vehicle Trajectories in Lane 4

Vehicle trajectories in lane 4 are shown in figure 5. The periods (i) through (iv) are shown in this figure as well. The darker trajectories represent F-R vehicles that maneuvered from lane 3 to 4. Thin trajectories represent all the other vehicles, including F-R vehicles that did not perform the above-stated maneuvers. All vehicles represented by thin trajectories were traveling in lane 4 upon entering the weaving section, and those that disappear in the midst of figure 5 are vehicles that maneuvered out of the lane.

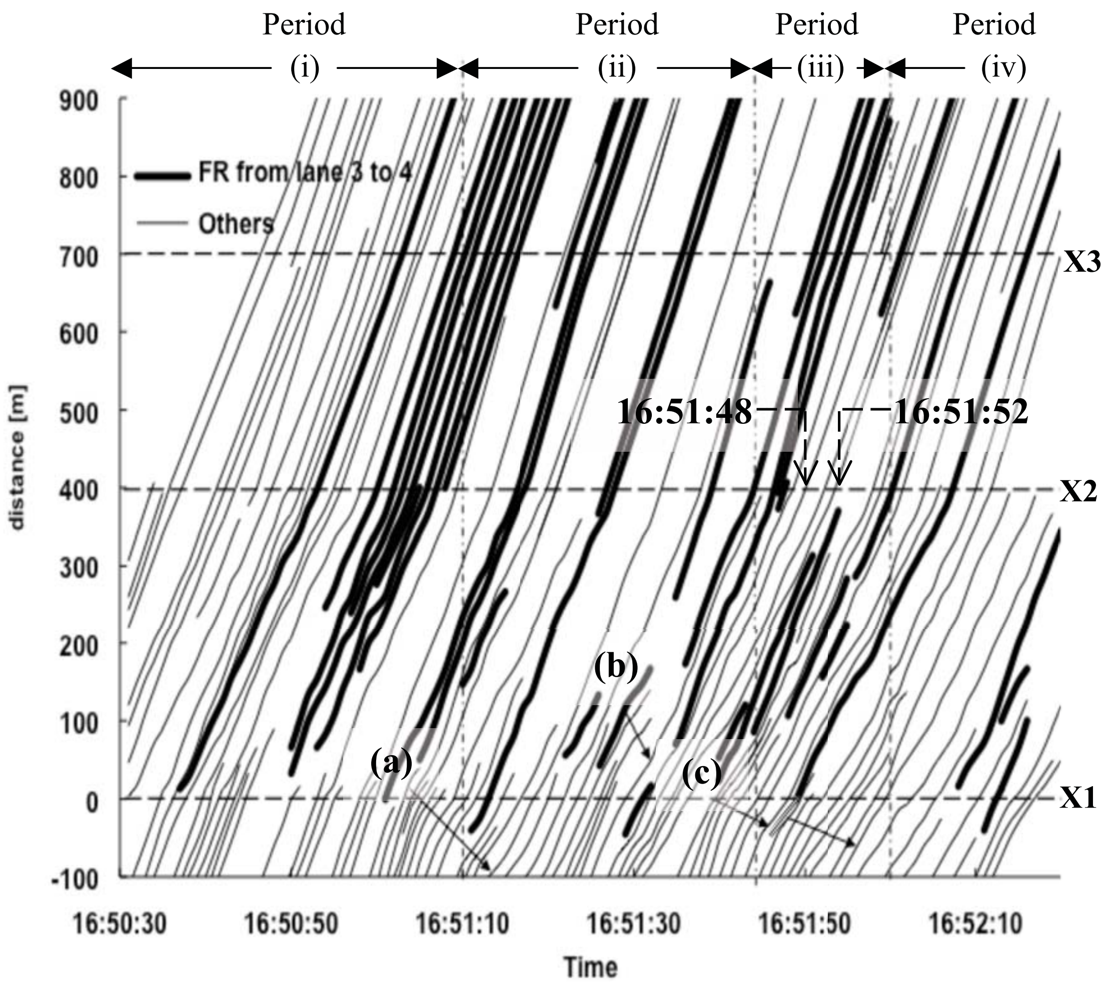
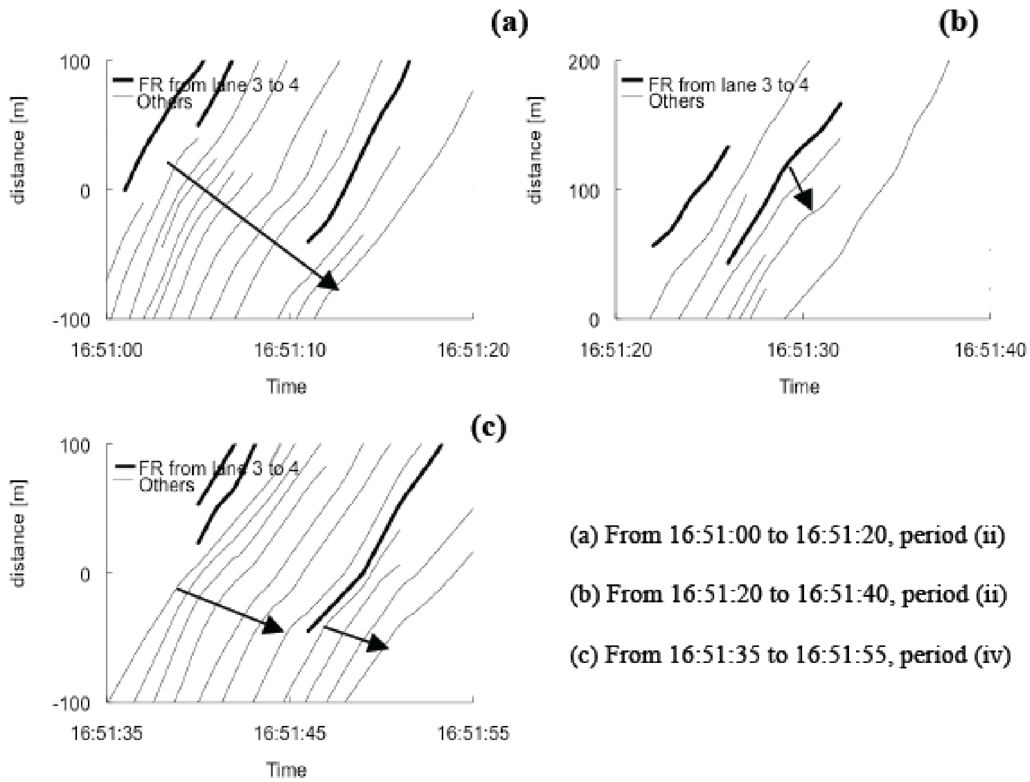


Figure 5. Trajectories of vehicles in lane 4, SR-55N

In period (i), a good many maneuvers out of lane 4 were observed near location X1. These left voids in the lane. These, however, were compensated by F-R vehicles that maneuvered from lane 3 to 4 at locations just downstream of X1, as shown by the thick trajectories. As a result, the lane 4's discharge flows at X2 did not decrease.



(a) From 16:51:00 to 16:51:20, period (ii)

(b) From 16:51:20 to 16:51:40, period (ii)

(c) From 16:51:35 to 16:51:55, period (iv)

Figure 6. Magnified vehicle trajectories in lane 4, SR-55N

During the low-flow periods (ii) and (iv), F-R vehicles maneuvering from lane 3 to 4 (dark trajectories) slowed the lane 4 vehicles behind them, generating deceleration waves. To see this, refer to the magnifications in figures 6a, b, and c. Figures 6a and b capture some of the lane 4 trajectories during period (ii), while figure 6c displays trajectories during period (iv). Notice from these figures how the lane entries of F-R vehicles (dark

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trajectories) triggered deceleration waves; these waves are shown with arrows. Soon after being slowed, many vehicles maneuvered out of lane 4; as can also be seen in figures 6a and b. Most of these lane changers went to lane 5. As they did so, they created voids in lane 4. And because these lane-changing vehicles were traveling slowly, they also created voids in their target lane 5, which reduced discharge flows in that lane as well.

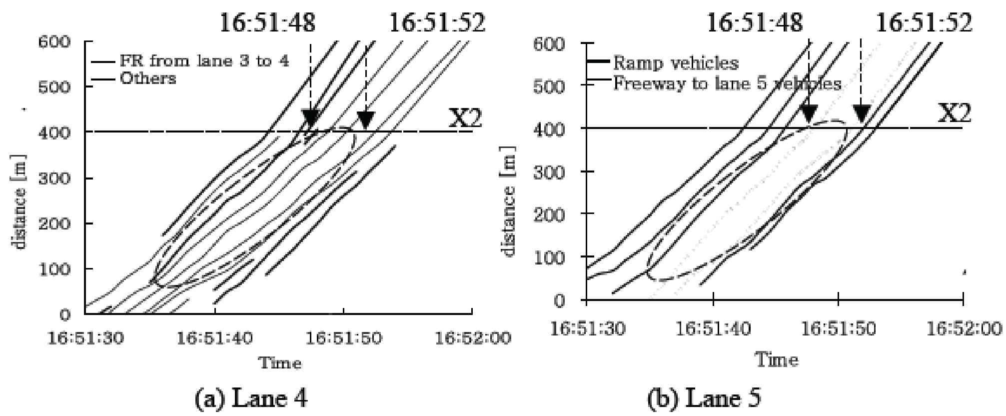

Figure 7. Vehicle Trajectories during period (iii) , SR-55N

Figures 7a and b show trajectories in lane 4 and lane 5 respectively during period (iii), a period of *higher* discharge flow as compared to the periods (ii) and (iv). Thin Trajectories in figure 7b represent F-R vehicles in lane 5, while dotted lines are vehicles from the on-ramp. Evidently, the discharge flows during period (iii) were high due to the presence of the two on-ramp vehicles in lane 5 (dotted lines). Note that these two vehicles passed location X2 at times 16:51:48 and 16:51:52. While they approached this location, there were no lane changes (from 4 to 5 and from 3 to 4), as can be seen by viewing the encircled regions in figure 7a and b. It seems that the presence of these on-ramp vehicles reduced F-R drivers' motivation for maneuvering toward lane 5; and this reduced disruptive lane changes from 3 to 4. The discharge flows in lane 4 stayed high as a result. Further evidence of this key mechanism is presented next.

3.1.4. Effects of Mandatory Lane Changes on Discharge Flows

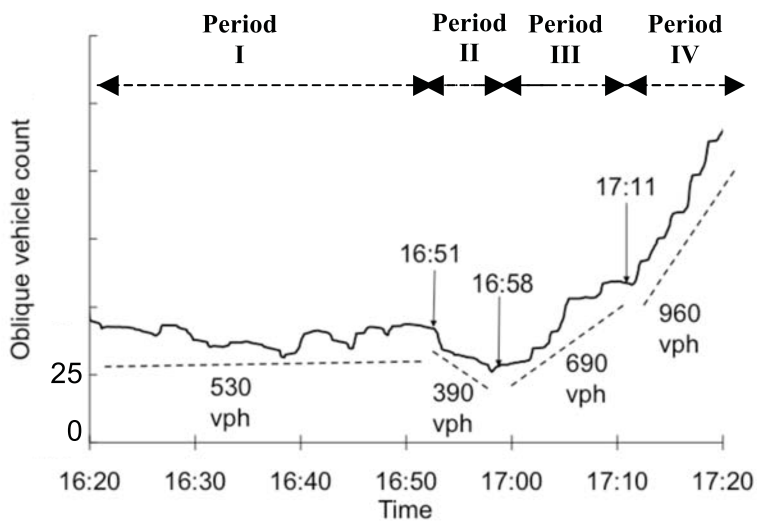

Figure 8. Oblique count curves of On-ramp flow, SR-55N

This section will discuss how bottleneck discharge flows depend on on-ramp flows. Figure 8 shows an O-curve of on-ramp counts for a 1-hr period that includes the period of bottleneck activation discussed in the previous section. The on-ramp flows decreased at 16:51 hrs (period II in figure 8), but increased at 16:58 hrs (period III) with a further increase at 17:11 hrs (period IV). Tellingly, these are the times when the weaving bottleneck's total discharge flows changed in the same direction, as shown in figure 3. Note how the bottleneck's initial discharge flow reduction at 16:51 hrs occurred when the on-ramp flows decreased. Note too that at 16:58 hrs and 17:11 hrs, the bottleneck flows (figure 3) increased by amounts that exceeded the increases in on-ramp (figure 8). During these same latter two periods, there were no significant changes in the rate of F-R maneuvers, indicating that the changes in on-ramp flows were the cause for the observed changes in bottleneck discharge.

To further explore this causality, two mandatory lane-changing maneuvers are examined:

i) F-R maneuvers from lane 3 to lane 4

ii) R-F maneuvers from lane 5 to lane 4

Figures 9, 10, 11, and 12 show cumulative distributions of the locations of these two maneuvers during period I-IV, and over the segment from X1 to X2. Before the bottleneck activated at 16:51 hrs (period I), most of F-R maneuvers occurred near the on-ramp location X1. The solid curve in figure 9 shows that 50% (0.5 in y-axis) of the total F-R maneuvers were performed within 160 m of the on-ramp. Figure 11 shows that for the same period (I), 50% of total R-F maneuvers were performed within 140 m of the on-ramp.

However, when the bottleneck activated (period II), locations for the F-R lane changes (from lane 3 to 4) moved even closer to the on-ramp, even though lane 4 was the lane with the highest traffic density. Note from figure 9 the significant concentration of F-R lane-changing maneuvers near the on-ramp: 50% of these maneuvers took place within

130 meters from the ramp as shown with the dotted curve. This concentration near the merge resulted in vehicle slow-downs and produced the discharge flow reduction during the period, as previously shown in the previous section. Figure 11 shows that during the same period (II), mandatory R-F lane changes migrated further downstream (compare the dotted curve to the solid one). It is conjectured that the different migration patterns shown in figure 9 and 11 occurred because lane 5 always exhibited relatively low density and high speed; i.e., lane 5 became "attractive" to F-R and R-F vehicles in period II.

Consider now period III. The attractiveness of lane 5 was reduced when the on-ramp flows increased during period III; traffic in lane 5 became denser and travel time increased there. As a result, the traffic patterns in period III returned (approximately) to those in period I. Figures 10 and 12 show that the patterns (dash-dotted curves) from 16:58 hrs to 17:11 hrs are similar to those (solid curves) before 16:51 in figures 9 and 11. Reduction in the concentration of disruptive F-R maneuvers near the merge, therefore, resulted in the discharge flow increase at 16:58 hrs (period III) from 8465 vph to 8965 vph (figure 3), which is greater than the on-ramp flow increase from 390 vph to 690 vph (figure 8) [5].

Consider next period IV. The additional increase in on-ramp flows at time 17:11 hrs (period IV in figure 8) again reduced lane 5's attractiveness. Consequently, many R-F

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[5] This outflow increase was caused by the reduction in the concentration of disruptive F-R maneuvers near the merge, not by a reduction in F-R maneuvers. The amount of mandatory F-R lane changes that took place between X1 and X2 remained the same, but increased downstream of X2 (from 154 vph to 234 vph).

maneuvers (the solid curve in figure 12) occurred further upstream as compared with previous time periods, as encircled in figure 12. In contrast, numerous F-R maneuvers (the solid curve in figure 10) took place further downstream, again reducing disruptive lane-changing maneuvers near the merge. Figure 10 also shows that the cumulative distribution of F-R maneuvers during the period IV became closer to a straight lane, indicating a more uniform distribution of F-R lane-changing maneuvers between X1 and X2 of the weaving section. The dispersion of disruptive F-R lane-changing maneuvers led to further increase in discharge flows at 17:11 hrs from 8965 vph to 9385 vph, greater than the increase in the on-ramp flows[6].

In summary, the data unveil the following mechanism. Reductions in on-ramp flows encourage F-R drivers to perform their maneuvers near the merge, and this concentration of disruptive F-R maneuvers near the merge triggers reductions in bottleneck discharge flows. Increases in on-ramp flows discourage F-R drivers to maneuver near the merge, and as a result bottleneck discharge flows increase. Further evidence of the relationship between on-ramp flows and bottleneck discharge rates are furnished for other days in the following section.

[6] Again, the cause of this increase was caused by the change in the distribution of F-R maneuvers, not by a reduction in F-R maneuvers. During this period IV, the amount of mandatory F-R lane changes between X1 and X2 did not change, but increased downstream of X2 (from 234 to 307 vph).

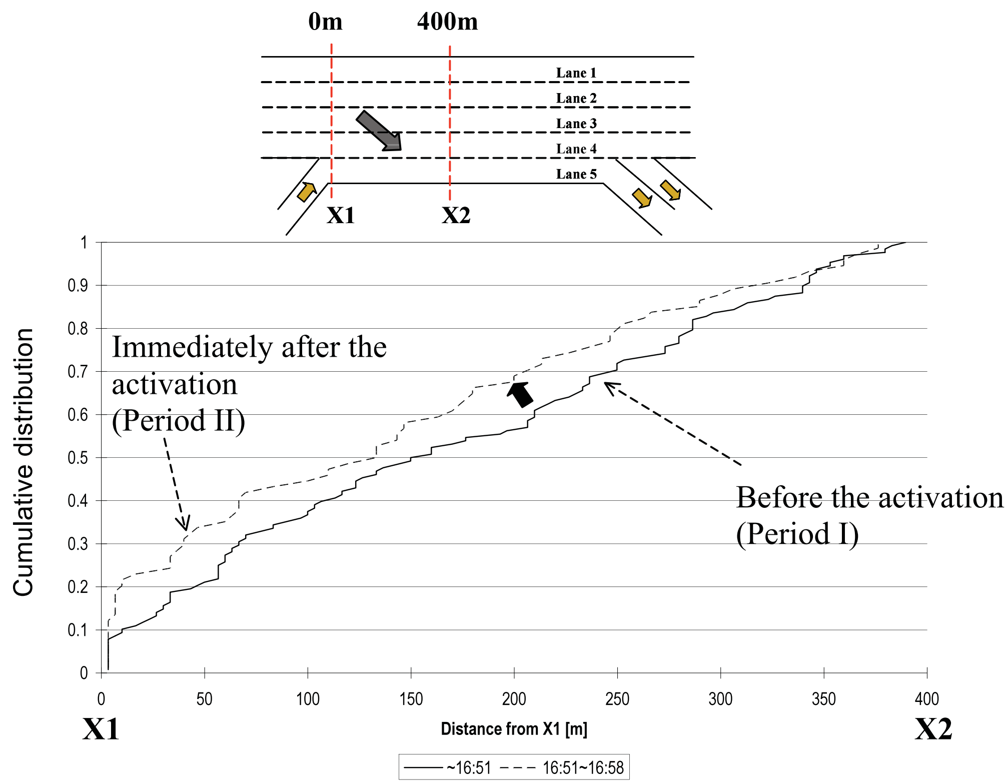


Figure 9. Cumulative distributions of F-R vehicles' lane changes from 3 to 4 before 16:58 hrs, SR-55N

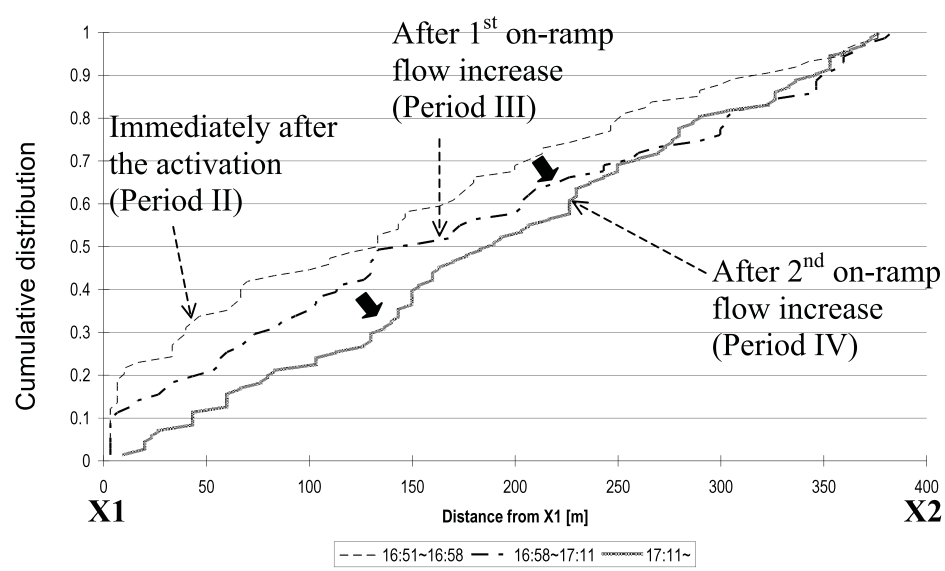


Figure 10. Cumulative distributions of F-R vehicles' lane changes from 3 to 4 after 16:51 hrs, SR-55N

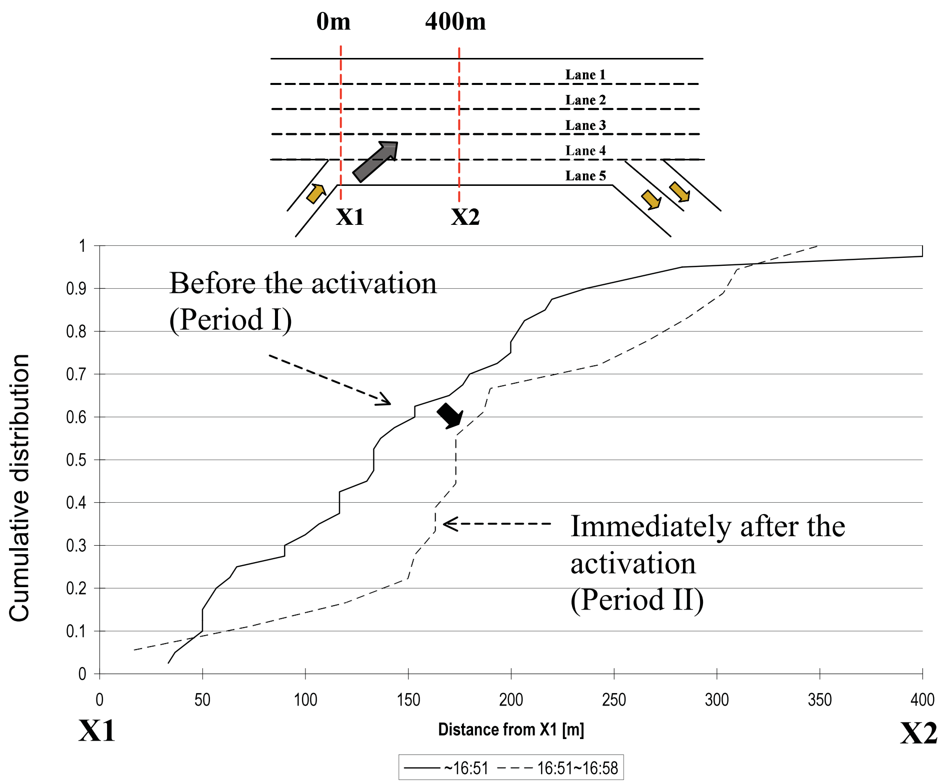


Figure 11. Cumulative distributions of R-F vehicles' lane changes from 5 to 4 before 16:58 hrs, SR-55N

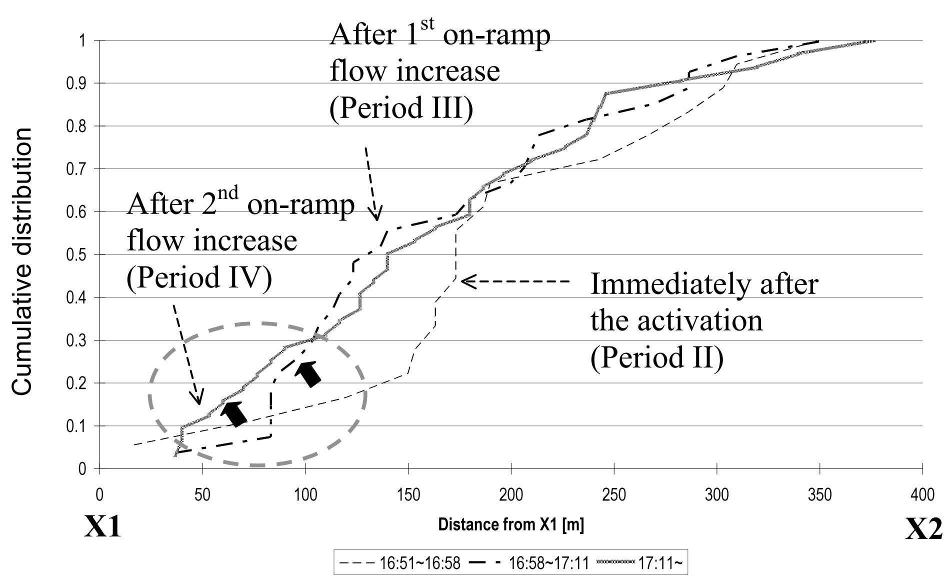
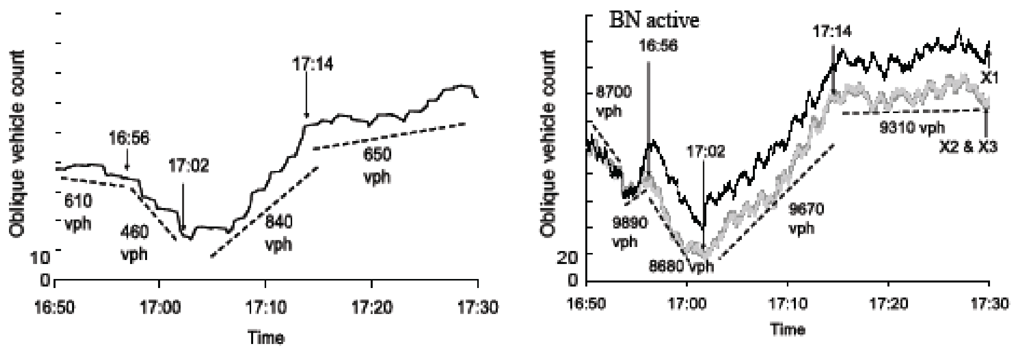


Figure 12. Cumulative distributions of R-F vehicles' lane changes from 5 to 4 after 16:51 hrs, SR-55N

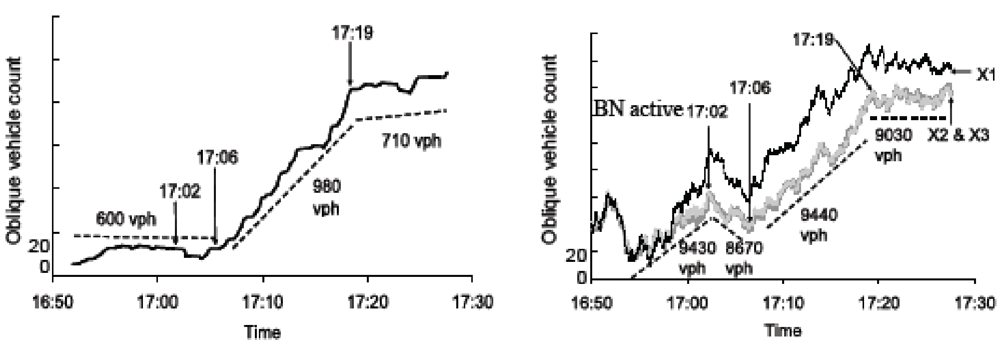
3.1.5. Further Evidence of the relationship between on-ramp flows and bottleneck flows

O-curves of on-ramp flows and discharge flows were measured for two additional days, as shown in figures 13 and 14. These curves confirm that the observed mechanism is reproducible (see figures 3 and 8): the positive (negative) changes in on-ramp flows apparently reduced (increased) the attractiveness of the auxiliary lane among F-R drivers, and as a result discharge flows increased (diminished).



(a) On-ramp flow (b) Freeway at X1, X2, and X3

Figure 13. O-curves of on-ramp and freeway flows from 5/17/2005, SR-55N



(a) On-ramp flow (b) Freeway at X1, X2, and X3

Figure 14. O-curves of on-ramp and freeway flows from 8/9/2005, SR-55N

Figures 13a and b show that when the on-ramp flows changed at 16:56 hrs, 17:02 hrs, and again 17:14 hrs, the total outflows changed in the same directions. Note that the bottleneck became active (figure 13b) when the on-ramp flows decreased at 16:56 (figure 13a). Note on another day shown in figures 14a and 14b, that when the on-ramp flows changed at 17:06 hrs and 17:19 hrs (figure 14a), further changes in the total outflow were observed (figure 14b). Note too that the bottleneck on this day became active at 17:02 without significant reductions in on-ramp flows. This activation was due to increased F-R demand.[7] The empirical results thus indicate that F-R lane changes became disruptive: i) when there are increased concentrations of F-R lane changes near the on-ramp merge triggered by reductions in on-ramp flows; or ii) when there are simply too many F-R lane changes, independent of the ramp flows.

Next, traffic data from another weaving study site with different geometry and different O-D demands will be examined to see if the observed mechanism is reproducible at this second site.

[7] At 17:02, the number of F-R lane changes from lane 3 to 4 between locations X1 and X2 increased from 548 vph to 951 vph

3.2. *Site 2: I-210W, Pasadena, CA*

To confirm the mechanism's reproducibility, we examine the stretch of westbound I-210 in Pasadena, CA, shown in figure 15. The on-ramp from Lake Ave was metered but rarely queued during the observation day. The median lane is reserved for High Occupancy Vehicle (HOV). The lane is separated from the other lanes by means of a solid painted stripe, and thus no vehicles entered, or exited the HOV lane between the locations labeled X1 and X3. No on-ramp vehicles from Lake Ave. were observed to use either off-ramp (to Marengo Ave. or I-210W). The two over-crossings (El Molino Ave. and Los Robles Ave.) offered suitable vantage points for videotaping traffic. Multiple video cameras were used to this end. Detailed traffic data were extracted from the morning rush period on June 28, 2002.

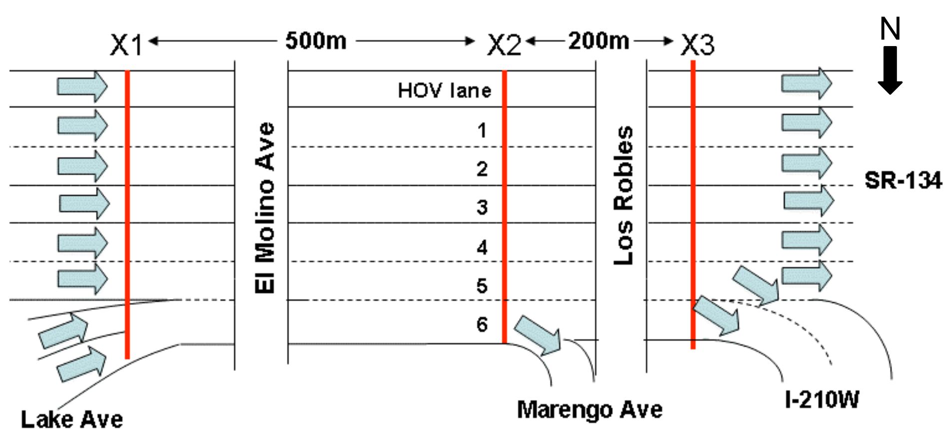


Figure 15. Study site, I-210W

3.2.1. Details of Bottleneck Activation and Discharge Flow Reduction

O-curves at locations X1, X2, and X3 were constructed for lanes 1 to 6 (excluding the

HOV lane) in the same manner described previously; see figure 16. Off-ramp flows observed at Marengo were added to the curve at X3 to maintain the conservation of flows. These O-curves reveal that the weaving segment between X1 and X2 became an active bottleneck accompanied by a discharge flow reduction at 6:54 hrs. Discharge flows dropped from 11100 vph to 10200 vph, an 8 percent reduction. When the bottleneck became active, no changes (reductions) in on-ramp flows were observed. However, F-R lane changes from lane 4 to 5 increased (from 521 vph to 962 vph) for a 3-min period beginning at 6:54 hrs. Since these observations are qualitatively consistent with those of the previous (see figures 14a and 14b), this is a clue that the diminished discharge (at 6:54 hrs) resulted from increases in disruptive F-R maneuvers. The discharge flow increase at 6:57 for 2 minutes was caused by reductions (fluctuations) in both the on-ramp and F-R flows; while the discharge flow reduction at 7:07 was triggered by a reduction in on-ramp flows. Evidence of this mechanism will be presented next.

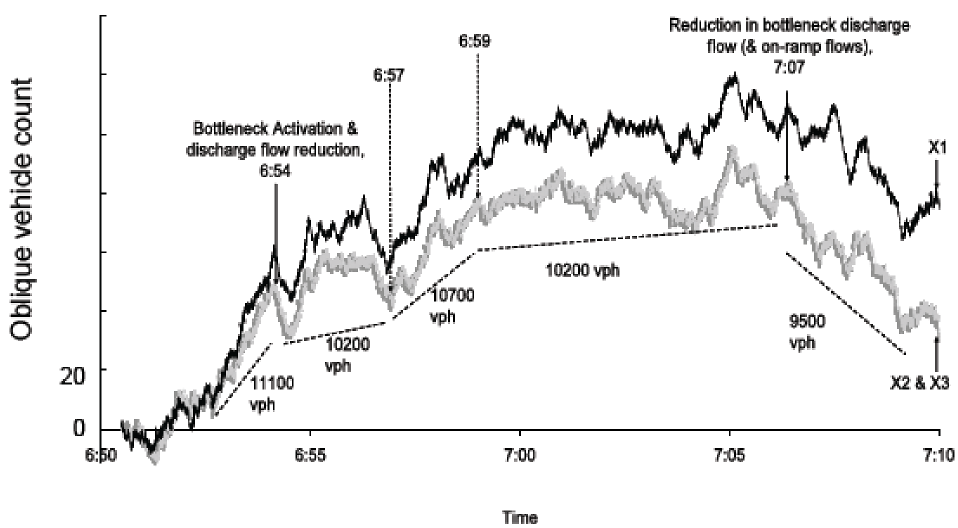


Figure 16. Discharge flows in individual lanes at X2, lanes 3, 4 and 5, I-210 W

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3.2.2. Discharge Flow Changes Due to Mandatory Lane Changes

Lane-changing patterns previously presented in section 3.1.4 were observed at the present site as well, thus confirming the disruptive effects of F-R maneuvers. Figure 17 shows the O-curve of on-ramp flows. It shows that a reduction in this flow occurred at 7:07 hrs. Tellingly, this is the time when the weave bottleneck's total discharge flows decreased (see again figure 16). Two mandatory lane-changing maneuvers are examined between locations X1 and X3 to confirm the causal relation between the changes in both the on-ramp flows and the bottleneck discharge flows:

i) F-R maneuvers (destined to either the Marengo Ave. or the I-210W off-ramp) from lane 4 to lane 5

ii) R-F maneuvers from lane 6 to lane 5

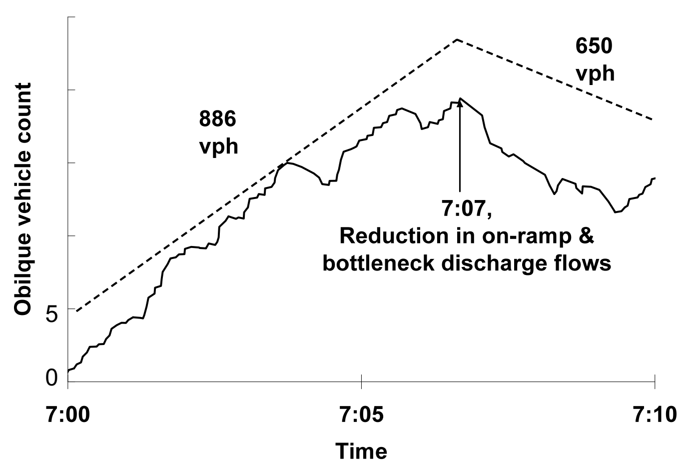


Figure 17. Oblique count curves of On-ramp flow, I-210W

Figures 18 and 19 show cumulative distributions of the locations of these two maneuvers during three distinct periods: before bottleneck activation at 6:54 hrs; the period after the activation extending to the reduction in on-ramp flows at 7:07 hrs; and the period after 7:07 hrs. For now, this middle period excludes all data measured from 6:57 hrs to 6:59 hrs, the 2-min period when reductions in both on-ramp and F-R demands created a short-term increase in bottleneck discharge flows (see figure 16). Details concerning the F-R and R-F maneuvers during this 2-min period will be presented momentarily.

The thick solid curve in figure 18 shows that before the bottleneck activated at 6:54 hrs, 50% of total F-R maneuvers were performed within 340 m of the on-ramp. As regarding the R-F maneuvers during this same time, the thick solid curve in the lower figure, figure 19, shows that 50% of these were performed within 180 m of the on-ramp.

The distributions of these two maneuvers changed in opposite directions after the bottleneck became active at 6:54 hrs: F-R lane changes migrated further upstream, while their R-F counterparts migrated further downstream. The dotted curve in figure 18 shows the distribution during the middle period; note how the dotted curve lies above the thick solid one (before the activation at 6:54 hrs) in the figure. The concentration of these disruptive F-R maneuvers nearer the on-ramp merge resulted in the discharge flow reduction during this period. During the same period, mandatory R-F lane changes migrated further downstream (see the dotted line in figure 19). It is conjectured that these observed lane-changing patterns emerged because lane 6 always exhibited lower densities due to low on-ramp flows during the period. Thus, the lane was attractive to both R-F vehicles (which stayed longer in the lane) and F-R vehicles (which entered the lane sooner).

Notably, when the on-ramp flows decreased at 7:07 hrs, the thin solid line in figure 18 shows that F-R lane changes migrated even further upstream. At the same time, R-F lane changes migrated yet further downstream; note from figure 19 how the thin solid line lies below its dotted counterpart. Again we see the familiar lane-changing pattern induced by a reduction in on-ramp demands. Note from figure 16 how this pattern that emerged after 7:07 hrs was accompanied by a discharge flow reduction.

We now turn our attention to the period with the short-term reductions in both the on-ramp demands (that dropped from 935 vph to 650 vph); and the corresponding reductions in F-R demands (that decreased from 2370 vph to 1930 vph) during the 2-min period from 6:57 hrs to 6:59 hrs). These decreases in demands were accompanied by an increase in total discharge flow, as shown in figure 16. As a result, lane-changing patterns during this 2-min period were similar to those before the bottleneck activation. Figures 20 and 21 show that F-R and R-F lane-changing patterns during this 2-min period (dashed curves) were similar to those measured prior to the bottleneck's activation (thick solid curves). As a result of these similar lane-changing patterns, discharge flows during the 2-min period were similar to those measured prior to the bottleneck's activation (see figure 16).

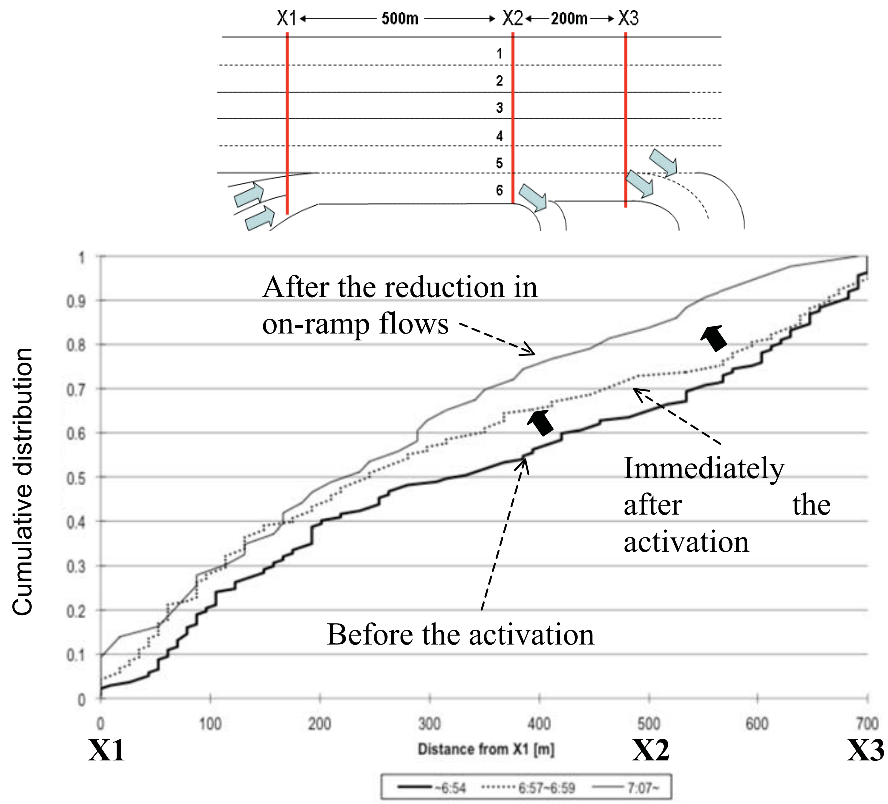


Figure 18. Cumulative distributions of F-R vehicles' lane changes from 4 to 5, I-210W

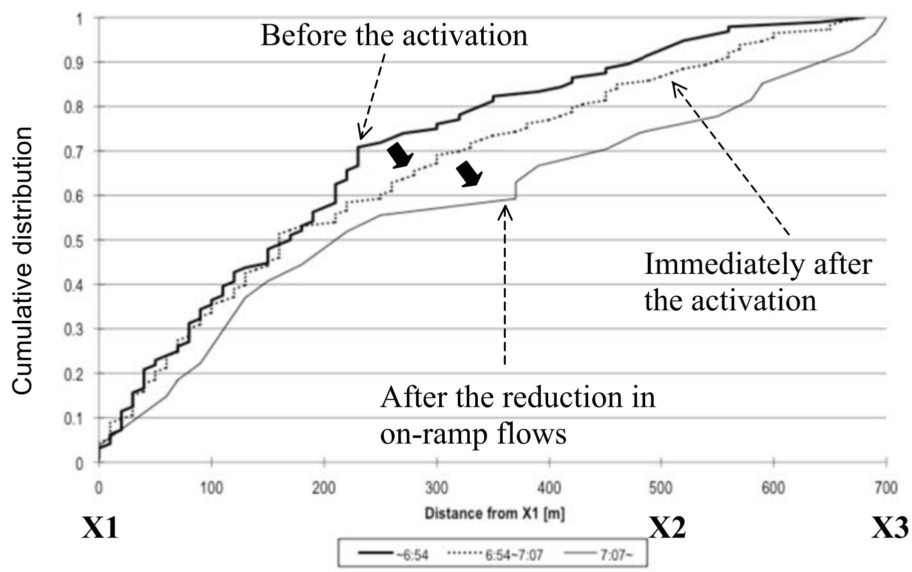


Figure 19. Cumulative distributions of R-F vehicles' lane changes from 6 to 5, I-210W

APPENDIX D

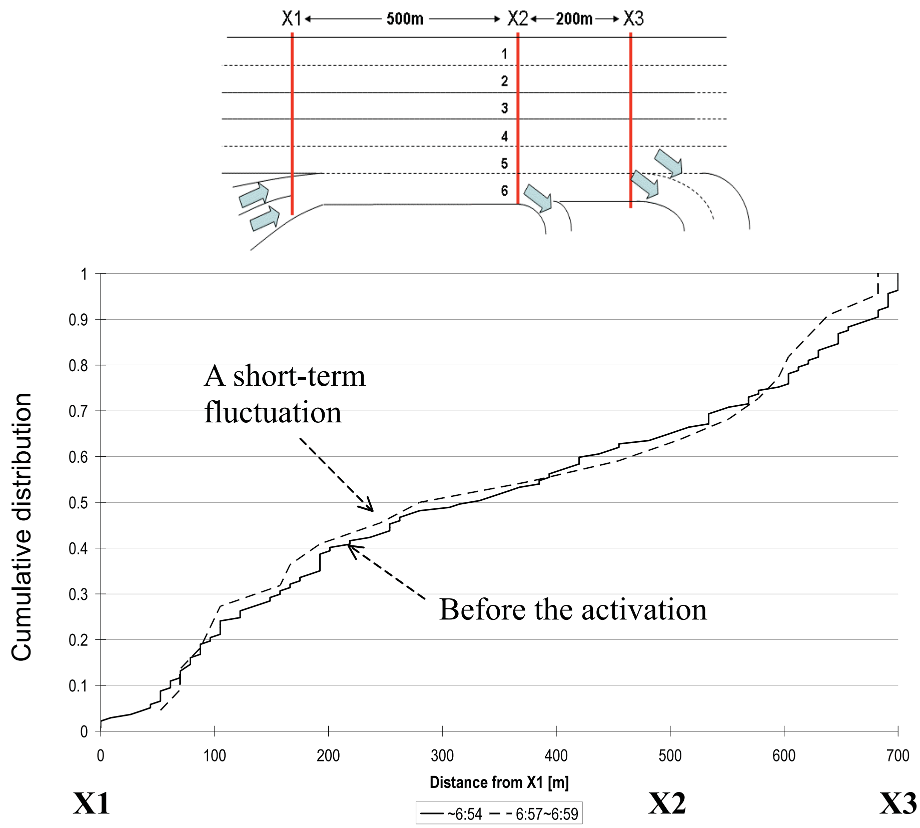


Figure 20. Cumulative distributions of F-R vehicles' lane changes from 4 to 5 between 6:57 hrs and 6:59 hrs, I-210W

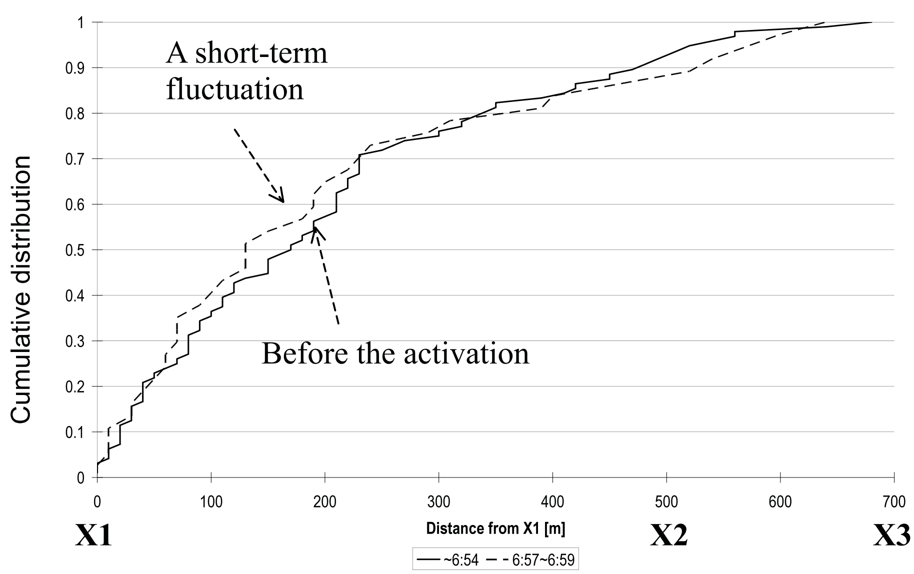


Figure 21. Cumulative distributions of R-F vehicles' lane changes from 6 to 5 between 6:57 hrs and 6:59 hrs, I-210W

3.3. Summary of Empirical Findings

The findings indicate that bottleneck activations at both weaving sections were triggered by disruptive F-R lane changes. These F-R lane changes became disruptive: i) when there were increased concentrations of F-R lane changes near the on-ramp merge triggered by reductions in on-ramp flows; or ii) when there were simply too many F-R lane changes, independent of the ramp flows. As a result, discharge flows in both weave study sites varied in response to the *distributions* of F-R maneuvers. Findings further indicate that the distributions of these lane changes, in turn, were influenced by the conditions (i.e., relative densities) of the weaving sections' auxiliary lanes. On-ramp flow reductions increased the attractiveness of the auxiliary lanes, thus motivating F-R drivers to perform their maneuvers nearer the on-ramp (fewer maneuvers downstream). This state of affairs produced the discharge flow reductions. In contrast, increases in on-ramp flows reduced the attractiveness of the auxiliary lanes, reducing the concentration of disruptive F-R maneuvers near the on-ramp (with more maneuvers occurring downstream). These reductions in disruptive maneuvers led to discharge flow increases.

The next Chapter presents a theoretical model based on the described mechanism and the model is tested with the traffic data at the two study sites.

CHAPTER 4. THEORETICAL MODELLING: MICROSIMULATION

This Chapter presents the car-following and lane-changing model adapted from *Menendez (2006)* to predict the observed mechanisms that activate bottlenecks in weaving sections and trigger changes in discharge flows. The model is tested with data from the two study sites, but data from only one of the sites (SR-55N) are used to estimate model parameters. The details of the new model will be described next. Test results will be presented in section 4.2.

4.1. Model Formulation

The model refined here, like the one originally developed by Menendez (summarized in section 2.4 and Appendix A), captures both the vehicle car-following and lane-changing processes. The model is discrete in time, but continuous in space such that it calculates the locations of individual vehicles over a stretch of freeway for every simulation interval. All drivers make decisions simultaneously, as in the original model.

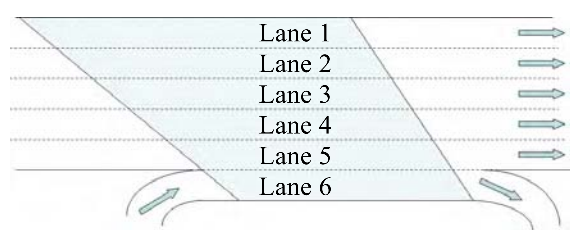


Figure 22. The original model's lane-changing cone for weaving sections

The original model assumes that the decisions of when to perform mandatory lane-changing maneuvers are based on the number of lanes that the vehicle must cross and the remaining distance to the destination. When used to describe F-R vehicles in a weaving section, the original model assumes that once these vehicles enter the cone shown in figure 22, they try to change lanes by searching for a sufficient gap in the adjacent right lane.

To better emulate the weaving mechanisms observed in the present study, the adapted model uses a revised description of mandatory lane change behavior. This additional feature is the focus of the theoretical work presented next.

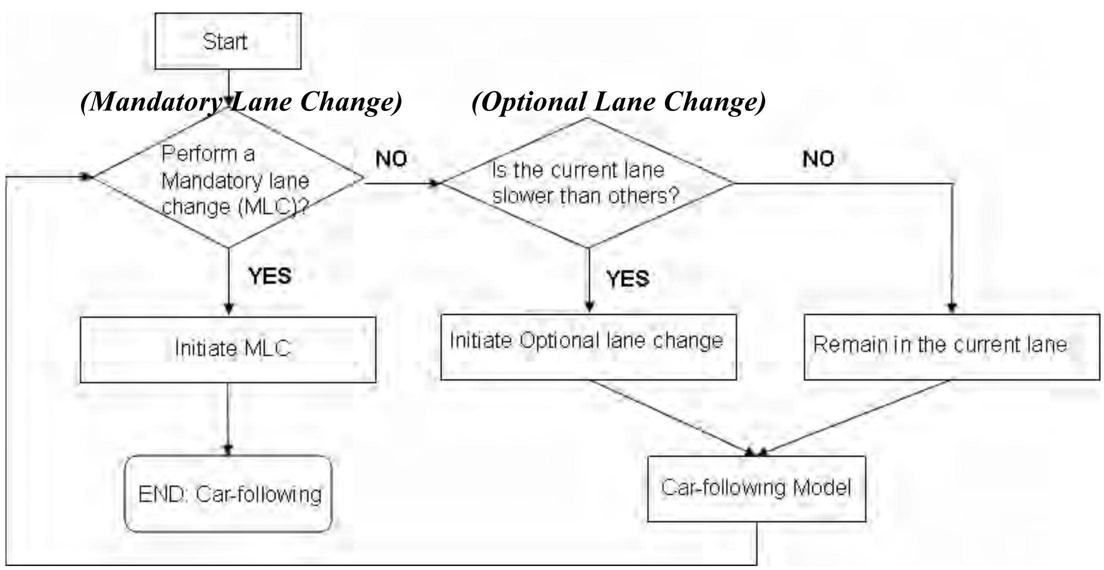
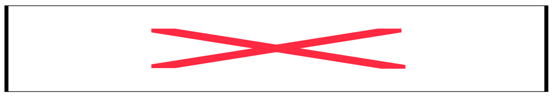


Figure 23. Flowchart of the adapted model

A flowchart of the adapted model is shown in figure 23. It includes a Logit model to determine the probability that each driver first attempts a mandatory lane change, P_{MLC}, at a given simulation interval, t (the diamond labeled (Mandatory Lane Change) in figure 23).[8] The formulation for the P_{MLC} for each driver and each time interval is:



[1]

Where β_0, β_1, β_2, and β_3 are the parameter estimates, and the three variables x_1, x_2, and x_3 are described below.

The first variable, x_1, is a proxy for the difference in densities between a driver's current lane and the right-most lane: it is the difference in the vehicle accumulations between these two lanes, as measured over a 100-m long stretch extending from the driver's current position.[9] Note that if a driver is upstream of the weaving section (where there is no auxiliary lane), the right-most lane is lane 5 (see figure 22). If the driver is within the weaving section, then lane 6, the auxiliary lane, is the right-most lane.

The second variable, x_2, is an inverse of a vehicle's remaining normalized distance to the diverge; i.e., it is the length of the weaving section divided by of the vehicle's distance from the end of the weave; and the variable is normalized so that the parameter β_2 (in the

[8] The choice of the Logit model, instead of a more complex discrete choice model such as the random parameter model, was to minimize the number of parameters. Only those parameters conjectured from the observed mechanism are included in this Logit model.

[9] No existing decision models for mandatory lane changes consider this difference as an explanatory variable, though the empirical findings of this study indicate that this difference plays an important role.

equation [1]) estimated for one site may be generalized across sites. Note that as the vehicle's distance to the end of the weave approaches 0, the variable, x_2, becomes infinite, forcing P_{MLC}= 1. This reflects a driver's increased motivation to perform her mandatory lane change maneuvers as she moves closer to the downstream end of the weaving section.

The third variable, x_3, is the number of lanes that must be crossed to finish a mandatory lane change maneuver. This reflects a driver's propensity to attempt lane-changing maneuvers early if she is required to maneuver through multiple lanes.

Once the driver decides to perform a mandatory lane change (when a Bernoulli trial of P_{MLC} is a success in the simulation process), she continues to try to change lanes for every time interval in the simulation based on the car-following algorithms of the original model. If these attempts fail after a certain elapsed time ψ, the driver reduces her speed or a cooperating vehicle in the target lane makes space for her by reducing its own speed.

Optional lane change maneuvers are generated in the refined (and original) model when traffic in a driver's current lane is moving slower than in adjacent lanes (the second diamond labeled (Optional Lane Change) in figure 23). The car-following component of the adapted model also follows the logic developed by Menendez.

4.2. Parameter Estimation

To estimate the β in the equation [1], parameter values for car-following and optional lane change were taken from the Menendez's model. Table 1 provides descriptions and values of these parameters. More detailed descriptions of these parameters can be found in *Menendez (2006)*.

Parameter	Description	Value
u	Free-flow speed	70 mph
s_{jammed}	Jammed spacing	20 ft
r	Dimensionless proxy for deceleration rate	1
a_U	Acceleration rate	10 $ft/\sec^2$
w	Backward wave speed	14 mph
ϕ	Sensitivity to relative differences in speed between adjacent lanes for optional lane changes	4 sec
ψ	Cooperation initiation time for mandatory lane changes	5 sec

Table 1. Parameters from the original model for weaving

A few additional assumptions were made for estimating the β. It was assumed that during congested periods, drivers who decide to perform lane changes may delay their maneuvers due to lack of sufficient gaps in the target lane. Therefore, data during congested periods were not used to estimate the parameters for the equation [1]. In contrast, it was assumed that locations of lane changes made during free-flow states mark the locations where drivers made decisions.

In light of these assumptions, $\boldsymbol{\beta}$ were estimated using those vehicle trajectories from SR-55N (described in section 3.1.4) that were measured *prior to the bottleneck activation* (during free-flow states). Variables x_1, x_2, and x_3 were measured from these trajectories at *one-second* intervals. Since in the model, individual drivers make decisions every *simulation interval* (not one second), linear interpolations of the measured $\boldsymbol{x}$ were applied to make the data compatible with the simulation.

The dataset contains 1512 observations of vehicle locations (specified at the intervals used in the simulation). These came from 310 mandatory lane changes made by numerous drivers. Maximum log-likelihood estimation was applied to these data to estimate the $\boldsymbol{\beta}$ in the equation [1], and the estimated values are shown in table 2.

Parameter	Description	Value
β_0	Constant	-8.0
β_1	Density difference	0.9
β_2	Inverse of normalized distance	6.3
β_3	Number of lanes to be crossed	1.2

Table 2. Estimated values of the parameters

The results of the simulation tests performed with the model are described below.

4.3. Model Testing

The model with its estimated $\boldsymbol{\beta}$ was applied to the two study sites. In section 4.3.1, model predictions were compared with empirical data at site 1 (SR-55 N). In section

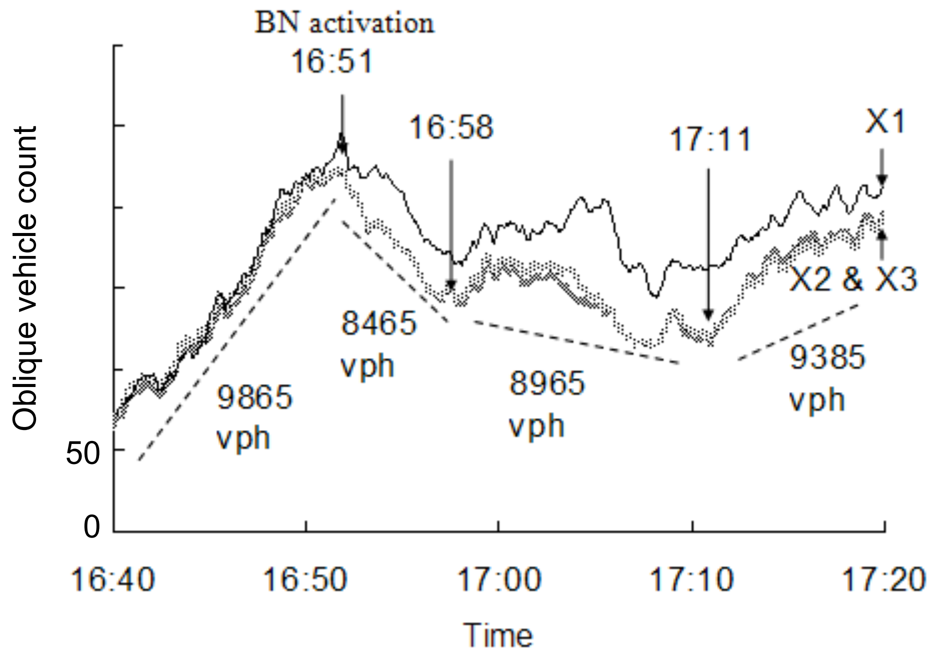
4.3.2, the transferability of the parameter estimates was tested for site 2 (I-210 W); i.e., the $\boldsymbol{\beta}$ estimated for site 1 were used to make predictions and these were compared with observations from site 2. At both sites, the model was found to reproduce qualitatively the observed phenomena. Although the empirical results were previously presented in Chapter 3, some of them are re-presented in the present section for the reader's convenience.

4.3.1. Simulation Results for Site 1, SR-55 N

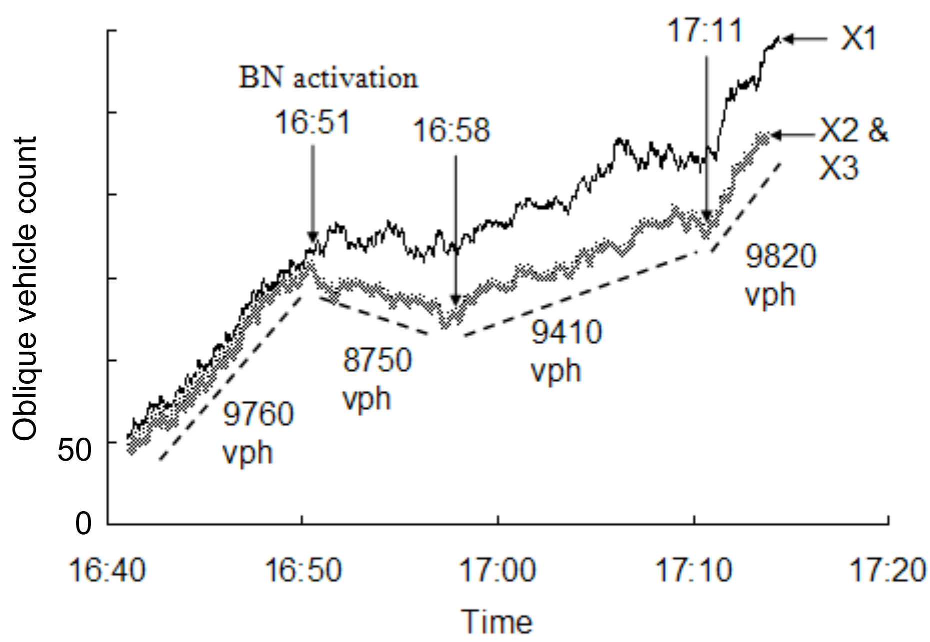
The input data for the simulations of site 1 consisted of on-ramp demand (R-R and R-F) and upstream freeway demand (F-F and F-R). The on-ramp was not queued during the observation periods, so the time-varying on-ramp demands were the on-ramp flows measured from videos. However, traffic in the upstream freeway segments was queued when the bottleneck became active, and thus upstream freeway demands were hidden. To resolve this issue, freeway demands prior to the bottleneck activation were used for the whole period, even after the bottleneck became active in simulation. Once the simulated queues propagated to the upstream boundary of the weaving area, the simulation model assigned incoming vehicles values of speed and spacing suitable for queued conditions.

The model was found to qualitatively replicate the site's observed O-curves (i.e. the bottleneck's activation time and the changes in its discharge flows); and the cumulative distributions of lane changes over space. Figure 24a re-presents the observed O-curves (at site 1; May, 16, 2005) and figure 24b displays O-curves predicted by the adapted model. By comparing these two figures, we see that the model accurately predicted the bottleneck activation time, the times when the discharge flows changed, and the directions of these flow changes. Figures 25 and 26 show observed and simulated cumulative distributions of F-R lane changes from 3 to 4 during the time periods marked by distinct discharge flows. Figures 27 and 28 show these cumulative distributions for the R-F maneuvers. Note that the figures labeled (a) present observed data, and that those labeled (b) present simulated curves. Visual comparisons of a figure (a) with its counterpart (b) show that the model qualitatively replicates the observations within at most 500 vph differences: the observed and simulated cumulative distribution curves moved in the same directions from one time period to the next. And consistent with the observations, the upstream (downstream) migration of F-R maneuvers consequently decreases (increases) bottleneck discharge flows.

The model predicted similar trends for F-R vehicles on the upstream freeway segment, as they approached the weave area. These simulated results are consistent with the conjecture drawn from the empirical observations: during congested periods, F-R drivers try to minimize their delays by staying longer in lane 3 since densities were lower (and speeds are higher) in that lane as compared with lane 4. Once these drivers pass the on-ramp where the auxiliary lane (with lower densities and higher speeds due to low on-ramp flows) begins, F-R drivers minimize their delays by promptly initiating maneuvers to lane 4, and then to the auxiliary lane soon thereafter. It seems that this driver behavior lies in the heart of the mechanisms that trigger bottleneck activation and subsequent changes in discharge flows.



(a) Observed Curves



(b) Simulated Curves

Figure 24. Comparison of oblique count curves at X1, X2, and X3, SR-55 N

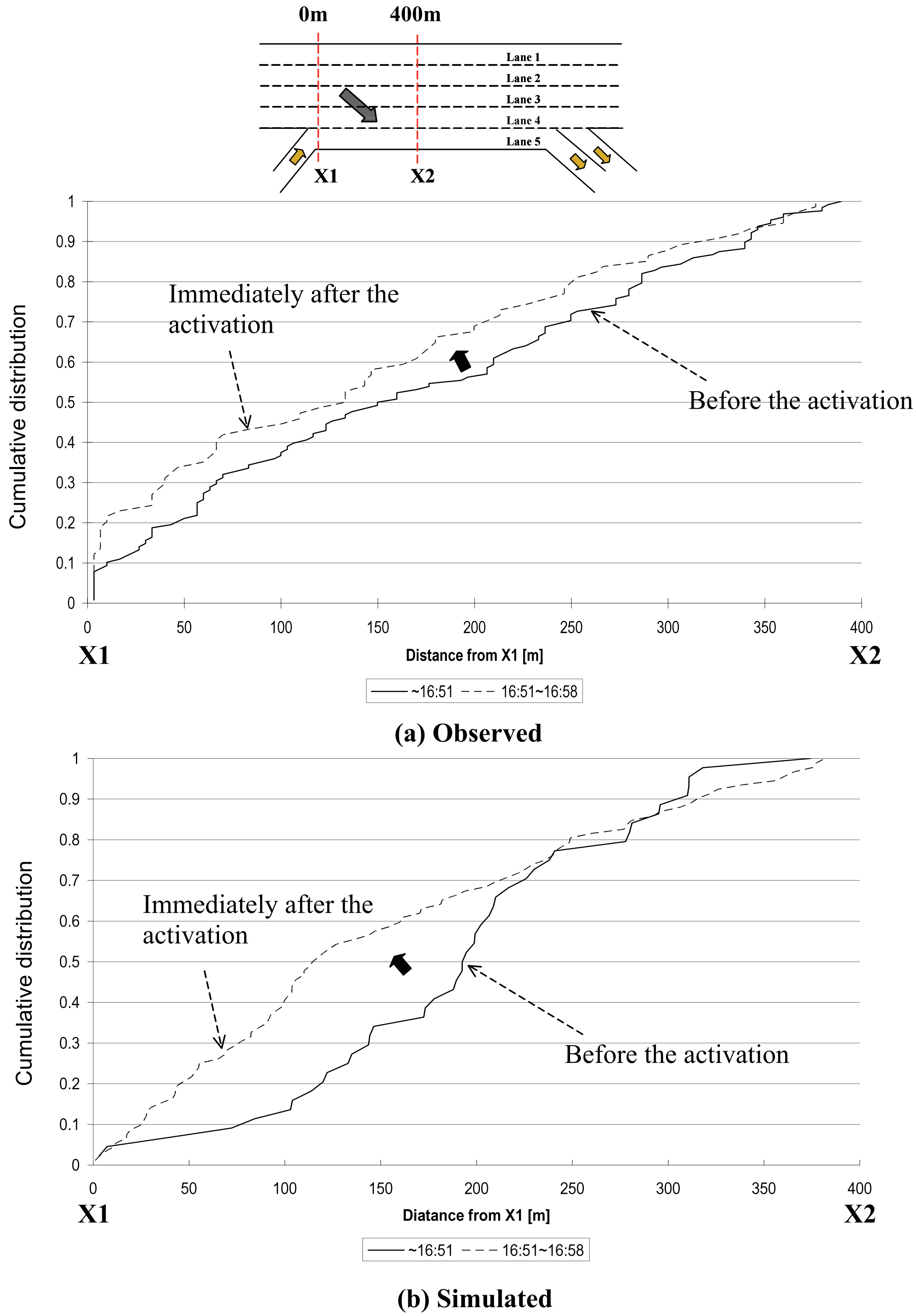
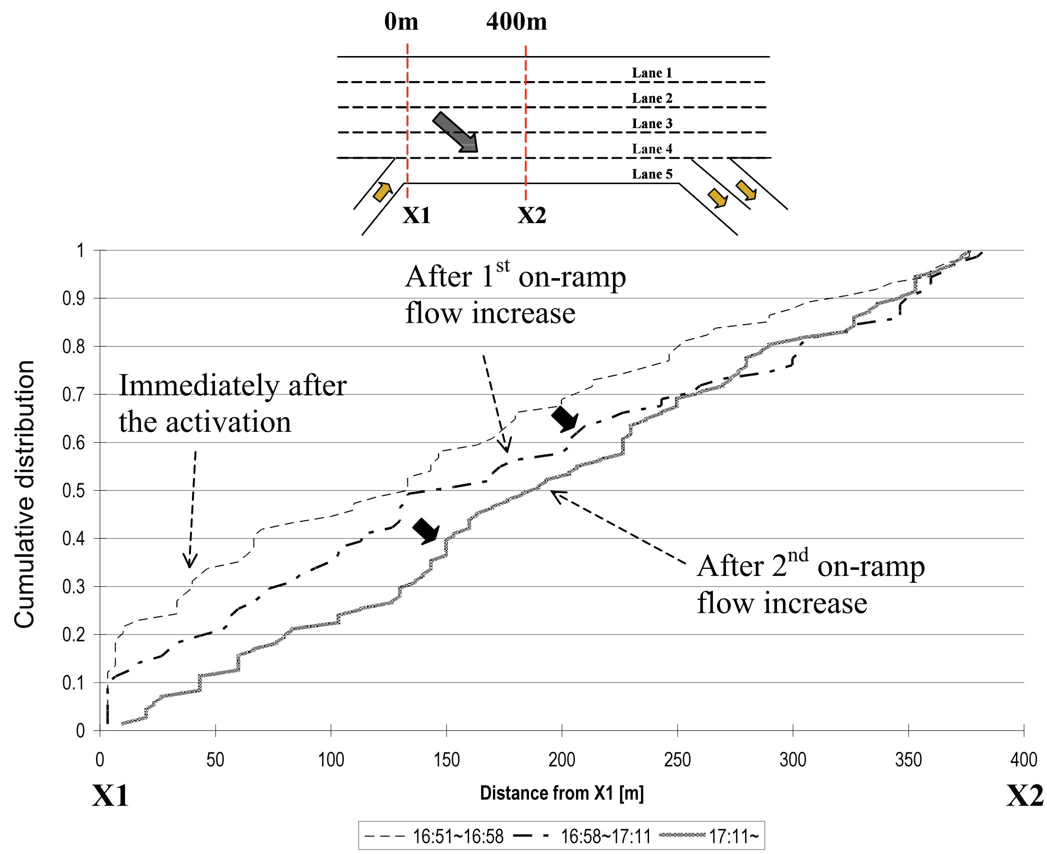
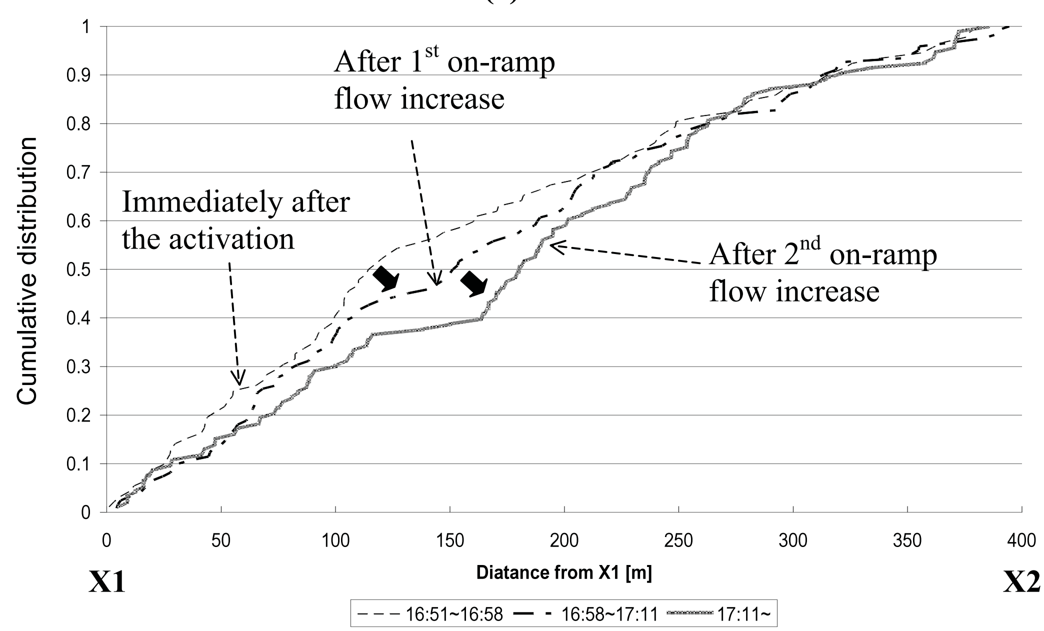


Figure 25. Comparison of cumulative distributions of F-R vehicles' lane changes from 3 to 4 before 16:58 hrs, SR-55N



(a) Observed



(b) Simulated

Figure 26. Comparison of cumulative distributions of F-R vehicles' lane changes from 3 to 4 after 16:51 hrs, SR-55N

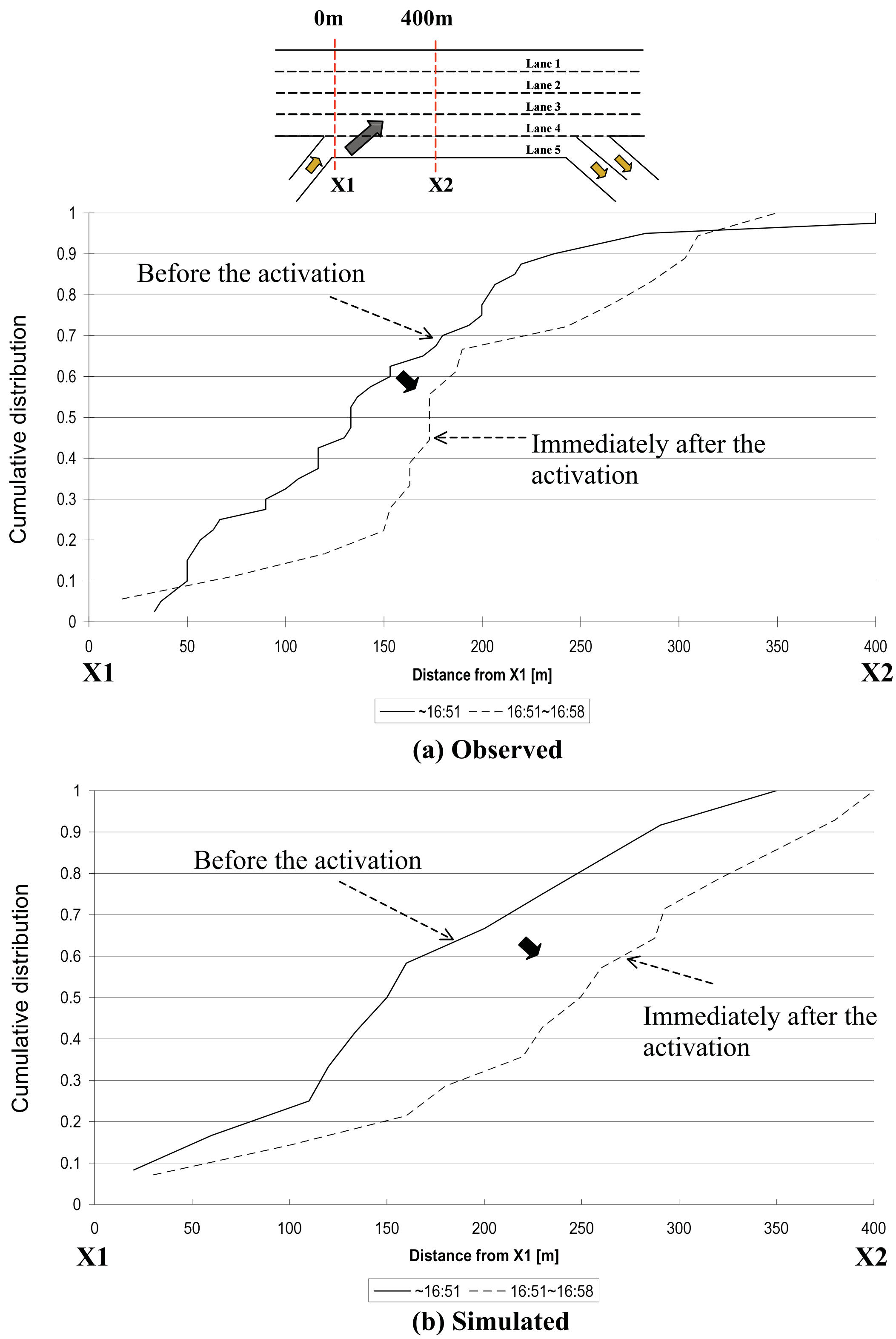


Figure 27. Comparison of cumulative distributions of R-F vehicles' lane changes from 5 to 4 before 16:58 hrs, SR-55N

APPENDIX D

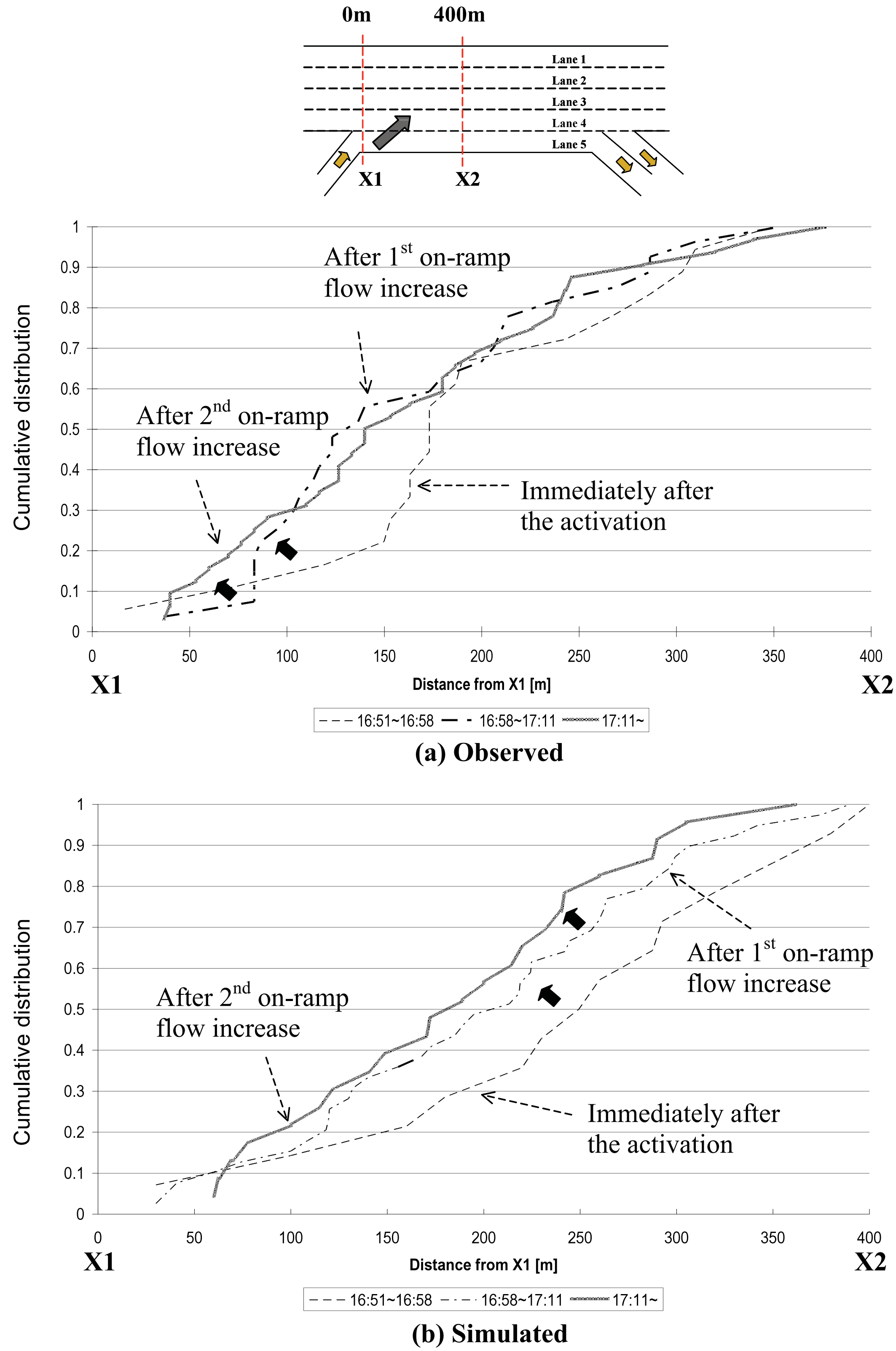


Figure 28. Comparison of cumulative distributions of R-F vehicles' lane changes from 5 to 4 after 16:51 hrs, SR-55N

4.3.2. Simulation Results for site 2, I-210 W

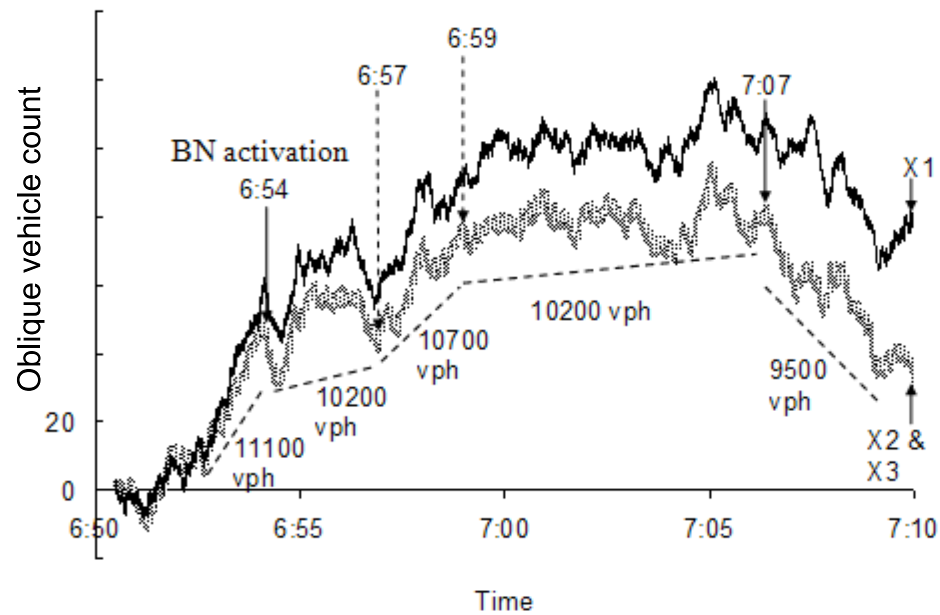
The model applied at site 1 (SR-55 N) was tested again at site 2 (I-210 W). Here the $\boldsymbol{\beta}$ estimated for site 1 were not altered in order to test the transferability of the estimated model; i.e., to investigate if this model can qualitatively replicate the traffic patterns at another site (site 2) without additional calibration. The input data for the simulations consisted of on-ramp demands (two R-R movements to account for the site's two off-ramps and one R-F movement, see again figure 15) and upstream freeway demands (one F-F and two F-R). Thus the site's two off-ramp junctions result in six distinct vehicular movements. Though the on-ramp was metered during the morning rush, on-ramp queues did not form during any of the observation periods. Hence, the measured on-ramp flows were equal to on-ramp demands. In contrast, queues formed in the upstream freeway segment during the rush periods, so freeway demands prior to the bottleneck activation were once again used for the whole simulated period, as previously explained in section 4.3.1.

Without the recalibration of the parameters, the model qualitatively replicated the O-curves and the cumulative distributions of lane changes observed at site 2. Figures 31a and b show the observed and simulated O-curves. The simulations accurately predicted the bottleneck activation time (6:54 hrs), the times when the discharge flows changed, and the directions of these changes. Figures 32a and b show the observed and simulated cumulative distributions of F-R vehicles' lane changes from 4 to 5, and figures 33a and b show these distributions for R-F maneuvers from 6 to 5. Figures 34 and 35 show these distributions for the period of demand fluctuation (reduction) from 6:57 to 6:59 hrs.

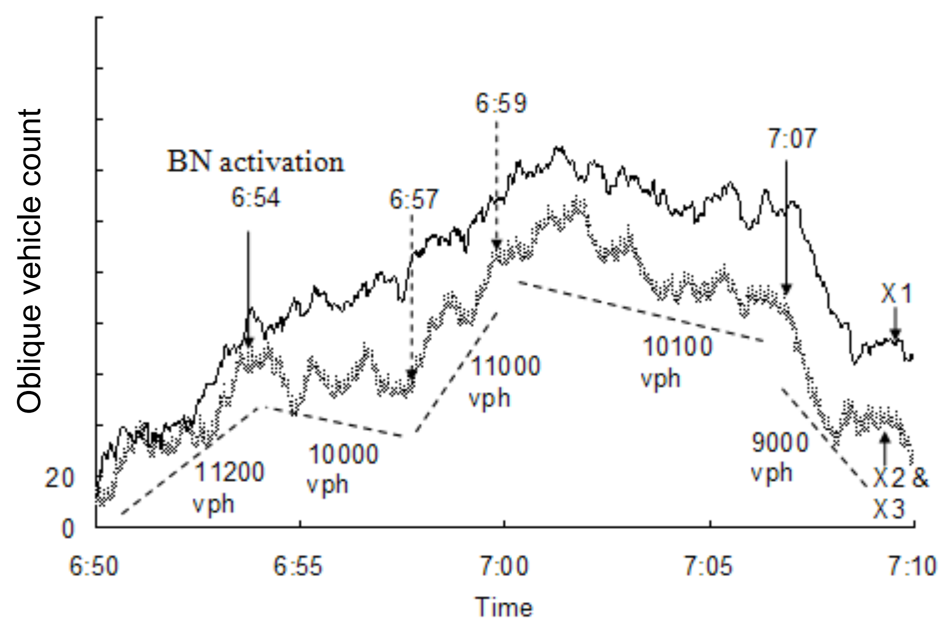
The simulated lane changes generally took place closer to the on-ramp than did their observed counterparts. These small discrepancies aside, the simulated maneuvers still qualitatively matched the observed ones fairly well: the cumulative distribution curves moved in the same directions from one time period to the next.

Further, the simulation results again showed that as F-R vehicles traveled on the upstream freeway segment and approached the merge, they postponed their maneuvers from lane 4 to 5 until reaching the location X1 where the auxiliary lane begins. Once these F-R vehicles passed the location X1 and encountered the auxiliary lane (with lower densities and higher speeds due to low on-ramp flows), they promptly maneuvered to lane 5, and then immediately onto lane 6, producing high concentrations of lane changes near the on-ramp.

In summary, the model qualitatively replicated observed lane-changing behavior and subsequent discharge flow changes at both weaving study sites.



(a) Observed curves



(b) Simulated curves

Figure 29. Comparison of oblique count curves at X1, X2, and X3, I-210 W

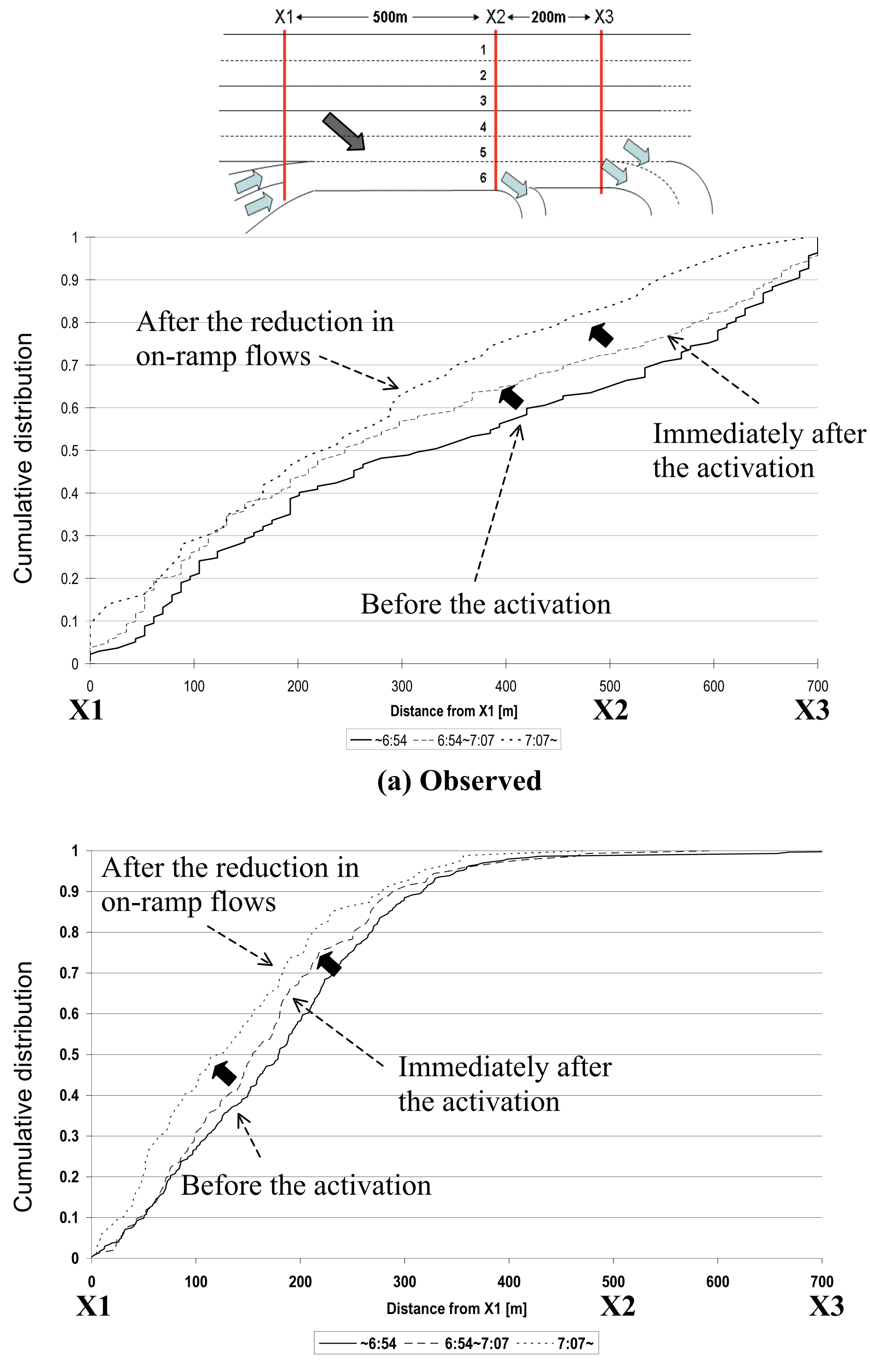
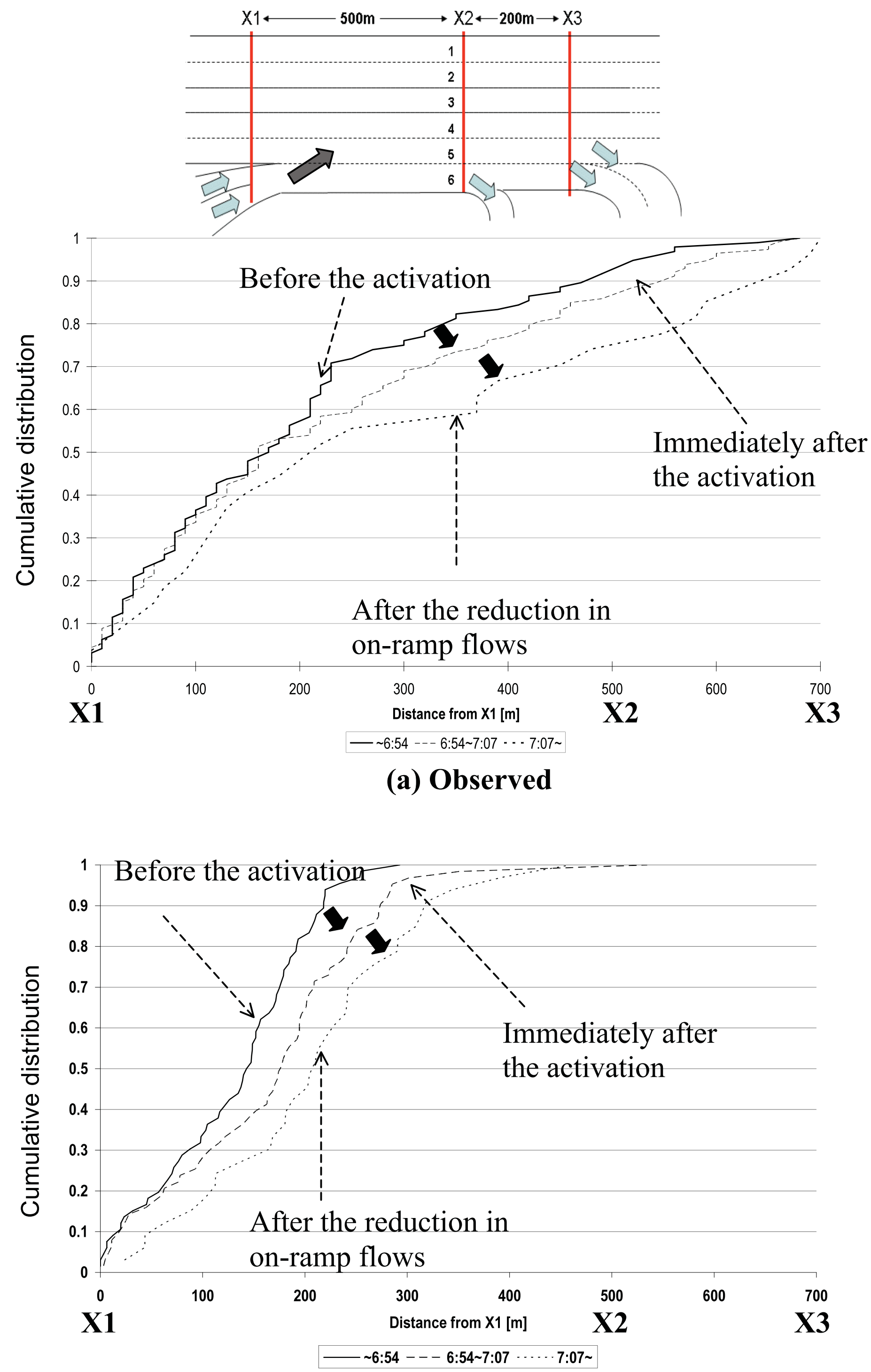
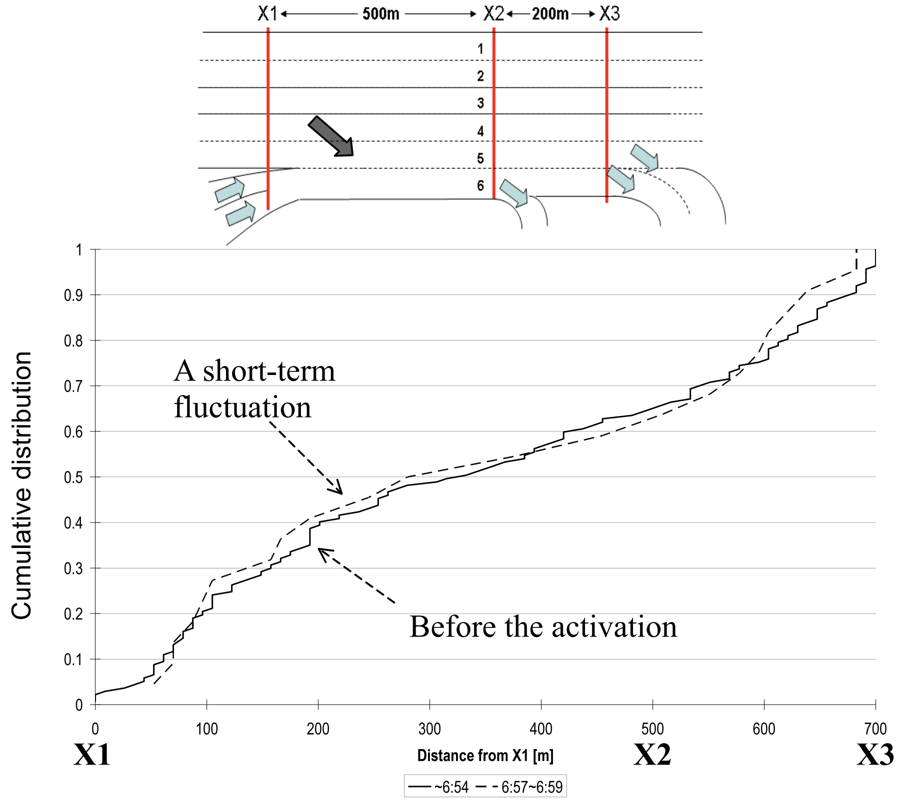


Figure 30. Comparison of cumulative distributions of F-R vehicles' lane changes from 4 to 5, I-210W

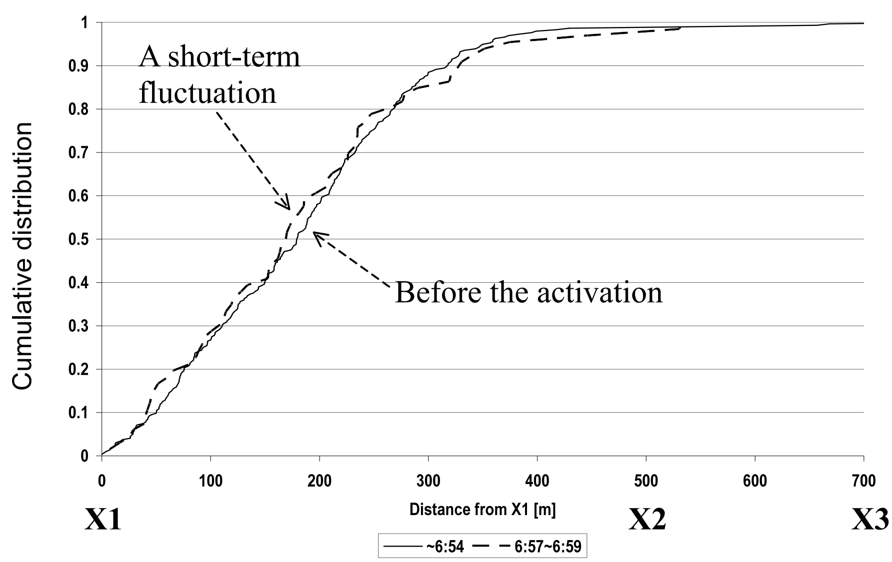


(b) Simulated

Figure 31. Comparison of cumulative distributions of R-F vehicles' lane changes from 6 to 5, I-210W

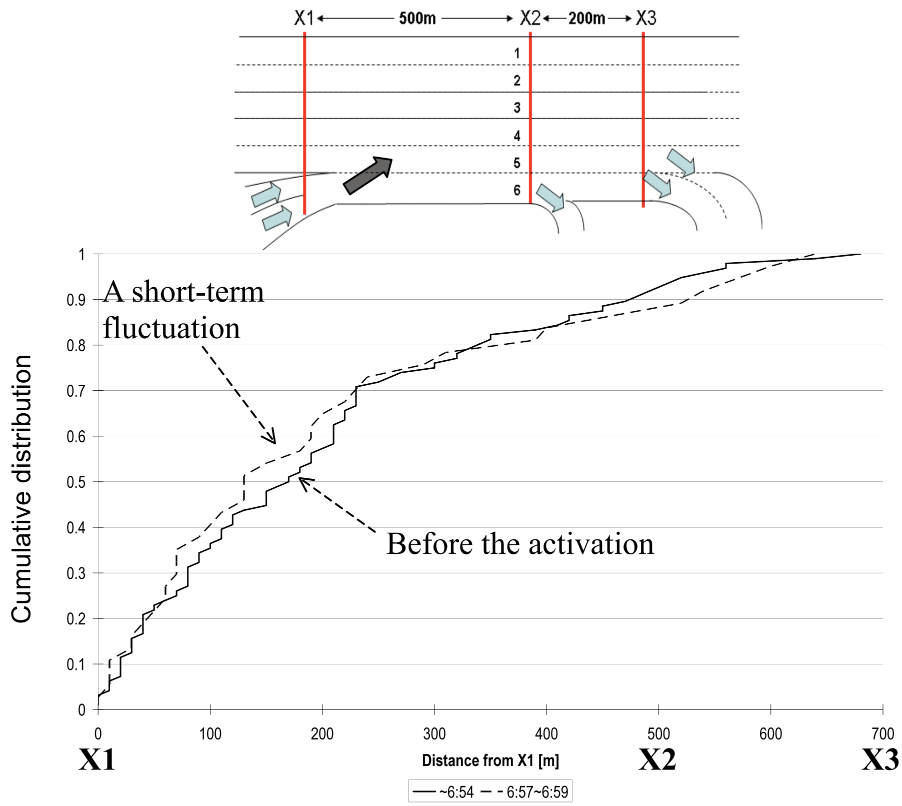


(a) Observed

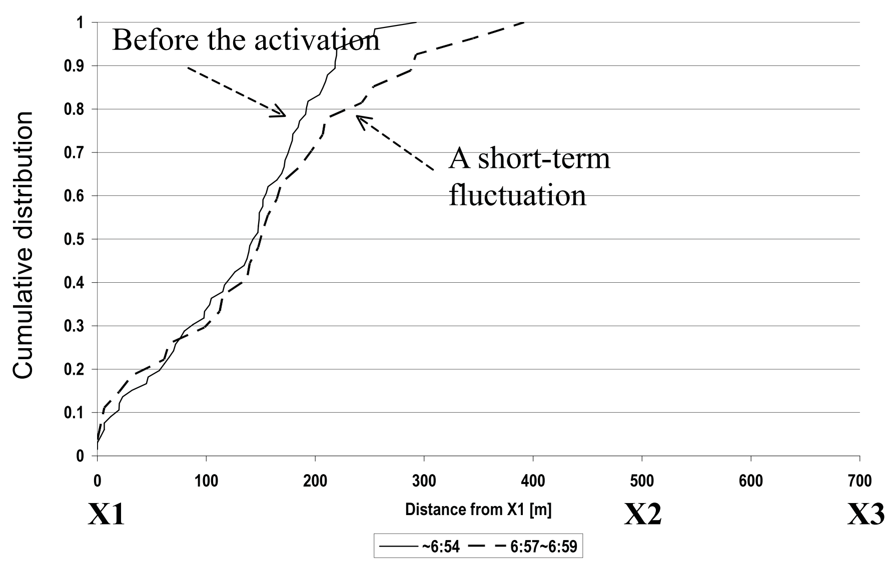


(b) Simulated

Figure 32. Comparison of cumulative distributions of F-R vehicles' lane changes from 4 to 5 between 6:57 hrs and 6:59 hrs, I-210W



(a) Observed



(b) Simulated

Figure 33. Comparison of cumulative distributions of R-F vehicles' lane changes from 6 to 5 between 6:57 hrs and 6:59 hrs, I-210W

CHAPTER 5. CONCLUSIONS

The investigations of the two weaving bottlenecks revealed that the bottleneck activations were triggered by disruptive F-R lane changes. F-R lane changes became disruptive: i) when there were increased concentrations of F-R lane changes near the on-ramp merge triggered by reductions in on-ramp flows; or ii) when there were simply too many F-R lane changes, independent of the ramp flows. The investigations further revealed that changes in the spatial distributions of mandatory lane changes, especially for the F-R maneuvers, also led to variations in bottleneck discharge flows. When the F-R maneuvers were concentrated near the on-ramp, they became more disruptive and resulted in discharge flow reductions. This cause and effect mechanism was verified from empirical findings in Chapter 3 and from the simulation results in Chapter 4.

Findings also indicate that the spatial distributions of these lane changes, in turn, were dictated by the traffic conditions in the auxiliary lane. On-ramp flow reductions evidently increased the attractiveness of the auxiliary lanes, thus motivating F-R drivers to perform their maneuvers nearer the on-ramp and to become more disruptive. In contrast, rising on-ramp flows reduced the attractiveness of the auxiliary lanes and reduced the amount of disruptive F-R maneuvers that took place near the on-ramp. These reductions led to discharge flow increases.

These mechanisms are contrary to the previous conjectures that higher on-ramp flows (more lane changes) decrease weaving bottleneck discharge flows. Yet, the data presented here are incontrovertible: it is not only the amount of lane changes that influence weaving bottleneck discharge flows, but also the spatial distributions (the concentrations) of these maneuvers.

The observed phenomena also suggest that metering on-ramps at weaving sections can sometimes be detrimental to their discharge flows, possibly when the metering is very restrictive. Regretfully, the two sites reported here exhibited only a limited range of on-ramp flows. Thus, additional study sites may need to be analyzed to further our understanding of weaving bottlenecks, and to determine desirable ramp metering rates for these bottlenecks.

The model estimated in this work was based on observations of real traffic, and qualitatively reproduced the mechanisms of weaving bottleneck activations and discharge flow changes. The simulation results at both study sites supported the two key conjectures that arose from the empirical findings: i) traffic conditions (especially densities) in an auxiliary lane influence drivers' decisions on where to perform mandatory lane changes; and ii) the spatial distributions of these lane changes determine weave bottleneck discharge flows.

The model was developed into an executable standalone program in MATLAB so that engineers and planners can readily analyze and design freeway weaving sections. The user manual for this program is in Appendix B of this report. The program and its manual can be downloaded at the author's homepage (http://www2.decf.berkeley.edu /~ljunho7/weaving/).

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APPENDIX A: MENENDEZ'S CAR-FOLLOWING MODEL

The overview of Menendez's model was presented in section 2.4. Presented in this appendix is a more detailed qualitative description of the theory. The reader can refer to the original source – Menendez (2006) – to see the equations of the model. Section B.1 describes the car-following component of Menendez's model; and section B.2 explains the choice model for lane-changing.

A.1. Car-following Model

Menendez's model has three components in its car-following model: simple car-following, car-following during the lane-changing process, and cooperation and forced car-following for lane changes. The following sections explain the logic behind these three components.

A.1.1 Simple Car-following

The simple car-following model determines the locations of vehicles when there are no vehicles performing or attempting lane changes. Under this model, drivers maximize their traveled distance for each time interval subject to their vehicles' mechanical limitations, safety, and comfort.

The vehicles' mechanical limitations refer to the maximum acceleration and deceleration rates. Vehicles can only accelerate or decelerate based on these rates.

As regards to safety, the Menendez model does not allow any collisions during simulation runs. Rather, simulated vehicles must be able to slow down at any time without crashing into the vehicle in front. This safety constraint is based on equations developed from the time-space trajectories of two vehicles, assuming that the lead vehicle decelerates with the maximum rate and the reaction time of the following vehicle is one simulation interval.

Comfort constraints describe the relationship between a vehicle's spacing and its speed. This relationship is based on the CF(L) car-following model, something equivalent to the kinematic wave model, in which the vehicles' most advanced locations are the function of the difference between their current spacings and the jam spacing. Vehicles can *comfortably* travel at faster speeds as their spacings becomes larger.

A.1.2 Car-following during Lane-changing Process

The lane-changing model shares two constraints with the basic car-following model described above: mechanical limitations (i.e., vehicles can accelerate and decelerate with the maximum rates.) and safety. Regarding the later, vehicles that perform lane changes should not collide with any vehicles in the target lane. Note that this lane-changing model neglects the comfort constraint, because drivers tend to drive aggressively with lesser spacings when they change lanes.

A.1.3 Cooperation and Forced Car-following for Lane Changes

Safety constraints under simple car-following and lane changes become more restraining under congested traffic condition, resulting in the unrealistically small number of lane changes. To realistically replicate traffic behavior in congestion (to generate more lane changes), a logic of cooperation and forced car-following with lane changes is incorporated into the Menendez's model.

This logic is activated when a vehicle continuously tries and fails to perform a lane change based on the model in A.1.2. In this case, the lane-changing vehicle either slows down, or the vehicle behind in the target lane slows down to make space for her.

A.2. Choice Model for Lane-changing

The choice model determines when or where individual vehicles decide to perform lane changes. The choice model for lane-changing is composed of three components: mandatory time-related lane changes, mandatory space-related lane changes, and optional lane changes.

A.2.1 Mandatory Time-related Lane changes

The choice model describes a driver's lane-changing decisions in response to her perceptions of the HOV lane activation times. Single Occupancy Vehicle (SOV) drivers migrated from an HOV lane when they deem the HOV lane active, resulting in mandatory lane changes. The model randomly generates HOV activation times perceived by individual drivers, and SOV drivers in the HOV lane perform lane changes according to these times.

A.2.2 Mandatory Space-related Lane changes

Vehicles perform mandatory space-related lane changes when there is a diverge or a lane-drop downstream. The decisions of where to perform these lane changes are determined by lane-changing cones (see figure 22). Note that this choice model is reworked in the present model, and for further explanations of this, see section 4.1.

A.2.3 Optional Lane changes

A driver's decision on optional lane changes is determined by the speed difference between her current lane and adjacent lanes, and her sensitivity to this difference; i.e., if a driver is sensitive, she reacts to slight differences in speeds.

APPENDIX B: THE MANUAL OF THE WEAVING SIMULATION PROGRAM

The following describes how to run the microscopic car-following and lane-changing simulation model of weaving traffic. Detailed algorithms for the simulation program were presented previously in this report. The program is only applicable to weaving sections with connected (full) auxiliary lanes. Applications of the program to acceleration or deceleration auxiliary lanes are not recommended. To download the zip file of the program, go to the following link: (http://www2.decf.berkeley.edu/~ljunho7/weaving/wsimv3.zip). First, extract the zip file onto your computer. If your computer does not have a zip program, go to this link to download one: (http://www.download.com/3001-2250_4-10631836.html). The program (a car-following with lane-changing model) simulates microscopic traffic behavior observed in freeway weaving sections.

To run this program, click the wsim.exe file and wait for a while (do not close the command prompt). If you receive any error messages while opening the program, go to the following link (http://www2. decf.berkeley.edu/~ljunho7/weaving/MCRInstaller.exe) and install the MCR installer program.

B.1. Inputs for the Program

Once the program is opened, users must specify several input items:

1) Traffic demands [veh/hr] by their Origin-Destination (i.e., Freeway-to-Freeway, Freeway-to-Ramp, Ramp-to-Freeway, and Ramp-to-Ramp) and the durations

[minutes] over which these rates persist. As many as 8 different OD tables can be run in a single simulation.

2) Geometric configurations:
    a. Length of the weaving section of interest [ft]
    b. Number of freeway lanes upstream of the on-ramp
    c. Number of off-ramp lanes
    d. Number of on-ramp lanes
    e. Free-flow speed for vehicles in simulation runs [mph]
    f. Reference speed for delay calculation [mph]

Two examples of geometric configurations are shown below in figure 38. Note that the program always assumes that there is at least one auxiliary lane from the on-ramp to the off-ramp.

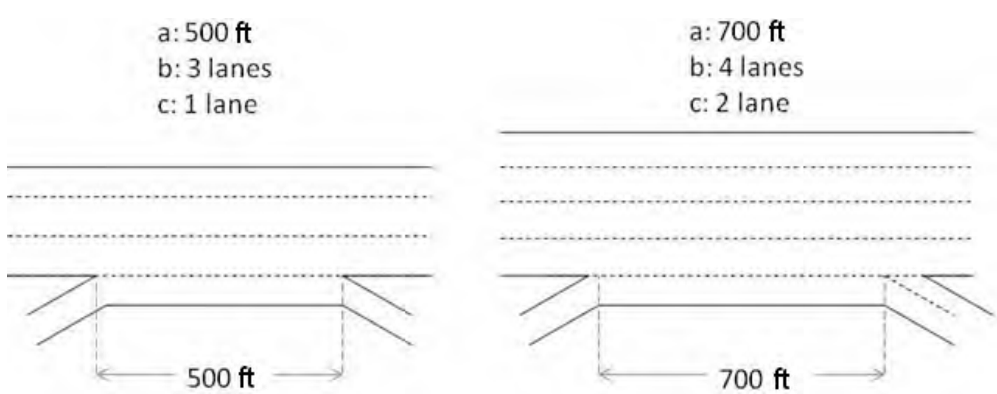

Figure 34. Examples of geometric configuration inputs for the program

B.2. Outputs of the Program

The program generates simulation results at one-minute intervals. It shows total delays [veh-hr] as well as delays [veh-hr] for each OD maneuver. Further, it plots oblique cumulative vehicle count curves (O-curves) that display freeway and off-ramp discharge flows [veh/hr]. It also displays time-series of one-minute average speeds by OD maneuvers:

1) Solid line in red: average speeds of F-F traffic
2) Solid line in green: average speeds of F-R traffic
3) Dotted line in blue: average speeds of R-F traffic
4) Dotted line in black: average speeds of R-R traffic

B.3. Program Reports

The report button on the main menu generates report of simulation results on two different windows. The first window displays:

1) Demands specified by the user
2) Geometric configurations of the weaving section
3) Total delays and delays by OD
4) Average freeway and off-ramp discharge flows
5) The O-curve of freeway flows of the weaving sections' downstream end
6) The O-curve of off-ramp flows
7) The time-series curve of the weaving section's total density
8) The time-series curves of vehicular speed by OD

The second window displays the following information for each user-specified period:

1) The O-curve of freeway flows of the weaving sections' downstream end & off-ramp flows
2) Average speeds of all vehicles and vehicular delays
3) The average speeds and delays for each OD maneuver

The report is automatically saved as a report.bmp file and a report_by_period.bmp file at the location where the program is installed. Users can easily import these image files into any software applications. Sometimes one of the report windows is not saved in the image files due to some unknown bugs in Matlab. If this happens, click the report button again without closing any windows.