FINAL REPORT

Project K2

Assessing & Addressing Deficiencies in the HCM Weaving Segment Analyses

Dr. Nagui Rouphail | North Carolina State University

Dr. Behzad Aghdashi | University of Florida

Dr. Lily Elefteriadou | University of Florida

Ehsan Amini | Student, University of Florida

Dezhong Xu | Student, North Carolina State University

STRIDE | Southeastern Transportation Research, Innovation, Development and Education Center

UF | Transportation Institute UNIVERSITY of FLORIDA

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7. Author(s)
Dr. Nagui Rouphail, Ph.D., North Carolina State University
Dr. Behzad Aghdashi, Ph.D., University of Florida
Dr. Lily Elefteriadou, Ph.D., University of Florida
Ehsan Amini, doctoral student
Dezhong Xu, doctoral student

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North Carolina State University
915 Partners Way
Raleigh, NC 27695-7908
University of Florida
365 Weil Hall
PO Box 116580
Gainesville, FL 32611

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365 Weil Hall,
P.O. Box 116580
Gainesville, FL 32611

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1200 New Jersey Avenue, SE
Washington, DC 20590
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16. Abstract
The Highway Capacity Manual 6th Edition (HCM6) provides methods for the evaluation of freeway segments and freeway facilities including weaving segments. Weaving segments are often critical components of freeway facilities because they can act as bottlenecks. Recent research has questioned the validity of the HCM6 weaving analysis methodology. The main objectives of this research project were to identify, document, and address the major deficiencies in the current HCM6 weaving method through improved modeling of key procedures and their calibration. The research team conducted a literature review to identify and document deficiencies in the procedure. Next, the team collected field data and obtained previously collected data at weaves and developed a new framework for evaluating operations at freeway weaves. This new framework uses the basic segment freeway model and a speed impedance factor that represents the weaving turbulence, which proved to be simpler and more accurate than the models in the HCM6. A model was developed for Type A or ramp weaves, which predicts the average speed of the weaving segment directly without using intermediate models to predict the number of lane changes. It was concluded that the HCM6 model tended to underestimate the speed within the weaving section compared to field data. A sensitivity analysis showed that the new model can predict the speed and capacity for ramp weaves reasonably well.

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LIST OF AUTHORS

Lead PI (February 2020–Present)

Dr. Nagui Rouphail, Ph.D.
Former Director, ITRE
Distinguished University Professor Emeritus
Civil & Environmental Engineering, Construction Engineering
North Carolina State University
rouphail@ncsu.edu
ORCID Number: 0000-0002-2420-9517

Lead PI (August 2018–February 2020)

Dr. Behzad Aghdashi, Ph.D.
Director at McTrans Center – University of Florida
Department of Civil and Coastal Engineering
University of Florida
saghdashi@ufl.edu
ORCID Number: 0000-0003-2650-8470

Co-PI:

Dr. Lily Elefteriadou, Ph.D.
Director, UF Transportation Institute
Barbara Goldsby Professor, Civil and Coastal Engineering
University of Florida
elefter@ce.ufl.edu
ORCID Number: 0000-0003-4045-3365

Additional Researchers:

Ehsan Amini, Ph.D. Student
Graduate Research Assistant
Civil and Coastal Engineering, University of Florida
amini.e@ufl.edu

Dezhong Xu, M.S.
Graduate Research Assistant
CCEE Department, NC State University
dxu7@ncsu.edu

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ABSTRACT

The Highway Capacity Manual 6th Edition (HCM6) provides methods for the evaluation of freeway segments and freeway facilities including weaving segments. Weaving segments are often critical components of freeway facilities because they can act as bottlenecks. Recent research has questioned the validity of the HCM6 weaving analysis methodology. The main objectives of this research project were to identify, document, and address the major deficiencies in the current HCM6 weaving method through improved modeling of key procedures and their calibration. The research team conducted a literature review to identify and document deficiencies in the procedure. Next, the team collected field data and obtained previously collected data at weaves and developed a new framework for evaluating operations at freeway weaves. This new framework uses the basic segment freeway model and a speed impedance factor that represents the weaving turbulence, which proved to be simpler and more accurate than the models in the HCM6. A model was developed for Type A or ramp weaves, which predicts the average speed of the weaving segment directly without using intermediate models to predict the number of lane changes. It was concluded that the HCM6 model tended to underestimate the speed within the weaving section compared to field data. A sensitivity analysis showed that the new model can predict the speed and capacity for ramp weaves reasonably well.

Keywords: Highway Capacity Manual, freeway weaving analysis, freeway systems analysis

1 INTRODUCTION

1.1 Background

The Highway Capacity Manual (HCM) is one of the most widely used references in transportation engineering, both for planning and operational analyses. The HCM 6th Edition (HCM6) provides methods for the evaluation of basic freeway segments, weaving segments, merge and diverge segments, freeway facilities, and travel time reliability evaluation of freeway facilities. Weaving segments are often critical components of freeway facilities because they can act as bottlenecks. Any bias or errors within this procedure can significantly impact facility-wide or reliability analyses and, in the process, bring into question the validity of the entire freeway facility analysis methodology. Researchers at North Carolina State University have been advised of this issue by multiple consultants when evaluating the implementation of the HCM6 freeway facility method in the FREEVAL software.

Project NCHRP 3-75 developed the most recent weave analysis method, which is used in the HCM6. The project used real-world data and provided analytical models to assess several weave segment configurations by estimating speeds, capacities, and level of service (LOS). The model was adopted in the HCM2010 and is included in the HCM6. In recent years, practitioners have found several cases where this method cannot model or show sensitivity to important parameters under certain operating conditions. For example, the non-weaving vehicles' speeds are not sensitive to the short length of the weaving section (which is the distance between two gore points in the weave segment). Also, the non-weaving speed is not sensitive to all lane changes within the segment, which is counterintuitive.

These deficiencies have led to questions about the validity of the HCM's weave segments analysis. Furthermore, these deficiencies have gradually led to wide-spread concerns with facility-wide or travel time reliability analyses that incorporate weaving segment analyses.

1.2 Research Objectives

The main objectives of this research project were to identify, document, and address the major deficiencies in the current HCM weaving method through improved modeling of key procedures and their calibration. The following tasks were undertaken:

1. Conduct a literature review to identify and document deficiencies cited in or reported by practitioners and other HCM users for the HCM6.

2. Test, review, and evaluate the HCM6 weaving analysis method for a variety of scenarios in order to identify and document inconsistencies and problems related to lack of sensitivity of various parameters to important independent variables. These parameters include the effects of short length and lane change rates.

3. Assemble a database using field data and previously collected data from the NCHRP 3-75 project to use in further analysis and methodology modification. The project focused on ramp weave configurations (also referred to as Type A weaves).

4. Adjust and modify the weaving analysis method using the database developed for this project.

5. Present the results of the research to the TRB ACP40 Committee (Highway Capacity and Quality of Service Committee) for review and potential inclusion into an upcoming edition of the HCM.

1.3 Scope

The scope of this research was limited to ramp weave (Type A) segments. The models developed from this research have not been evaluated for other types of weaving segments.

1.4 Organization of the Report

The remainder of this document is organized as follows. Chapter 2 summarizes the literature review that focuses on the historical development of HCM-related weaving operational analysis, other weaving analysis models developed, and recent research that critically analyzed the HCM6 weaving analysis method. Chapter 3 describes the data collection effort and summarizes the database assembled, while Chapter 4 provides the conceptual model formulation and the development of the calibrated model. Chapter 5 documents the model validation and sensitivity analysis and compares the results to those in the HCM6. Chapter 6 summarizes the research conducted, presents the final recommended model, conclusions from the study, and recommendations for future research.

2 LITERATURE REVIEW

This chapter presents a review of the published literature on weaving segment analysis models. The review includes models that have been adopted in various editions of the HCM and other macroscopic and microscopic models developed.

2.1 History of Weaving Operational Analysis in the HCM

The HCM was first introduced in 1950 (Bureau of Public Roads, U.S. Department of Commerce, 1950). Until now, there have been six major versions of the HCM (in addition to minor revised editions) published. The HCM1950 analyzed weaving segments using six sites and data collected from the Pentagon Network and the San Francisco Bay Bridge. The method considered weaving vehicle behavior and the impact of speed on segment capacity. The relationships between traffic volumes and speed from the six sites are presented in Figure 2-1.

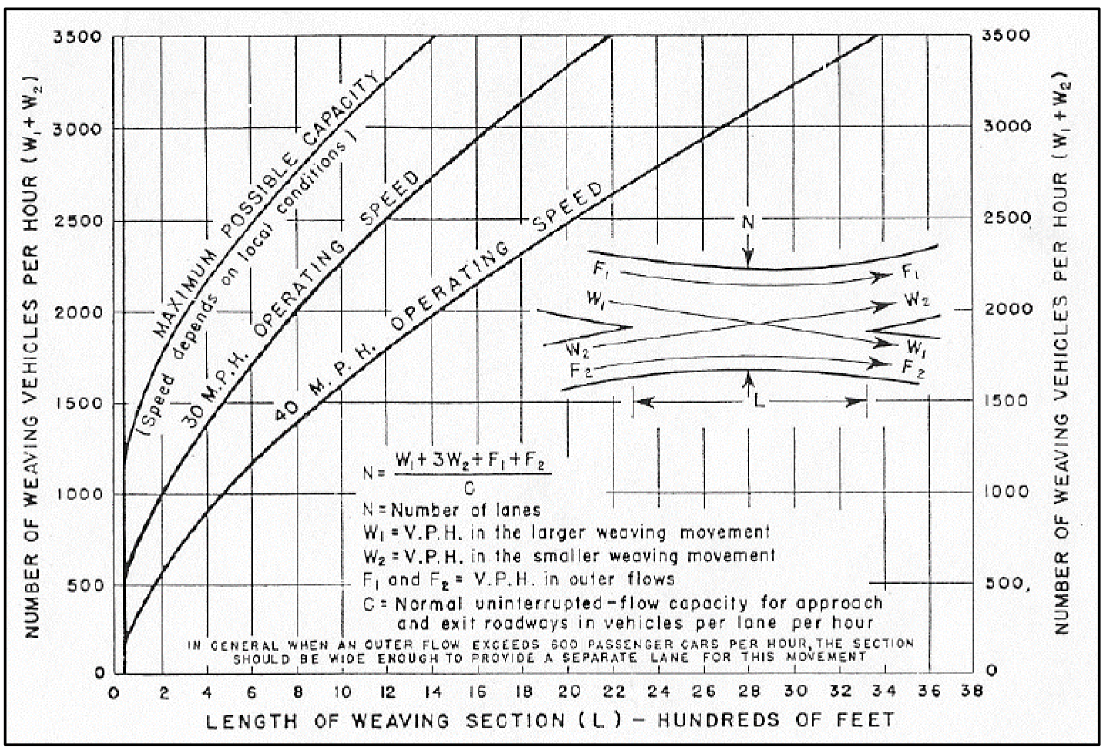


Figure 2-1: HCM1950 traffic volumes and speed relationship plot

In 1965, Leisch and Normann developed a method based on the analysis results of the HCM1950 (Normann, 1957) and their method was added in HCM1965 (Highway Research Board, National Research Council, 1965). The HCM1965 defined many new concepts for weaving segments. For example, it divided weaving segments into two types: simple weaving sections and multiple weaving sections. Both types could be further subdivided into one-sided or two-sided sections. The traffic flows in the weaving segment were distinguished as weaving movements and non-weaving movements. The method defined and used the weaving segment length. However, the most important concept in HCM1965 was the development of basic procedures and methodologies to design and evaluate weaving segments. The quality of flow was introduced as a measure of the weaving section operation. As Figure 2-2 shows, the quality of flow had five designated classes (I to V), which represent the congestion level from light to heavy. Each curve in the figure contained a number known as the k-factor. As stated in the HCM 1965: “The k-factor, in effect, is an equivalency factor expanding the influence of the smaller flow up to a maximum of three times its actual size in number of vehicles.” The steps for measuring the weaving section performance were as follows: First, the user locates a point based on segment length and weaving demand. Then, by finding the nearest curve to the point, the class of the quality of flow and the estimated speed can be identified. From Table 7.3 of the HCM1965, which is shown in Table 2-1, the known quality of flow can be converted to the LOS. The capacity of the segment is determined using Table 2.2 (Table 7.2 of HCM1965). However, the capacity was not used in determining the LOS. Even though the HCM1965 included a method for evaluating the segment performance, it was mostly focused on the design of the segment.

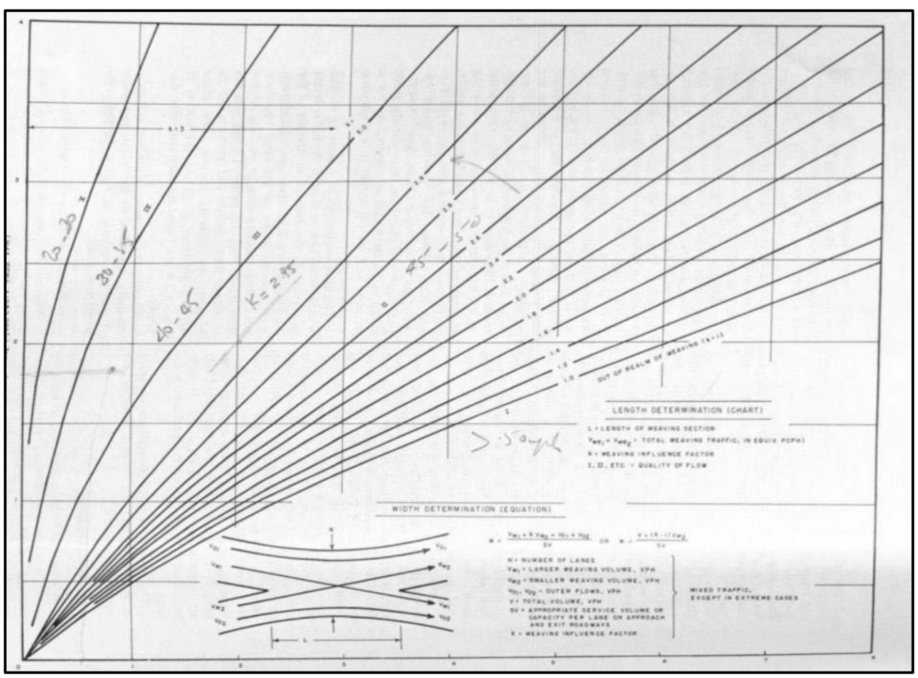


Figure 2-2: Quality of flow curves and relative estimated speeds (HCM1965)

Table 2-1: HCM1965 relationship between LOS and quality of flow on a weaving section (HCM1965)

<table>
<tr><th rowspan="2"></th><th colspan="4">Quality of Flow</th></tr>
<tr><th colspan="2">Freeways and Multilane Rural Highways</th><th colspan="2"></th></tr>
<tr><th>Level of Service</th><th>Highway Proper</th><th>Connecting Collector-Distributor Roads and Other Interchange Roadways</th><th>Two-Lane Rural Highways</th><th>Urban and Suburban Arterials</th></tr>
<tr><td>A</td><td>I–II</td><td>II–III</td><td>II</td><td>III–IV</td></tr>
<tr><td>B</td><td>II</td><td>III</td><td>II–III</td><td>III–IV</td></tr>
<tr><td>C</td><td>II–III</td><td>III–IV</td><td>III</td><td>IV</td></tr>
<tr><td>D</td><td>III–IV</td><td>IV</td><td>IV</td><td>IV</td></tr>
<tr><td>E</td><td>IV–V</td><td>V</td><td>V</td><td>V</td></tr>
<tr><td>F</td><td colspan="4">Unsatisfactory</td></tr>
</table>

Table 2-2: Quality of flow and maximum lane service volumes in a weaving section (HCM1965)

Quality of Flow Curve	Max Lane SV Value (pc/h)
I	2,000
II	1,900
III	1,800
IV	1,700
V	1,600

From 1965 to 1985, several weaving analysis models were developed. Roess and McShane's model appeared in several forms, and its final form was introduced in Circular 212 (Transportation Research Board, 1980). The model was iterative and intended to predict the average speed of weaving and non-weaving vehicles. In 1984, Reilly developed a model that utilized a density concept tied to weaving intensity to predict the average speed for weaving and non-weaving traffic (Reilly, Johnson, & Kell, 1984). The HCM1985 merged these two models

(Transportation Research Board, 1985). Reilly et al.'s model was stratified to different configurations and types of operations. The following equation was used in the HCM1985 to estimate speeds:

$$S_i = 15 + \frac{50}{1 + a(1 + VR^b)\left(\frac{v}{N}\right)^c / L^d} \tag{2}$$

where

S_i is the average speed in the weaving section i

VR is the volume ratio

v is the total traffic volume

N is the number of lanes

L is the length of the weaving section

$a, b, c,$ and d are model's parameters.

The equation implies that the traffic speed is related to the volume ratio, traffic demand, number of lanes, and the length of the segment. The four constant parameters (*a*, *b*, *c*, and *d*) in the equation were calibrated considering the type of the segment and type of operation. First, the speed was predicted by using unconstrained operation parameters. Then, by comparing two variables, the number of lanes required for the weaving segment, N_w, and the maximum number of weaving lanes, N_w(max), the assumption for the predicted speed under the unconstrained condition was justified.

The HCM1985 distinguishes between 3 types of weaves (Figure 2-3). For Type A weaving sections, the weaving vehicles in each direction must make one lane change, while in Type B sections one of the weaving movements can reach its destination without making lane changing and the other requires one lane change. In Type C weaving sections one of the weaving movements can reach its destination without any lane changes, while the other movement requires at least two lane changes.

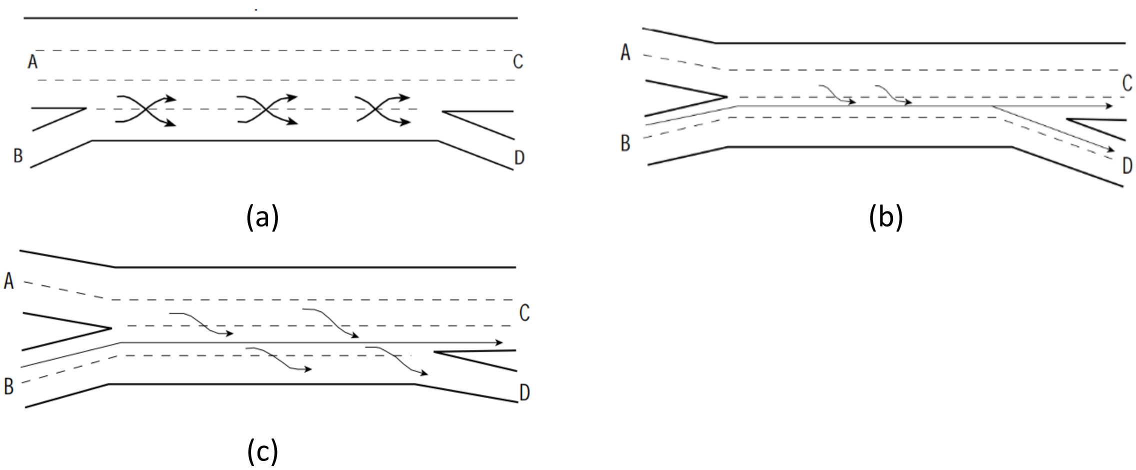


Figure 2-3: Schematic of weaving section a) type A; b) type B; and c) type C

Table **2-3** shows the equations for calculating N_w and $N_w(max)$ for different types of configurations. The speed was predicted using the parameters of the constrained operation if it was shown that traffic was constrained. The predicted speed was then used in the determination of LOS for weaving and non-weaving traffic. Table 2-4 shows the LOS criteria in the HCM1985. The segment's final LOS was the worse LOS between the two.

Table 2-3: Criteria for unconstrained vs. constrained operation of weaving areas
(Transportation Research Board, 1985)

Type of Configuration	**No. of Lanes Required for Unconstrained Operation, N_W**	**Max. No. of Weaving Lanes, $N_W(max)$**
Type A	$2.19\, N\, VR^{0.571}\, L_H^{0.234} / S_W^{0.438}$	1.4
Type B	$N\{0.085 + 0.703\, VR + \left(\frac{234.8}{L}\right) - 0.018\,(S_{NW} - S_W)\}$	3.5
Type C	$N\{0.761 - 0.011\, L_H - 0.005(S_{NW} - S_W) + 0.047\, VR\}$	3.0

Table 2-4: LOS criteria for freeway weaving sections in HCM1985 (Transportation Research Board, 1985)

Level of Service	Minimum Average Weaving Speed, S_W (mph)	Minimum Average Non-Weaving Speed, S_{NW} (mph)
A	55	60
B	50	54
C	45	48
D	40	42
E	35	35
F	<35	<35

The HCM1985 also provided a table of limitations for the analysis of weaving segments, shown in **Table 2-5**. The table includes various limitations or maximum values for input parameters to indicate the conditions under which the LOS predictions were valid.

Table 2-5: HCM1985 Limitations on weaving analysis (Transportation Research Board, 1985)**.**

Type of Configuration	Weaving Capacity Maximum, v_W	Maximum, v/N	Maximum Volume Ratio, VR	Maximum Weaving Ratio, R	Maximum Weaving Length, L
Type A	1,800 pc/h	1,900 pc/h/ln	*N* *VR* 2 1.00 3 0.45 4 0.35 5 0.22	0.5	2,000 ft
Type B	3,000 pc/h	1,900 pc/h/ln	0.80	0.5	2,500 ft
Type C	3,000 pc/h	1,900 pc/h/ln	0.50	0.4	2,500 ft

The HCM1985 method was revised several times, but the model form was still used in HCM2000. In 1997, the HCM revised the table of limitations and the LOS criteria (Transportation Research Board, 1997). The HCM1997 used the average density of all the vehicles as the criterion for determining the LOS (shown in **Table 2-6**), and the same criteria were used until the publication of the HCM6. The average density was computed using the total flow divided by the average space mean speed. The HCM2000 further revised the model by updating the constants for computation of the weaving intensity factors and the coefficient in the equation estimating the number of lanes required for the unconstrained condition (Transportation Research Board, 2000). In addition, the HCM2000 updated the limitation of application for analysis of the weaving segments and added capacity estimation tables. The capacity was defined as any combination of flows that cause the density to reach LOS F, using the boundary density of 43 pc/ln/mi. Based on the configuration, the number of lanes, free flow speed (FFS), segment length, and volume ratio, the user could estimate the segment capacity. However, the capacity prediction did not impact the determination of the LOS.

Table 2-6: LOS criteria in HCM1997 (Transportation Research Board, 1997)**.**

Level of Service	Maximum Density (pc/mi/ln)	
	Freeway Weaving Area	Multilane and C-D Weaving Areas
A	10	12
B	20	24
C	28	32
D	35	36
E	≤43	≤40
F	>43	>40

After the HCM2000, the NCHRP 3-75 project was launched to develop a revised method in order to simplify model calibration as well as the consistency of predictions with other types of freeway segments (Roess, et al., 2008). The research was based on Fazio's speed estimation model (1985). To eliminate the need for determining the configuration type, Fazio recalibrated Reilly's model by adding lane change parameters (Fazio, 1985). The HCM2010 adopted NCHRP 3-75's approach (Transportation Research Board, 2010). In the HCM2010, the speed of weaving and non-weaving was predicted based on the estimated lane changes. The following equations determine the weaving and non-weaving speeds (HCM2010):

$$S_{\mathrm{w}} = 15 + \frac{FFS - 15}{1 + W}$$

$$\text{where } W = 0.226\left(\frac{LC_{\mathrm{ALL}}}{L_{\mathrm{s}}}\right)^{0.789} \tag{3}$$

$$S_{\mathrm{nw}} = \mathrm{FFS} - (0.0072LC_{\min}) - (0.0048\frac{V}{N}) \quad (4)$$

In addition, the HCM2010 changed the method for predicting the segment capacity and estimated capacity to be the lower of the following two estimates:

$$c_{\mathrm{IWL}} = c_{\mathrm{IFL}} - [438.2(1 + VR)^{1.6}] + (0.765L_{\mathrm{s}}) + (119.8N_{\mathrm{wl}}) \quad (5)$$

$$c_{\mathrm{IW}} = \frac{2{,}400}{\mathrm{VR}}(for\ N_{\mathrm{wl}} = 2\ \mathrm{lanes}) \quad \text{or} \quad \frac{3{,}500}{\mathrm{VR}}(for\ N_{\mathrm{wl}} = 3\ \mathrm{lanes}) \quad (6)$$

where:

c_{IW} is the capacity (per lane) of the weaving segment under equivalent ideal conditions (pc/h/ln)

c_{IFL} is the capacity (per lane) of a basic freeway segment with the same FFS as the weaving segment under equivalent ideal conditions (pc/h/ln)

L_{s} is the short length of the weaving segment (ft)

N_{wl} is the number of lanes from which a weaving maneuver may be made with one or no lane changes

Other variables are as previously defined.

Equation (5) estimates capacity based on density, while Equation (6) estimates capacity based on weaving demand. Moreover, the predicted capacity became an important factor in determining the final LOS. If the volume exceeded capacity, then the traffic was considered to operate at LOS F.

2.2 Related Studies

Various macroscopic and microscopic models have been developed in addition to those included in various editions of the HCM. In 1963, Hess developed a regression-based model that used lane distribution to estimate the merge, diverge, and freeway volume in the auxiliary lane and the adjacent freeway lane (Hess, 1963). In 1983, Leisch independently recalibrated his 1965 Leisch-Norman model, however the concept and form of the model did not change significantly.

The first microscopic model was developed by Moscowitz and Newman (Moskowitz & Newman, 1962). The model defined the lane-changing distribution between the auxiliary lane and the adjacent freeway lane. However, the model tied the lane-changing distribution solely to the length of the segment. This model was then further calibrated in other studies undertaken between 1988 and 1995 (Cassidy, Chan, Robinson, & May, 1990; Cassidy & May, Proposed Analytic Technique for Estimating Capacity and Level of Service of Major Freeway Weaving Sections, 1991; Windover & May, 1995; Ostrom, Leiman, & May, 1994). All these studies were funded by the California Department of Transportation (CALTRANS) and conducted by the University of California at Berkley. The calibrated models were all focused on lane changing in the rightmost lane of the freeway and auxiliary lanes. Those models were well-calibrated and provided far greater precision than the model by Moscowitz and Newman. However, the workload to calibrate the model for different sites was huge.

In the early 2000s, Lertworawanich and Elefteriadou introduced a methodology that used linear optimization and gap acceptance modeling to predict the weaving capacity (Lertworawanich, P., 2003; Lertworawanich & Elefteriadou, 2001; Lertworawanich & Elefteriadou, 2003). The methodology is theoretically rational, and the authors concluded that the ramp-to-freeway weaving demand affects operations more than the freeway-to-ramp weaving demand. However, the gap acceptance model in the methodology was based on an older gap acceptance model by Drew (Drew, 1967) and Raff and Hart (Raff & Hart, 1950). Therefore, the capacity estimates may need to be adjusted to consider current driver behavior and vehicle characteristics.

In 2020, Dezhong Xu et al., proposed a new framework for modeling the speed of weaving segments. In this method, the speed in the weaving section is related to the speed in the equivalent basic segment. They generated 12 models and recommended the following four models to predict the speed within ramp weave sections (Xu et al., 2020):

$$S_{\mathrm{o}} = S_{\mathrm{b}} - 0.0579 * \mathrm{FFS} * \left(\frac{\mathrm{VR}}{L_s\ (\text{in miles})}\right)^{0.838} \tag{7}$$

$$S_{\mathrm{o}} = S_{\mathrm{b}} - 0.0555 \times \mathrm{FFS} \times \left(\frac{V_{\mathrm{aux}}}{V * L_s\ (\text{in miles})}\right)^{0.831} \tag{8}$$

$$S_{\mathrm{o}} = S_{\mathrm{b}} - 0.125 \times FFS \times \left(\frac{\frac{V_{\mathrm{rf}}}{V}}{L_s\ (\text{in miles})}\right)^{0.455} \times \left(\frac{\frac{V_{\mathrm{fr}}}{V}}{L_s\ (\text{in miles})}\right)^{0.409} \tag{9}$$

$$S_{\mathrm{o}} = S_{\mathrm{b}} - 0.109 \times \mathrm{FFS} \times \left(\frac{\frac{V_{\mathrm{on-ramp}}}{V}}{L_s\ (\text{in miles})}\right)^{0.515} \times \left(\frac{\frac{V_{\mathrm{off-ramp}}}{V}}{L_s\ (\text{in miles})}\right)^{0.370} \tag{10}$$

While these models generally work well, they provide some counterintuitive results because they estimate increasing speeds when the through or non-weaving volume increases without an increase in weaving traffic.

2.3 Literature Evaluating the HCM6 Weaving Analysis Method

Even though the weaving segment operational analysis method in the HCM6 was updated relatively recently, some studies have found that the speed and capacity models are not accurate. Field data collected from 93 sites in California showed that the HCM6 over-predicted the density by 8% for balanced weaving segments and by 24% for unbalanced weaving segments

(Skabardonis & Mauch, 2015). Additional Bluetooth and video-recorded data revealed that the method over-predicted the density by an average of 13.4%. The researchers did a follow-up study using data collected from Athens, Greece (Skabardonis, Papadimitriou, Halkias, & Kopelias, 2016). The follow-up study showed that the HCM6 overestimated density by 17% for situations where the volume ratio (*VR*) was high. These studies also concluded that the HCM6 underestimates the capacity of weaving segments, especially in cases where the *VR* is high.

The possible causes of these discrepancies are that the HCM6 overemphasizes the impact of the *VR*, and that it uses a high value of the basic freeway segment capacity. A study based on field observations of capacity revealed that the observed basic freeway capacity is significantly lower than the recommended number in the HCM (Kondyli, St. George, Elefteriadou, & Bonyani, 2017). In addition, several studies have questioned the assumption of using a density of 43 pc/mi/ln to estimate the weaving segment capacity (Lertworawanich & Elefteriadou, 2001; Lertworawanich & Elefteriadou, 2003; Lertworawanich & Elefteriadou, 2007). They found this density assumption has not been justified in the literature and there are no data to validate it.

The HCM6 speed models have also been criticized. Zhou (Zhou, Rong, Wang, & Feng, 2015) found that, compared to field data, the HCM6 weaving speed prediction has an error as high as 40% for some scenarios. In addition, the study found that in some cases, the predicted weaving speed is higher than the predicted non-weaving speed, which is counterintuitive. Another study found that the HCM6 speed estimation has low sensitivity to the weaving segment length (Ahmed, Xu, Rouphail, & Karr, 2018). The authors found that the average space mean speed only increased by 7% when the segment length was quadrupled, even with high levels of weaving demands. This occurs because the non-weaving lane change model does not include the segment length as a variable.

In summary, the literature review showed that the HCM6 method needs further improvement regarding the accuracy of capacity estimation models, speed estimation models, and consistency with the performance estimates for basic freeway segments. In addition, the models are not as sensitive to the geometric characteristics of the sites as field data indicate.

3 Data Collection

This research is intended to develop and test a new operational analysis for ramp weaves (also referred to as Type A weaves). Due to the limited availability of ramp weave sites in NCHRP 3-75, additional data were collected for this project from 14 sites located in North Carolina, Utah, and California. The traffic data were collected using cameras (ground and drone), loop detectors, radars, and GPS. Each method has its advantages and disadvantages. Video recordings can be used to monitor the origin and destination of each vehicle in a weaving section. Loop detectors are used for obtaining traffic parameters, such as traffic volume, occupancy, and speed, at a given point. Data collection at the microscopic level requires video observations, while loop detectors are often used at the macroscopic level (El Faouzi, Leung, & Kurian, 2011; Amini, Tabibi, Khansari, & Abhari, 2019; You, 2000). For this study, both methods are used for collecting data. In addition, the research team used the limited data available from the NCHRP 3-75 project. The data obtained by each of these methods are described next.

3.1 NCHRP Database

To develop and calibrate the ramp weave models, this study used the data collected in NCHRP 3-75, which is the same dataset used to develop the HCM6 methodology. Even though NCHRP 3-75 collected data from 14 sites nationwide, only three sites were Type A weaving segments. Among the three segments, one was a collector distribution (CD) road, and two were freeway weaving segments. However, of the two freeway weaving segments, one site used the NGSIM data, which was collected at US-101 in California during oversaturated conditions. Thus, there was practically only one ramp weave site available. **Table 3-1** provides the location and configuration information along with the number of data points for this site.

Table 3-1: Summary of configuration and data points for Type A weave in NCHRP 3-75

Site Name	Site Number	Location	Road Name (on-ramp)	Road Name (off-ramp)	Length (ft)	Number of Lanes	Number of Data Points
NCHRP 3-75 Sky03	1	Baltimore, MD	I-95 SB	I-95 NB	360	3	12

3.1 Data Collected Using Drone-Based and Ground-Based Videos

This subsection presents the process of data collection using drone-recorded and ground-recorded videos.

3.2.1 Site locations

Six sites were identified for data collection. Those sites were selected to ensure variability in the segment length and traffic conditions. Due to a limited research budget, sites were selected only in North Carolina. The location of each site is shown in Table 3-2. The short length of the segments varied from 268 to 2028 feet. The number of lanes for these sites varied from three to five. Traffic conditions varied from light to moderate, with a flow rate that ranged from 418 to 1,740 pc/h/ln. The VR ranged from 0.08 to 0.54. The fraction of heavy vehicles in most sites was from 2% to 4%, except for the I-95 site, which had 14% to 28% heavy vehicles. The data were collected using both ground-based and drone-based videos.

Table 3-2: Location of study sites for data collection by drone

Site Name	Site Number	Location	Road Name (on-ramp)	Road Name (off-ramp)
I-440 EB @ Ridge Rd	2	Raleigh, NC	Ridge Rd	Glenwood Ave
I-40 EB @ Saunders St	3	Raleigh, NC	S Saunders St	Hammond Rd
I-40 WB @ Saunders St	4	Raleigh, NC	Hammond Rd	S Saunders St
Wade Ave WB	5	Raleigh, NC	I-440	Blue Ridge Rd
I-40 EB @ Cary Town Blvd	6	Raleigh, NC	Cary Town Blvd	I-440
I-95 SB @ Spring Branch Rd	7	Dunn, NC	E Cumberland St	Spring Branch Rd

3.2.2 Data Collection and Extraction

At the I-440 Ridge Road site, the data were collected by two cameras mounted on the bridge crossing above the middle of the segment. Each camera recorded one portion of the directional traffic. The data were collected between 3:00 pm to 6:00 pm from Wednesday to Friday. In total, nine hours of videos were collected. Excluding the period where traffic was congested, approximately six hours of videos were used in the model development.

The other sites' data were collected using a drone. The drone used in the study was the DJI Inspire V-1 drone, shown in **Figure 3-1**. It recorded 4k resolution videos at an elevation of 400 ft above the segment. It recorded 10 to 15 minutes of video for each battery cycle. The drone also required time to land, replace the battery, and take off. Thus, there is a difference between the video length and the data collection period. At the I-40 Saunders sites, the drone recorded the traffic from 4:00 pm to 6:00 pm in both directions at the same time. A total of 89 minutes of videos were collected. The team captured one-hour videos from 7:00 am to 8:30 am at the I-95 SB site. At the Wade Avenue site, 2 hours of footage was collected from 8:00 am to 11:00 am. Also, approximately 46 minutes of videos were collected from 4:30 pm to 5:30 pm at the I-40 Cary Town Blvd site. In general, one hour of drone data collection in the field output approximately 45 minutes of video.

Figure 3-1: Image of the drone

The data were aggregated into five-minute intervals to maintain sufficient sample sizes and consistency with the NCHRP 3-75 dataset. The data were reduced manually from videos. The volumes were counted based on origin-to-destination (OD) movements in five-minute intervals. The number of heavy vehicles was also counted in the OD. The timestamps were recorded when the vehicle entered the on-ramp gore point and exited the off-ramp gore point. Therefore, space-mean-speed (SMS) for each vehicle was calculated by dividing the gore-to-gore distance by the difference in the respective timestamps. Because the traffic volumes were high, only a random sample of vehicles' timestamps were recorded by OD. The speed samples were then weighted by the OD volumes to obtain the average space mean speed of the traffic in the weaving segment in five-minute intervals.

The length of each segment was measured from the on-ramp gore point to the off-ramp gore. The FFS for each site was estimated using the 85th percentile speed in the speed data that was downloaded from HERE.com, since the data collected did not include very low volumes. Thus, the prepared dataset contained the volume, number of heavy vehicles, space mean speed information for each OD in five-minute intervals, length of the segment, number of lanes, and the site's FFS.

In addition to the manual data reduction, some automatic image processing methods were also tested. The tested video image processing tools were machine learning code that was developed by the University of Florida and a commercial service, GoodVision Video Insights (GoodVision Ltd., 2019). However, both tools proved to be time consuming and require highly stable drone footage. Based on our experience of using these, we found that the optimal weather for drone data collection and automatic image processing is cloudy and non-windy days.

3.2.3 Data Filtering

Since some of the videos were recorded during peak hours, parts of the prepared data were found to be during oversaturated conditions. Because the methodology is focused on under-saturated conditions, data points that had a density higher than 43 mi/h/ln or average space mean speed lower than 40 mi/h were excluded. The two data points that followed the congested data point were considered as "congestion recovery conditions" and were also excluded. After removing these, a total of 140, five-minute data points (equivalent to 11 hours 40 minutes) remained in the dataset. Those data points were used in model development and calibration. Table 3-3 shows a summary of the configuration and data points for each site.

Table 3-3: Summary of Configuration and Data Points for the Video-Based Dataset

Freeway Weaving Sites	Site Number	Segment Short Length (ft)	Number of Lanes	Range of Flow Rate (pc/h/ln)	VR Range	Number of 5-min Observations
I-440 @ Ridge Road	2	268	4	1,236–1,665	0.16 - 0.28	66
I-40 EB @ Saunders	3	976	5	1,060–1,360	0.23 - 0.3	13
I-40 WB Saunders	4	1,285	5	801–1,047	0.17 - 0.27	13
I-95 SB @ Spring Branch	5	1,234	3	418–604	0.08 - 0.37	11
Wade Avenue WB	6	1,135	3	716–1,428	0.47 - 0.73	16
I-40 EB @ Cary Town Blvd	7	2,028	4	1,518–1,740	0.27 - 0.34	9
					Total	128

3.3 Data Collection Using Loop detectors

3.3.1 Study Sites Locations

The database was augmented using data obtained from loop detectors. Data were collected at eight additional ramp weave sections. As shown in **Table 3-4**, these sections are located in California and Utah, with length ranging from 1,083 ft. to 2,697 ft. The data were collected on September 12–18, 2019, in 5-min time intervals (2,016 data points for each site). A simple rolling average of these volumes was then used to obtain the average of the speed and flow in 15-min intervals. The range of the number of lanes was three to five. Traffic demands ranged from 3 to 1,827 pc/h/ln. For the sensor data we assumed 5% of the traffic consists of heavy vehicles (as suggested by HCM6 for the percentage of heavy vehicles on urban freeways) and converted all values to PCEs for modeling.

Table 3-4: Location of study sites for data collection by loop detectors

Site Name	Site Number	Location	Road Name (on-ramp)	Road Name (off-ramp)	Length (ft)	Number of Lanes	Number of 5-min Observations
CA-92 SB@ De Anza Blvd	8	San Mateo, CA	De Anza Blvd	Ralston Ave	1,083	3	2,016
CA-92 NB@ Ralston Ave	9	San Mateo, CA	Ralston Ave	De Anza Blvd	1,148	3	2,016
I-215 NB @ Wasatch Blvd	10	Salt Lake City, UT	Wasatch Blvd	Lincoln Hwy	1,332	4	2,016
I-215 SB @ California Ave	11	Salt Lake City, UT	California Ave	2100 S Fwy	1,394	5	2,016
I-215 NB @ 2100 S Fwy	12	Salt Lake City, UT	2100 S Fwy	California Ave	1,985	5	2,016
I 84 SB @ Pennsylvania Ave	13	Ogden, UT	Penn. Ave	31st St	2,188	5	2,016
I 84 SB @ 31st St	14	Ogden, UT	31st St	Penn. Ave	2,657	5	2,016
Bayshore Fwy@ Old Bayshore Hwy	15	Burlingame, CA	Old Bayshore Hwy	Millbrae Ave	2,697	5	2,016

3.3.2 Data Collection and Extraction

Each of the weaving segments studied has at least four loop detectors located upstream, downstream, at the on-ramp, and at the off-ramp. Weaving sections 6, 7, and 8 have an additional loop detector within the section. Figure 3-2 shows a schematic of a weaving section with loop detectors.

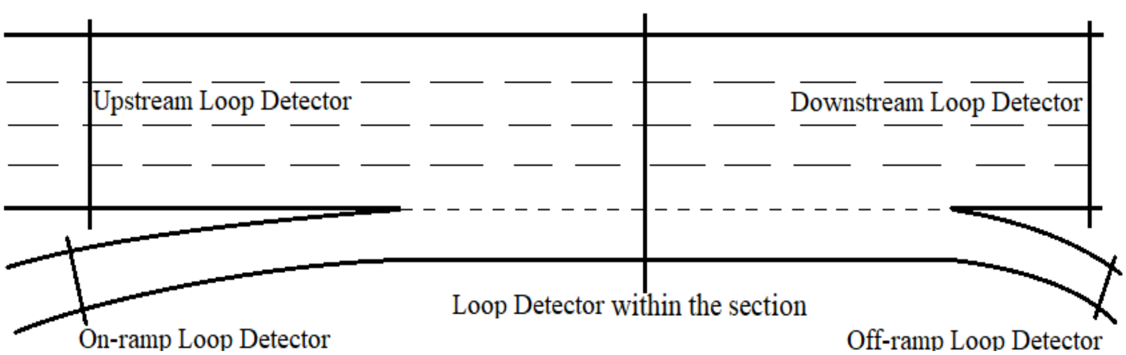


Figure 3-2: Illustration of weaving section and detectors

To estimate each of the four traffic flows in the weaving sections (freeway-to-freeway flow (F_{ff}), freeway-to-ramp flow (F_{fr}), ramp-to-freeway flow (F_{rf}), and ramp-to-ramp flow (F_{rr})) using detector data, it was assumed that the F_{rr} is 2 percent of the on-ramp flow:

$$F_{\mathrm{rr}} = 0.02 \times (\text{on-ramp flow}) \tag{11}$$

$$F_{\mathrm{rf}} = 0.98 \times (\text{on-ramp flow}) \tag{12}$$

The flow through the downstream side of the section is equal to the summation of F_{ff} and F_{rf}. Therefore, F_{ff} can be calculated as:

$$F_{\mathrm{ff}} = \text{Downstream flow} - F_{\mathrm{rf}} \tag{13}$$

Finally, to obtain the freeway-to-ramp flow, F_{fr}, F_{ff} is subtracted from the upstream side flow:

$$F_{\mathrm{fr}} = \text{Upstream flow} - F_{\mathrm{ff}} \tag{14}$$

Any negative values of F_{ff} and F_{fr} are set to zero.

One of the main parameters used to model weaving operations is the speed within the weaving section. From those sections listed in **Table 3-4**, only three sites (I-84 SB @ Pennsylvania Avenue, I-84 SB @ 31st St, and Bayshore Freeway @ Old Bayshore Highway) have loop detectors within the section. To obtain this speed for weaving sections with no loop detector at this location, we used the data from the other weaving sections to develop a model relating the speed within the weave to the speed at the upstream detector. Figure 3-3 shows the speed within the weaving section versus the speed observed at the upstream detector for the sections with a loop detector within the section. The data points with the same color are for the same weaving section. As shown in this figure, the speed within the weaving section is 1 to 3 mi/h greater than that observed at the upstream detector. Therefore, we assume that the speed within the weaving sections is 1.86 mi/h (3 km/h) greater than the speed at the upstream detector.

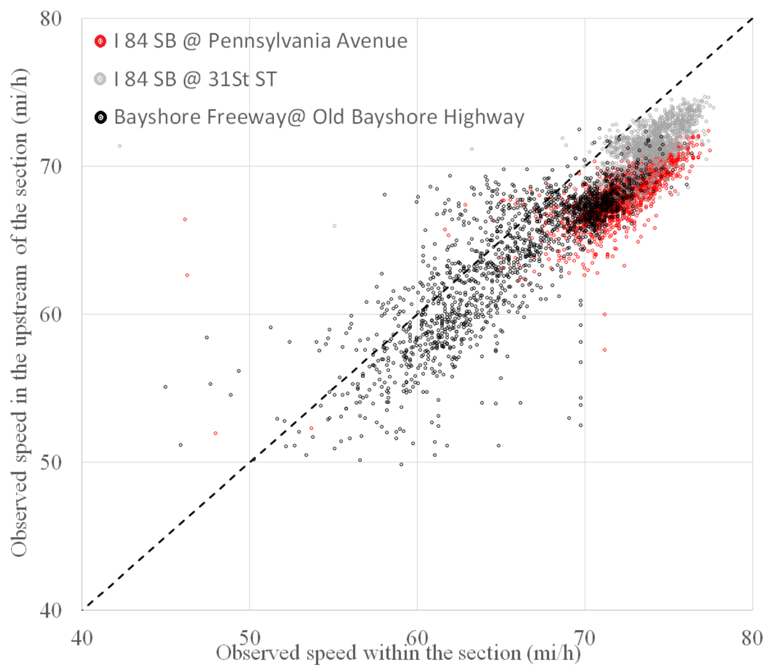


Figure 3-3: Speed within the weave vs. speed at the upstream detector

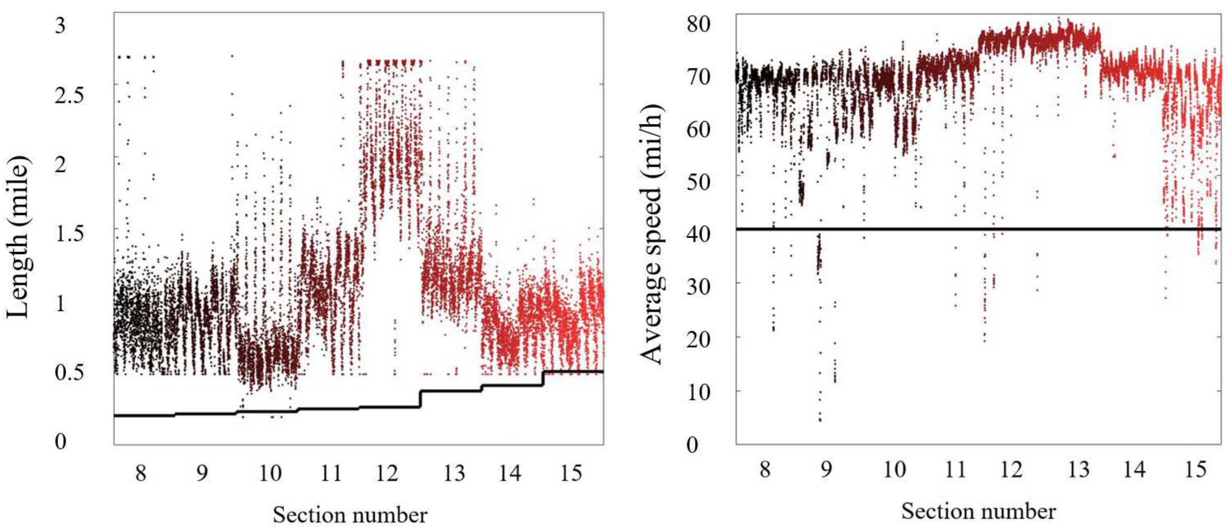
3.3.3 Data Filtering

The data points where one of the loops was not working and reporting zero flow were removed from the database. Then, two more filters were applied on the database: maximum length of the weaving section and oversaturated conditions.

Based on the HCM definition of weaving sections, if the distance between the on-ramp and the off-ramp is more than the "maximum length of the weaving section" (which is related to weaving configuration and flow streams in the section), the section should be analyzed as separate on-ramp and off-ramp segments (HCM6). Therefore, for each data point collected, the maximum length of the weaving section was calculated, and if it was found to be less than the actual length of the weaving section, the corresponding data point was removed from the analysis. Figure 3-4a shows the maximum length of the weaving section for each data point as well as the actual length of each study section as a thick black line. If the maximum length of the section is below the actual length of the section, that data point is removed from the data set.

Figure 3-4b shows the operating speed for each data point. To evaluate the weaving section for only undersaturated conditions, the data points with speed below 40 mph (64.37 km/h) were removed. The coloring in Figure 3-4 changes gradually from black to red as the length of the section increases. Black represents the shorter sections, while red represents the longer ones.

Table 3-5 shows the removed and retained data points for each section. A total of 1,449 data points were removed, and 14,534 data points were retained for modeling.



(a) (b)

Figure 3-4: Data cleaning based on the maximum length of the weaving section and operating speeds

Table 3-5: Total number of data points obtained by loop detectors and total number of data points used for each weaving section

Site Name	Site Number	Location	Length (ft)	Number of 5-min Observations	Removed Data Points	Used Data Points
CA-92 SB@ De Anza Blvd	8	San Mateo, CA	1,083	2,016	290	1,827
CA-92 NB@ Ralston Ave	9	San Mateo, CA	1,148	2,016	607	1,324
I-215 NB @ Wasatch Blvd	10	Salt Lake City, UT	1,332	2,016	117	1,934
I-215 SB @ California Ave	11	Salt Lake City, UT	1,394	2,016	61	1,955
I-215 NB @ 2100 S Freeway	12	Salt Lake City, UT	1,985	2,016	3	2,013
I-84 SB @ Penn. Ave	13	Ogden, UT	2,188	2,016	74	1,954
I-84 SB @ 31St St	14	Ogden, UT	2,657	2,016	103	1,898
Bayshore Fwy@ Old Bayshore Hwy	15	Burlingame, CA	2,697	2,016	194	1,629
				Total	1,449	14,534

3.4 Summary

To model the speed in the weaving section, two methods of data collection were used. After filtering the data, 14,819 data points from 15 different weaving sections were used for modeling. These data points were randomly assigned into training and validation sets, with an 80-20 split. The training set was used to calibrate the model, and the validation set was used to evaluate the calibrated model.

4 RESEARCH METHODOLOGY

This chapter first describes the conceptual model formulation and then presents the proposed models to predict the speed within the weaving section. The third subsection describes the calibration process, while the last subsection provides the capacity estimation process and results based on the proposed model.

4.1 Conceptual Model Formulation

The two main motivations of this research were to simplify the current weaving analysis methodology and ensure consistency between freeway segment analysis and weaving segment analysis. Conceptually, with the same volumes and number of lanes and lengths, a weaving segment would have a lower average space mean speed than a basic freeway segment. The difference between speeds is caused by the turbulence of the weaving flows. In addition to the configuration type and the length of the segment, the turbulence is sensitive to the weaving demand. If the weaving segment contains zero weaving traffic, then its operation would be identical to that of a basic freeway segment. In other words, as the weaving demand approaches zero, the predicted average speed of the weaving segment should approach the speed of the equivalent basic freeway segment. The following equation provides the conceptual relationship between the weaving segment speed (S_{o}) and the equivalent basic segment speed (S_{b}), where the SIW is the speed impedance term that represents weaving turbulence:

$$S_{\mathrm{o}} = S_{\mathrm{b}} - \mathrm{SIW} \tag{11}$$

The parameters in SIW should represent the geometric characteristics and traffic demand at the weaving section. These parameters are explained in detail in the following paragraphs.

4.1.1 Impact of Geometric Characteristics on Traffic Operations

The geometric characteristics of the weaving section that impact operations include the short length of the weaving section and the number of lanes. We expect that a weaving section with long L_{s} would yield a higher speed than a section with short L_s. Therefore, the variable L_{s} should be in the denominator of SIW. On the other hand, increasing the number of lanes provides non-weaving vehicles more opportunities to increase their speed by changing lanes to a non-weaving lane and avoid the conflict area[1]. Additional lanes also will provide more space for weaving vehicles to maneuver. Conversely, fewer lanes would result in lower speeds within the weaving section. Therefore, the number of lanes should be in the numerator of SIW.

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[1] The area of the weaving section extending from the rightmost auxiliary lane to the lane directly to the left of the diverge gore.

4.1.2 Impact of Traffic Volumes

Total traffic volume has a varying relation with speed reduction. At very low volumes, the speed in the weaving section is similar to the equivalent basic freeway segment. Under those conditions, there are adequate gaps so that even a relatively high volume of weaving movements can complete their maneuvers without a major speed reduction. However, when the traffic volume increases, even a small number of weaving vehicles can cause a drop in speed. The field data collected confirm this general trend (Appendix A).

In addition, each origin-destination within a weave impacts operations differently. The HCM6 assumes that the two weaving volumes (V_{rf}, and V_{fr}) have the same effect on operations. However, previous studies show that the ramp-to-freeway movement has a stronger influence on weaving segment speed than the freeway-to-ramp movement because its speed is likely constrained by the design features of the on-ramp. This has been reported in the literature, and it is also supported by the loop data collected in this study (Appendix B). Therefore, because increasing weaving movements result in reduced speed, they should be in the numerator of SIW.

4.2 Proposed Models

The following two candidate models were proposed and evaluated:

$$\text{Model 1: } S_{\mathrm{o}} = S_{\mathrm{b}} - \alpha \times (\beta * V_{\mathrm{rf}} + V_{\mathrm{fr}})^{\gamma} \times \left(\frac{V}{N_{\mathrm{l}}} - 500\right)^{1} \times (\frac{1}{L_{\mathrm{s}}})^{\delta} \quad (12)$$

$$\text{Model 2: } S_{\mathrm{o}} = S_{\mathrm{b}} - \alpha \times \left(\frac{\beta * V_{\mathrm{rf}} + V_{\mathrm{fr}}}{N_{\mathrm{l}}{}^{\epsilon}}\right)^{\gamma} \times \left(\frac{V}{N_{\mathrm{l}}} - 500\right)^{1} \times (\frac{1}{L_{\mathrm{s}}})^{\delta} \quad (13)$$

As shown, in these models, the weaving volumes (V_{rf} and V_{fr}) are presented as independent variables and eliminating one of those cannot remove the entire SIW. Moreover, parameter β is included to enable the models to represent the different effects of V_{rf} and V_{fr}. The difference between the two models is in N_{l}, which in model 2 is presented in the denominator. Both models assume that when the volume per lane ($\frac{V}{N_{\mathrm{l}}}$) is less than 500 pc/h/ln, the speed in the weaving section is equal to the speed in the equivalent basic freeway segment. This value may change for different weaving sections (based on FFS, N_{l}, L_{s}, etc.). However, for all sites in our database, when the volume is less than 500 pc/h/ln, the value of SIW approaches zero, and speed in the weaving section is equal to the equivalent basic freeway section. In addition, to calculate the capacity of the weaving section analytically, the power of this variable is best set to one. Finally, the term ($\frac{1}{L_{\mathrm{s}}}$) represents the effect of the length of weaving section. Because we expect a weaving section with longer L_{s} to have higher speed than a section with shorter L_{s}, L_{s} is included in the denominator. The advantages of the proposed models compared to previous models, including the HCM6 method, are as follows:

- The process of calibrating the proposed model is easier
- The proposed model does not require calculation of the number of lane changes in the section, which is prone to errors and is difficult to calibrate with field data

- The proposed model aligns with the HCM speed model for basic freeway sections
- The model considers the impacts of the two weaving flows (V_fr and V_rf) separately. These have different effects on capacity and speed, and having separate calibration parameters for each results in a more accurate model

4.3 Calibration of the Proposed Models

In order to calibrate these models, the root mean square error (RMSE) is used as a criterion for obtaining the model parameters through the optimization process.

RMSE is obtained from the following equation:

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \overline{Y_i})^2 \quad (14)$$

Where: Y_i is the predicted speed

$\overline{Y_i}$ is the observed speed

n is the number of data points, each representing a 5-minute observation.

The three databases (NCHRP database, drone database, and loop detectors database) were combined. Of these, 20% of the data were randomly selected for validation, while the remaining 80% were used for training. **Table 4-1** shows the summary of data used for training. In total, 11,742 data points were used to calibrate the models.

Table 4-1: Training dataset

Freeway Weaving Site	Site Number	Location	Segment Short Length (ft)	Sample Size in the Validation Dataset
I-440 @ Ridge Road	1	Raleigh, NC	268	1
NCHRP Sky03	2	Raleigh, NC	360	63
I-40 EB @ Saunders	3	Raleigh, NC	976	11
I-40 WB Saunders	4	Raleigh, NC	1,285	12
I-95 SB @ Spring Branch	5	Raleigh, NC	1,234	7
Wade Avenue WB	6	Dunn, NC	1,135	13
I-40 EB @ Cary Town Blvd	7	Baltimore, MD	2,028	8
CA 92 SB@ De Anza Boulevard	8	San Mateo, CA	1,083	1,510
CA 92 NB@ Ralston Avenue	9	San Mateo, CA	1,148	1,072
I-215 NB @ Wasatch Boulevard	10	Salt Lake City, UT	1,332	1,519
I-215 SB @ California Avenue	11	Salt Lake City, UT	1,394	1,568
I-215 NB @ 2100 S Freeway	12	Salt Lake City, UT	1,985	1,598
I-84 SB @ Pennsylvania Avenue	13	Ogden, UT	2,188	1,578
I-84 SB @ 31St St	14	Ogden, UT	2,657	1,512
Bayshore Freeway@ Old Bayshore Highway	15	Burlingame, CA	2,697	1,270
			Total	**11,742**

In the training dataset, data points with traffic flow less than 500 pc/he/ln were removed (we assume that when the volume is less than 500 pc/h/ln, S_0 is equal to S_b). **Table 4-2** provides the estimated parameters for the proposed models. The value of RMSE in this table is based on the predicted speed of each model for all data points in the training dataset.

Table 4-2: Parameters estimation for proposed models

Model	α	β	γ	δ	ϵ	RMSE (mph)
Model 1	0.022	16.767	0.250	0.446	-	4.140
Model 2	0.025	17.302	0.344	0.369	3	4.003

The value of RMSE for models 1 and 2 shows that model 2 results in the best fit. The researchers conducted an F test to examine whether the two models are statistically different, and it was concluded that model 2 is significantly better at the 5% significance level. Therefore, model 2 is the final recommended model with calibrated parameters as follows:

$$\text{Model 2: } S_{\text{o}} = S_{\text{b}} - 0.025 * \left(\frac{17.3 \times V_{\text{rf}} + V_{\text{fr}}}{{N_{\text{l}}}^3}\right)^{0.344} \times \left(\frac{V}{N_{\text{l}}} - 500\right)^1 \times \left(\frac{1}{L_{\text{s}}}\right)^{0.369} \quad (15)$$

4.4 Capacity Calculation

When segment capacity is reached, we estimate the segment speed at capacity to be $\frac{C_W}{43}$ where C_W is the weaving segment capacity per lane.

Substituting in the speed equation gives:

$$\frac{C_W}{43} = S_b(C_W) - \propto \left(\frac{\beta \times V_{rf} + V_{fr}}{{N_l}^{\epsilon}}\right)^{\gamma} (C_W - 500)\left(\frac{1}{L_s}\right)^{\delta} \quad (17)$$

Since the basic segment speed, S_b is known to be proportional to the square of the per lane flow rate C_W, the above relationship is a quadratic equation in C_W. We define some intermediate parameters as follows:

$$\text{Let } A = 43 \times \frac{(FFS - \frac{C_B}{45})}{(C_B - BP)^2}\ ; B = 43 \times \propto \left(\frac{\beta \times V_{rf} + V_{fr}}{{N_l}^{\epsilon}}\right)^{\gamma}\left(\frac{1}{L_s}\right)^{\delta}\ ; F = 43 \times FFS \quad (18)$$

Where FFS, C_B, and BP represent the free-flow speed, basic segment capacity, and basic segment breakpoint, respectively. The quadratic equation solution is expressed as:

$$C_W = \frac{-b + \sqrt[2]{b^2 - 4\,ac}}{2\,a} \quad (19)$$

where it can be shown in that equation that:

$a = A$
$b = 1 + B - 2A \times BP$
$c = A \times BP^2 - 500B - F$.

The application of the speed model is limited to the case where $v/c \leq 1.0$, or $V/N_l < C_W$.

Numerical Example:

We use the example problem for a ramp weave included in the HCM6 (Example Problem 4 in Chapter 27) with 4 lanes, FFS= 75 mph, and a short length of 1,000 ft. The OD adjusted flow rates are shown in Figure 4-1.

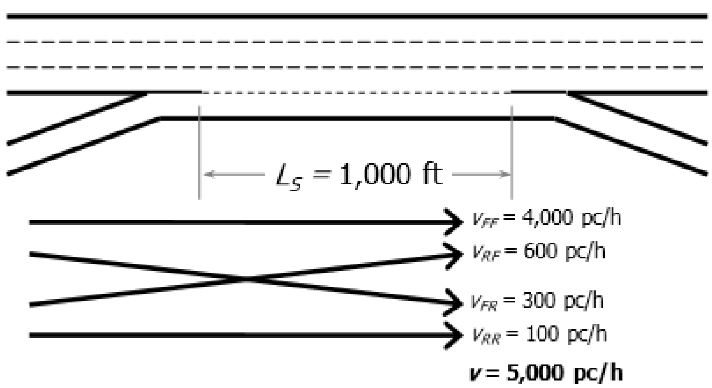


Figure 4-1: Example: OD adjusted flow rates at capacity

In this example, V/N_l=1,250 per lane; C_B=2,400; BP=1,000; V_{rf}=600; V_{fr}=300; L_s=1,000.

The intermediate parameters computed from the above equations are as follows:

A = 0.0004753; B = 0.4886; and F = 3,225, yielding the quadratic coefficients as follows:
a = 0.0004753; b = 0.5379 and c = −2,993.95.

Substituting in the equation for C_W yields a weave segment capacity of 2,007 pc/h/ln. This compares to the reported HCM6 capacity of 2,145. Because V per lane < C_W in both cases, the analysis can continue. The resulting segment average speed from the proposed model is 65.78 mph, compared to 61.9 mph in the HCM6. The speed value estimated by the proposed model appears to be consistent with the v/c ratio of 0.62 (HCM6 v/c is 0.58). The respective equivalent basic freeway segment speed is 74.3 mph.

5 MODEL RESULTS

This chapter first provides an evaluation of the recommended model using the validation data set, and the results are compared with the HCM6 predictions. Following this comparison, a sensitivity analysis is conducted to evaluate how the overall speed is affected by changes in the section's length, number of lanes, weaving movements, and total traffic volume. The last subsection provides a summary of the findings.

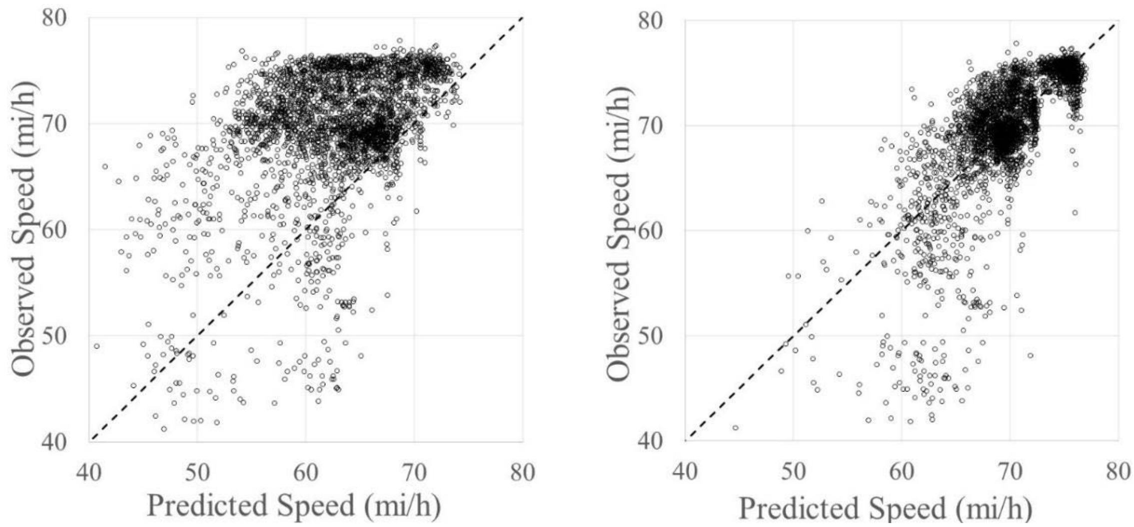
5.1 Model Validation

Model validation was conducted using the validation data set to compare the results from the recommended model to observed speeds and to the HCM6 method. **Table 5-1** shows the summary of the data used in the validation dataset. In total 2,932 data points were used for this part of the analysis.

Table 5-1: Model validation dataset

Freeway Weaving Site	Site Number	Location	Segment Short Length (ft)	Sample Size in the Validation Dataset
I-440 @ Ridge Rd	1	Raleigh, NC	268	11
NCHRP Sky03	2	Raleigh, NC	360	3
I-40 EB @ Saunders St	3	Raleigh, NC	976	2
I-40 WB Saunders St	4	Raleigh, NC	1,285	1
I-95 SB @ Spring Branch St	5	Raleigh, NC	1,234	4
Wade Ave WB	6	Dunn, NC	1,135	3
I-40 EB @ Cary Town Blvd	7	Baltimore, MD	2,028	1
CA-92 SB@ De Anza Blvd	8	San Mateo, CA	1,083	317
CA-92 NB@ Ralston Ave	9	San Mateo, CA	1,148	252
I-215 NB @ Wasatch Blvd	10	Salt Lake City, UT	1,332	415
I-215 SB @ California Ave	11	Salt Lake City, UT	1,394	387
I-215 NB @ 2100 S Fwy	12	Salt Lake City, UT	1,985	415
I-84 SB @ Pennsylvania Ave	13	Ogden, UT	2,188	376
I-84 SB @ 31st St	14	Ogden, UT	2,657	386
Bayshore Fwy@ Old Bayshore Hwy	15	Burlingame, CA	2,697	359
			Total	2932

Figure 5-1 shows a comparison between the model-predicted average segment speed and the observed speed. Figure 5-1a shows that the HCM6 method significantly underpredicts the average segment speed. On the other hand, Figure 5-1b shows that the recommended model predicts the ground truth speed quite well. This conclusion is also supported by the RMSE for each prediction. The RMSE for the HCM6 is 9.18 mph, while the RMSE of the new recommended model is 3.98 mph.



(a) (b)

Figure 5-1: Predicted speed in comparison with observed speed: (a) HCM6 prediction; (b) recommended model prediction.

A closer look at the HCM6 prediction revealed that by increasing the traffic volumes, the predicted speed for the non-weaving movement decreases significantly. For high traffic volumes, the predicted speed of the non-weaving movement is even lower than the predicted speed for the weaving movement (Figure 5-2). This counterintuitive HCM6 result is mostly observed for long segments.

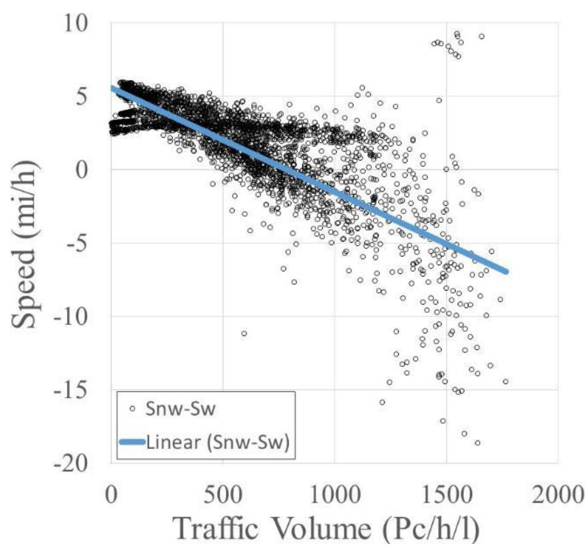


Figure 5-2: Difference between the HCM6 prediction of S_{nw} and S_w vs. freeway-to-freeway volume.

Figure 5-3a shows that by increasing the overall per lane traffic volume, the value of square error in the HCM6 predictions increases. However, Figure 5-3b suggests that this issue is solved using the new recommended model.

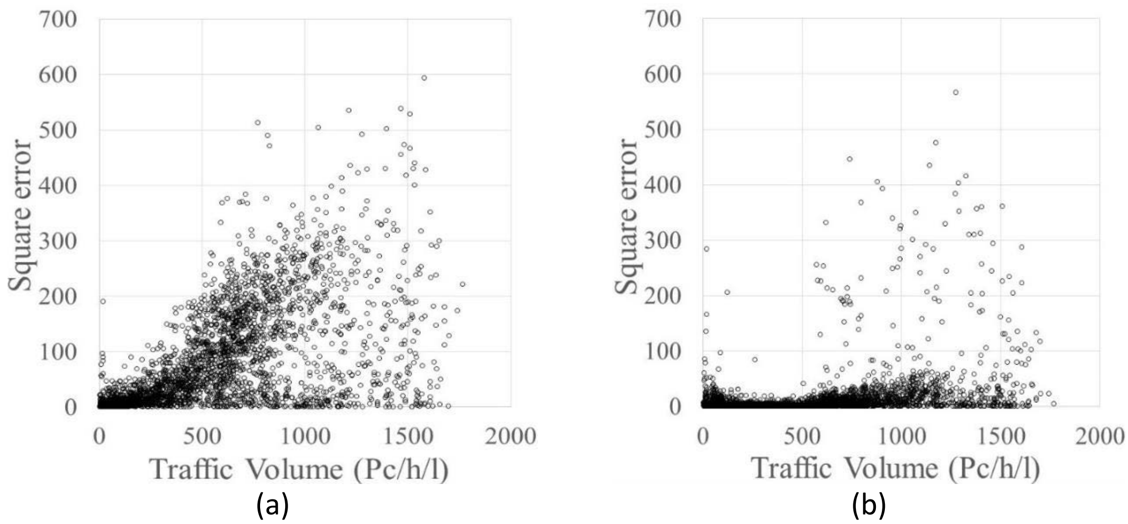


Figure 5-3: Comparing square error with traffic volume: (a) HCM6 prediction; (b) recommended model prediction.

5.2 Sensitivity Analysis of the Recommended Model to L_s and N

In this section, numerical experiments were performed to compare the sensitivity of the recommended model speeds and the HCM6 model speeds to L_s and N. The test assumes an urban ramp weave with three to five lanes, with FFS equal to 70 mph. The short length of the segment is varied between 300 ft and 3,300 ft, while the demands are:

$$\text{Flowrate per lane } V/N\text{l} = 1{,}400 \text{ pc/h/ln}$$
$$V_{\text{FR}} = 600 \text{ pc/h}$$
$$V_{\text{RF}} = 600 \text{ pc/h}$$

Intuitively, by increasing the weaving length, vehicles have more opportunities to change lanes within the weave, and speeds are expected to increase. Also, when increasing the number of lanes in the weaving section, non-weaving vehicles would have more opportunities to shift to a non-weaving lane and avoid entering the conflict area[2]. This would result in higher speeds for non-weaving vehicles and lower demands within the higher turbulence area, which would also result in higher speeds for weaving vehicles. Therefore, we expect that by increasing the weaving length and the number of lanes, the speed in the weaving section would increase.

[2] The area of the weaving section extending from the rightmost auxiliary lane to the lane directly to the left of the diverge gore.

Figure 5-4 and 5-5 depict the results of this evaluation. The HCM6 prediction shows that not only is there no meaningful difference between weaving sections with different numbers of lanes, but there is no significant difference in speeds for weaving sections longer than 600 ft. On the contrary, the HCM6 predicts slightly lower speeds for weaving sections with more lanes. Figure 5-4 shows that when there is a 3,000-ft change in the segment's length, the HCM6 prediction of speed changes by 5%–7%. On the other hand, the recommended model speed is more sensitive to the length of the segment (23%, 16%, and 12% for sections with 3, 4, and 5 lanes). Furthermore, there is a meaningful difference between the predicted speed of the weaving sections with 3, 4, and 5 lanes, which are in accordance with expectations.

Figure 5-5 shows a comparison between the capacity prediction of the recommended model and HCM6. As shown, the recommended model is more sensitive to L_s and to the number of lanes in the section than the HCM6. Also, the recommended model predicts slightly lower capacity than the HCM6, which is consistent with field observations.

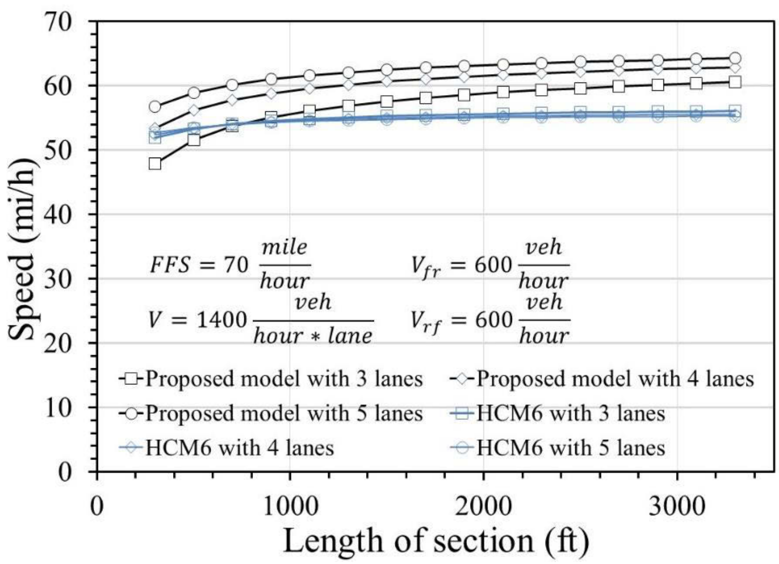


Figure 5-4: Speed prediction of HCM6 and recommended model by segment length

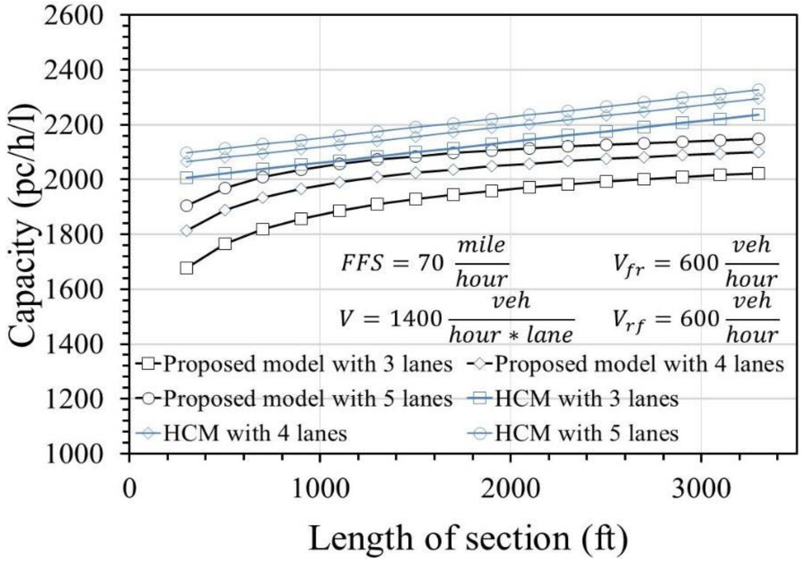


Figure 5-5: Capacity prediction of HCM6 and recommended model by segment length

5.3 Sensitivity Analysis to Weaving Movements (V_{fr} and V_{rf})

In this section, the sensitivity of the recommended model to the weaving movements is compared with that of the HCM6 model. A weaving section with L_s equal to 1,000 ft, FFS = 70 mph, and flow rate of 1,400 pc/h/ln was tested under two different scenarios. In the first, the freeway-to-ramp movement was fixed at 600 pc/h, while the ramp-to-freeway movement was varied from 0 to 1,800 pc/h (Figure 5-6). In the second scenario, the ramp-to-freeway movement was fixed at 600 pc/h/ln and the freeway-to-ramp movement varied from 0 to 1,800 pc/h/ln (Figure 5-7). As expected, for the recommended model, the effect of the ramp-to-freeway movement is more pronounced than the freeway-to-ramp movement. The HCM6 prediction shows the same effect for these two movements.

The recommended model has very low sensitivity to the freeway-to-ramp movement. Also, the results show that the number of lanes in the weaving section changes the effect of the weaving movements. In the first scenario, the recommended model shows that increasing the ramp-to-freeway movement to 1,800 pc/h causes a decrease of 23%, 17%, and 13% in the speed of the weaving section with 3, 4, and 5 lanes, respectively. On the other hand, the HCM6 predicts 17%, 18%, and 19% decrease in the speed of the weaving section with 3, 4, and 5 lanes, respectively, when increasing the ramp-to-freeway movement to 1,800 pc/h. In other words, the HCM6 predicts that increasing the ramp-to-freeway or freeway-to-ramp movements causes a higher drop in speed for a weaving section with five lanes than a weaving section with three lanes, which is counterintuitive.

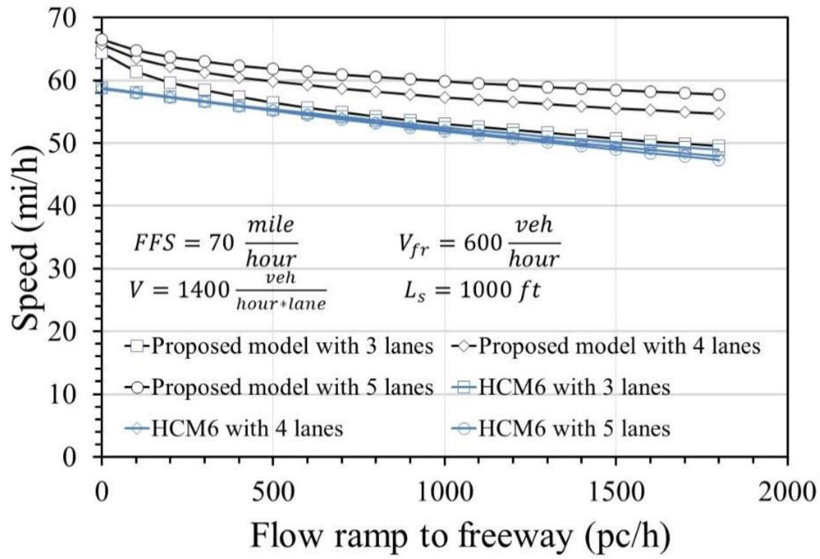


Figure 5-6: Effect of ramp-to-freeway movement on speed prediction of recommended model and HCM6

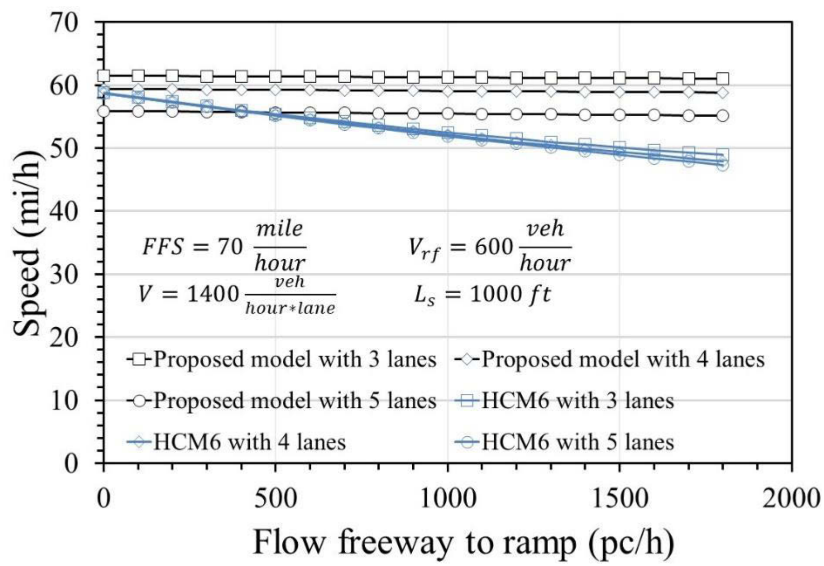


Figure 5-7: Effect of freeway-to-ramp movement on speed prediction of recommended model and HCM6

5.4 Sensitivity Analysis to Total Traffic Volume

This section evaluates the impact of overall traffic volume on speed. By considering a fixed value of weaving demands ($V_{\mathrm{fr}} = 400\ \mathrm{pc/h}$ and $V_{\mathrm{rf}} = 600\ \mathrm{pc/h}$) for a weaving section with 1,000 ft in length and FFS = 70 mi/h, the recommended model and HCM6 are used to predict the speed in the weaving section when the total flow rate (i.e., the sum of weaving and non-weaving movements) changes from 350 pc/h/l to the capacity of the section (Figure 5-8). The relationship between flow rate and speed in the HCM6 model is linear.

Figure 5-9 shows the capacity prediction for the recommended model and the HCM6 when the weaving movements are fixed, and the non-weaving flow rate is increased. While the predicted capacities using the recommended model are, as expected, fixed and independent of overall traffic flow, the capacity predicted by the HCM6 varies as a function of the overall demand per lane. As traffic increases, the HCM6 predicts a higher capacity for the weaving section. It should be noted that weaving demands can change the capacity of weaving sections. However, in the HCM6, the capacity of the weaving section increases as the overall demand increases. The reason for this is that in the weaving section's capacity formula, HCM6 uses the VR parameter in the negative side of the capacity equation, and when the weaving movements are fixed, by increasing the non-weaving movements, the value of VR is decreased and as a result, the predicted capacity increases.

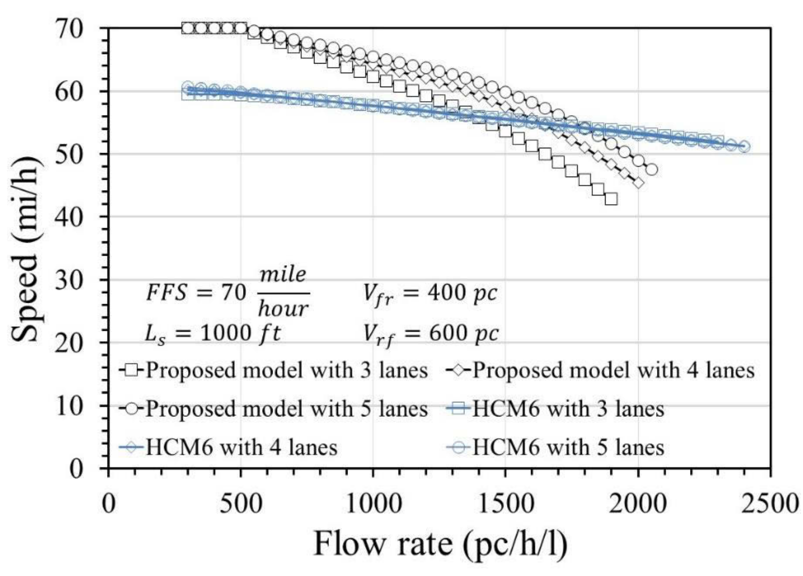


Figure 5-8: Effect of segment flow rate on speed prediction of recommended model and HCM6

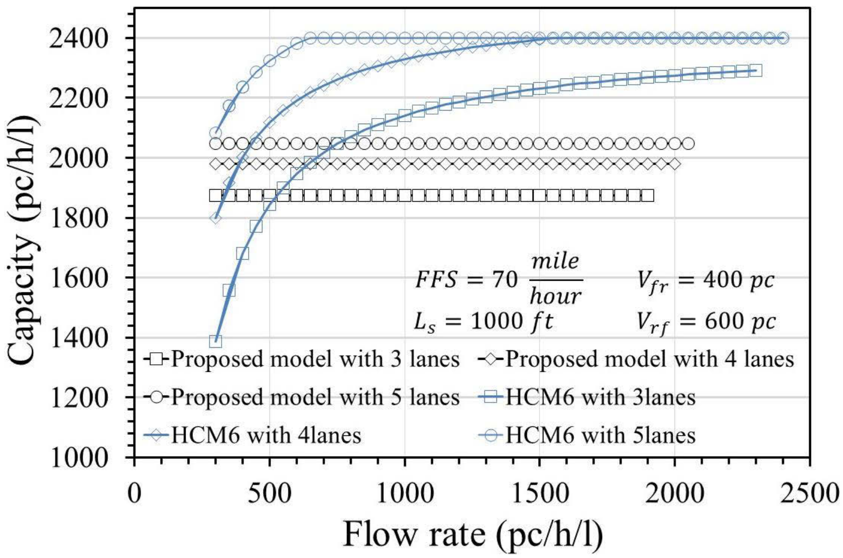


Figure 5-9: Effect of segment flow rate on capacity prediction of recommended model and HCM6

5.5 Summary

The research team tested the proposed recommended model to evaluate its robustness. The results showed that the value of RMSE for the predicted speed in the validation dataset is similar to the respective value in the training data set. Comparisons between the recommended model results and the current HCM6 predictions against field data show that the HCM6 model tends to underestimate the speed within the weaving section compared to field data. A sensitivity analyses on L_s, weaving movement flow rates, and overall traffic flow showed that the recommended model was able to reasonably predict the speed and capacity for ramp weaves, while highlighting important deficiencies with the HCM6 speed and capacity predictions.

6 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to develop simple models and a framework for ramp weave segments that can provide more accurate speed estimation than the HCM6 method, while also showing better sensitivities to pertinent traffic and geometric design parameters. The study proposes a new model form that connects the operation of ramp weave segments to an equivalent basic segment which serves the same volume with the same number of lanes and the same free flow speed. The recommended model directly predicts the average segment speed by using the equivalent basic segment estimated speed minus a weaving turbulence speed impedance term (SIW). This model form ensures consistency of predictions with the basic freeway segment and avoids the need for predicting the number of lane changes and estimating weaving and non-weaving flow speeds. The study initially generated two candidate speed models. Based on evaluating each model's goodness of fit, the following model was recommended:

$$\text{Model 2: } S_{\mathrm{o}} = S_{\mathrm{b}} - 0.025 \times \left(\frac{17.302 \times V_{\mathrm{rf}} + V_{\mathrm{fr}}}{N_{\mathrm{l}}^{3}}\right)^{0.344} \times \left(\frac{V}{N_{\mathrm{l}}} - 500\right)^{1} \times \left(\frac{1}{L_{s}}\right)^{0.369} \quad (20)$$

6.1 Conclusions

The main conclusions from this research are as follows:

1. The drone video technology has proven to be a useful tool for freeway weaving data collection. It captured traffic in a segment with a length of up to 3,000 ft. However, manual data extraction from the drone video was time consuming. The experience of using automatic image processing showed that it is highly sensitive to wind speeds. The best day for drone data collection was found to be cloudy with no wind. This weather ensures that no shades appear on the segment and there is high image stability during the recording. In addition, the camera should preferably not change the shooting angle during data collection.

2. Using loop detector data has the following advantages: cheaper to obtain large amounts of data and easier to obtain data for very long sections when a single video camera cannot capture the entire weave. However, the most important disadvantage of this method is that it does not provide the volume of each origin-destination and thus those must be estimated manually.

3. The proposed framework, which uses the basic freeway model and a speed impedance factor that represents the weaving turbulence, proved to be simpler and more accurate than the existing HCM6 method. This model form ensures prediction consistency with the basic freeway segment. Moreover, the proposed procedure is much simpler than the current HCM6 model. The model directly predicts the average speed of the weaving segment, while the HCM6 uses intermediate models to predict

the number of lane changes and then estimates the non-weaving and weaving traffic speeds based on the estimated number of lane changes.

4. The HCM6 speed predictions were found to deviate from field observations, especially for speeds more than 50 mph. The HCM6 model estimating the number of non-weaving lane changes implies that the longer the segment length and the higher the number of non-weaving lanes, the more non-weaving lane changes will occur. Thus, the HCM6 model significantly overpredicts the number of lane changes for long weaving segments and weaving sections with more than four lanes, which causes under-prediction of weaving speed. When traffic volume is high, the HCM6 predicted speed for non-weaving vehicles is even lower than the predicted speed for weaving vehicles. Because NCHRP 3-75 only has one ramp weave site, the lack of ramp weave sites to calibrate the model may cause this problem.
5. Based on the exponents of the proposed model, the ramp-to-freeway demand was found to have a higher impact on segment speed than the freeway-to-ramp demand. All the parameters for ramp-originating traffic had a higher value than those for freeway-originating traffic. This confirms previous observations in the literature that the on-ramp demand has a higher contribution to the speed impedance than other movements, especially on short weaving segments.
6. The sensitivity tests indicated that the HCM6 has little sensitivity to the segment short length. By increasing the segment length from 300 ft to 3,300 ft, the HCM6 predicted that the average speed only increases by about 3.5 mph while the new recommended model shows an average speed increase of 10 mph. For very long segments (3,300 ft), the HCM6 also showed inconsistency with basic freeway segment speed prediction, as produced a 14-mph deviation from the FFS, while the proposed model had an average 7 mph difference (Figure 5-4).
7. The HCM6-predicted capacity showed a linear trend with weave length. However, the recommended model predicted capacity changed significantly when the segment was short and barely changed when the segment was in excess of 2,000 ft. This nonlinear trend was also observed in speed prediction.
8. The sensitivity analysis to flow rate revealed that for a fixed value of weaving movements the HCM6 predicts higher capacity when the flow rate increases, which is counterintuitive.

6.2 Recommendations for Future Research

The following are recommendations for future research:

1. The framework developed in this project can be applied to other types of weaving segments (Type B and C), to ramp junctions, and to collector-distributor segments. This may require further data collection and model calibration and validation. In this

case, a different formulation with different variables should be developed to estimate SIW.

2. The framework developed can be further extended to evaluate the operation of oversaturated operations at weaving sections.

3. In this study, the value of the breakpoint was selected as 500 pc/h/l. However, this value may change based on the weaving geometry and the volume of traffic movements. Additional data collection is needed to obtain a formula or recommendations for providing this value.

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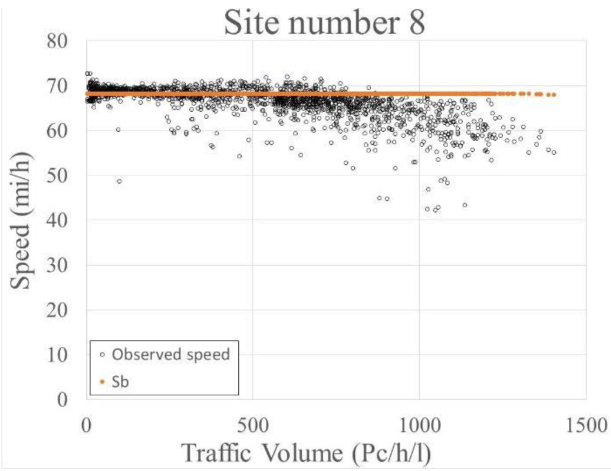
APPENDIX A – Investigating the Effect of Traffic Volume on Speed in the Weaving Sections



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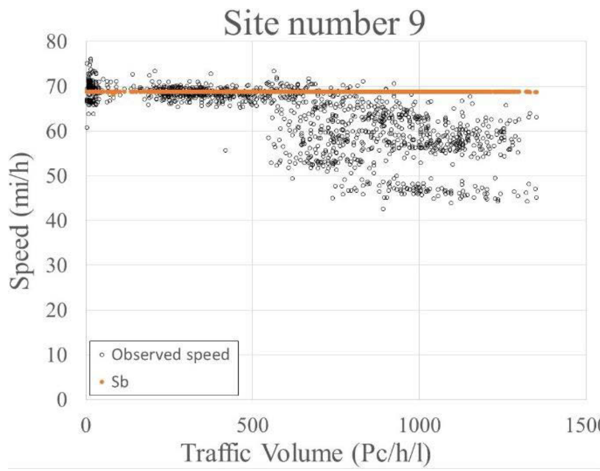

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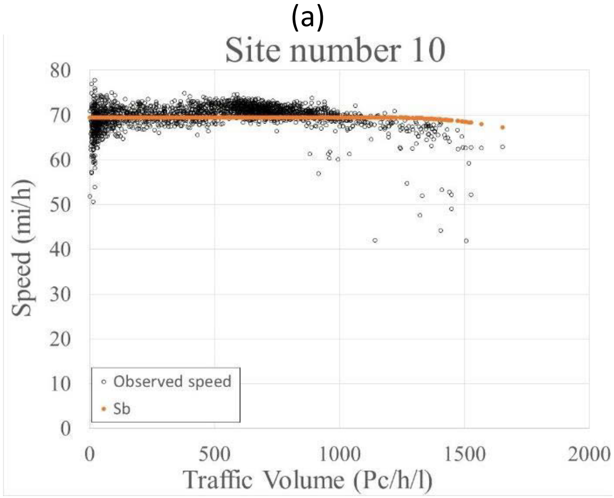

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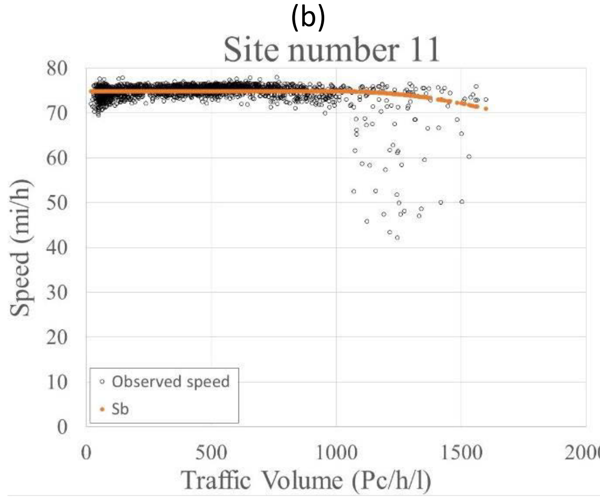

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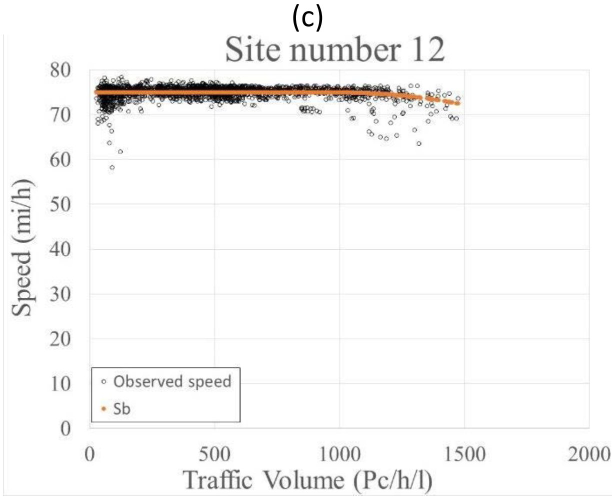

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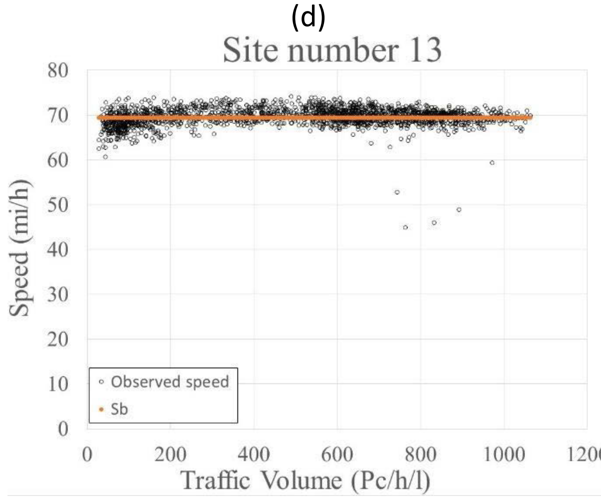

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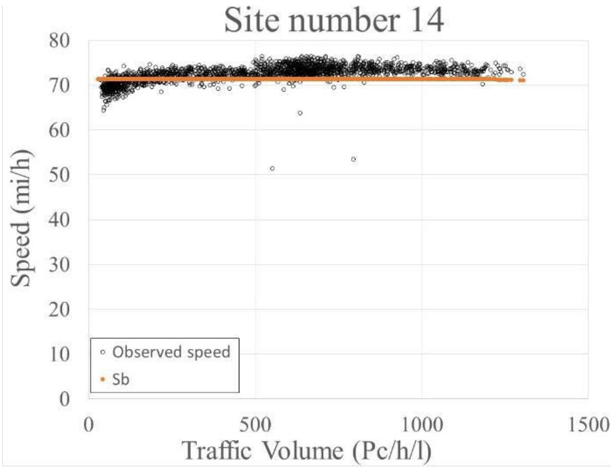

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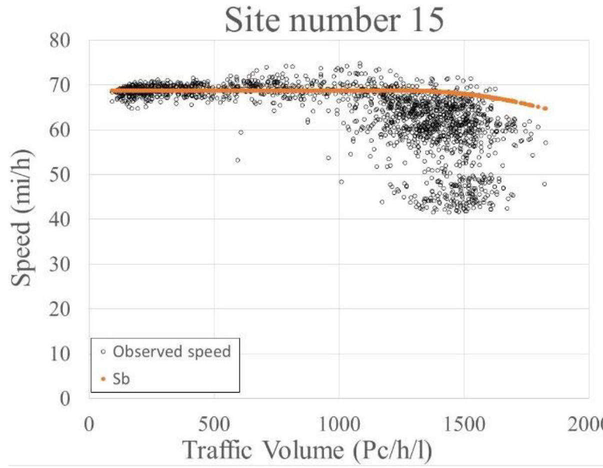

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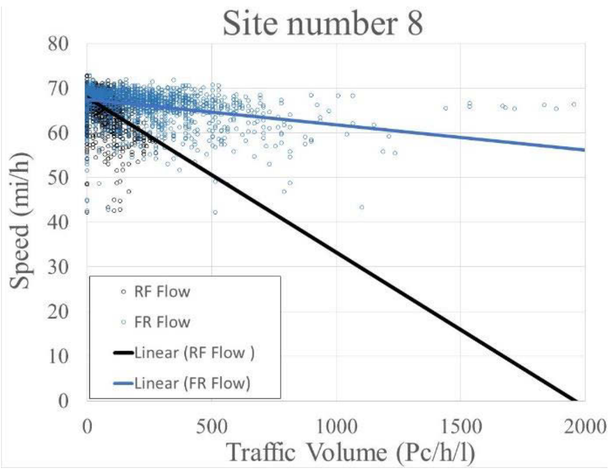
Figure A-1: Speed vs. *V* for eight weaving sections

APPENDIX B – Comparing the Effect of V_{rf} and V_{fr} in the Loop Detector Database



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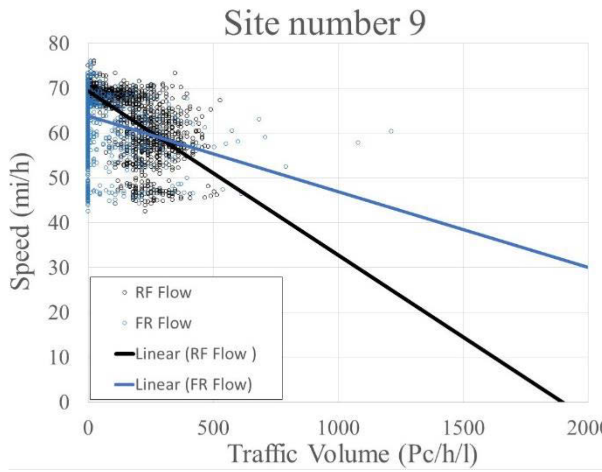

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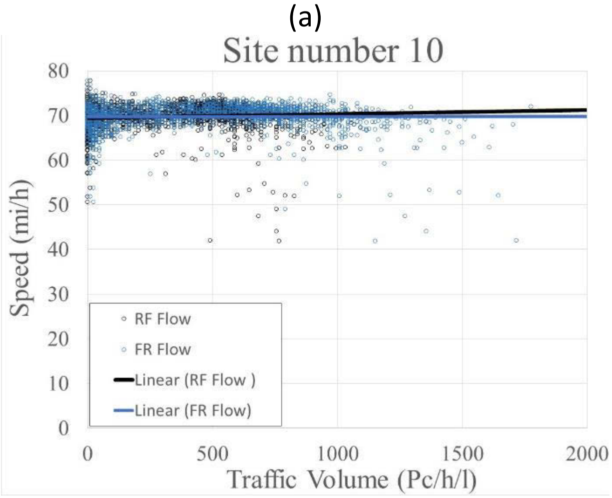

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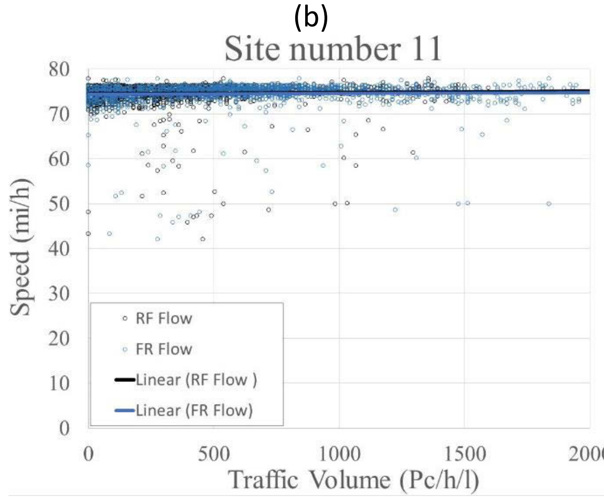

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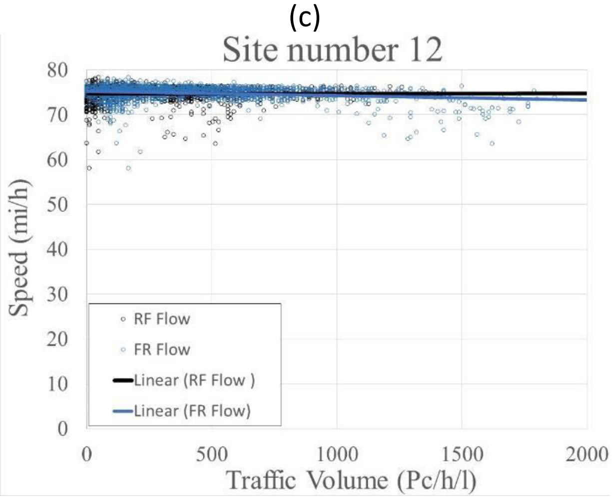

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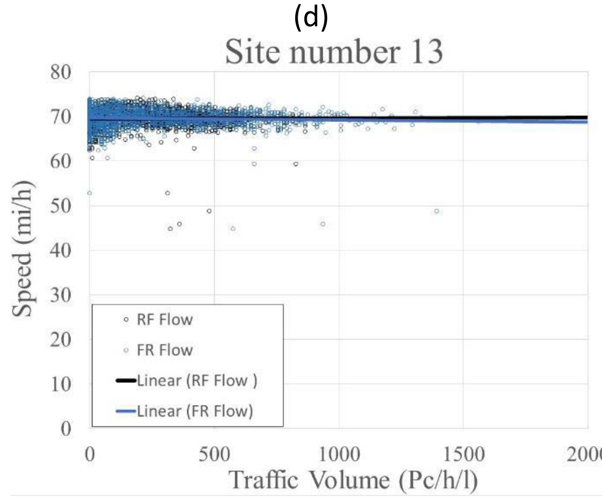

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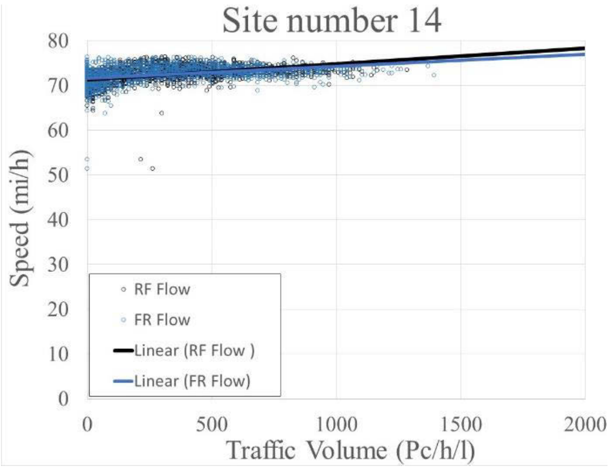

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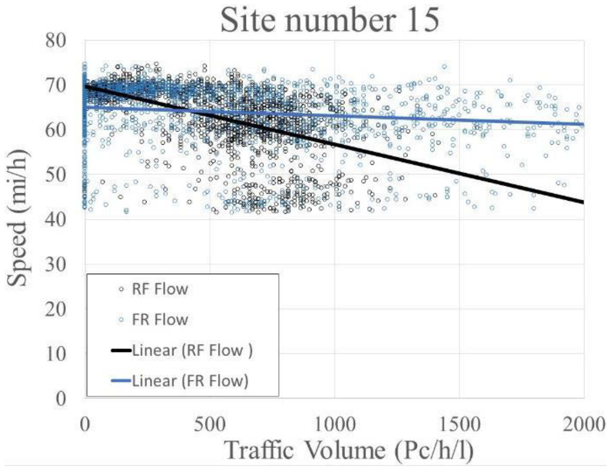

(h)

Figure A-2: Speed vs. V_{rf} and V_{fr} for eight weaving sections