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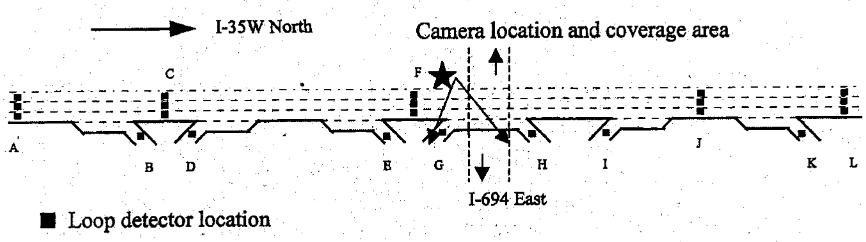

Estimation of Capacity in Freeway Weaving Areas for Traffic Management and Operations

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16. Abstract (Limit: 200 words)

This research developed an online procedure to estimate the weaving capacity through time for a simple ramp-weave section, the most common type of weaving areas in the Twin Cities[1] freeway network. The field observations and the analysis of the traffic data collected from a sample weaving section indicate that the freeway-to-ramp and ramp-to-freeway vehicles first merge and travel together at the beginning portion of the auxiliary lane before they split to the mainline or exit ramp. The length of the shared portion of the auxiliary lane, called an "effective weaving zone," varied depending on the length of an auxiliary lane and the amount of weaving volume.

The above merge-split behavior and the resulting mixed flow on the auxiliary lane for a short time period explains the fact that the maximum possible weaving volume in a simple ramp-weave section equals the maximum through volume that the auxiliary lane can handle. Researchers used a Kalman Filter to obtain estimated weaving volume data from three weaving, which supported this observation. Based on the above findings, an online procedure was developed to estimate the maximum possible weaving volume for a given ramp-weave area through time using the volume and occupancy measurements from the loop detectors. The proposed procedure assumes that the maximum possible weaving volume for a given time interval is a function of downstream traffic conditions that can be quantified by estimating the time-variant merging and diverging capacities of a given weaving section. Test results with the five-minute data from a ramp-weave site indicate that the maximum possible weaving volume can be estimated with reasonable accuracy during congested peak periods.

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ESTIMATION OF THE CAPACITY IN THE FREEWAY WEAVING AREAS FOR TRAFFIC MANAGEMENT AND OPERATIONS

Final Report

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EXECUTIVE SUMMARY

The complex flow patterns and the resulting capacity reduction in weaving areas have been one of the major issues in freeway operations. While there have been several research efforts to address the issues in weaving areas, most studies to date have focused on enhancing the Highway Capacity Manual procedures whose main objective is to provide a guideline for assessing level of services for given weaving areas. Further, most research efforts in the past resulted in regression-based models without incorporating the casual interaction between two crossing flows in a weaving area. In addition, very few studies have addressed the effects of the time-variant traffic conditions on the maximum possible weaving volume, which is of critical importance in freeway operations.

This report summarized the findings of the current research effort to address the flow behavior and capacity issues in a short ramp-weave section. First, the major weaving areas in the Twin Cities' freeway network were identified and classified depending on the length and geometric configuration of weaving areas. Next, a group of six weaving sites containing short ramp-weave sections were selected for detailed analysis and a spread-sheet database was developed with the loop data collected from those sites. In particular, the speed data of weaving flows were collected for two days from one of the short ramp-weave sections using a video recorder mounted on a 44 foot-mast, which was assembled and installed on a special trailer by the engineers at Mn/DOT. Further, a prototype video detection system developed in the University of Minnesota was used to measure the speed of individual vehicles changing lanes in the sample weaving area. The major findings from the analysis of the data and field observations include the following.

The exiting vehicles first merge with the entering vehicles on the auxiliary lane and a variable portion of the auxiliary lane is shared by the mixed flow for a short time period before the entering vehicles split to the mainline. This merge-split behavior was consistently observed through various levels of traffic, i.e., low to heavy conditions, and the length of the shared portion of the auxiliary lane varied depending on the amount of the weaving flow.

Because of the above merge-split behavior of the weaving flows, the maximum possible weaving volume, i.e., sum of exiting and entering vehicles, in a short ramp-weave section is limited by the maximum through volume of the auxiliary lane in a given weaving section. This phenomenon was confirmed by the volume data collected from the sample weaving section that showed the amount of the maximum weaving volume was very close to that of the left-most-lane immediately upstream of the sample weaving section.

The analysis of the speed data indicates that the exit speed under the free flow condition is primarily affected by the geometric configurations of a weaving section, i.e., the length of an auxiliary lane and exit ramp capacity. Further, a wide range of exit volumes, including the maximum, was observed at the free flow speed level, which ranged from 30 to 40 mph. The speed of the merging flow was very close to that of the exiting flow and the speed level of both flows were directly affected by the downstream conditions, i.e., mainline and exit ramp.

Because of the merge-split behavior in a weaving section, the weaving conflict directly affected the flow of the right-most lane just upstream of the weaving area. The volume-occupancy data showed that the right-most lane had the lowest volume and highest occupancy values compared with the middle and left-most lanes. Further, the congestion at the right-most lane also caused side-friction to the middle lane flow, which showed substantially lower maximum volume than the left-most lane. The above observations indicate that the most significant reduction of mainline capacity because of the conflict in a short ramp-weave section happens immediately upstream of the weave section.

Based on the above analysis, an on-line estimation model for the weaving capacity, i.e., maximum possible weaving volume through time, was developed and tested with the data collected from the sample weaving section. The model assumes that the maximum weaving volume under free flow conditions is the same as the maximum through volume of the auxiliary lane in a given weaving section. It further assumes that the maximum possible weaving volume varies through time depending on the downstream traffic conditions, i.e., both mainline and exit ramp, which were represented by a time-variant merging and exit capacity. The resulting model was tested with the data collected from the sample weaving section and showed a 4-5% difference between the predicted maximum weaving volume and actual measured data during congested periods.

A preliminary study to develop an on-line prediction procedure for the maximum possible volume at the mainline location upstream of the weaving section was also conducted and an adaptive procedure with the Klaman Filter was developed. The procedure adjusts the volume-occupancy relationship for a given location using historical and current day measurements and predicts the possible maximum volume for the next time period. Comparing the test results with actual data showed that the estimated maximum volume pattern followed the weather and traffic patterns on a given day, indicating the adaptability of the proposed procedure.

Future research needs include extensive testing of the on-line estimation models developed in this study with different locations of the same weave type and extending the procedure to different types of weave areas, such as mainline weave areas with medium to long sections. Further, the adaptive prediction procedure for the capacities of non-weave areas also needs to be refined to incorporate the effects of side friction explicitly. Finally, for comprehensive understanding of traffic behavior at congested bottlenecks, there is a strong need to collect time and space headway data for a flow moving through different types of bottlenecks.

TABLE OF CONTENTS

List of Tables

List of Figures

I. INTRODUCTION

I. 1 Background

Weaving is generally defined as the crossing of two flows in the same general direction without the aid of traffic control devices (HCM, 1997). Such a weaving flow generates intense lane-changing activities, whose resulting conflict significantly reduces the capacity of a weaving area. While the types of weaving patterns depend on the geometric configuration of given weaving areas, the most common type of weaving happens at a ramp-weave section where the merging flow from an on-ramp needs to cross the mainline vehicles diverging to an exit ramp through an auxiliary lane. For example, approximately 40 % of weaving areas in the Twin Cites' freeway network are short ramp-weave sections, where the conflicts between merging and diverging flows directly affect the operational conditions of given areas.

While the complex flow patterns and the resulting capacity reduction in weaving areas present significant operational problems on freeways, there have been very few studies that address the determination of the weaving capacity for freeway operations. The current Highway Capacity Manual (HCM) provides a methodology to estimate the level of service in a weaving section by estimating speed and density for a given set of weaving flows. However, it has been found that there is no clear relationship between speed and the weaving flow rate in real observed data. Further, the HCM method, originally developed for design analysis, does not reflect dynamically changing operational environments. Although some researchers have used microscopic simulation to estimate the capacity of weaving areas, the validity of their results is limited by the inherent simplifications in microscopic traffic models.

Understanding the behavior of weaving flows and developing a procedure to estimate the capacity of a weaving area is of critical importance in managing congestion in freeways. For example, the current Minnesota Department of Transportation (Mn/DOT) metering algorithm tries to maintain the flow levels at predefined bottlenecks under their capacities by adopting a zone-based approach, which simultaneously adjusts metering rates of all the ramps in a zone defined by bottlenecks, depending on the flow levels on the mainline. Therefore, accurate estimation of bottleneck capacities is one of the key elements affecting the effectiveness of the metering control.

I.2 Research objectives

The ultimate goal of the current research is to develop an automatic procedure that can determine the capacity values in various weaving areas in real time. In the current phase, due to the time and budget limitations, only type-A ramp-weave sections are analyzed in detail. Specific objectives of the current phase include:

- Identification of the major weaving areas in the Twin Cities' freeways.
- Collection of traffic data in selected weaving areas using loop detectors and video cameras.
- Analysis of weaving data and identification of relationship among traffic quantities in weaving areas.
- Development of a procedure to estimate the capacity in the weaving areas.

I.3 Report Organization

Chapter II includes the overview of the major research results found in the literature on weaving capacity. The weaving areas in the Twin Cites' freeway network are identified in Chapter III. Chapter IV contains the selection of sample weaving sites for detailed analysis and collection of traffic data, which are analyzed in Chapter V. Chapter VI describes the development and testing results of the on-line estimation procedures for the capacities in a weaving area. Chapter VII includes conclusions and future research needs.

II. OVERVIEW OF LITERATURE IN WEAVING

The current HCM defines weaving capacity as the maximum total weaving flow beyond which acceptable operations are unlikely to occur. The HCM further provides the density thresholds, determined with the estimated speeds for weaving and non-weaving flows for a given weaving zone, as the Level of Service (LOS) criteria. Most past research activities have focused on the improvement of the HCM methodologies by proposing specific definitions of weaving capacity and/or models to estimate speed and flow levels within a weaving zone. Alternative LOS evaluation criteria have also been proposed by some researchers. This chapter summarizes the major research results found in the literature.

The definition of weaving capacity was addressed by very few groups of researchers. Cassidy and May (1991) defined weaving capacity as 1) the maximum flow of vehicles that can travel at any point (within a lane) of roadway within a subject weaving area, and 2) the maximum rate of lane changing (between two adjacent lanes) that can occur over any 250-ft segment within the weaving area. In the same study, the authors also proposed a procedure predicting flow rates at different locations within a weaving section based on prevailing traffic and geometric conditions. For this purpose, the authors developed a family of curves using empirical and simulated data to estimate spatial distributions of each traffic movement. Another definition of weaving capacity was proposed by a group of Canadian researchers, who defined weaving capacity as the outflow that could be expected during a 15-minute period when total demand to a weaving section could be changed without affecting the section's discharge rate (Van Aerde, Baker and Stewart, 1996).

Several researchers proposed models to estimate speed and flow rates within a weaving zone by incorporating new indices designed to quantify weaving conflicts. A speed estimation model incorporating a "Lane Shift Index" was proposed by a group of researchers (Fazio and Rouphail, 1986). The "Lane Shift Index" represents the minimum number of lane shifts that a driver of a weaving vehicle must execute from the lane of origin to the closest desired lane. The proposed model estimates speeds of weaving and non-weaving flows as follows:

$$S_w = 15 + \{50 / [(1 + \{[1 + (V_3 + V_4) / V]^{3.045} (V/N)^{0.605} \times (LS/L)^{0.902}\}) / 75.959 [1 + (LS_3/V)]^{3.94}]\}$$

$$S_{nw} = 15 + \{50 / [1 + (\{[1 + (V_4/V)]^{5.08} [1 + (V_w/V)]^{2.019\,m} \times (V/N)^{1.523}\} / \{60.995[1 + (LS_3/LS0)]^{0.916} L^{1.07}\})]\}$$

where,

S_w = Speed of weaving flow

S_{nw} = Speed of non-weaving flow

N = number of lanes in weaving section

V = total volume in weaving section

L = length of weaving section

V_1 = volume of non-weaving traffic from major approach

V_2 = volume of weaving traffic from major approach

V_3 = volume of weaving traffic from entrance ramp

V_4 = volume of non-weaving traffic from entrance ramp

V_w = sum of weaving traffic ($V_2 + V_3$)

V_{w2} = smaller of weaving traffic [$\min(V_2, V_3)$]

LS = lane shift indices

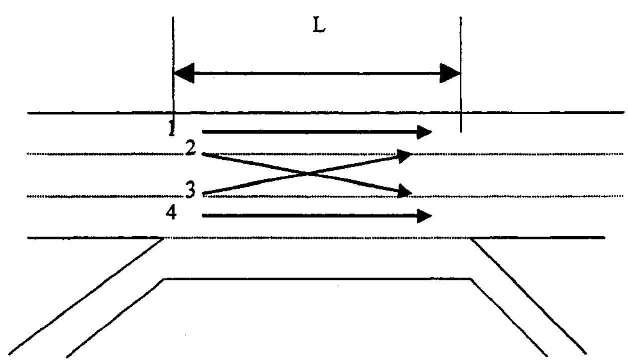


Figure 2.1 Flow configuration in Fazio's model

The same authors also proposed to use 'conflict rate' as a Measure Of Effectiveness (MOE) in a weaving area for simple one-sided freeway weaving sections (Fazio and Rouphail, 1990). 'Conflict rate' was defined as,

$$Conflict\ rate = (15\text{-}min\ conflict\ count) / [15\text{-}min\ volume\ count * (L/5280)$$

where L is the length of the weaving section.

Osrom, Leiman and May (1993) proposed two methods to estimate flow rates in a weaving area, the point flow by movement and the total point flow methods. The point flow by movement method estimates the total volume at a point by modeling the distribution of movements and number of lane changes. The total point flow method estimates point flows for all weaving and non-weaving flows using the following regression model:

$$Flow\ in\ lane\ N\ at\ location\ X ft = \theta_0 + \theta_1 FF + \theta_2 FR + \theta_3 RF + \theta_4 RR$$

where,

θ_I = coefficients

FF = freeway-to-freeway movement

FR = freeway-to-offramp movement

RF = onramp-to-freeway movement

RR = onramp-to-offramp movement

Fitzpatrick and Nowlin (1996) proposed a regression model to predict lane changes for a given set of weaving flows as follows:

$$LC = 1.33\ (W)$$

where,

LC = average number of lane changes per hour

W = weaving volume.

The authors also suggested that the desired length of a weaving section to apply the above model is greater than 300 meters and needs not to be less than 200 meters.

Fredericksen and Ogden (1994) developed three regression-based models for different lengths of weaving sections to estimate Lane Changing Intensity, which was proposed as an alternative MOE for analyzing type A weaving sections on frontage roads. The proposed models are:

1). *122.0 to 182.6m :* $LCI = 10.46\ (V/N) + 372$

2). *182.9 to 274.1m:* $LCI = 8.552\ (V/N) + 79$

3). *274.4 to 365.9m:* $LCI = 391\ (V/N) + 590$

where,

LCI = lane changes per hour per mile

V = hourly volume entering weaving section, and

N = number of lanes in weaving section.

As reviewed in this chapter, most studies in the past focused on the development of models that could estimate speed-volume levels and/or alternative measures of effectiveness at different locations within a given weaving area. These models were mostly intended for design analysis by providing estimates of Level of Service for given traffic and geometric conditions. Further, most past research efforts resulted in regression-type models based on the implicit assumption that the lane-changing maneuvers by weaving vehicles would occur at any location within a given weaving area. These regression models estimate combined effects of weaving flows without explicitly addressing the interaction between two flows crossing each other within a given weaving area. It should also be noted that most data used in the past studies were collected from weaving areas whose entrance ramps were not metered.

In summary, this literature review identified a list of issues that have not been explicitly addressed in the past research on weaving capacity. They include:

- the behavioral characteristics of drivers in different types of weaving areas,
- the causal interaction between merging and diverging flows in a weaving area, i.e., the effects of the merging flow entering from an on-ramp on the diverging flow,
- the effects of metering on weaving flow patterns,
- the effects of weaving on the mainline flow upstream of the weaving section,
- the effects of time-variant traffic conditions on maximum possible weaving volume, which is of critical importance in determining metering rates in real time.

III. IDENTIFICATION OF MAJOR WEAVING AREAS IN TWIN CITES

Weaving areas can be classified into two categories, i.e., simple ramp-weave and multiple-weave areas, depending on the number of lane changing requirements for the weaving flows. The simple ramp-weave areas, the most common type of weaving area, require only one lane-changing maneuver and can have different types of geometric configuration as shown in Figure 3-1. The simple ramp-weave areas can be further classified into short, medium and long weaving sections depending on the length of an auxiliary lane connecting two ramps. Type E in Figure 3.1 is a special geometry where an off-ramp is located right after an on-ramp without any auxiliary lane. While type E is not treated as a weaving area in the current Highway Capacity Manual, this type of area can generate substantial amount of weaving activities depending on the magnitude of ramp volumes.

Multiple weaving areas in general consist of multiple ramps and/or freeway merge/split areas. Figure 3-2 shows two example multiple-weaving areas located at freeways TH-77 and TH-62 in the Twin Cities metro area. This type of weaving area generates multiple lane-changing maneuvers, which result in complicated traffic patterns that are location-specific and vary through time. Table 3-1 shows the summary statistics of all the weaving areas in the Twin Cites metro freeways and Appendix A includes the type and location of each weaving area. Further, Appendix B has the schematic diagram of major, multiple-weaving areas located in the current metro freeway network.

Table 3.1 Types of weaving sections in Twin Cities

	weave type						
	A	B	C	D	E	Multiple	Total
Short	52	32	1	4	0	1	90
Medium	45	11	3	0	3	13	75
Long	22	17	2	0	0	20	61
Total	119	60	6	4	3	34	226
(cloverleaf)	44	27	1	4	0	1	

* All cloverleaf sections are classified as short (S)

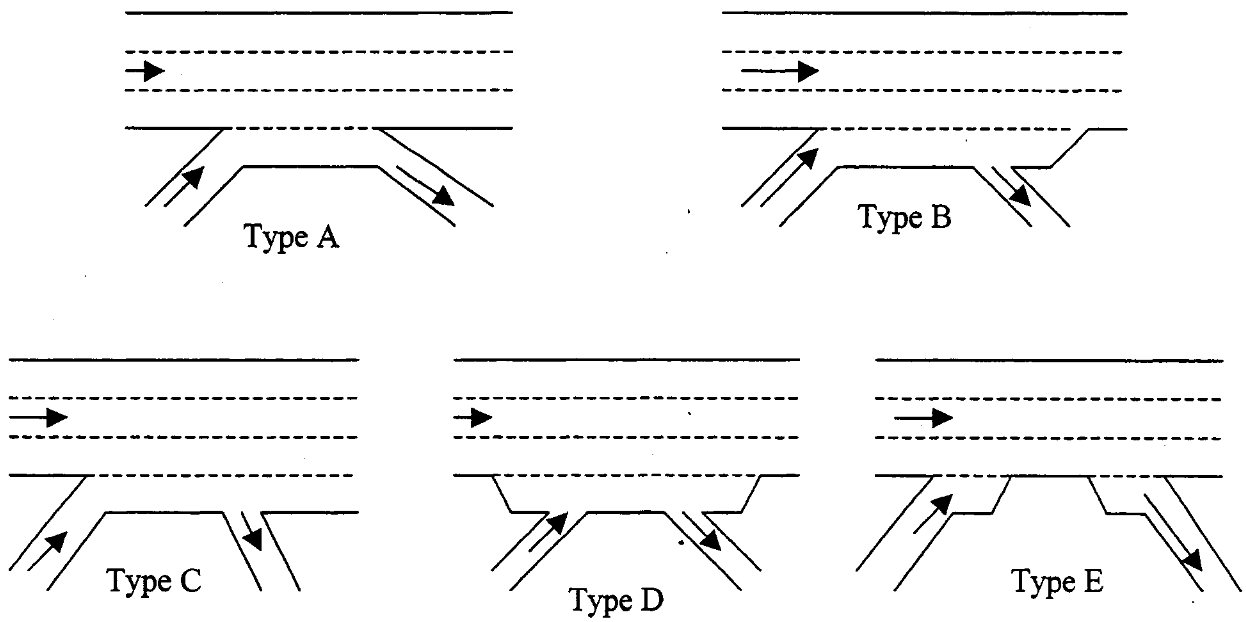


Figure 3.1 Types of Simple Ramp-Weave Areas

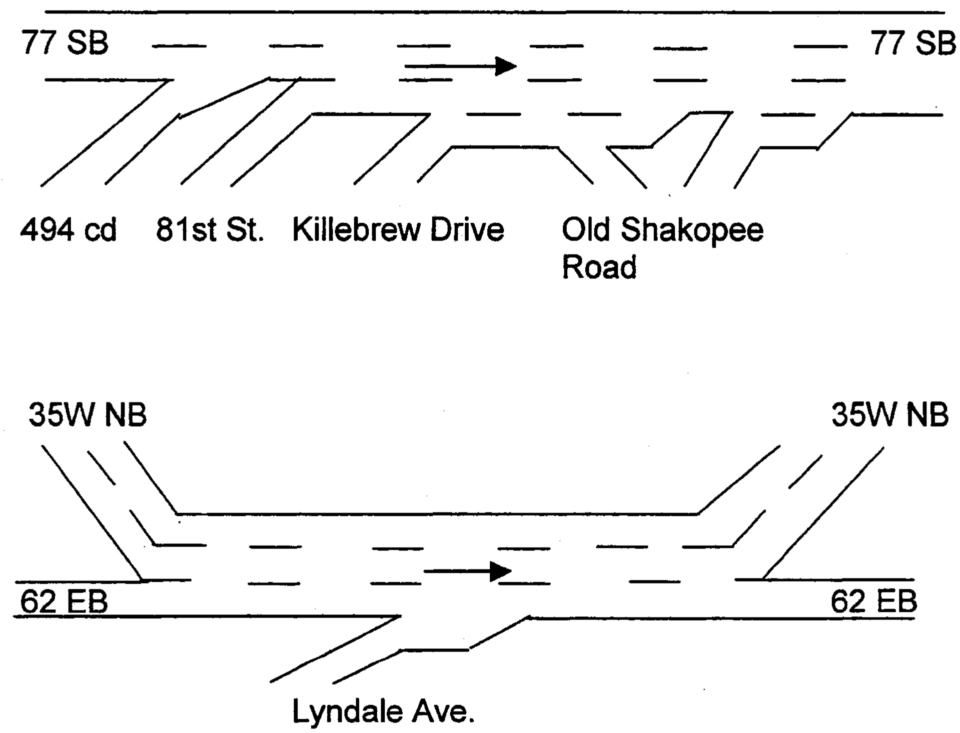


Figure 3.2 Example multiple weaving areas in Twin Cities' metro freeway network

IV. DATA COLLECTION FROM SELECTED WEAVING AREAS

IV.1 Selection of weaving sites and data collection

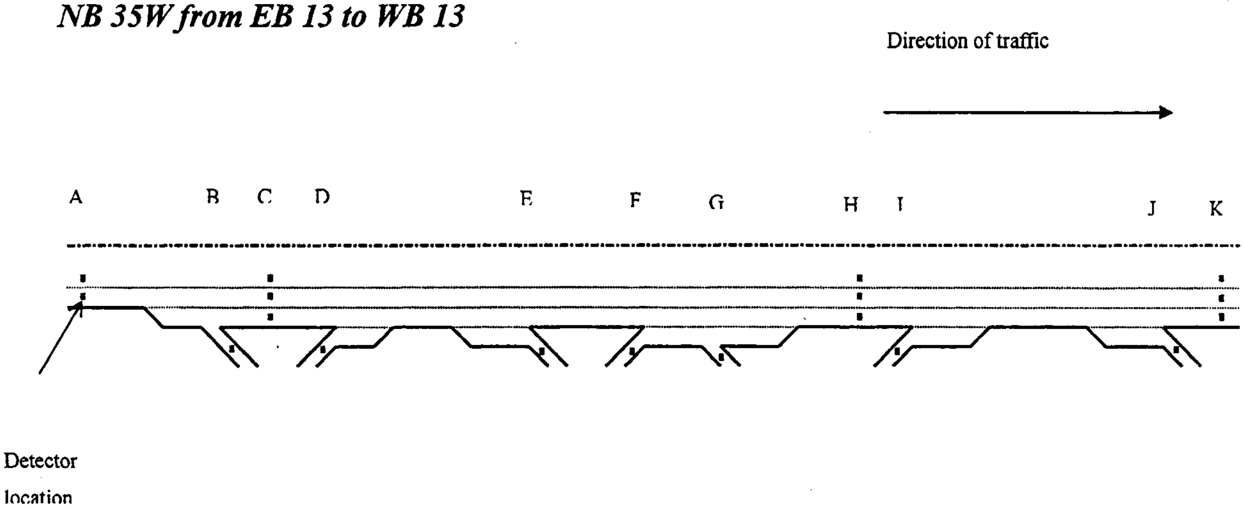
In this research, a total of six, simple ramp-weave sites were selected in consultation with the engineers at the Traffic Management Center, Mn/DOT, for detailed analysis of weaving traffic behavior. The traffic characteristics of multiple weaving areas will be addressed in the subsequent phases of this research. The selected sites are typical cloverleaf ramp-weave sections, most commonly found in the Twin Cities' metro freeway network. The list of those six sites is as follows:

- Northbound I-35W from Eastbound I-694 to Westbound I-694
- Eastbound TH-62 from Southbound TH-100 to Northbound TH-100
- Northbound I-35W from Eastbound TH-13 to Westbound TH-13
- Westbound TH-62 from Southbound TH-77 to Northbound TH-77
- Eastbound I-494 from Southbound I-35W to Northbound I-35W
- Westbound I-494 from Northbound TH-100 to Southbound TH-100

Figure 4.1.1 shows one of the six weaving sites located on I-35W northbound at Hwy 13. Appendix C includes the geometry and the location of the loop detectors for all six sites.

First, the volume-occupancy data were collected from the loop detectors located in each site for a period of two months, November 1996 and November 1997, in cooperation with the Traffic Management Center, Mn/DOT. The collected data covers weekdays both upstream and downstream of a weaving section from 6:00a.m. until 8:00p.m. The collected data were stored in a spreadsheet format shown in Figure 4.1.1. While the Mn/DOT control system has the capability to collect 30-second data, due to the limitations of the current configuration, only 5-minute volume-occupancy data were collected for each lane. Further, no speed data could be collected with the current detection system that has single-loop configurations. It was also noted that the locations of the mainline detectors near each weaving section were not uniform, i.e., two sites had the detectors upstream of their weaving areas, while three had them downstream. There is also one site, Hwy 62 at Hwy 100, that does not have any mainline detectors near the weaving section. It should be noted that none of six weaving areas has any detectors within the weaving zone, i.e., between on and off ramps.

NB 35W from EB 13 to WB 13



Right lane detector

Section	A		B	C			D	E	F	G		K		
Station	72		***				***	***	***	***	...			
Detector #	131	132	162	258	259	461	111	153				264	265	500
Time														
605														
610														
615														
620														
↓														
1955														
2000														

Figure 4.1.1 Geometry of one weaving site and database format

IV.2 Development of a trailer-based, video recording system and collection of speed data

The data collected in the previous section contains only volume and occupancy information from the loop detectors located outside of a weaving section. To understand the behavior of traffic within a weaving section, it is of critical importance to measure the performance of the weaving flows, e.g., the number of vehicles changing lanes, speed of diverging and merging flows, and the location of lane changes. In this research, it was decided to use a machine-vision detection technology with the video-tapes recorded from the field. It was further decided to develop a trailer-based, video recording system that can be moved to any place to record traffic images with a video camera. Figure 4.2.1 shows the design diagram of the trailer with a 44-foot mast, where a video camera can be mounted. In this project, the trailer and the material to build the mast were purchased from a private manufacturer, while the mast itself, consisting of a three-section aluminum tower, was assembled by the engineers at Mn/DOT. The resulting trailer-mast system was attached to the data collection van in Mn/DOT. Figure 4.2.2 shows a photo of the mobile recording system being used to collect data at the I-35W weaving area.

Using the mobile trailer system, the weaving traffic at the I-35W @ I-694 weaving site was recorded for four days in October 1998 by Mr. Len Palek, the data analysis engineer at the Traffic Management Center, Mn/DOT. Figure 4.2.3 shows the layout of the weaving site and the area covered by the camera. As indicated in the figure, due to the bridge crossing over the weaving section, the camera could not cover the entire weaving area. However, the covered area was large enough to capture most of the vehicles changing lanes in the weaving section. The video-tapes were processed using the image processing system developed by a group of researchers at the University of Minnesota (Osama, Papanikolopoulos, Kwon, 1999). This system adopts a vehicle tracking technology with Kalman Filtering and is capable of measuring the speed of each vehicle changing lanes in a weaving zone. Because of the limitations of the current prototype system, which can not handle moving-shadows of the object images, only two tapes from October 20 and 29, 1998, were processed. This resulted in two sets of one-minute speed data for the diverging and merging flows from 3:00p.m. until 5:30p.m. for two days. The analysis results of the speed-volume data for the selected weaving site are presented in the next chapter.

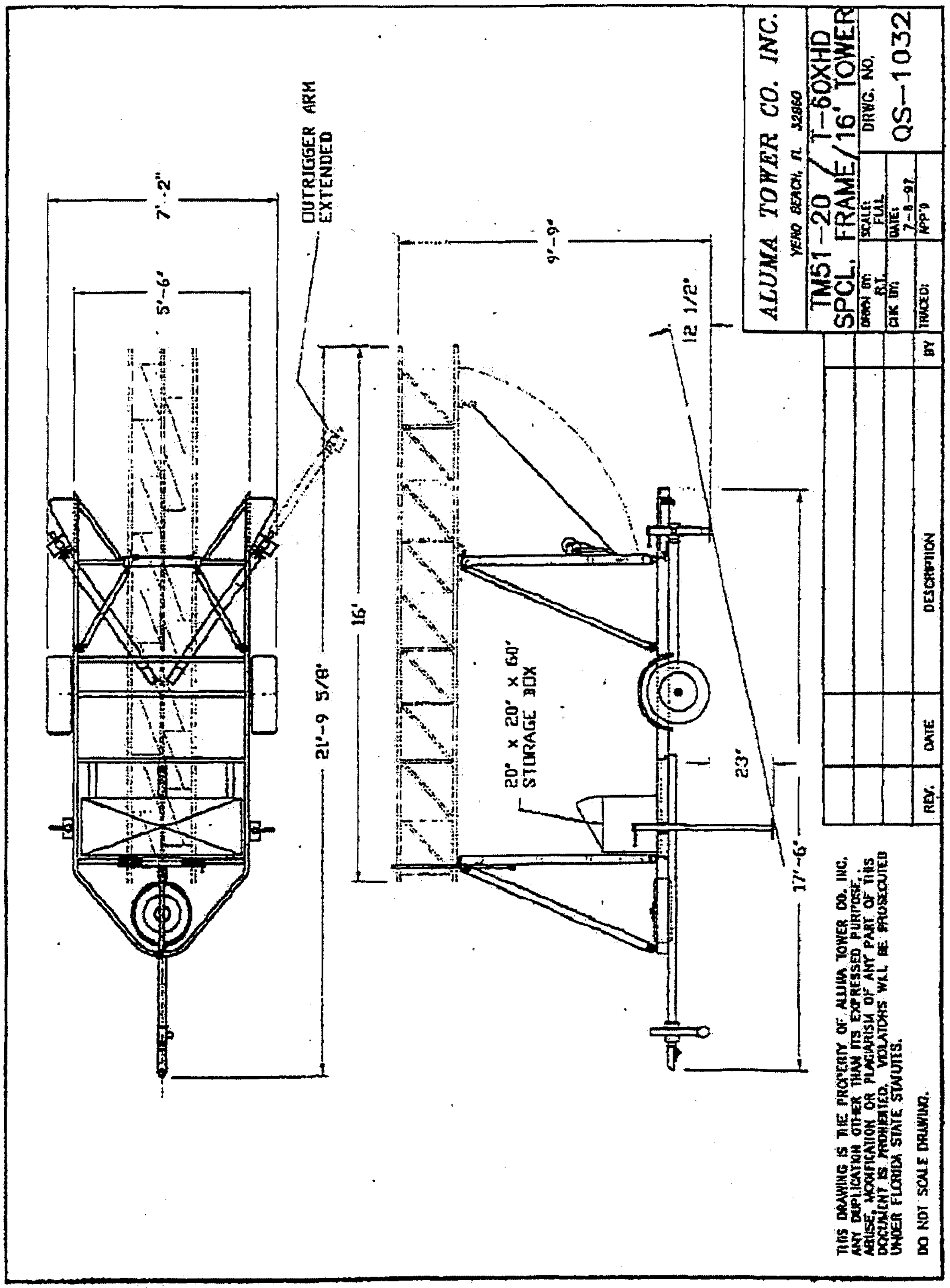


Figure 4.2.1 Trailer-Mast design sketch

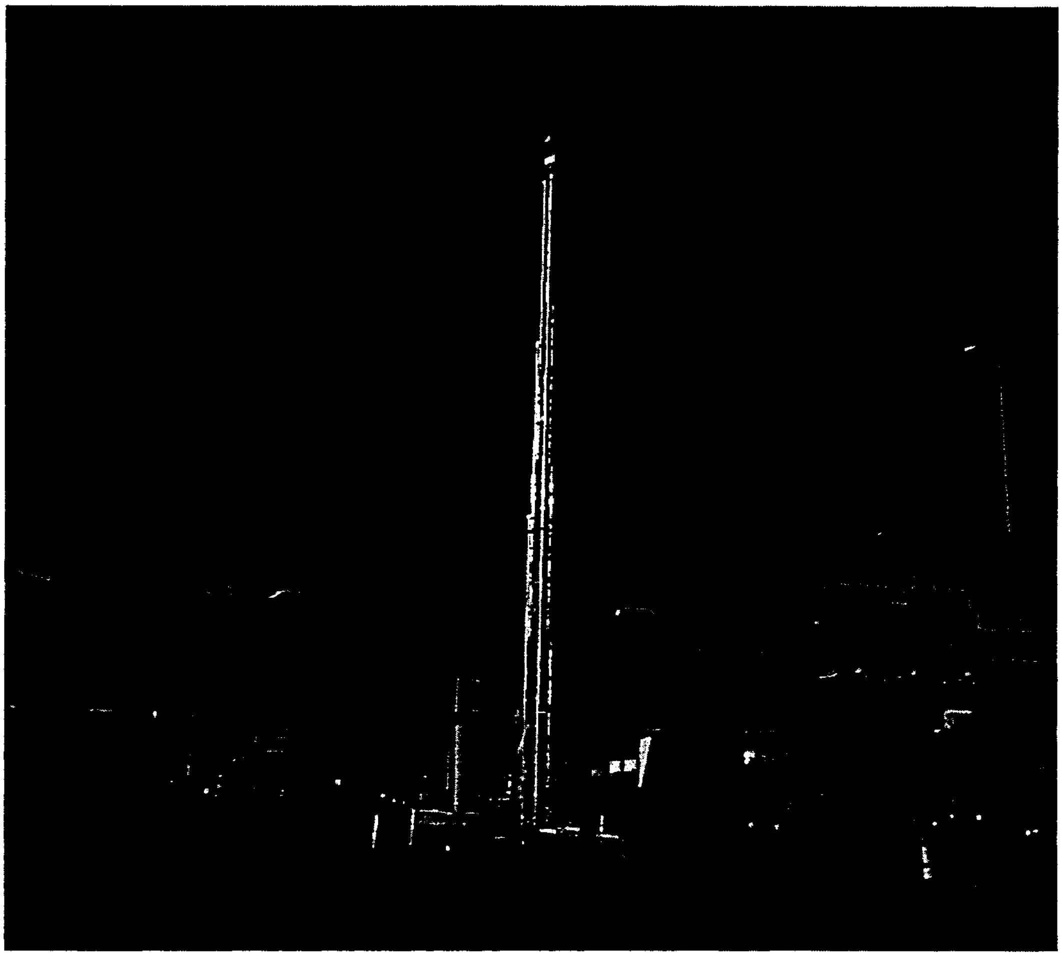


Figure 4.2.2 Mobile traffic recording system being operated at I-35W at I-694 weaving section

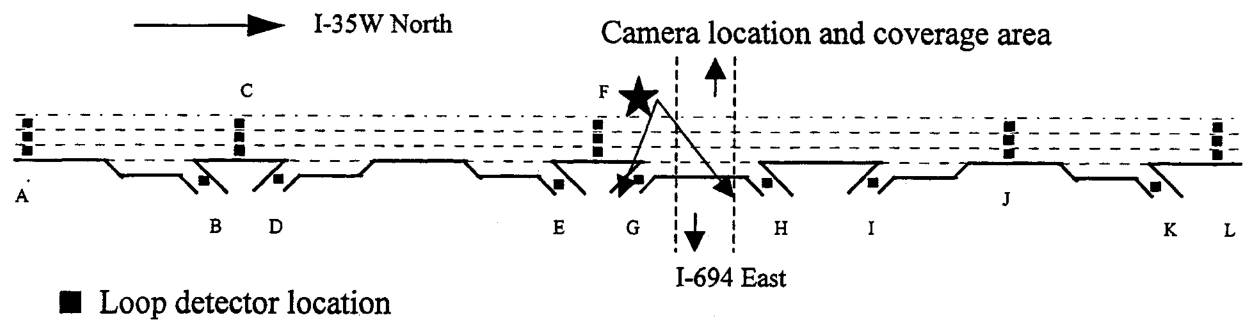


Figure 4.2.3 I-35WNB weaving site at I-694 and the location of video camera

V. ANALYSIS OF TRAFFIC BEHAVIOR AT SHORT RAMP-WEAVE AREAS

V.1 Sample weaving site

In this chapter, the traffic behavior in the vicinity of short ramp-weave areas as well as the lane-changing behavior of the entering and exiting vehicles from the ramps is analyzed using the data collected in the previous chapter. For this analysis, a ramp-weave area with heavy traffic demand was selected and the collection of the detailed data including speed measurements of the weaving flows was performed. The subject weaving area is located at the cloverleaf interchange between I-35W and I-694. Figure 5.1.1 shows the geometrics of the subject weaving site and the locations of the loop detectors on the mainline and ramps.

As indicated in the figure, the subject weaving area has the typical Type A configuration defined in the current Highway Capacity Manual with three mainline lanes and one 650-feet auxiliary lane. There is one mainline detector station with three detectors located immediately upstream of the weaving zone and each ramp also has one detector measuring volume and occupancy values. Both entrance and exit ramp have high traffic demand during afternoon peak periods and the entrance ramp has been metered in a centrally controlled, traffic-responsive manner, while there is no control with the exit ramp. The posted speed limit at both ramps is 25 miles/hour, but the observed speed levels under free-flow conditions reached 30 miles/hour at both ramps. The speed limit of the main freeway is 65 miles/hour, while the observed free flow speed ranged from 65 to 75 miles/hour. The loop detector at the entrance ramp is located immediately after the meter stop line. The loop detector data collected from this weaving area consists of the volume-occupancy measurements at every 5-minute intervals from 6:00a.m. to 8:00p.m for a period of two months in November 1996 and November 1997. Two days' worth of speed data for the entering and exiting vehicles within the weaving zone was obtained from the video tapes recorded with the camera mounted on the 44-foot mast on the trailer. The rest of this chapter summarizes the major findings from the analysis.

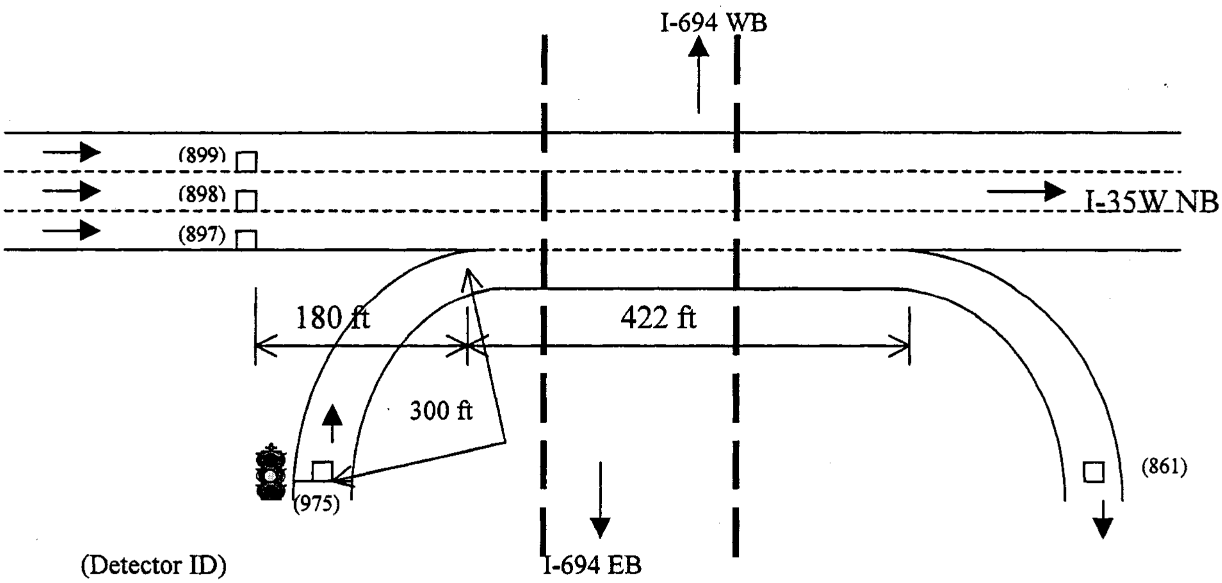


Figure 5.1.1 Geometrics of the subject weaving area

V.2 Analysis of speed-volume measurements for weaving flow

Figures 5.2.1 and 5.2.2 show the speed-volume relationships measured from the weaving traffic on two days in October 1998. As indicated in these figures, no significant pattern can be found between speed and volume measurements for the weaving flows, whose 5-minute speed ranged from 22 to 35 miles/hr. This can be explained with the fact, due to the geometric conditions of the sample weaving area, the free merging/diverging speed ranges from 30 to 40 miles/hr and a wide range of volume, including ramp capacity volume, can be observed within the free-flow speed range. The above finding indicates that within a short ramp weave area, the speed levels are not sensitive to the amount of weaving vehicles.

Figures 5.2.3-5.2.5 show the speed variations of the weaving vehicles measured within the weaving area and their relationships with other quantities collected from the same weaving site. Figure 5.2.3 includes one-minute average speed variations for both merging and diverging vehicles. Figures 5.2.4a – 5.2.5d show the relationships between 5-minute speed levels of weaving flows and volume/occupancy measurements from the mainline upstream detector. It can be seen that, at any given time interval, the speed levels of merging and diverging flows are very close to each other, while the speed levels of both flows have significant variations through time (Figures 5.2.3, 5.2.4b and 5.2.5b). This confirms the observed behavior of the diverging drivers who try to match their speed levels with those of the merging drivers, or vice versa, at the beginning point of the weaving area. It should be noted that the entrance ramp in this weaving area has been metered throughout the data collection periods and the merging vehicles entered the weaving area one at a time after stopping at the meter. Therefore, the merging drivers have enough time to adjust their speed levels to those of the mainline drivers diverging to the exit ramp. Without metering, it can be expected that the merging vehicles would directly proceed to the merge point, where they need to slow down or wait to find suitable gaps in diverging flow to change lanes. Since the diverging drivers need to adjust their speed levels to those of the merging flow in order to complete safe weaving maneuvers, the resulting weaving flow would have lower speed levels than that of the controlled weaving flow.

Finally, Figures 5.2.4c-f and 5.2.5c-f indicate that the speed of both diverging and merging flows is decreased when the right-most lane upstream of the weaving area has high occupancy values, while no significant pattern can be found with the occupancy values of the middle lane.

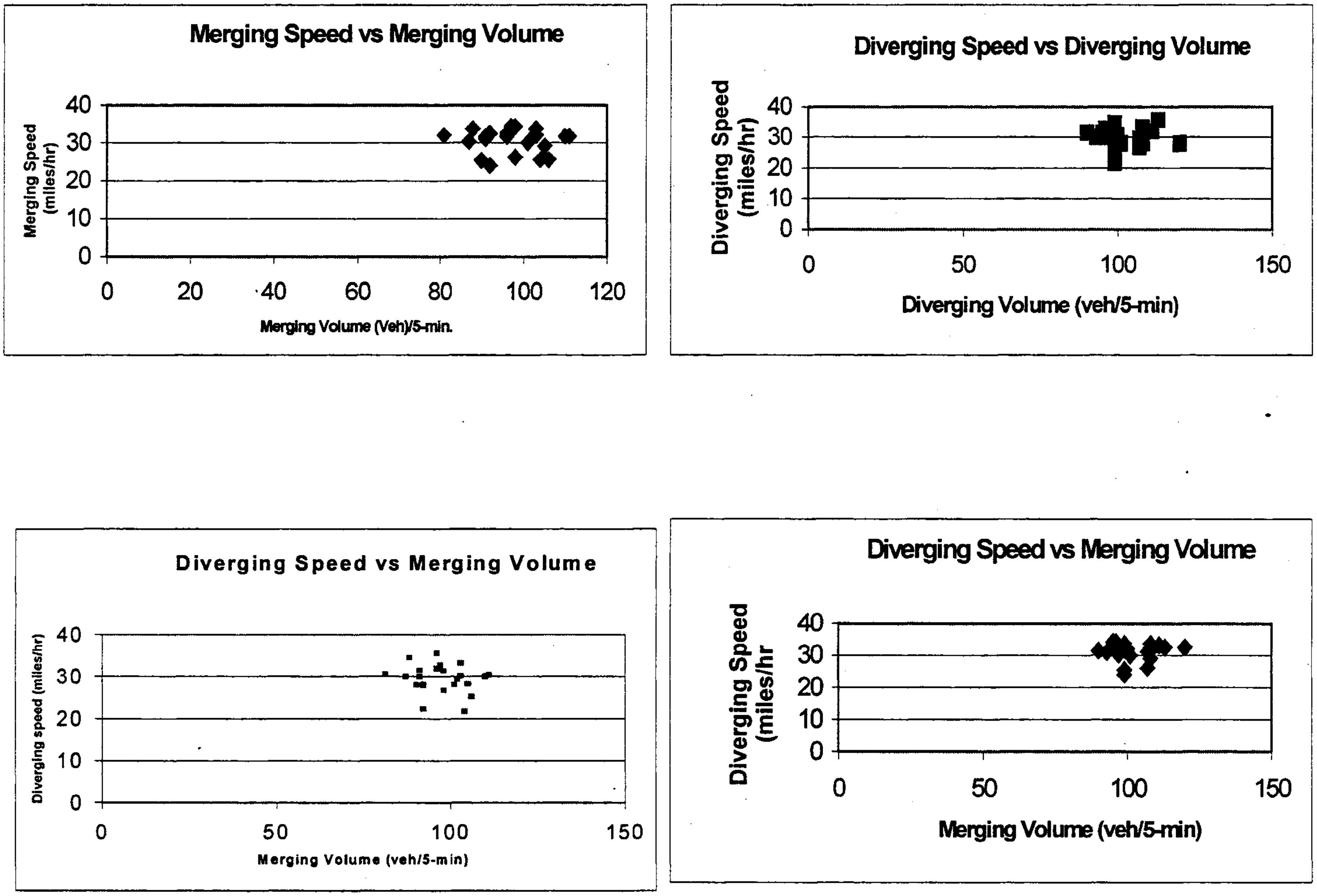


Figure 5.2.1 Speed-Volume relationships in weaving flow on October 20, 1998

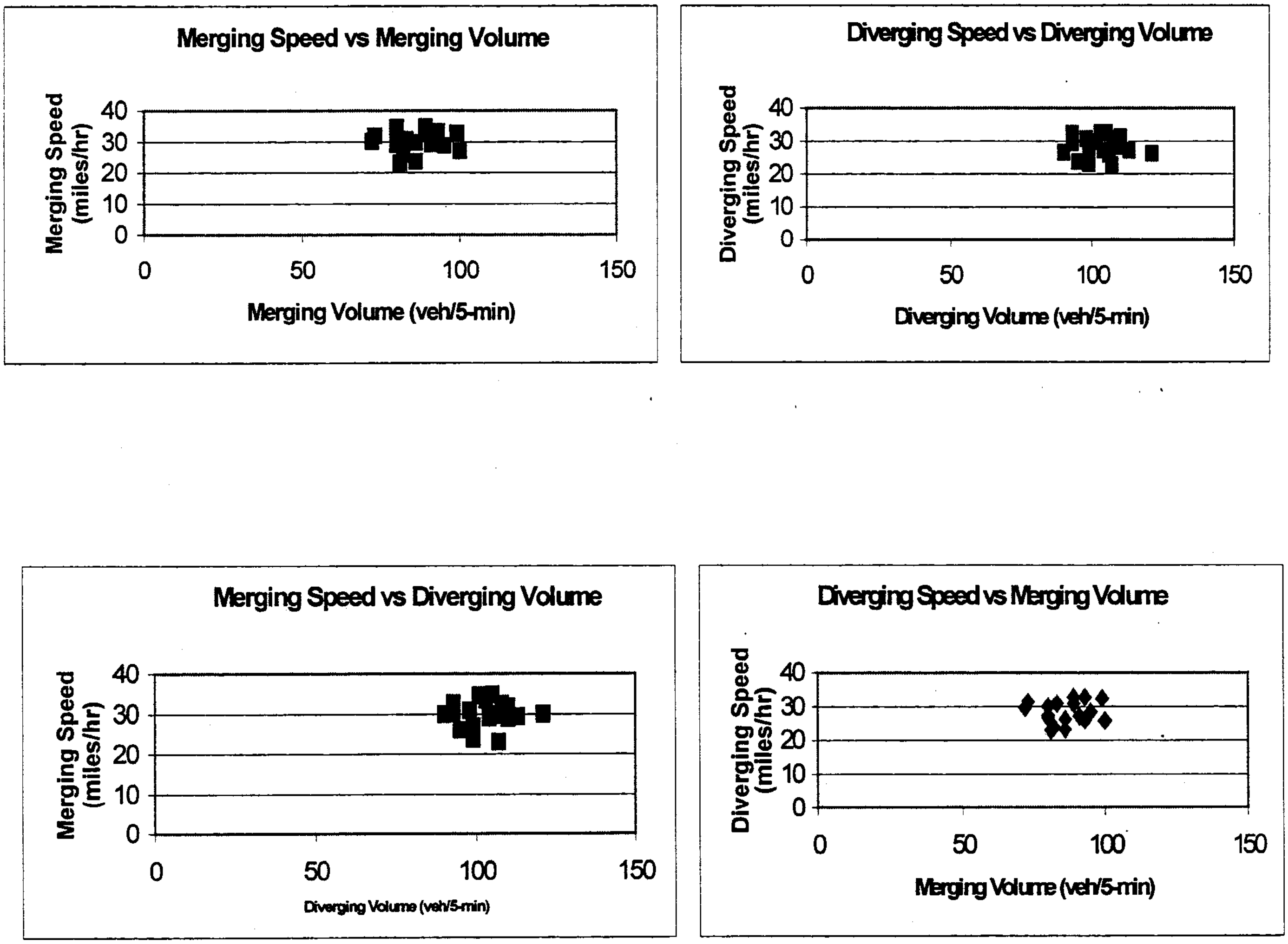
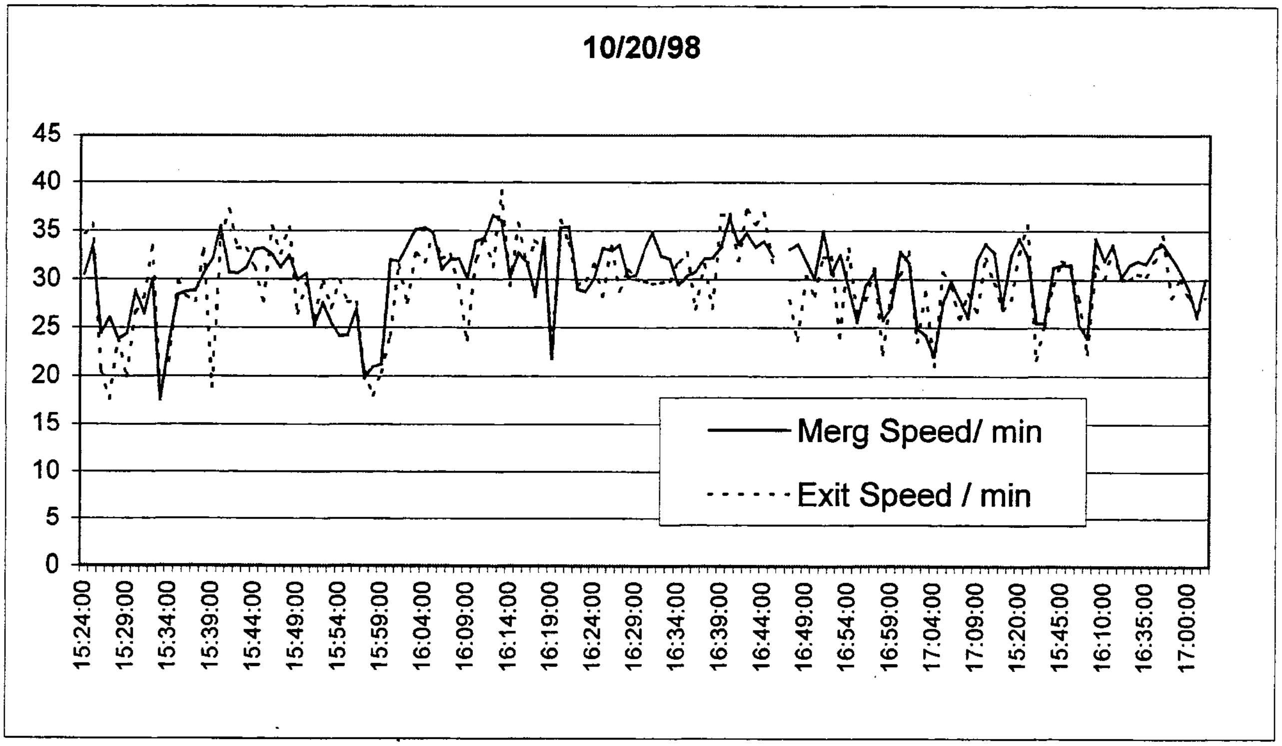


Figure 5.2.2 Speed-Volume relationships of weaving flow on October 29, 1998



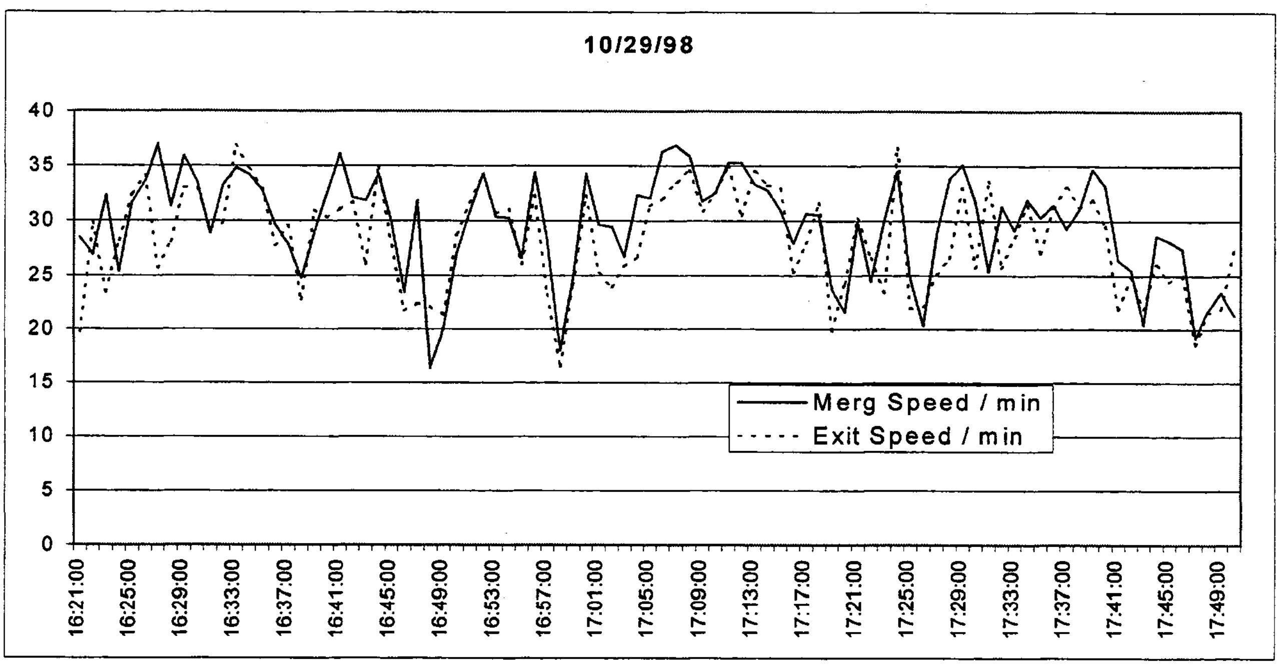


Figure 5.2.3 Speed Comparison between merging and diverging vehicles within weaving area

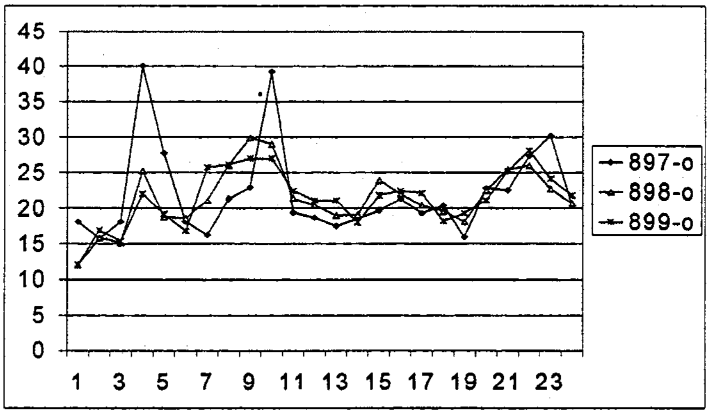


Figure a

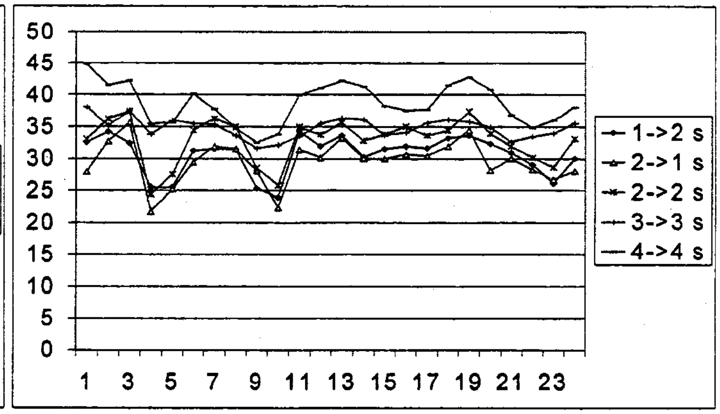


Figure b

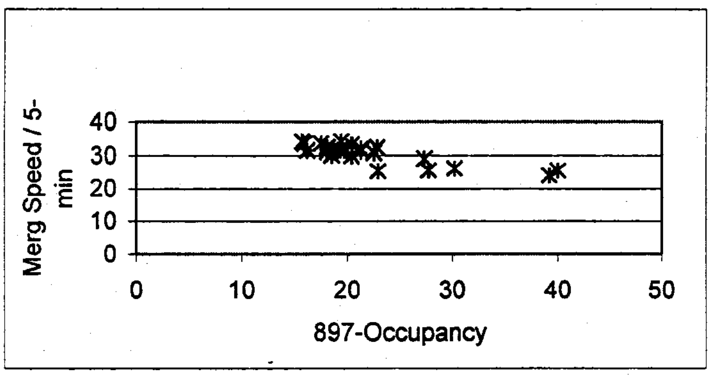


Figure c

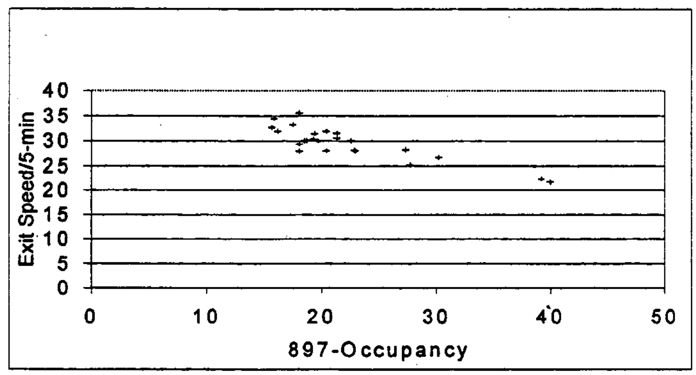


Figure d

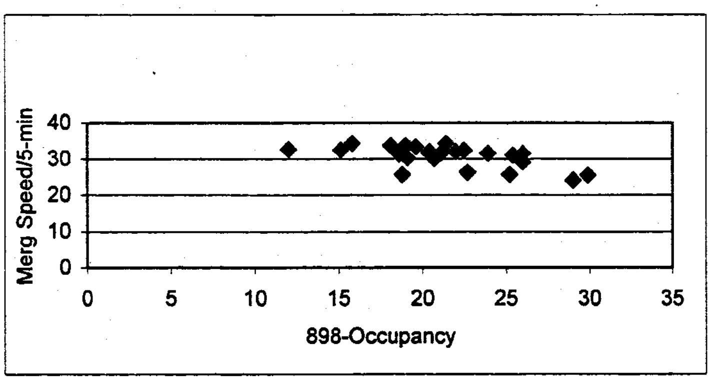


Figure e

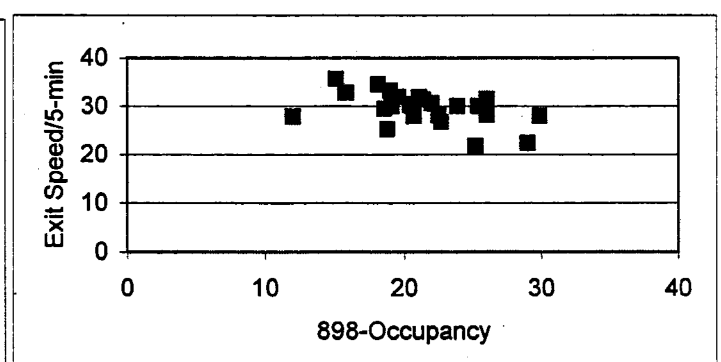


Figure f

Figure 5.2.4 Speed-volume/occupancy relationships between weaving and mainline volumes on October 20, 1998

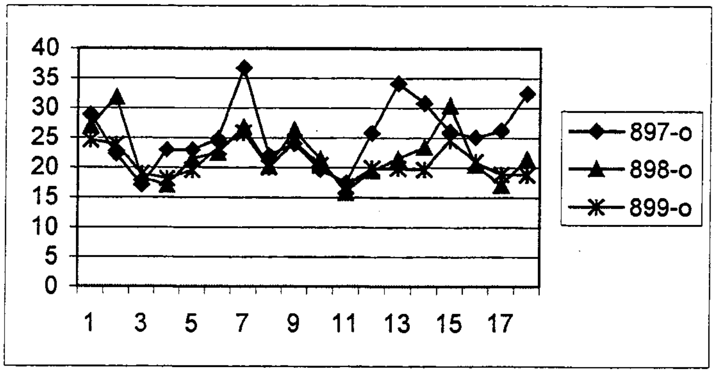
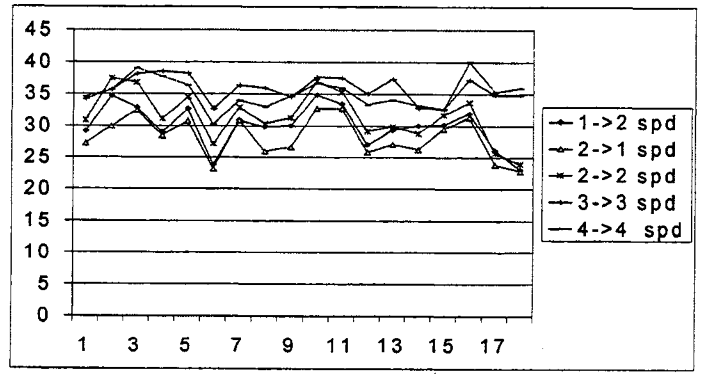


Figure a



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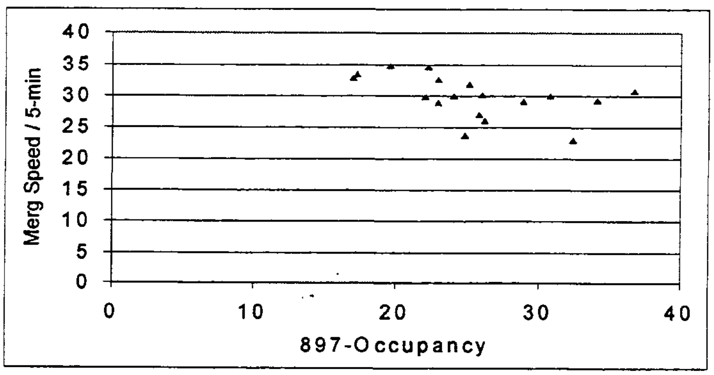

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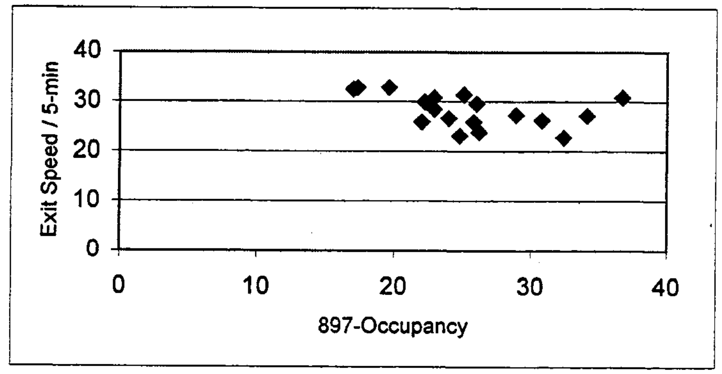

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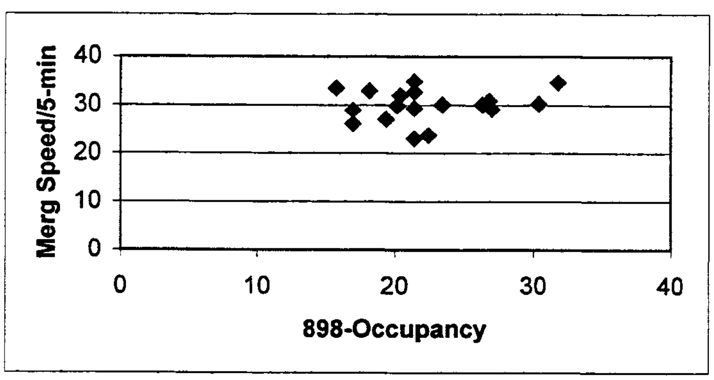


Figure e

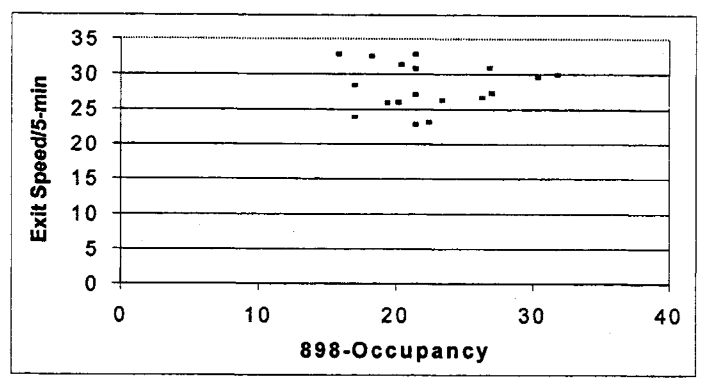


Figure f

Figure 5.2.5 Speed-volume/occupancy relationships between weaving and mainline volumes on October 29, 1998

V.3 Traffic behavior on the mainline upstream of the weaving zone

Figure 5.3.1 shows the typical volume-occupancy (V-O) plots at two locations upstream of the weaving site on two different days. It can be noticed that the V-O plots show almost the same patterns at each location after one year. The V-O plots from Location C show typical V-O relationships that can be found in most non-weaving sections in a freeway. That is, the right and middle lanes have almost the same V-O patterns, while the left lane shows higher volumes than those of the right or middle lanes. However, the V-O plots from Location F, which is immediately upstream of the weaving area, clearly show that the right-most lane has a lower V-O relationship than that of the middle lane. Further, the maximum right-lane volume was on average 20% less than the middle lane volume, which indicates substantial reduction of the capacity at Location F. Based on the V-O relationships and the observed traffic behavior at the mainline, it was noted that:

- Most lane changes by exiting vehicles were already completed before they arrived at location F, thus the reduction of the volume of the right-lane at F could be mostly attributed to the weaving conflict. Figure 5.3.2a shows the V-O relationship at F during the off-peak period on November 3, 1997. As indicated in this figure, the V-O relationships of all three lanes have very similar patterns, while the same data collected from the peak period as shown in Figure 5.3.2b indicates clear differences among three lanes.
- The occupancy values of the right-lane flow at F is directly affected by the amount of the weaving volume, i.e., sum of the vehicles exiting and merging within the weaving area.
- At the right-most-lane at F, a wide range of occupancy values were observed with the maximum volume, indicating different levels of speed exist at capacity.
- The middle lane flow also showed the effects of "side friction" from the right-most-lane, i.e., when the right-most-lane is congested, the middle lane flow also slows down.
- The most significant capacity reduction at the mainline because of the weaving conflict happens at the location immediately upstream of the weaving area, i.e., before the merging pint between the right-most lane and the on-ramp.

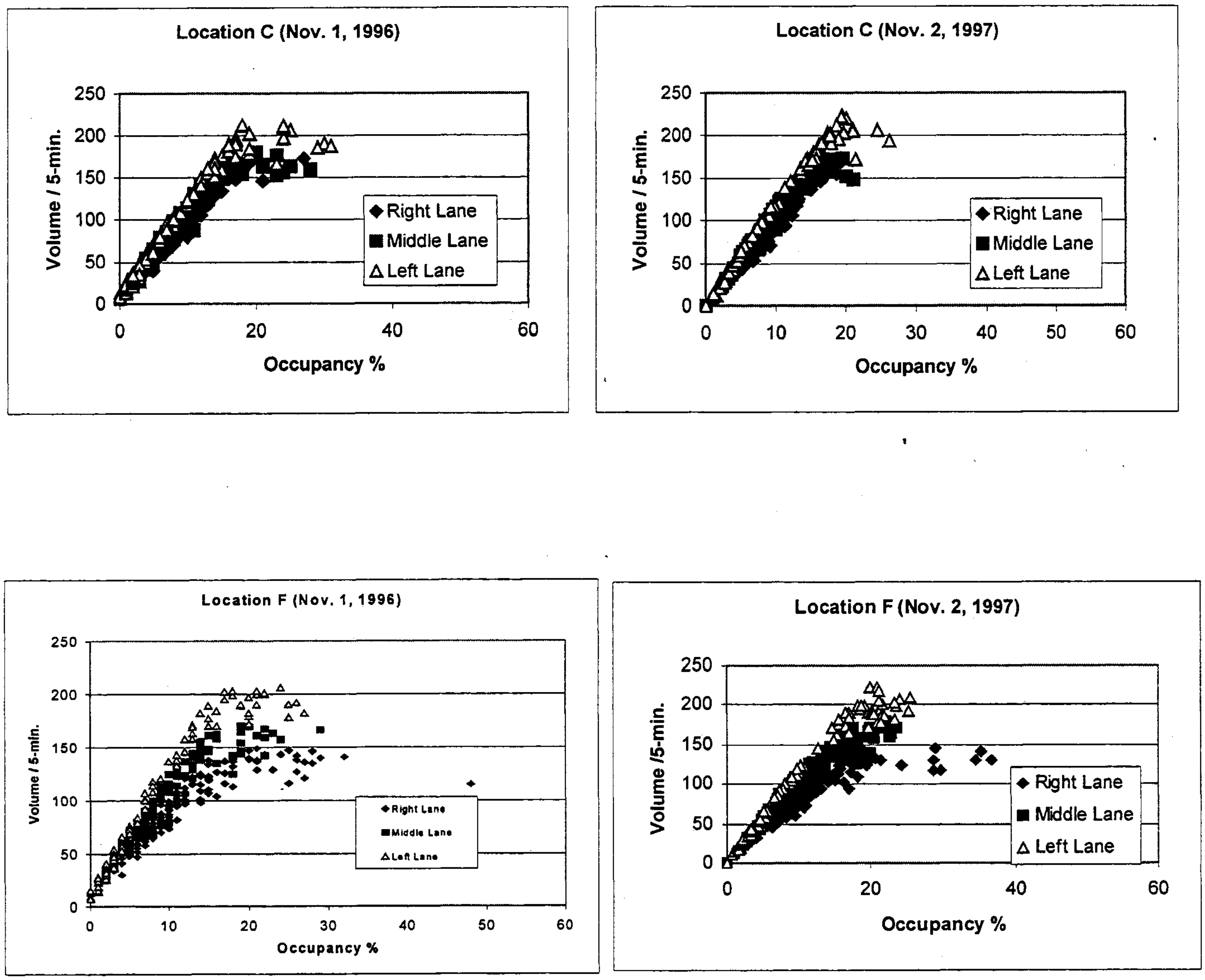


Figure 5.3.1 Volume-Occupancy relationships on the mainline upstream of weaving area

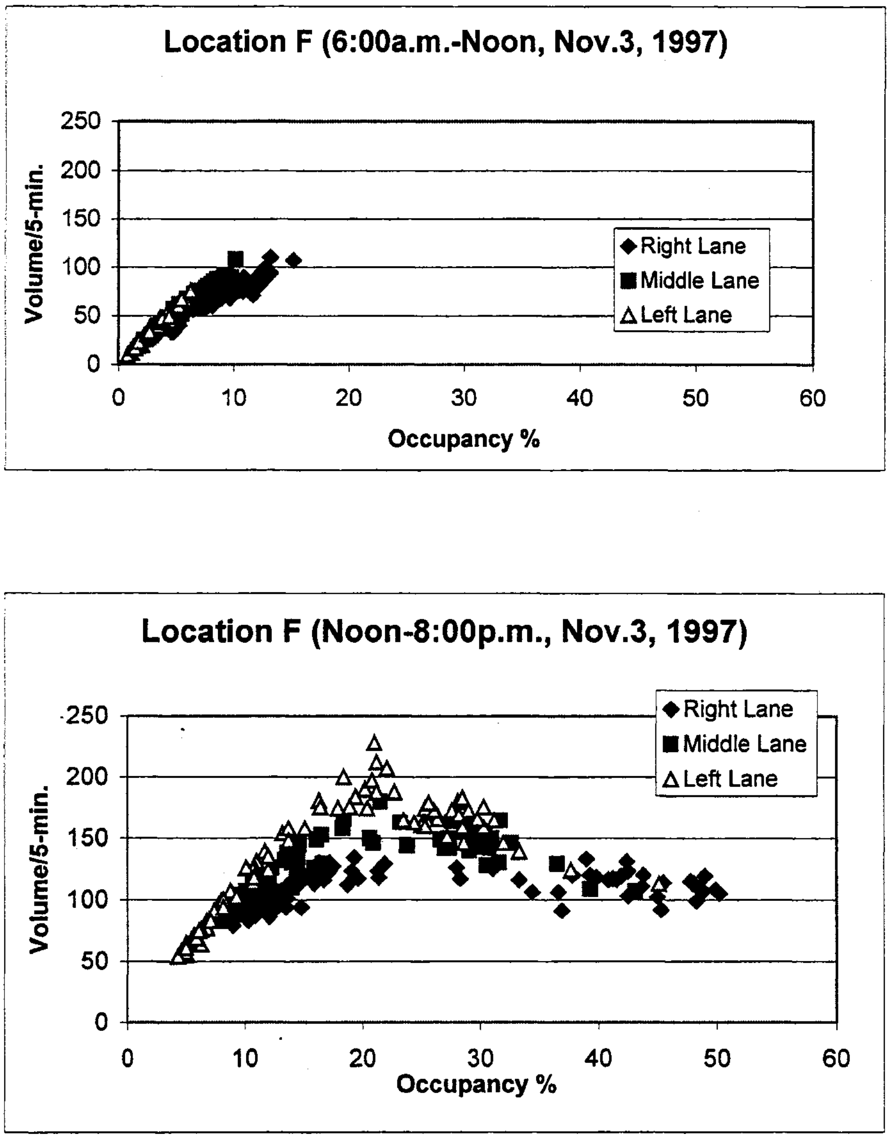


Figure 5.3.2 Effects of weaving conflict on volume-occupancy relationships on mainline

V.4 Driver lane-changing behavior

The weaving behavior at the northbound I-35W weaving site was analyzed with the observations from the field and the video tapes collected for speed data measurements. It was first observed that most diverging, i.e., freeway to ramp, vehicles change lanes to the right-most-lane before they reach the weaving zone. Further, under the free flowing conditions, where merging, i.e., ramp to freeway, and diverging vehicles can freely change lanes, the most significant factor affecting the speed of diverging vehicles is the geometric conditions of the exit ramp, e.g., speed limit, while the length of the auxiliary lane affects the acceleration level of the merging vehicles. For example, the observed speed levels of the diverging vehicles under free flow conditions within the weaving zone ranged from 40 mph at the upstream end of the weaving zone to 30 mph at the beginning point of the exit ramp, whose posted speed limit was 25 mph. The speed levels of the ramp-to-freeway vehicles under free flow conditions also ranged from 30 mph at the beginning of the auxiliary lane to 40 mph at the end of the weaving zone due to the short length of the auxiliary lane. It was also noted that the merging vehicles, even under free flowing conditions, first enter the auxiliary lane before they move to the mainline. Further, most merging and diverging vehicles complete their lane changes before they reach approximately the middle point of the weaving zone (Figure 5.4.1).

As weaving volume increases, it was clearly observed that the diverging vehicles changed to the auxiliary lane as soon as they entered the weaving zone, i.e., they merged with the entrance ramp vehicles right after the merge gore. This resulted in a mixed flow traveling a short portion of the auxiliary lane before the ramp-to-freeway vehicles split to the right-most-lane of the mainline. As indicated in Figure 5.4.2, the 'merge first, then split' behavior resulted in an empty space at the right-most-lane of the mainline that was frequently observed under heavy weaving flow conditions at the subject weaving area. Further, it was also noted that only a front portion of the auxiliary lane was used for lane-changing maneuvers within the weaving zone, while the length of this 'effective weaving zone' decreased as the amount of weaving flow increased. However, the effective weaving zone did not decrease beyond a certain value needed for safe weaving maneuvers. The tendency of the diverging vehicles to change lanes as soon as they enter weaving areas was also observed at other ramp-weave areas in Twin Cities that have longer auxiliary lanes than the I-35W site. It was also noted that with longer auxiliary lanes, the ramp to freeway vehicles stay longer on

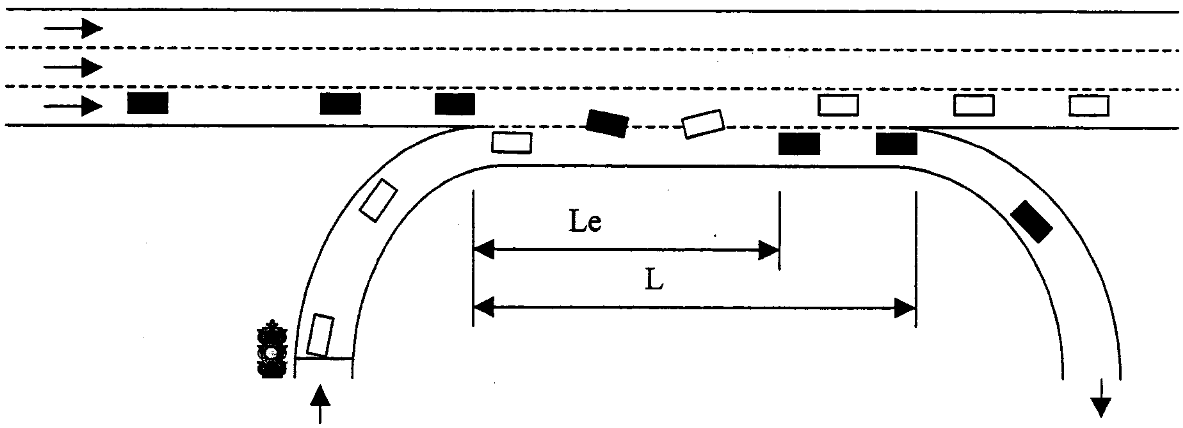


Figure 5.4.1 Lane changing behavior under free-flow conditions

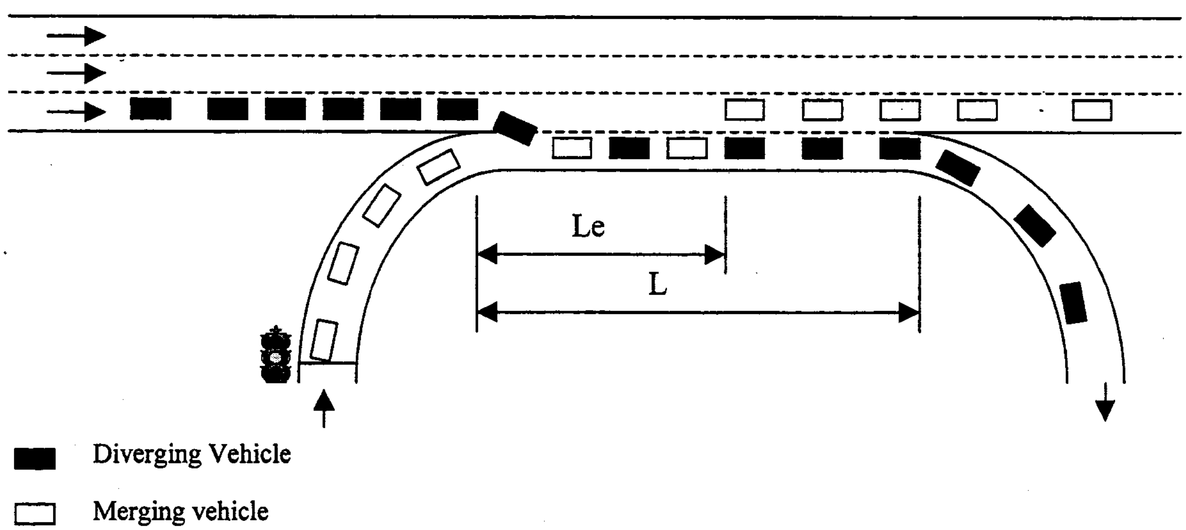


Figure 5.4.2 Lane changing behavior under moderate to heavy flow conditions

the auxiliary lane before they move to the mainline, but most of them completed lane changes before they reach the middle of the combined weaving area including the escape lane.

V.5 Variations of weaving volume through time

Figure 5.5.1 shows the variation of the total weaving flow as well as that of the left-most-lane flow (Detector 899) in the mainline immediately upstream of the subject weaving area on a typical weekday in October 1997, and October 1998. It can be noted that the two figures have very similar flow patterns even though there is one-year time gap between them. Further, during the peak periods, both ramp-to-freeway and freeway-to-ramp volumes have similar values at each time interval, while the total amount of weaving volume fluctuates through time. This indicates the effects of the downstream traffic conditions within the weaving zone, i.e., the exit ramp and the mainline merge area, on the maximum weaving volume.

In particular, as noted in both graphs in Figure 5.5.1, the maximum value of the total weaving volume is very close to that of the left-most-lane of the mainline immediately upstream of the weaving area. This phenomenon has been consistently observed with the data collected from the subject weaving area on different days and can be explained by the merge-then-split behavior of the weaving vehicles. Since the front portion of the auxiliary lane is shared by both diverging and merging vehicles for a short-time period before the merging vehicles split to the mainline, the maximum weaving volume, i.e., the sum of ramp-to-freeway and freeway-to-ramp volumes, needs to be equal to the maximum volume that can be accommodated by the auxiliary lane in a given weaving zone.

To confirm the above phenomenon, the weaving volumes at two other ramp-weave sections that have high ramp volumes were examined. Figure 5.5.2-3 shows the geometrics of these two weaving areas and the configuration of the loop detectors located at each site. Unlike the I-35W weaving zone, these two sites have significant amount of ramp-to-ramp volumes coming from the connected freeways to the local destinations. The ramp-to-ramp volume at the I-694 weaving site mostly consists of the vehicles coming from the I-94 freeway heading to the local residential areas across

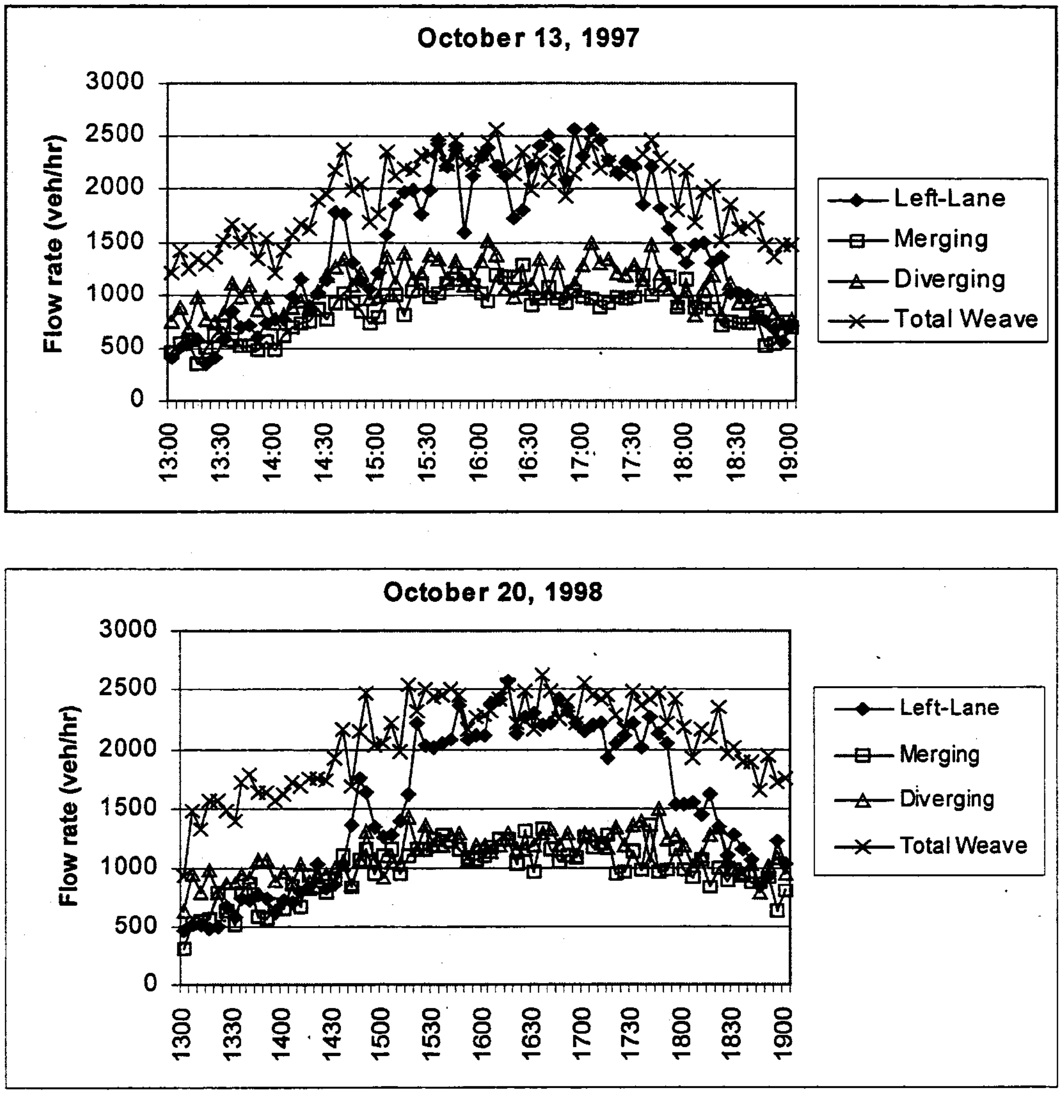


Figure 5.5.1 Comparison of weaving and mainline (Left-most-lane) volume at I-35W site

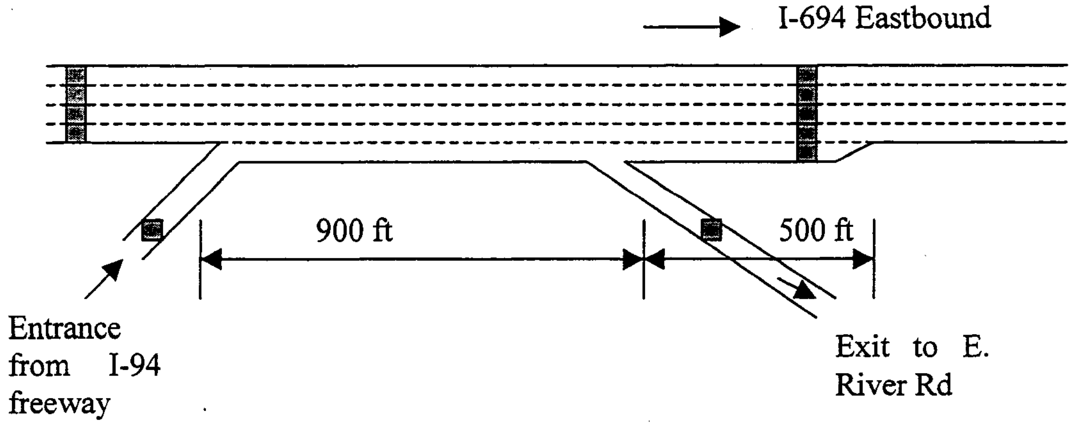


Figure 5.5.2. I-694 weaving site

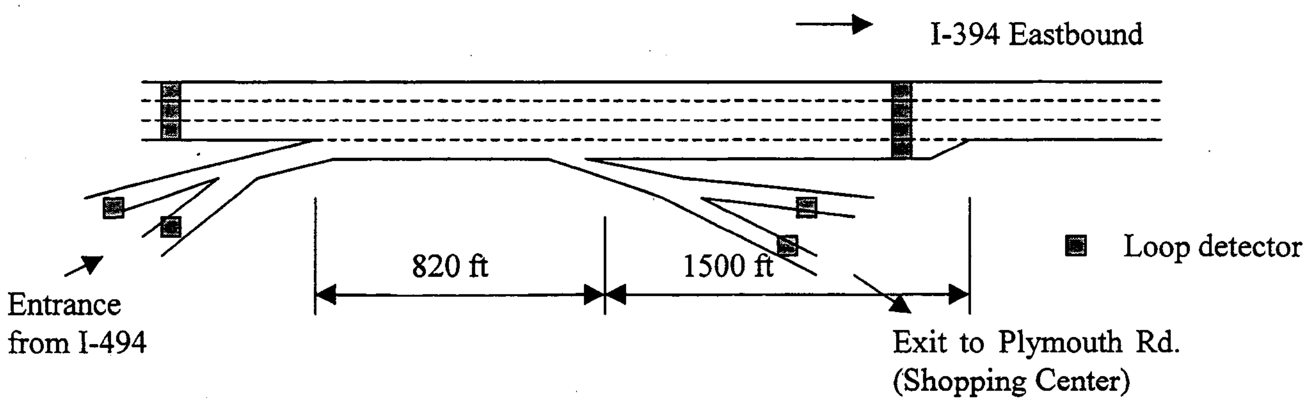


Figure 5.5.3 I-394 weaving site

the Mississippi River. Further, a shopping complex is located near the exit ramp of the I-394 weaving site whose on-ramp volume includes the substantial amount of the I-494 freeway traffic heading to the shopping complex. In this research, a Kalman Filter is applied to estimate the ramp-to-ramp volume through time from the loop detector counts collected from each site. The Kalman Filter-based approach has been widely used to estimate origin-destination flows at intersections and freeways and has been proven to be effective when the variability of travel time between origin and destination can be ignored (Nihan and Davis, 1987, Zijpp and Hammerslag, 1994). Considering the short length of the weaving areas, the off-ramp volume of a weaving area during time interval k, X_k, can be described as

$$X_k = \theta_{1,k} U_k + \theta_{2,k} O_k$$

where, for each time interval k,

$\theta_{1,k}$ = proportion of freeway-to-ramp volume in upstream mainline volume,

$\theta_{2,k}$ = proportion of ramp-to-ramp volume in on-ramp volume,

U_k = upstream mainline volume entering weaving zone,

O_k = on-ramp volume entering weaving zone.

In this research, the time-variant parameters, $\theta_{i,k}$, are estimated using a Kalman Filter with the measurements from the loop detectors located in each site. The filter formulation includes:

$$\theta_{i,k+1} = \theta_{i,k} + w_{i,k}$$

$$X_k = \theta_{1,k} U_k + \theta_{2,k} O_k + v_k$$

where, $w_{i,k}$, v_k are state and observation noise vectors assumed to be for white noise. The above formulation assumes the state variables follow a random walk process. Further, the initial values for θ_i and the covariance matrices for state and observation noise were calibrated using a linear regression analysis with the data from each weaving site. The resulting estimation procedure can be summarized as follows:

1) Initialize (k=0): $\theta_{k/k} = \theta_0$, $P_{k/k} = P_0$, where P is the covariance matrices of θ.
2) Predict X_{k+1} using updated $\theta_{i,k+1/k}$, and measured U_{k+1} and O_{k+1}, where $\theta_{i,k+1/k} = \theta_{i,k/k}$.
3) Estimate the Kalman Gain, K_{k+1}, as follows,

$$P_{k+1/k} = P_{k/k} + q_k$$

$$K_{k+1} = P_{k+1/k} H^T_{k+1}[H_{k+1}P_{k+1/k}H^T_{k+1} + R_k]^{-1}$$

where, $H_{k+1} = [U_{k+1}, O_{k+1}]$, q_k and R_k are the covariance matrices of state and observation noise.

4) Obtain error e_{k+1} using measured X_{k+1}.

5) Update $\theta_{i,k+1/k}$ on the basis of e_{k+1}.

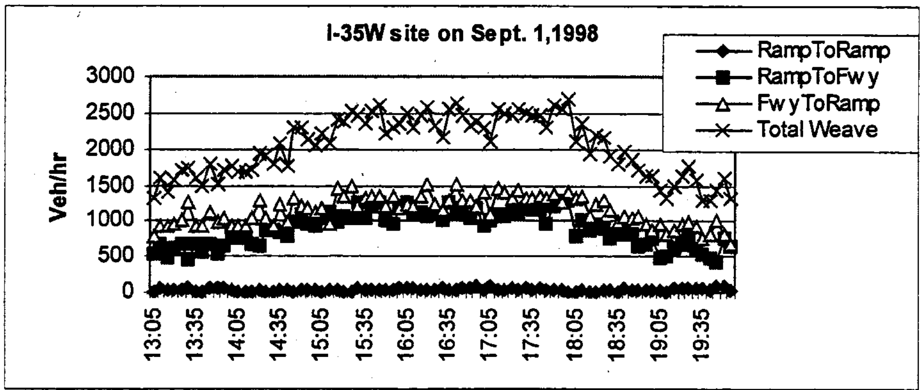
$$\theta_{i,k+1/k+1} = \theta_{i,k+1/k} + K_{k+1} e_{k+1}$$

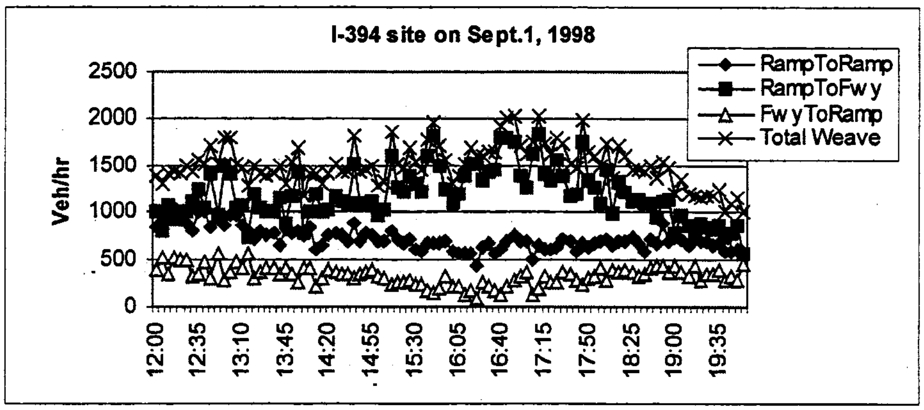
6) Update $P_{k+1/k}$ and go back to step 2)

$$P_{k+1/k+1} = (I - K_{k+1} H_{k+1}) P_{k+1/k}$$

The above procedure was applied to the three weaving sites and their weaving volumes during peak periods in September 1998 were estimated. Figure 5.5.4 shows the estimation results of the weaving volumes at the three weaving areas on September 1, 1998, which showed typical weaving flow patterns for each site. As shown in the figure, the estimated ramp-to-ramp volume on the I-35W site has very little values throughout the peak period, which is consistent with the field observation, while the other two weaving sites show substantial amount of the ramp-to-ramp volumes. As indicated in Figure 5.5.4, the maximum estimated weaving flow rate for a 5-minute interval from the other two weaving sites is approximately 2,100 veh/hr, which is less than that of the I-35W weaving site. The estimation results for other days in September 1998 showed similar patterns.

In summary, the weaving process in short ramp-weave areas consists of merging and split procedures by the vehicles entering and exiting freeway through a given weaving zone and the conflict caused by the weaving process directly affects the flow condition at the right-most-lane upstream of the weaving zone. It was also shown that, due to the "side friction" effect from the congestion at the right-most-lane, the capacity of the middle lane upstream of a weaving zone is also reduced compared with the left-most-lane. Therefore, the most substantial amount of capacity reduction on a mainline in a short ramp-weave area occurs at the location immediately upstream of the merge point between the right-most-lane and the auxiliary lane. Further, the maximum possible weaving volume can vary through time depending on the traffic conditions of the exit ramp and the mainline downstream of the entrance ramp.





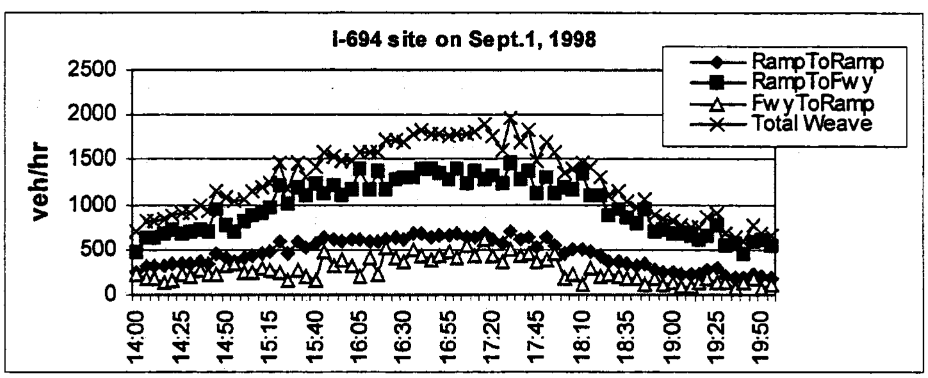


Figure 5.5.4. Estimated weaving flow rates for three weaving sites on September 1, 1998

VI. ON-LINE ESTIMATION OF CAPACITIES IN A SHORT RAMP-WEAVE AREA

VI.1 Development and testing of on-line estimation procedure for weaving capacity

In this section, a macroscopic procedure is developed to estimate the time-variant weaving capacity, defined as the maximum possible weaving volume, i.e., sum of entering and exiting volumes in a ramp-weave section, for a given time interval. Based on the analysis results of the traffic data collected from the sample weave area, the following assumptions were made:

- The maximum weaving volume at time t, Wmax,t, is less than or equal to the maximum through volume of the auxiliary lane, Wmax, in a given weaving section.
- The maximum possible weaving volume is directly affected by both merging and exit capacities that also vary through time.
- The merging capacity at time t, Mc,t, is limited by the entrance ramp capacity, Mc, and changes through time depending on the traffic conditions at the mainline downstream of an entrance ramp.
- The Exit capacity at time t, Xc,t, is also limited by the exit ramp capacity, Xc, and depends on the traffic conditions at ramp or further downstream.

Based on the above assumptions, the following model was developed to estimate time-variant weaving capacity:

$$Wmax,t = Wmax * [(Mc,t + Xc,t)/(Mc + Xc)]$$

In the above model, Wmax, Mc and Xc are assumed to be constants that are dependent on mainly geometric conditions, i.e., maximum possible volumes at each location under no restrictions by downstream traffic conditions. Figure 6.1.1 shows the general relationships for Mc,t and Xc,t. In this research, the following procedures were developed to predict both merging and exit capacities at time t, Mc,t and Xc,t, using the data collected until time t-1.

For Mc,t : Merging capacity during time t	*For Xc,t : Exit Capacity during time t*
If Om,t-1 <= Om,cr	*If Ox,t-1 <= Ox,cr*
then Mc,t = Mc	*then Xc,t = Xc*
else if Om,t-2 <= Om,cr, then Mc,t = Mc,	*else if Xc,t-2 <= Ox,cr, then Xc,t = Xc,*
else Mc,t = (Mt-1 + Mt-2) /2	*else Xc,t = (Xt-1 + Xt-2)/2*

where, Om (x),t = Occupancy measurement during time interval t at the detector located at merge (exit ramp) area,

Om (x),cr = Occupancy threshold for merging (exit) capacity.

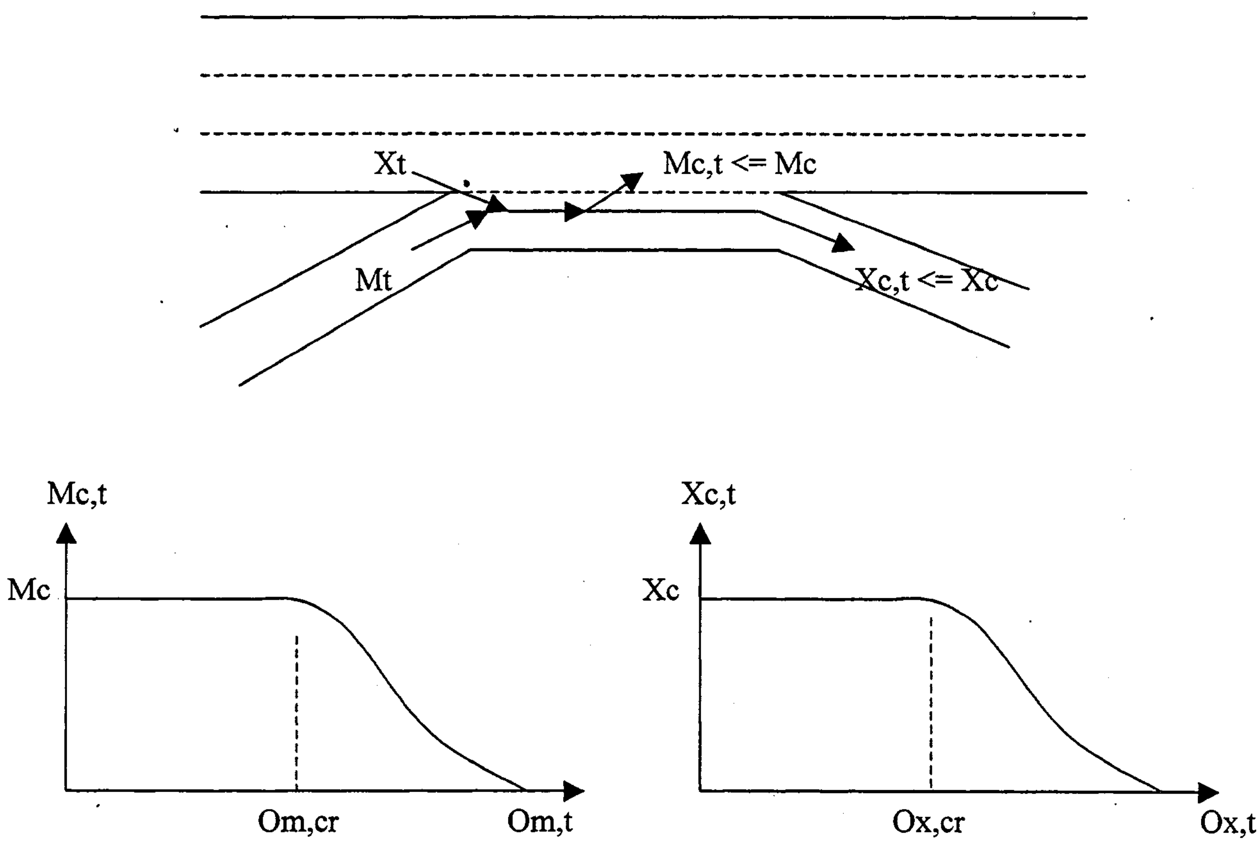


Figure 6.1.1 General relationships between merging/exit capacities and downstream traffic conditions

The above on-line estimation procedure developed for the weaving capacity was tested with the data collected from the sample weaving section for two days in October, 1998. Since the sample weaving area does not have loop detectors at the merge area downstream of the entrance ramp, the occupancy measurements from the detector ID 898, i.e., the middle-lane detector located immediately upstream of the merge point, was used to estimate the merging conditions at the downstream mainline, i.e., for $O_{m,t}$. For the detection of merging and exit volumes, M_t and X_t, the loop detectors at the entrance and exit ramp were used. Further, based on the historical data collected from the sample weaving area, the following values were used for the constants in the procedure:

Occupancy threshold for merging area, $O_{m,cr}$ = 17%,

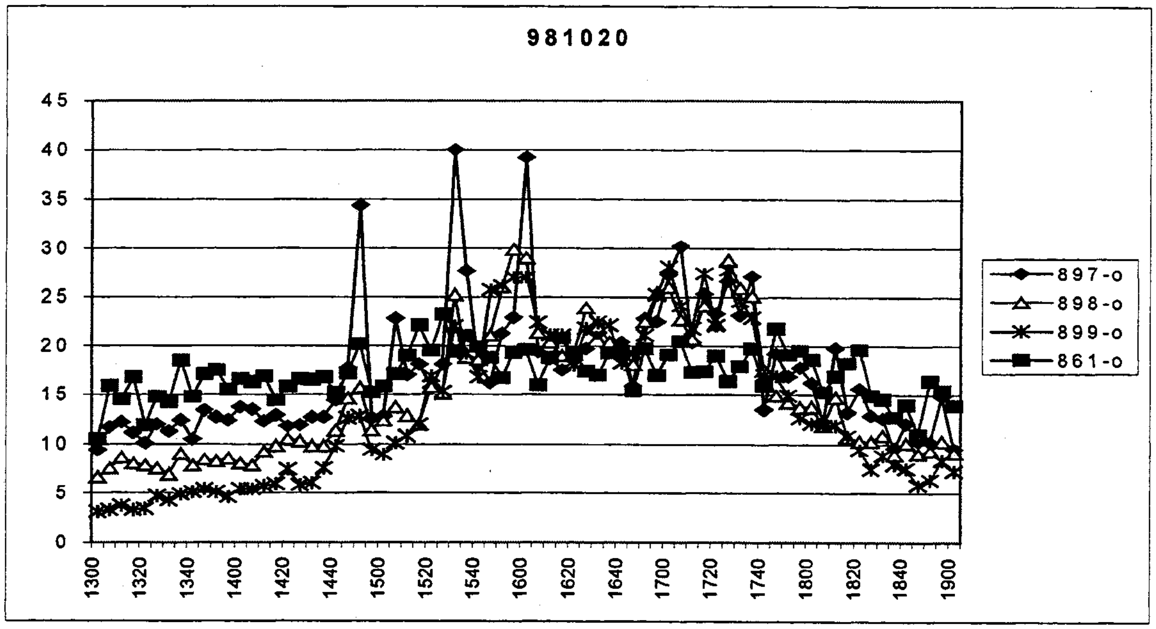
Occupancy threshold for exit ramp area, $O_{x,cr}$ = 22%,

Entrance Ramp Capacity, M_c = 120 vehicles/5-minute,

Exit Ramp capacity, X_c = 130 vehicles/5-minute,

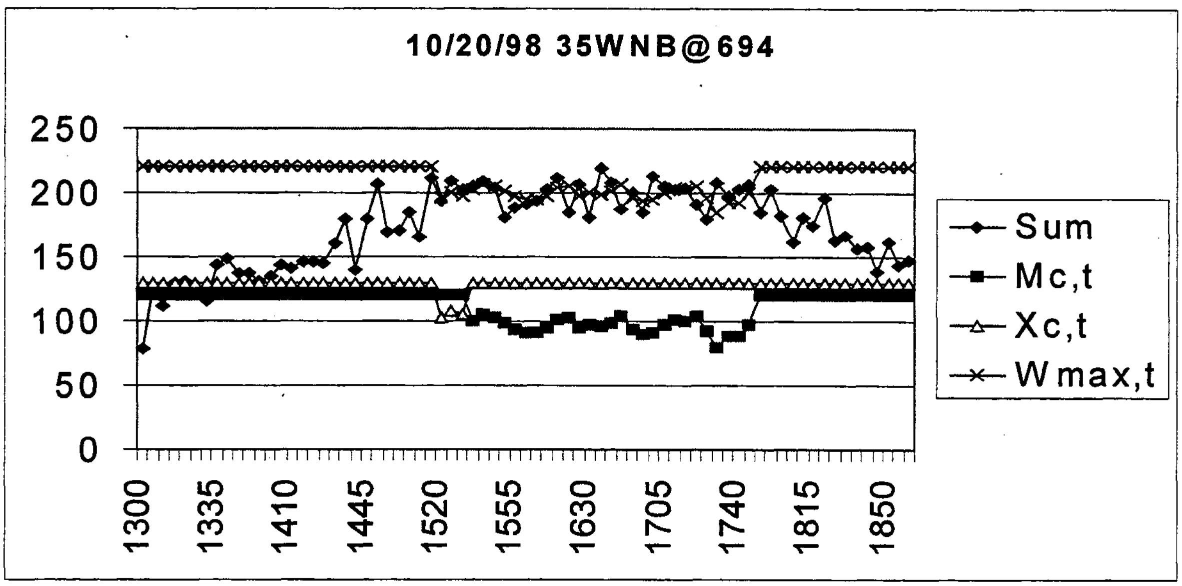
Maximum through volume for Auxiliary lane, W_{max} = 220 vehicles/5-minute.

Figures 6.1.2 shows the occupancy variations through time on October 20, 1998, at three lanes upstream of the weave area as well as at the exit ramp. As noted in the figure, during the afternoon period from 3:30p.m. until 5:30p.m. all mainline detectors show higher occupancy values than the threshold, $O_{m,cr}$, indicating congested conditions at the mainline portion of the weaving area. The measurements from the exit ramp detector also indicates slight congestion around 3:30p.m. Figure 6.1.3 shows the estimation results through time for three quantities, i.e., merging capacity, $M_{c,t}$, exit capacity, $X_{c,t}$, and the maximum possible weaving volume, $W_{max,t}$. It also shows the observed weaving volume, i.e., sum of the merging and diverging volumes, measured at 5-miunte intervals. As indicated in Figure 6.1.3, the on-line estimation results with the proposed procedure closely follow the observed weaving volume during the congested period and the mean percentage difference between the estimates and the real data during the congested period was 4.4%. Figures 6.1.4 and 6.1.5 show the occupancy variations and the test results with the data collected on October 29, 1998, which had a congested period from 5:40p.m. until 6:10p.m. The mean percentage difference on October 29 for the maximum weaving volume during the congested period was 4.7% .



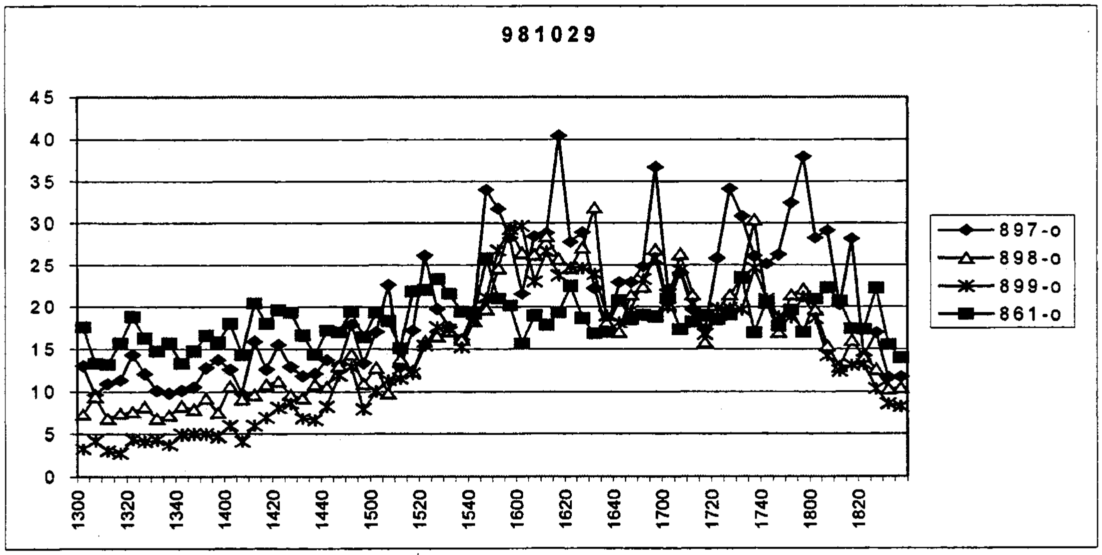
897-899: Mainline detectors, 861: Exit ramp detector

Figure 6.1.2 Occupancy variations at the mainline upstream weave and exit ramp



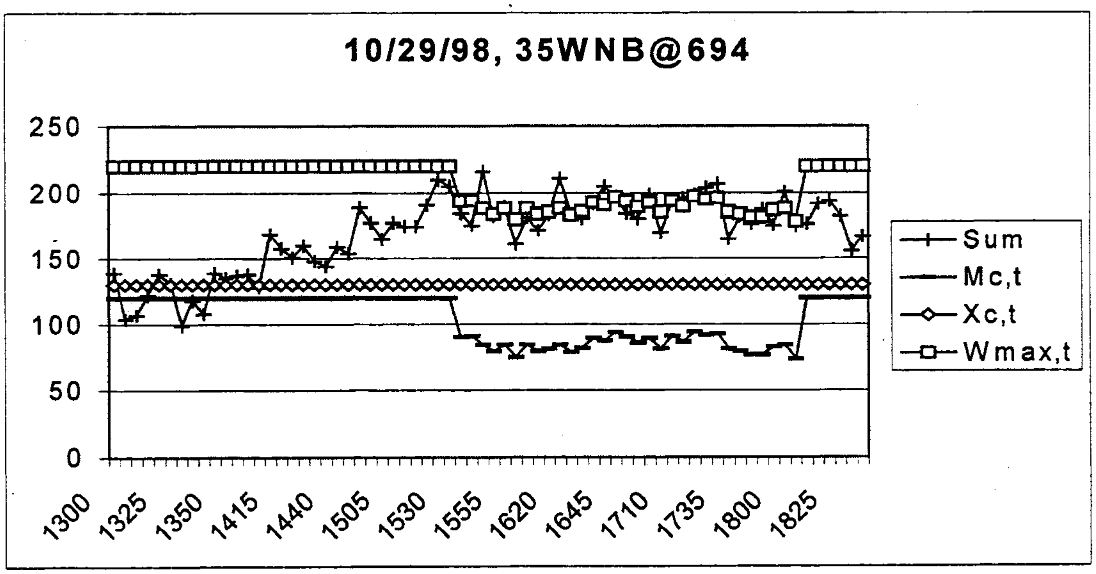
Sum: Measured sum of exit and entrance ramp volumes
Wmax,t: Predicted Maximum possible weaving volume

Figure 6.1.3 Weaving capacity prediction test results, October 20, 1998



897-899: Mainline detectors, 861: Exit ramp detector

Figure 6.1.4 Occupancy measurements at the mainline and exit ramp, October 29, 1998



Sum: Measured sum of exit and entrance ramp volumes
Wmax,t: Predicted Maximum possible weaving volume

Figure 6.1.5 Weaving capacity prediction test results, October 29, 1998

VI.2 Preliminary development of on-line estimation procedure for mainline capacity

In this section, an adaptive method is developed to estimate the capacity of the mainline immediately upstream of the weaving area using the Kalman Filter. Based on the statistical analysis with historical volume-occupancy data, it is assumed that the critical occupancy value, O_{cr}, i.e., the occupancy corresponding to the observed maximum volume, remains constant for a given location. Further, the volume-occupancy relationship was modeled with a simple quadratic function as follows;

$$V_{max} = \gamma_k [\alpha * O_{cr}^2 + \beta * O_{cr}] \quad ------ [1]$$

Where, V_{max} = Maximum possible volume estimated at time interval k,

γ_k = Adjustment factor updated in real time,

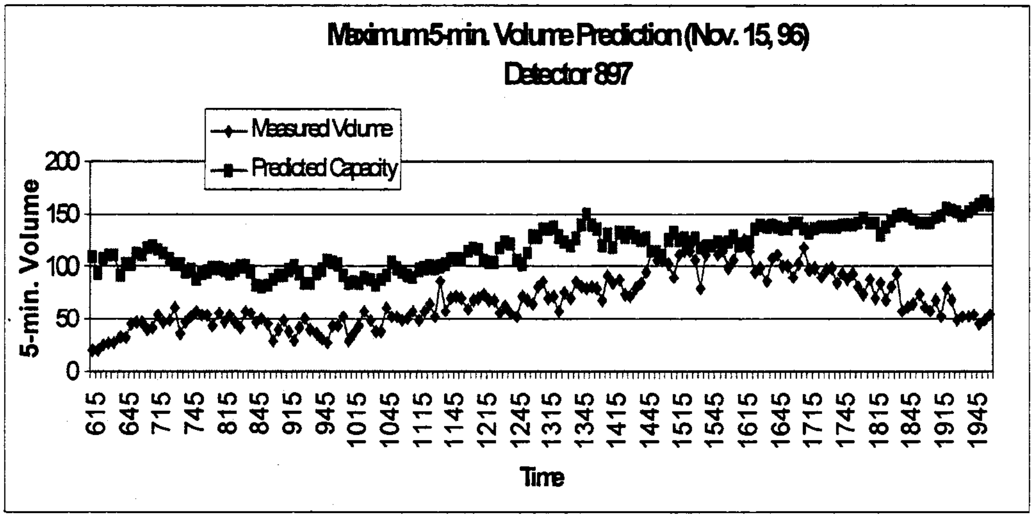
α and β = Coefficients calibrated with historical data.

The algorithm recursively determines γ_k by comparing the estimated volume $\hat{V}_k$ with the measured V_k, at each time step using the Kalman Filter, which treats γ_k as the state variable following the random work process, i.e.,

$$\hat{V}_k = \gamma_k [\alpha * O_k^2 + \beta * O_k] + v_k$$

$$\gamma_{k+1} = \gamma_k + w_k$$

After the adjustment factor is determined with the data up to the time interval k, the algorithm predicts V_{max} using Equation [1] and repeats the process continuously through time. Figure 6.2.1 shows the test results at one detector location upstream of the sample weaving area for two days in November, 1996. The volume-occupancy data from November 1 was used to calibrate the reference volume-occupancy relationship in the predictor. In particular, there was snow in the morning period on November 15, while November 4 had clear weather. In both days, the weaving traffic peaked in the afternoon between 3:00 and 4:30p.m. As indicated in the figures, the prediction results show the adaptability of the predictor to the prevailing weather and traffic conditions. Further study needs to be done at different lanes and locations. Further, the prediction model needs to incorporate the time-variant effects of 'side friction' because of the congestion in the right-most lane.



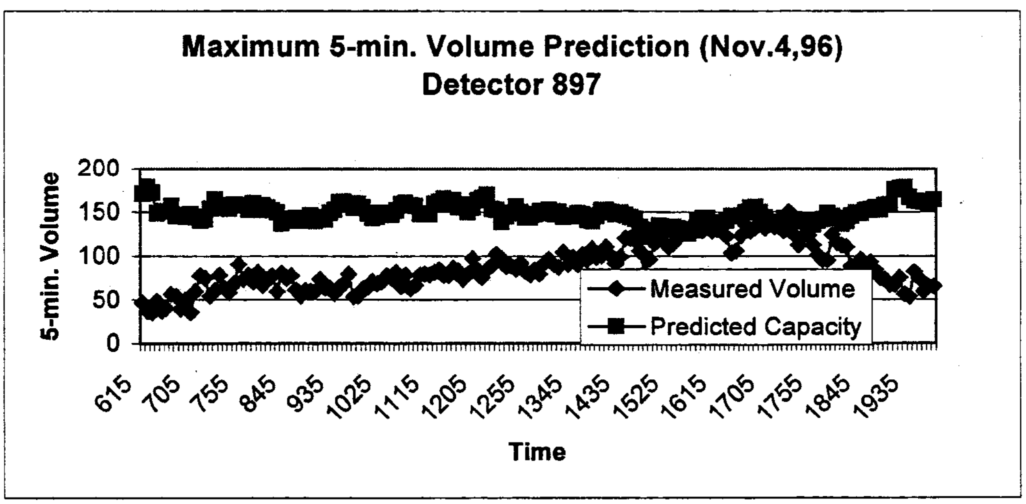


Figure 6.2.1 Example test results for on-line capacity prediction for mainline

VII. CONCLUSIONS AND FUTURE RESEARCH NEEDS

Understanding the behavior of drivers in a weaving area and the resulting weaving flow patterns is of critical importance in estimating the capacity of a weaving section, which is a major type of bottleneck in freeways. This report summarized the findings of the current research effort to address the flow behavior and capacity issues in a short ramp-weave section. First, the major weaving areas in the Twin Cities' freeway network were identified and classified depending on the length and geometric configuration of weaving areas. Next, a group of six weaving sites containing short ramp-weave sections were selected for detailed analysis and a spread-sheet database was developed with the loop data collected from those sites. In particular, the speed data of weaving flows were collected for two days from one of the short ramp-weave sections using a video recorder mounted on a 44 foot-mast, which was assembled and installed on a special trailer by the engineers at Mn/DOT. Further, a prototype video detection system developed in the University of Minnesota was used to measure the speed of individual vehicles changing lanes in the sample weaving area. The analysis of the data and field observations resulted in the important findings in terms of the weaving behavior in short ramp-weave sections. They include the "merge-split" procedure between the merging and diverging flows on the auxiliary lane in a ramp-weave section. This phenomenon lead to the fact that the maximum possible weaving volume of a short ramp-weave section is approximately equal to that of the auxiliary lane. Further, it was found out that the most important factor affecting exit capacity is the capacity of the exit ramp, rather than the length of the auxiliary lane. It was also determined that the maximum possible weaving volume varies through time depending on the traffic conditions downstream of a given weaving area, i.e., mainline merge area and exit ramp.

Based on the findings from the data analysis, an on-line procedure was developed to estimate the maximum possible weaving volume through time and tested with the real data from the sample weaving section. A preliminary study to develop an adaptive procedure to estimate the mainline capacity upstream of a weaving section was also conducted and resulted in a Kalman Filter-based on-line prediction model.

Future research needs include the extensive testing of the on-line estimation models developed in this study with different locations of the same weave type and extending the procedure to different types of weave areas, such as mainline weave areas with medium to long sections. Further, the adaptive prediction procedure for the capacities of non-weave areas also needs to be refined to incorporate the effects of side friction explicitly. Finally, for comprehensive understanding of traffic behavior at congested bottlenecks, there is a strong need to collect time and space headway data for a flow moving through different types of bottlenecks.

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Appendix A : Classification of weaving sections in Twin Cities' metro freeway network

mainline	direction	begin	end	weave type	weave class	cloverleaf
36	EB	Snelling SB	Snelling NB	B	S	Y
36	EB	Snelling NB	Hamline	A	S	N
36	EB	35E SB	35E NB	B	S	Y
36	EB	61 SB	61 NB	A	S	Y
36	EB	Cleveland	Fairview	A	M	N
36	EB	Fairview	Snelling SB	A	M	N
36	EB	Hamline	Lexington	A	M	N
36	WB	Cleveland NB	Cleveland SB	A	S	Y
36	WB	Snelling NB	Snelling SB	B	S	Y
36	WB	Lexington	Hamline	A	S	N
36	WB	35E NB	35E SB	B	S	Y
36	WB	61 NB	61 SB	A	S	Y
36	WB	Fairview	35W NB	A	M	N
36	WB	Snelling SB	Fairview	A	M	N
36	WB	Hamline	Snelling	A	M	N
52	NB	494 EB	494 WB	D	S	Y
52	NB	55th st.	494 EB	A	M	N
52	NB	494 WB	Southview	B	L	N
52	SB	494 WB	494 EB	D	S	Y
52	SB	494 EB	55th st.	A	M	N
52	SB	Southview	494 WB	A	L	N
62	EB	212 EB	169 SB	A	S	N
62	EB	169 SB	169 NB	A	S	Y
62	EB	100 SB	100 NB	A	S	Y
62	EB	77 SB	77 NB	A	S	Y
62	EB	169 NB	Gleason	*	M	N
62	EB	35W SB	Portland	*	M	N

mainline	direction	begin	end	weave type	weave class	cloverleaf
62	WB	169 NB	169 SB	A	S	Y
62	WB	100 NB	100 SB	A	S	Y
62	WB	77 NB	77 SB	B	S	Y
62	WB	169 SB	212 WB	*	M	N
62	WB	Gleason	169 NB	A	M	N
62	WB	35W NB	Penn	A	M	N
62	WB	Portland	35W NB	*	M	N
77	NB	35E NB	35E SB	B	S	Y
77	NB	13 EB	13 WB	B	S	Y
77	NB	494 EB	494 WB hov	A	S	Y
77	NB	62 EB	62 WB	A	S	Y
77	NB	Diffley	13 EB	A	L	N
77	NB	Old Shakopee	Killebrew	*	L	N

mainline	direction	begin	end	weave type	weave class	cloverleaf
77	SB	35E SB	35E NB	B	S	Y
77	SB	13 WB	13 EB	B	S	Y
77	SB	62 WB	62 EB	A	S	Y
77	SB	13 EB	Diffley	A	L	N
77	SB	Killebrew	Old Shakopee	*	L	N
94	EB	169 SB	169 NB	A	S	Y
94	EB	Jackson	7th st.	A	S	N
94	EB	169 NB	Boone	B	M	N
94	EB	Cedar	25th ave.	A	M	N
94	EB	Broadway	Mounds	*	M	N
94	EB	White Bear	Ruth	A	M	N
94	EB	Hennepin	35W SB	*	L	N
94	EB	5th ave.	Hiawatha	A	L	N
94	EB	Riverside	Huron	B	L	N
94	EB	Dale	Marion	*	L	N

mainline	direction	begin	end	weave type	weave class	cloverleaf
94	WB	169 NB	169 SB	A	S	Y
94	WB	Boone	169 NB	B	M	N
94	WB	25th ave.	Cedar	A	M	N
94	WB	Ruth	White Bear	A	M	N
94	WB	35W NB	Hennepin	*	L	N
94	WB	Hiawatha/35W cd	11th st./Grant	*	L	N
94	WB	Huron	Riverside	B	L	N
94	WB	Lexington	Hamline	*	L	N
94	WB	52 NB	35E NB/Jackson	A	L	N
100	NB	494 EB	494 WB	A	S	Y
100	NB	62 EB	62 WB	A	S	Y
100	NB	7 EB	7 WB	A	S	Y
100	NB	394 EB	394 WB	B	S	Y
100	NB	55 EB	55 WB	A	S	Y
100	NB	494 WB	77th st.	C	M	N
100	NB	36th st.	7 EB	B	M	N
100	NB	394 WB	Glenwood	*	L	N
100	SB	494 WB	494 EB	A	S	Y
100	SB	62 WB	62 EB	A	S	Y
100	SB	7 WB	7 EB	B	S	Y
100	SB	County 5	7 WB	A	S	N
100	SB	55 WB	55 EB	A	S	Y
100	SB	7 EB	36th st.	A	M	N
169	NB	62 EB	62 WB	A	S	Y
169	NB	394 EB	394 WB	B	S	Y
169	NB	394 WB	Betty Crocker	B	S	N
169	NB	Betty Crocker	55 EB	B	S	N
169	NB	55 EB	55 WB	A	S	Y

mainline	direction	begin	end	weave type	weave class	cloverleaf
169	NB	County 9 EB	County 9 WB	B	S	Y
169	NB	County 10 EB	County 10 WB	B	S	Y
169	NB	94 EB	94 WB	A	S	Y
169	NB	62 WB	Bren	A	M	N
169	NB	36th st.	County 5	A	M	N
169	NB	County 5	Cedar Lake	A	M	N
169	NB	55 WB	13th ave.	A	M	N
169	NB	Excelsior	7	A	L	N
169	NB	36th ave. N	County 9	A	L	N
169	NB	County 9	49th ave. N	A	L	N
169	SB	62 WB	62 EB	A	S	Y
169	SB	394 WB	394 EB	B	S	Y
169	SB	Betty Crocker	394 WB	B	S	N
169	SB	55 EB	Betty Crocker	A	S	N
169	SB	55 WB	55 EB	A	S	Y
169	SB	County 9 WB	County 9 EB	B	S	Y
169	SB	County 10 WB	County 10 EB	B	S	Y
169	SB	94 WB	94 EB	A	S	Y
169	SB	Bren	62 WB	A	M	N
169	SB	13th ave.	55 WB	A	M	N
169	SB	7 EB	Excelsior	A	L	N
169	SB	Minnetonka Blvd.	36th st./7	A	L	N
169	SB	County 9	36th ave. N	A	L	N
169	SB	49th ave. N	County 9	A	L	N
212	EB	494 EB	494 WB	A	S	Y
212	EB	494 WB	Valley View	A	M	N
212	EB	Shady Oak	62 EB	A	L	N

mainline	direction	begin	end	weave type	weave class	cloverleaf
212	WB	494 WB	494 EB	A	S	Y
212	WB	Valley View	494 WB	A	M	N
212	WB	62 WB	Shady Oak	A	L	N
394	EB	Penn	Dunwoody	C	M	N
394	EB	494 cd	Plymouth	A	L	N
394	EB	Ridgedale	County 73	B	L	N
394	EB	County 73	169 cd	B	L	N
394	EB	169 cd	Louisiana	B	L	N
394	EB	Louisiana	100 cd	B	L	N
394	WB	Plymouth	494 cd	B	L	N
394	WB	County 73	Ridgedale	B	L	N
394	WB	169 cd	County 73	B	L	N
394	WB	100 cd	Louisiana	*	L	N

mainline	direction	begin	end	weave type	weave class	cloverleaf
494	EB	394 WB	394 EB	D	S	Y
494	EB	7 WB	7 EB	A	S	Y
494	EB	212 WB	212 EB	A	S	Y
494	EB	100 SB	100 NB	A	S	Y
494	EB	35W SB	35W NB	B	S	Y
494	EB	77 SB	77 NB	B	S	Y
494	EB	Carlson	12 WB	B	M	N
494	EB	E Bush Lake	Normandale SB	A	M	N
494	EB	Penn	35W SB	B	M	N
494	EB	35W NB	Lyndale	B	M	N
494	EB	Lyndale	Nicollet	A	M	N
494	EB	12th ave.	77 SB	*	M	N
494	EB	5th ave.	Concord	A	M	N
494	EB	Concord	Hardman	B	M	N
494	EB	Maxwell	61 SB	A	M	N

mainline	direction	begin	end	weave type	weave class	cloverleaf
494	EB	Prairie Center	169	A	L	N
494	EB	24th ave.	34th ave.	*	L	N
494	EB	Pilot Knob	35E cd	A	L	N
494	EB	35E cd	149	A	L	N
494	WB	394 EB	394 WB	D	S	Y
494	WB	7 EB	7 WB	A	S	Y
494	WB	212 EB	212 WB	A	S	Y
494	WB	100 NB	100 SB	A	S	Y
494	WB	35W NB	35W SB	B	S	Y
494	WB	77 NB	77 SB	B	S	Y
494	WB	61 NB	61 SB	A	S	Y
494	WB	394 WB	Carlson	B	M	N
494	WB	100 SB	E Bush Lake	A	M	N
494	WB	35W SB	Penn	A	M	N
494	WB	Lyndale	35W NB	B	M	N
494	WB	Nicollet	Lyndale	B	M	N
494	WB	77	12th ave.	C	M	N
494	WB	Concord	5th ave.	A	M	N
494	WB	Hardman	Concord	A	M	N
494	WB	61 SB	Maxwell	A	M	N
494	WB	169	Prairie Center	A	L	N
494	WB	34th ave.	24th ave.	*	L	N
494	WB	35E SB	Pilot Knob	*	L	N
494	WB	149/Dodd	35E	A	L	N
694	EB	252 SB	252 NB	B	S	Y
694	EB	65 SB	65 NB	B	S	Y
694	EB	35W SB	35W NB	A	S	Y
694	EB	36 WB	36 EB	A	S	Y
694	EB	10 Eb	Hamline SB	*	M	N
694	EB	Hamline SB	Lexington	*	M	N

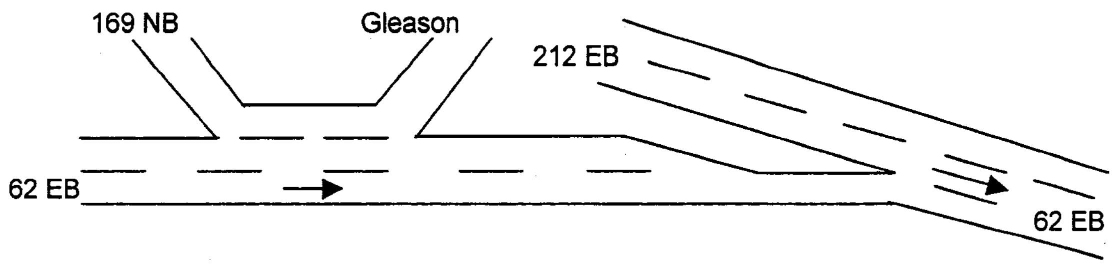
mainline	direction	begin	end	weave type	weave class	cloverleaf
694	EB	Rice	35E	*	M	N
694	EB	Minnehaha/10th	94 WB	E	M	N
694	EB	94 WB	East River Road	B	L	N
694	EB	East River Road	University	B	L	N
694	EB	University	Central SB	B	L	N
694	WB	65 NB	65 SB	B	S	Y
694	WB	35W NB	35W SB	C	S	Y
694	WB	36 EB	36 WB	A	S	Y
694	WB	Hamline NB	10 WB	*	M	N
694	WB	Lexington	Hamline	A	M	N
694	WB	35E	Rice	*	M	N
694	WB	94 WB	Minnehaha/10th	A	M	N
694	WB	East River Road	252 NB/94 EB	*	L	N
694	WB	University	East RIver Road	B	L	N
694	WB	Central SB	University	B	L	N
35E	NB	36 EB	36 WB	A	S	Y
35E	NB	Larpenteur	Roselawn	A	M	N
35E	NB	77 cd	Cliff	C	L	N
35E	NB	Lone Oak	494 cd	*	L	N
35E	NB	7th st.	Randolph	A	L	N
35E	SB	36 WB	36 EB	A	S	Y
35E	SB	Roselawn	Larpenteur	A	M	N
35E	SB	Cliff	77 cd	*	L	N
35E	SB	494 cd	Lone Oak	C	L	N
35E	SB	Randolph	7th st.	*	L	N
35W	NB	13 EB	13 WB	B	S	Y
35W	NB	494 EB	494 WB	*	S	Y
35W	NB	35th st.	31st st.	B	S	N
35W	NB	694 EB	694 WB	A	S	Y

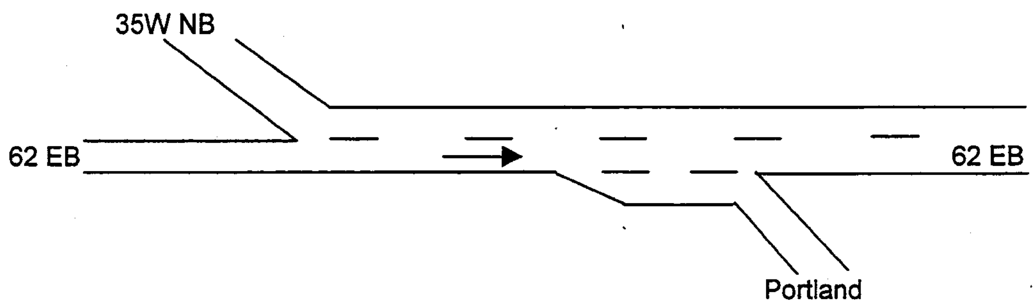
mainline	direction	begin	end	weave type	weave class	cloverleaf
35W	NB	Burnsville Pkwy	13 EB	A	M	N
35W	NB	98th st.	94th st.	A	M	N
35W	NB	94th st.	90th st.	A	M	N
35W	NB	82nd st.	494 EB	A	M	N
35W	NB	60th st.	Diamond Lake	A	M	N
35W	NB	94 EB	94 EB	*	M	N
35W	NB	96	10	E	M	N
35W	NB	County I	118	*	M	N
35W	NB	Washington	University	*	L	N
35W	NB	4th st. SE	Hennepin	B	L	N
35W	NB	62EB joins	62EB exits	*	L	N
35W	NB	Cleveland/36 WB	County C/Cleveland	A	L	N

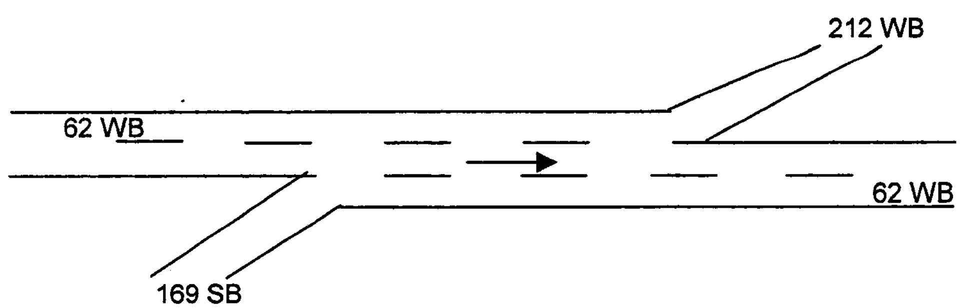
mainline	direction	begin	end	weave type	weave class	cloverleaf
35W	SB	13 WB	13 EB	B	S	Y
35W	SB	494 WB	494 EB	B	S	Y
35W	SB	62 EB	66th st.	A	S	N
35W	SB	31st st.	35th st.	B	S	N
35W	SB	694 WB	694 EB	A	S	Y
35W	SB	County H	10 EB	A	S	N
35W	SB	13 EB	Burnsville Pkwy	B	M	N
35W	SB	94th st.	98th st.	A	M	N
35W	SB	90th st.	94th st.	A	M	N
35W	SB	494 EB	82nd st.	A	M	N
35W	SB	Diamond Lake	60th st.	A	M	N
35W	SB	10	96	E	M	N
35W	SB	62WB joins	62WB exits	*	L	N
35W	SB	University	Washington	*	L	N
35W	SB	Hennepin	4th st. SE	B	L	N
494/694	NB	94 EB	94 WB	A	S	Y
494/694	SB	94 WB	94 EB	A	S	Y

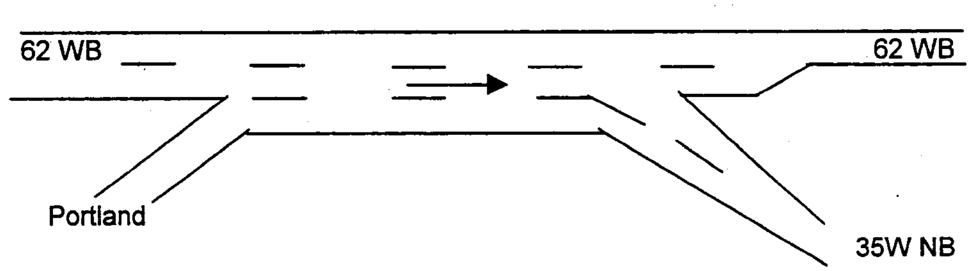
Appendix B: Multiple Weaving Sections in Twin Cities Freeway Network

B-1: Major weaving areas in Freeway 62

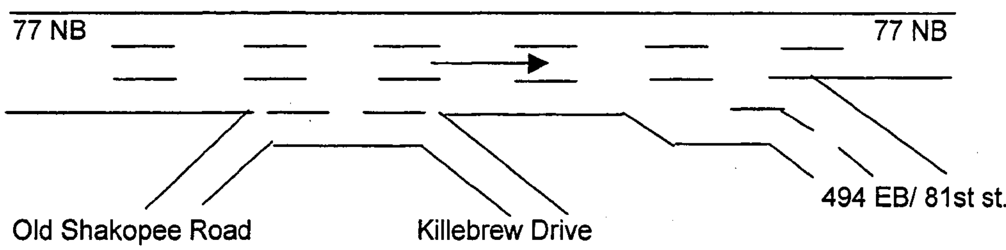


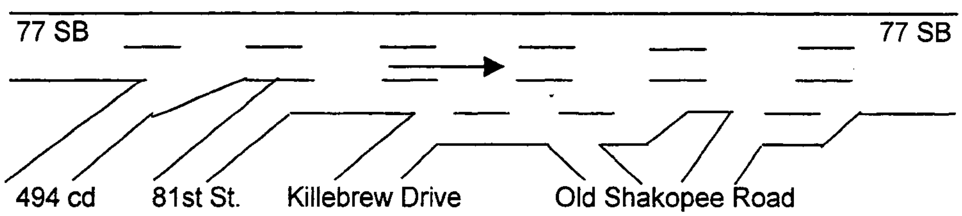




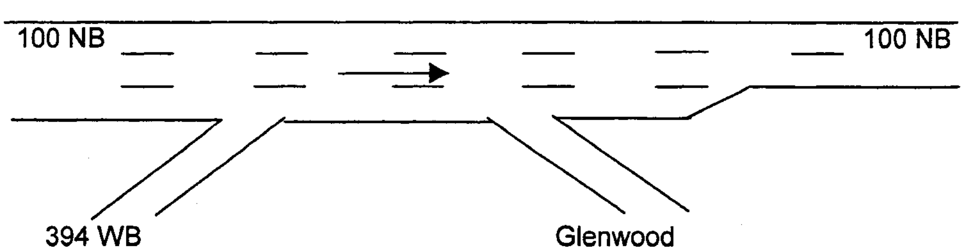


B-2: Major weaving areas in Freeway 77

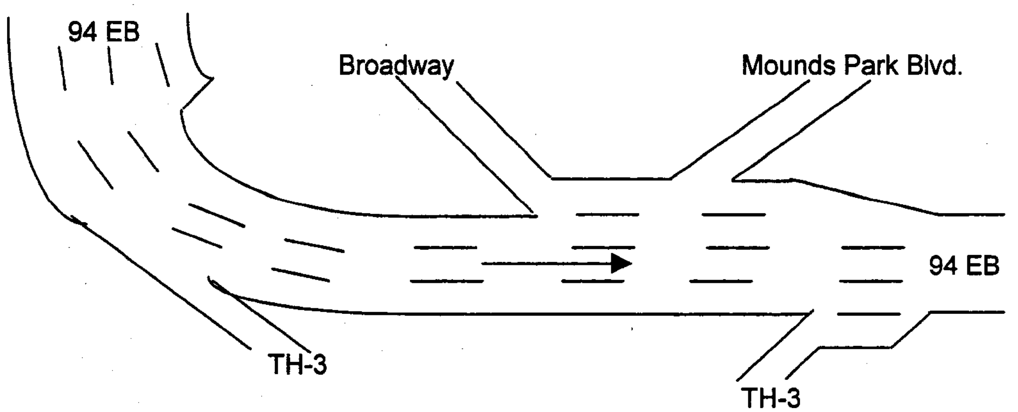


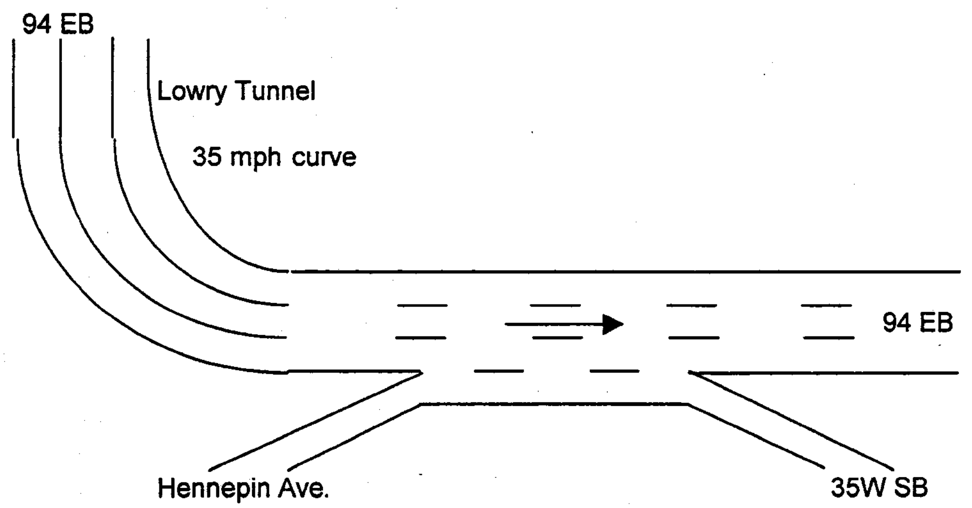


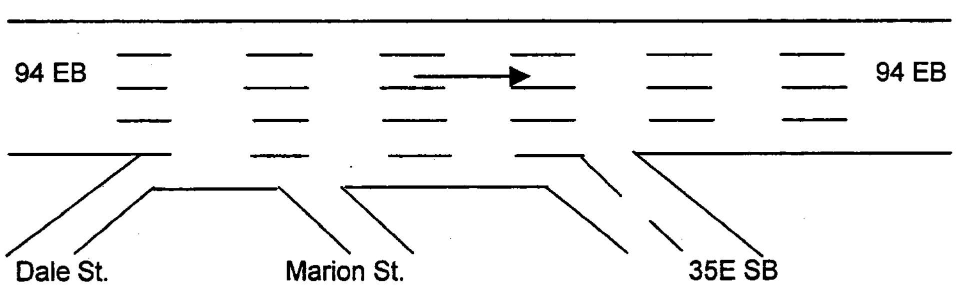
B-3 Major Weaving Area in freeway 100



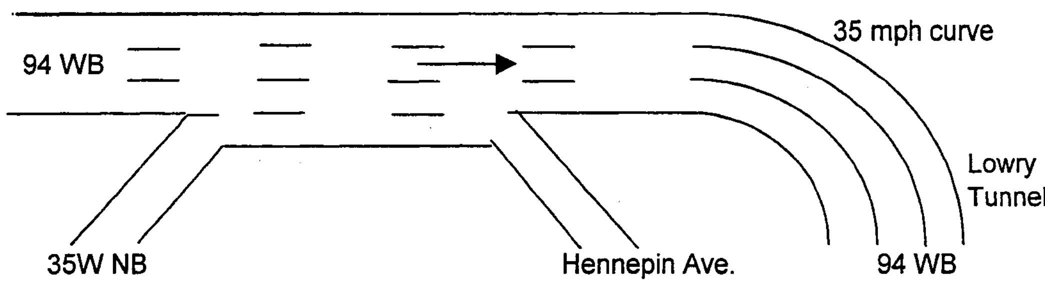
B-4: Major weaving areas in I-94

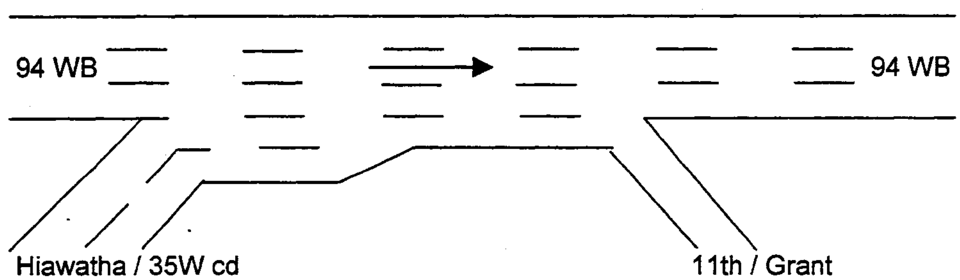


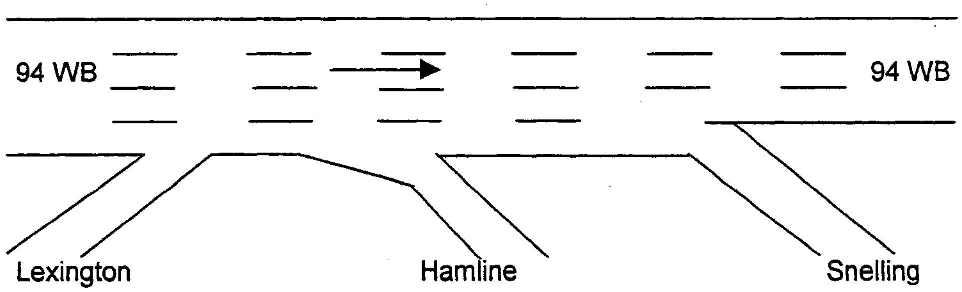




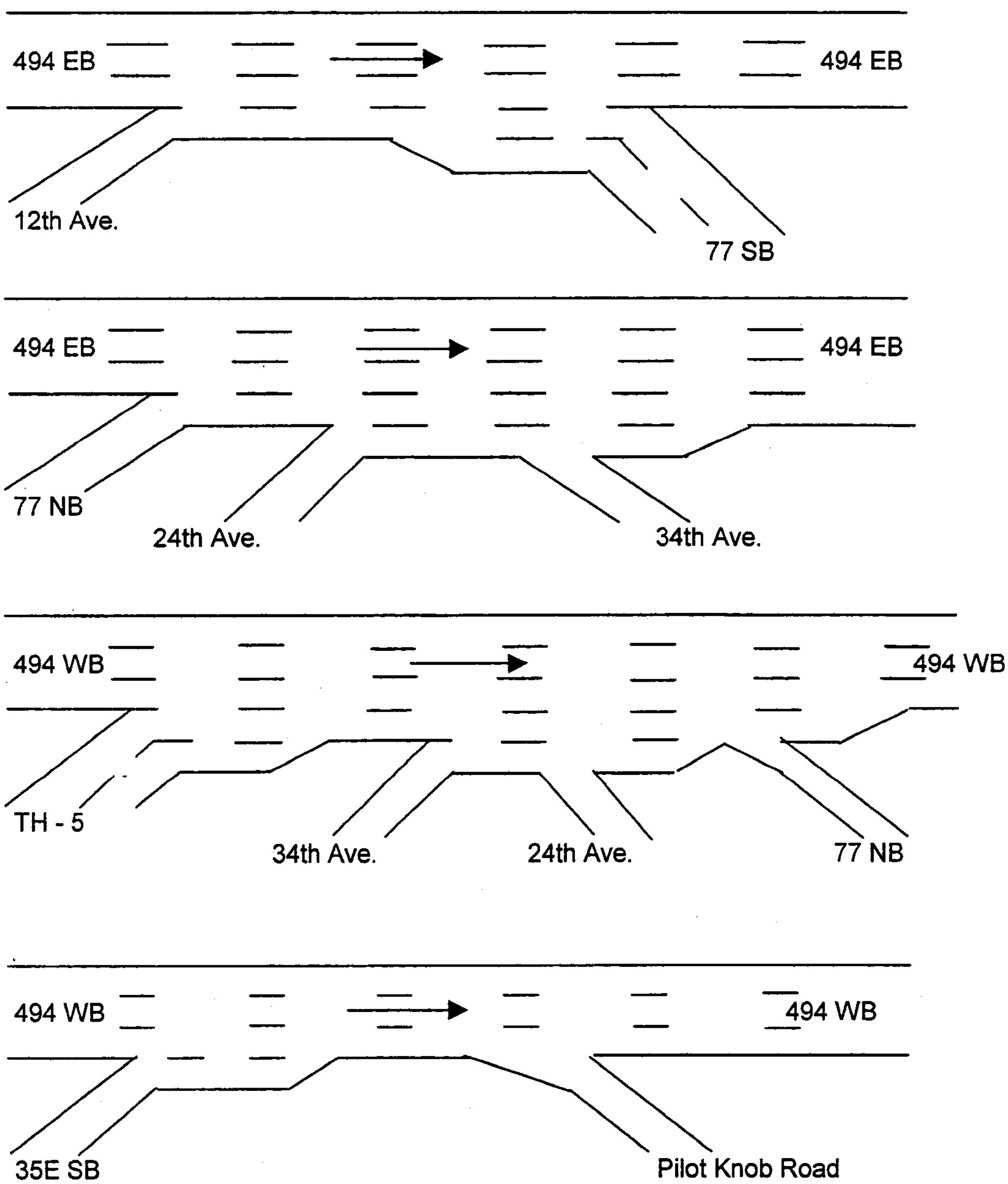
B-5: Major Weaving Areas in I-94



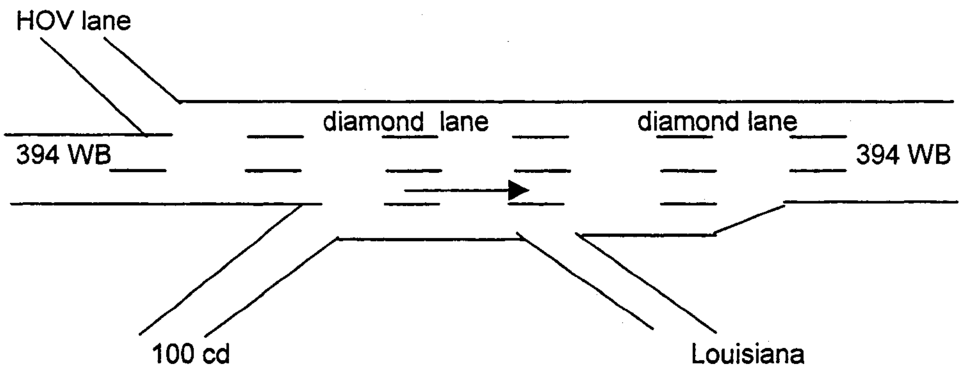




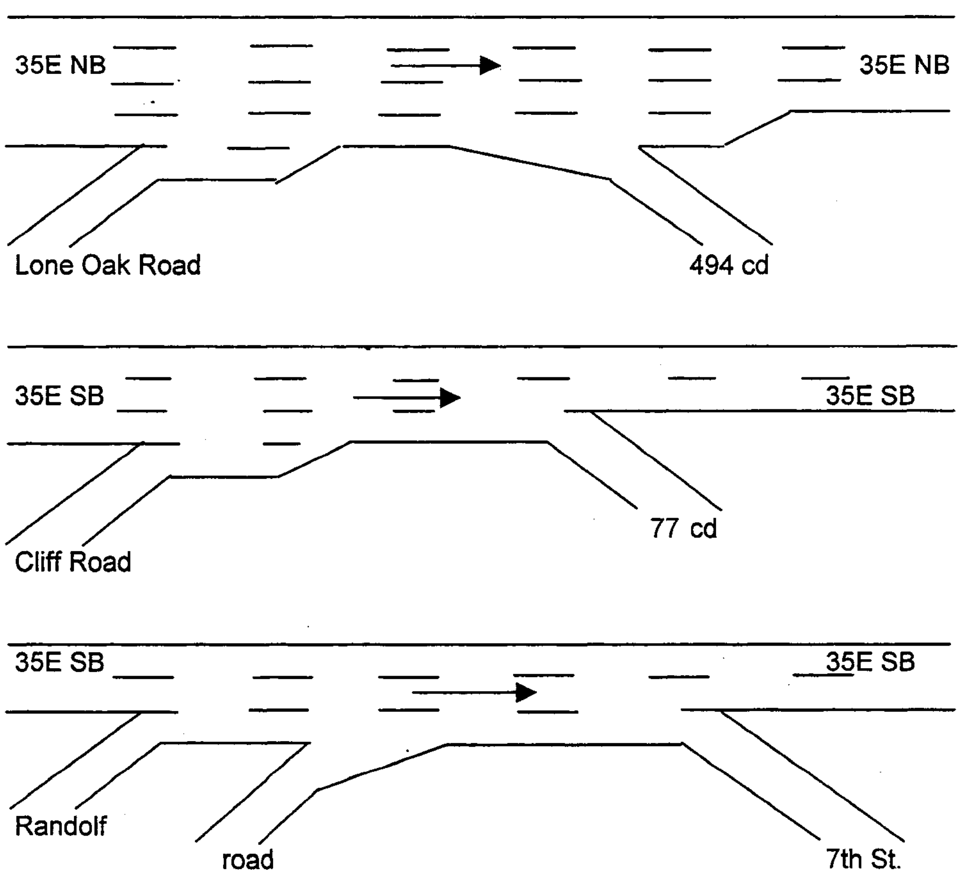
B-6: Major weaving areas in I-494



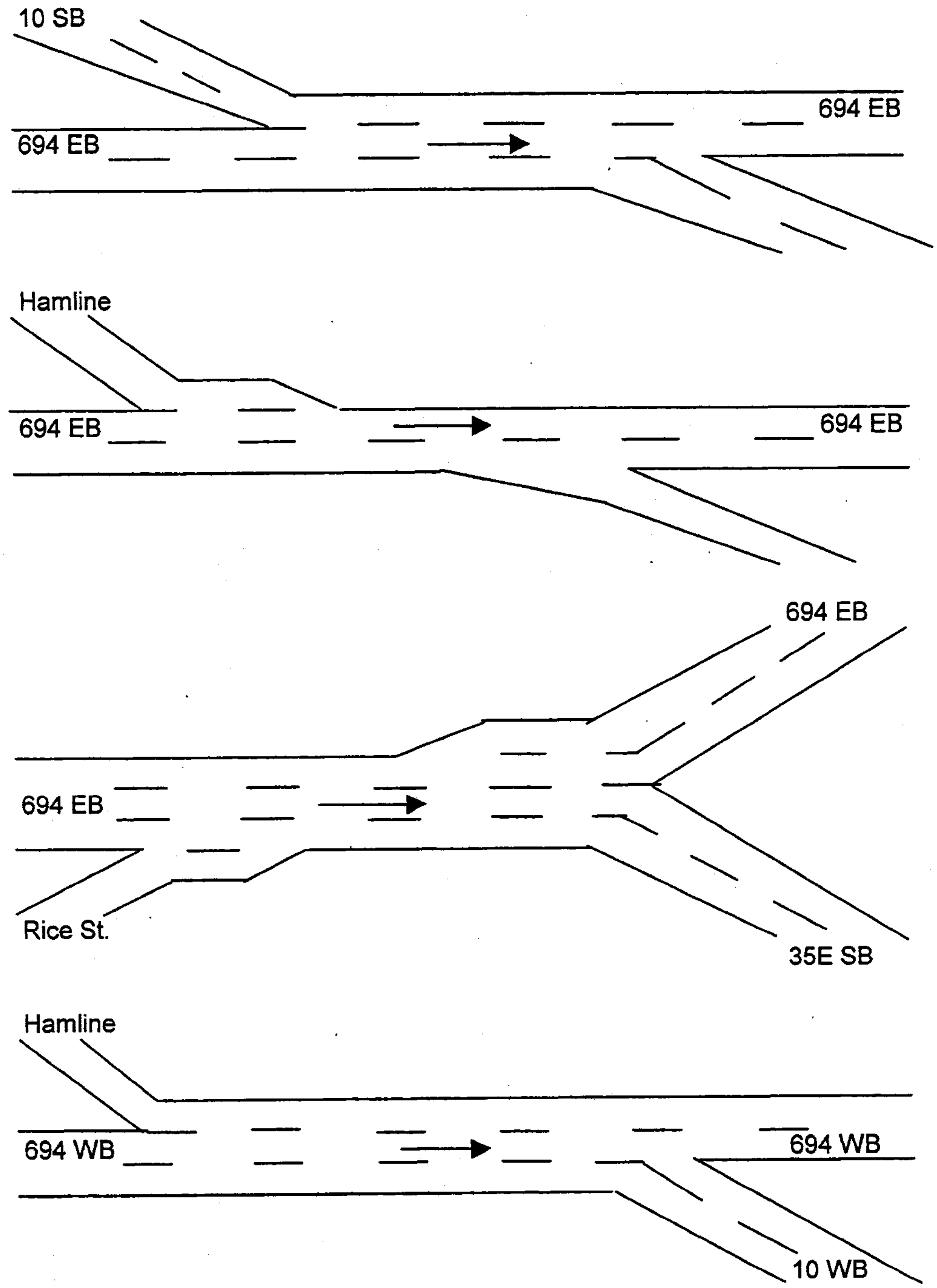
B-7: Major weaving areas in I-394



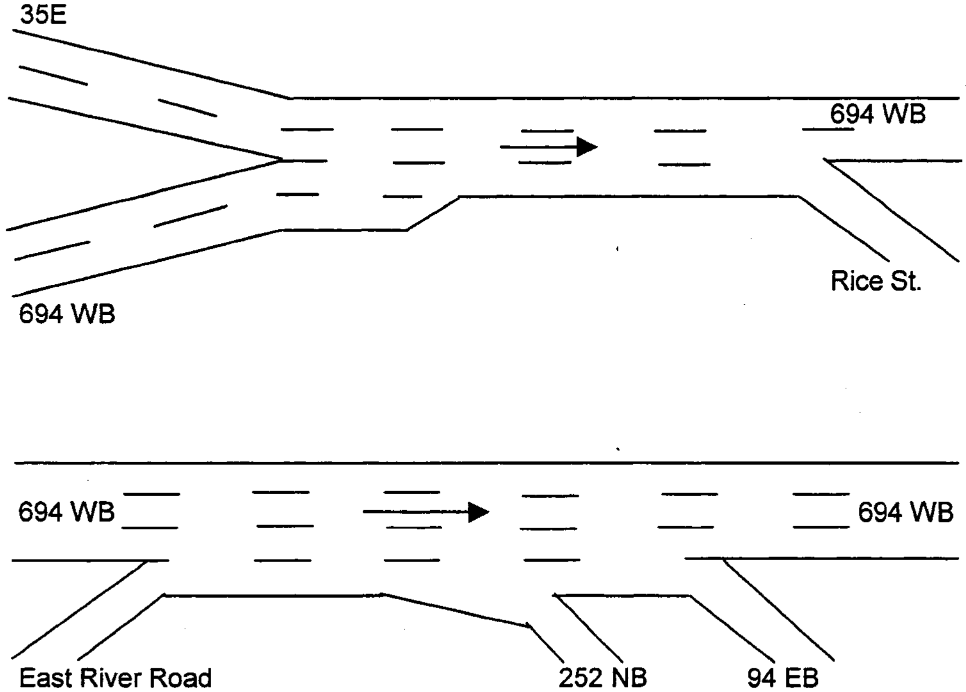
Major weaving areas in I-35E



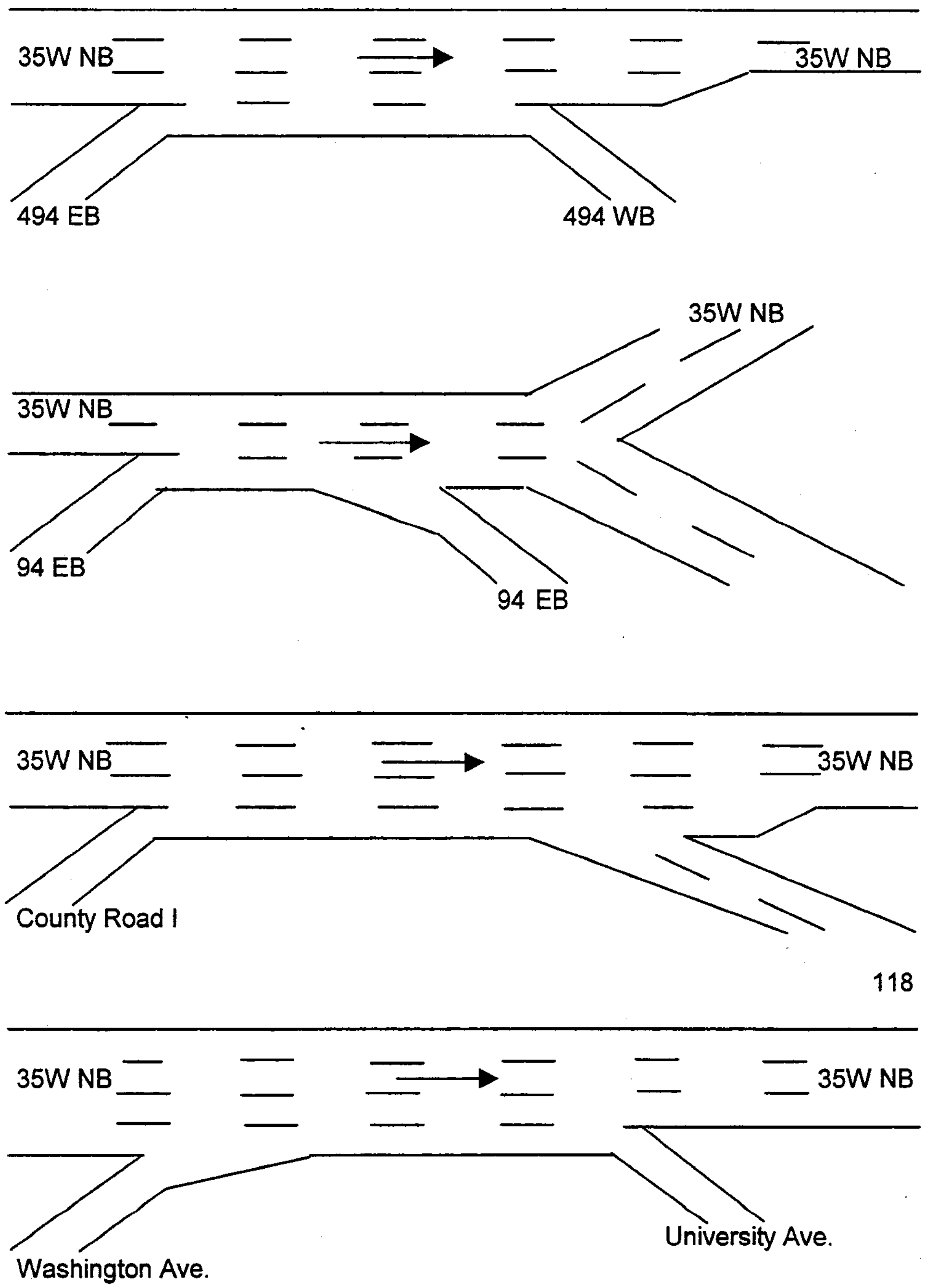
B-8: Major weaving areas in I-694



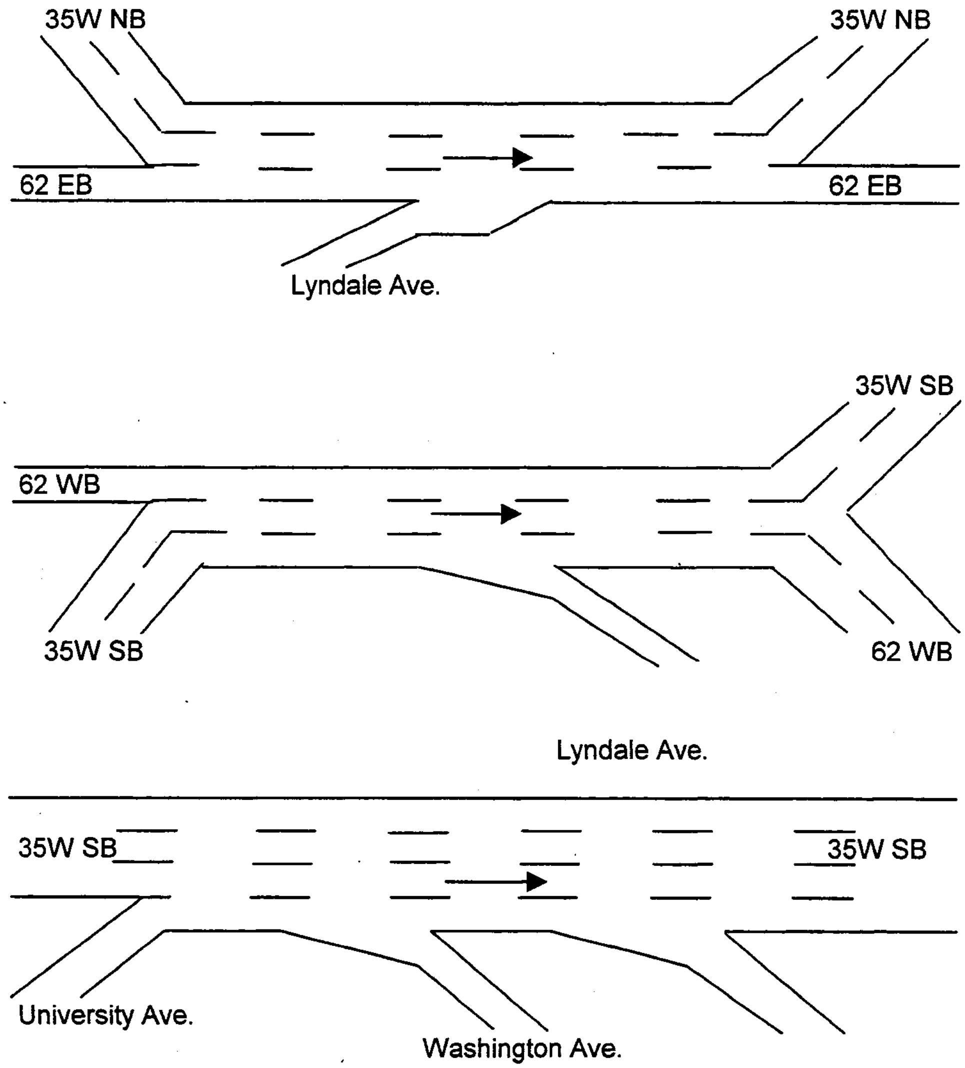
B-9: Major Weaving Areas in I-694



B-10: Major weaving areas in I-35W

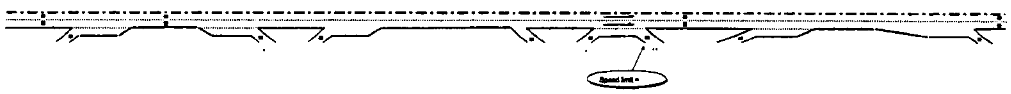


B-11: Major Weaving Areas in I-35W



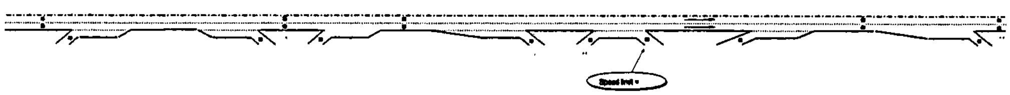
Appendix C: Selected sites for short-ramp weave analysis

EB 62 from SB 77 to NB 77



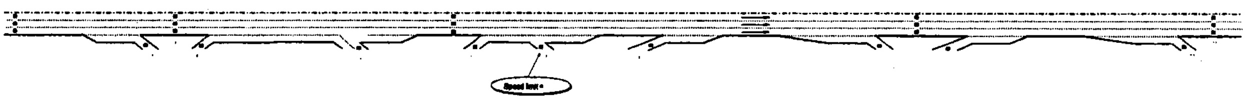
SECTION	A		B	C		D	E	F	G	H	I		J	K	L	
STATION #	322		——	323		——	——	——	——	——	324		——	——	325	
DETECTOR	1134	1135	1136	1137	1138	1139	1140	1466	1141	1453	1142	1143	1144	1145	1146	1147
TIME	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O

EB 62 from SB 100 to NB 100 (Type A, Short)



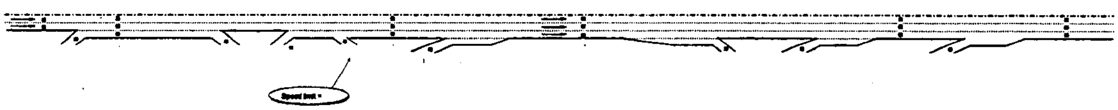
SECTION	A		B	C	D		E	F		G	H	I	J	K		L	M	
STATION #	313		——	——	314		——	315		——	——	——	——	316		——	317	
DETECTOR	1041	1042	1043	1046	1044	1045	1047	1048	1049	1297	1050	1263	1051	1052	1053	1056	1054	1065
TIME	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O

EB 494 from NB 35W to SB 35W



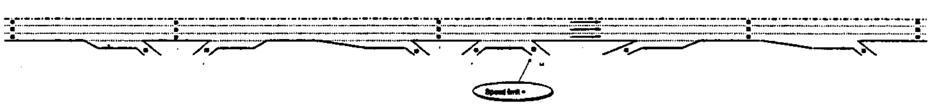
SECTION	A			B	C			D	E	F			G	H	I	J	K			L	M	N		
STATION #	197			——	198			——	——	120			——	——	——	——	200			——	——	201		
DETECTOR	846	847	848	853	849	850	851	852	106	462	463	464	862	120	863	877	873	874	875	876	887	883	884	885
TIME	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O

WB 494 from NB 100 to SB 100



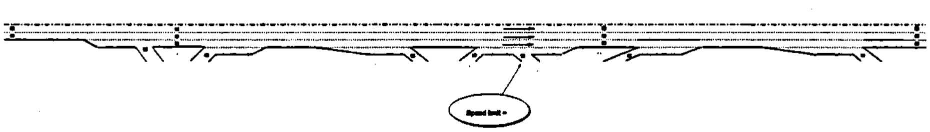
SECTION	A		B	C			D	E	F	G			H	I			J	K	L			M	N		
STATION #	192		——	193			——	——	——	194			——	195			——	——	196			——	197		
DETECTOR	803	804	805	811	812	813	824	822	825	819	820	821	823	834	835	836	842	840	837	838	839	841	846	847	848
TIME	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O

NB 35W from EB 694 to WB 694



SECTION	A			B	C			D	E	F			G	H	I	J			K	L		
STATION #	657			——	658			——	——	214			——	——	——	664			——	665		
DETECTOR	2722	2723	2724	2725	2726	2727	2728	2729	896	897	898	899	975	861	900	2732	2733	2734	2735	2736	2737	2738
TIME	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O

NB 35W from EB 13 to WB 13 (Type B, Short)



SECTION	A		B	C			D	E	F	G	H			I	J	K		
STATION #	72		——	32			——	——	——	664	33			——	——	35		
DETECTOR	131	132	152	258	259	481	111	153	112	154	260	261	480	113	156	264	265	500
TIME	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O	V O