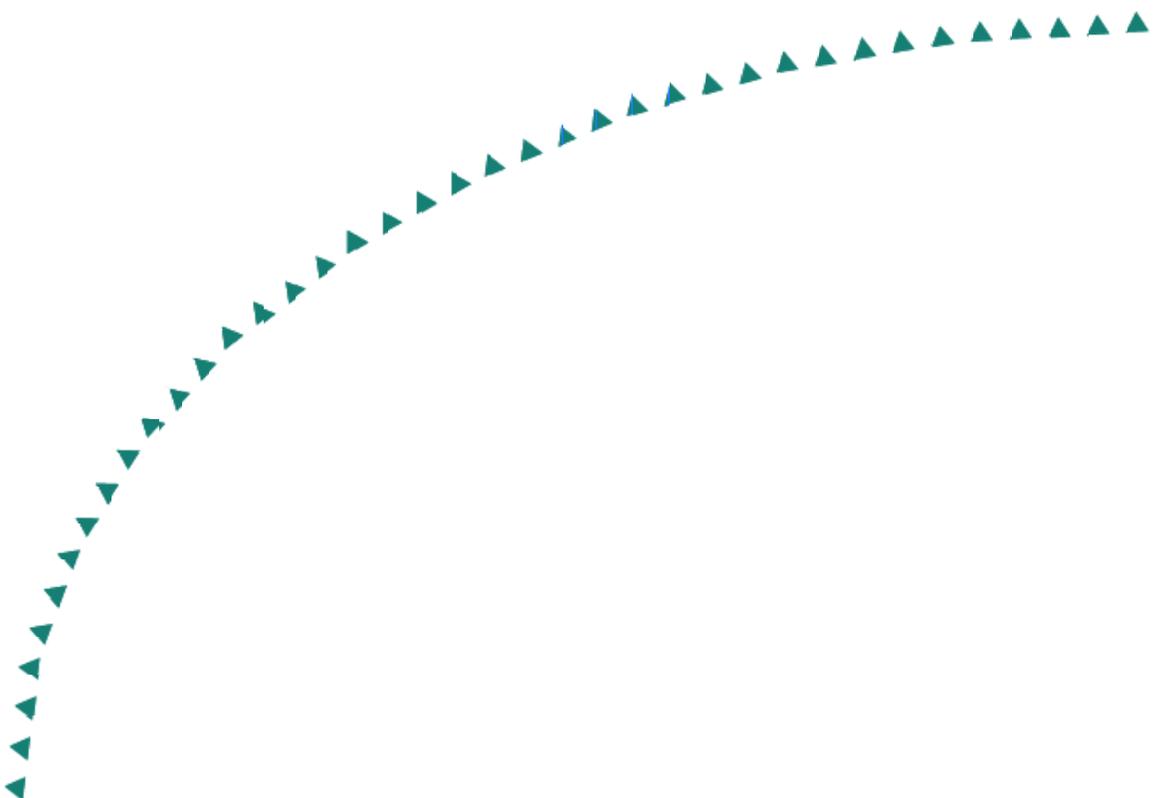# Dynamic Estimation of Freeway Weaving Capacity for Traffic Management and Operations, Phase II

Research

Technical Report Documentation Page

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16. Abstract (Limit: 200 words)

An adaptive procedure is presented to estimate the time-variant capacity at consecutive weaving areas in real time. The proposed procedure uses the volume/occupancy data commonly available from single loop detectors and estimates the maximum total volume that can enter a given freeway weaving segment through time. The behavior at several weaving sites with consecutive weaving segments were analyzed, using loop and video data as well as visual observation. The online identification process with a Kalman Filter reduces estimation errors by continuously updating the parameters of the underlying models with the most recently measured data. The test results with real data show that the proposed procedure can estimate the upper limit values of the mainline flow approaching given weaving segments with reasonable accuracy. This procedure addresses the effects of entrance ramp flows, which can be controlled through ramp metering, on the maximum possible mainline volume approaching weave areas. The procedure may be directly applicable in improving ramp metering operations, and in the development of better design of freeway weaving segments.

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DYNAMIC ESTIMATION OF FREEWAY WEAVING CAPACITY FOR TRAFFIC MANAGEMENT AND OPERATIONS, PHASE II

Final Report

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July 2003

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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 capacity issues in weaving areas, there is still lack of a practical on-line procedure that can be used to estimate the time-variant maximum volume that can enter a given weave area with the data currently available. To be sure, most studies in weaving 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 under pre-specified weaving demand patterns. Further, most research efforts in the past resulted in regression-based models without incorporating the casual interaction between two crossing flows and the impacts of exit ramp capacity on weaving flows (Fazio and Rouphail, 1986, Ostrom, et al., 1993, Fredericksen and Ogden, 1994). A recent study by Letworawarich and Elefteriadou (2003) applied a linear optimization approach to estimate maximum flows in a given weaving section under different flow patterns, but this approach also requires origin-destination information that is difficult to be obtained in real time.

For this research an adaptive procedure was developed to estimate the time-variant capacity of freeway weaving areas using commonly available data from single loop detectors. First, a set of both loop and video data were collected to analyze the behavioral characteristics of traffic flows in sample weaving sites. In particular, a video-detection system developed by a research group at the University of Minnesota (Masoud, et al., 1999) was used to measure speed levels of the lane-changing vehicles at the consecutive second weaving segment in the 169 NB weave site. The major qualitative features of the traffic behavior observed from those weaving sites and the volume-speed data can be summarized as follows:

- At most consecutive weaving segments, the right-most-lane flow approaching a first weaving segment contains the vehicles exiting through the first and second exit ramps in a given consecutive weaving segment. This reduces the merging capacity at the mainline portion of the first weaving section and therefore results in a smaller weaving capacity than that of the second weaving segment. The level of capacity reduction depends on complex traffic patterns, including the amount of vehicles exiting through the second off-ramp.

- The reduction of weaving capacity at the first weaving segment also results in increased congestion at the right-most-lane before the first weaving segment. The right-most-lane congestion can cause 'side friction' effects on the adjacent lanes, i.e., middle and left-most lanes, whose capacities decrease as a function of the congestion level at the right-most-lane.

- It was noted that there existed a clear and consistently linear pattern between the volume/occupancy values, which can be considered as pseudo-speed measurements, of the right-most lane and the adjacent lanes just upstream of a weaving segment.

- Most lane-changing within a consecutive weaving segment, i.e., after the merge gore point of a first weaving section, is discretionary and no clear pattern was found between the amount of lane-changing and the capacity reduction of the merged lane.

Based on the above findings, an adaptive process was formulated to estimate the time-variant capacity of mainline just upstream of a given weaving segment. The proposed procedure explicitly addresses the effects of entrance ramp flows, which can be controlled through metering, on the maximum possible mainline volume approaching weave areas. Further, the effects of the right-most-lane, whose capacity is directly affected by the weaving flows, on the capacity of the adjacent lanes are also modeled. The test results with real data indicate that the proposed procedure can estimate the time-variant capacity of the weaving segment in a consecutive weaving area with reasonable accuracy. In particular, the results clearly exhibit the adaptability of the proposed procedure to the prevailing traffic conditions in determining the upper boundaries of the flows entering a given weave area through time. Further, the use of the volume/occupancy ratio in determining the time-variant capacity of the adjacent lane showed promising results along with the simplified representation of volume-occupancy relationships.

The proposed capacity estimation procedure can be directly applicable in improving the ramp metering operations, which currently use fixed capacity at mainline detector stations. The complex flow patterns at consecutive weaving areas, identified in this research, can also be used to develop better designs of freeways involving weaving segments. Future research needs to include improvement of the ramp metering algorithm to reflect time-variant capacities and continuous enhancement of adaptive estimation procedures to improve the accuracy of the procedure.

1. INTRODUCTION

1. 1 Background

Freeway weaving sections are the most frequently congested bottlenecks whose complex traffic patterns and capacity variations present significant operational problems on freeways. While various research efforts have tried to estimate weaving capacities, most procedures developed to date require origin-destination flow data that is difficult to be collected or predicted in real time (Fazio, et al., 1990, Fredericksen, et al., 1994, Ostrom, et al., 1993, Lertworawanich, et al., 2003). In particular, very few studies have addressed the impacts of time-variant traffic conditions on maximum possible volume that can enter a given weaving section. Such an operational capacity of weaving sections, which varies through time, is of critical importance in determining effective freeway control strategies, such as optimal metering rates, in real time.

The previous phase of this research has focused on addressing the capacity and traffic behavior issues in Type I ramp-weave areas, where a pair of on- and off-ramps is connected by an auxiliary lane. The analysis of the traffic data and driver lane-changing behavior from sample weaving sections indicate that the beginning portion of an auxiliary lane is shared by weaving vehicles, i.e., both merging and diverging vehicles, which merge first and travel as a mixed flow for a short period before they split. The shared portion of the auxiliary lane, identified as the 'effective weaving zone', varies depending on the amount of weaving volume and the length of the auxiliary lane, while there exists a minimum length. Further, the speed levels of both merging and diverging vehicles are very similar to each other at any given time interval, and no significant pattern can be found between speed and volume measurements of weaving flows.

It was also noted that the most important factor affecting the capacity of Type I weaving areas is the capacity of an exit ramp rather than the length of the auxiliary lane. The above merge-split behavior and the resulting mixed flow pattern on the auxiliary lane for a short time period lead to the conclusion that the maximum possible weaving volume in a simple ramp-weave section is limited to the maximum through volume that the auxiliary lane can handle. Further, the maximum possible weaving volume for a given weaving section varies depending on the traffic conditions downstream, i.e., at exit ramp and mainline merge areas. The above findings were verified with the estimated weaving volume data from three other weaving sites using a Kalman Filter (Kalman, 1960). The Phase 1 study finally resulted in an on-line procedure that can estimate the maximum possible weaving volume for a given ramp-weave area through time using the volume and occupancy measurements from the loop detectors. Phase II of this research extends the previous study on weaving capacity issues to 'consecutive' weaving sections, whose spacing is close enough to cause complex interaction including multiple lane-changes. Such double weaving sections can be found frequently in the Twin Cities freeway network and form moving bottleneck sections with time-variant capacity.

1. 2 Research Objectives

The major objectives of the current Phase II research include:
- Analysis of traffic behavior and lane-changing patterns at consecutive weaving sections,
- Identification of factors affecting capacities in consecutive weaving sections,
- Development of adaptive estimation procedures for capacities at weaving sections.

2. ANALYSIS OF TRAFFIC BEHAVIOR AND CAPACITY CHANGES AT CONSECUTIVE WEAVING SECTIONS

2. 1 Data Collection and Processing from Selected Weaving Sites

For this research the following freeway segments containing double weaving sections, defined as freeway segments with two consecutive weaving sections whose spacing is close enough to cause multiple lane-changes, were reviewed as potential sample sites for analyzing traffic behavior and capacity changes. The location and general schematic diagram of each site are as follows:

1) 169 NB including I-394 and Hwy 55 interchanges
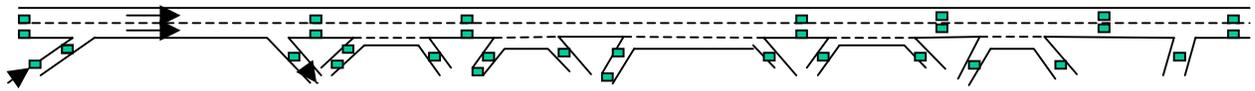
2) I-35W SB between 31st and 46th Street
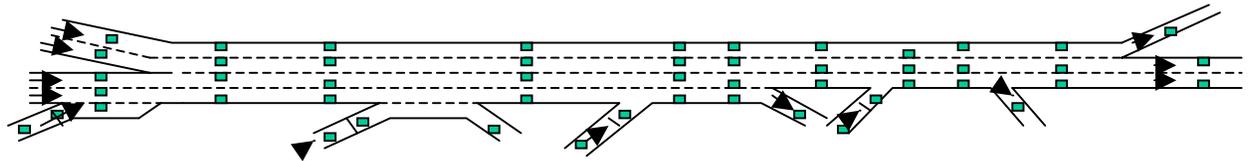
3) I-394 WB at Louisiana Avenue
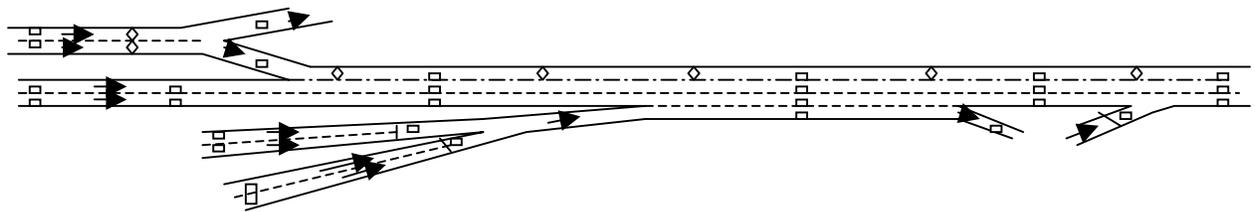
4) I-694 WB at River Road and I-94 Interchange
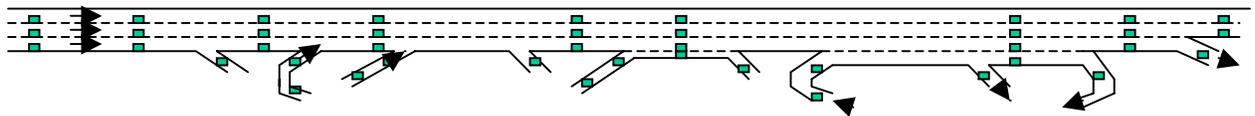
The key issue in determining sample weaving sites was the feasibility to collect video data to study lane-changing behavior of drivers in double weaving sections. For this study, the prototype video detection system developed by a research group at the University of Minnesota (Masoud, et al., 1999) was used for collecting the speed and amount of lane-changing vehicles. To find out if it would be feasible to collect and process video data using the University of Minnesota system, which adopts vehicle-tracking technology, initial video data collection was performed at the above freeway sections in cooperation with Mr. Len Palek, Traffic Management Center, Minnesota Department of Transportation. At each freeway segment, several locations where a data-collection van with a 40-foot mast attached could be parked were selected and 3-4 hours of traffic videotapes were recorded from each site. The videotapes were then processed by the University of Minnesota group, who checked the angle and resolution of the recording areas of each tape to see if it would be feasible to extract vehicle trajectory data with their tracking system.   Figure 2.1 shows the data collection van used for this study.

Based on the initial test results, and also considering the generality of double weaving section geometry, the 169 NB section at I-394 was selected as the primary sample site for video data collection, and three days of videotapes, which recorded afternoon peak-period traffic, were collected in cooperation with Mr. Len Palek on 12/27/02, 1/06/03 and 1/07/03. Further, the I-694 WB section was also selected as an additional analysis area and the 30 second loop detector data was collected from selected normal weekdays during four months in 2002 and three months in 2003 at both 169 NB and I-694 WB sections. The loop data collected for this research includes lane volume and occupancy for every 30 seconds from all the detectors in each sample site for 24-hour periods on selected weekdays.

Processing of videotapes for speed measurements using video detection system

The videotapes collected from the 169 NB section were processed using the video tracking system developed by the research group at the University of Minnesota (Masoud, et al., 1999). The processed data includes lane-by-lane volume/speed, and volumes and speed levels of lane-changing vehicles every 30 seconds/1 minute/5 minutes for three afternoon peak-periods. Figures 2.2 and 2.3 show the data collection location and the view of the video camera at the 169 NB site.

Figure 2.1 Data collection van used for this study (installed at the I-394 site)
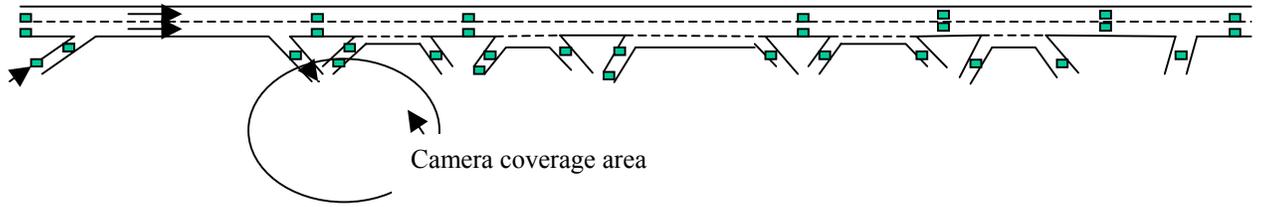
Figure 2.2 Video data collection area at 169 NB site

Figure 2.3 View of video screen used for data collection

The following figures show some of the video data collected and processed in this study. Figure 2.4 indicates the relationship between left-most lane speed and right-to-left lane changing volume, while Figure 2.5 shows the 1 minute speed level variations through time for right lane (R to R), left lane (L to L), and the lane-changing vehicles from right to left lane (R to L) for a one and one-half hour period on the afternoon of 1/06/03. Figures 2.6 - 2.9 also show the speed variations of each lane and lane-changing vehicles on two other days.
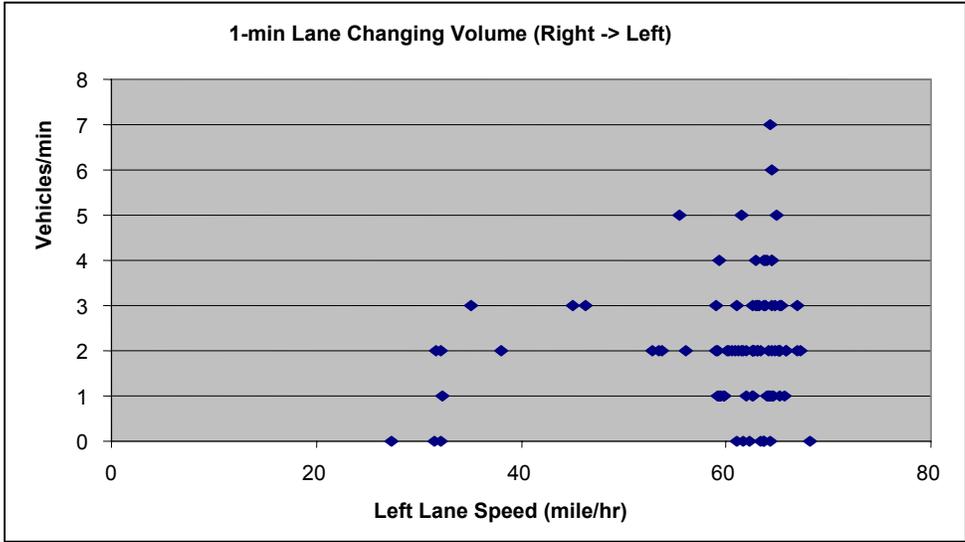
Figure 2.4 Right-to-left lane-changing volume vs. left-lane speed
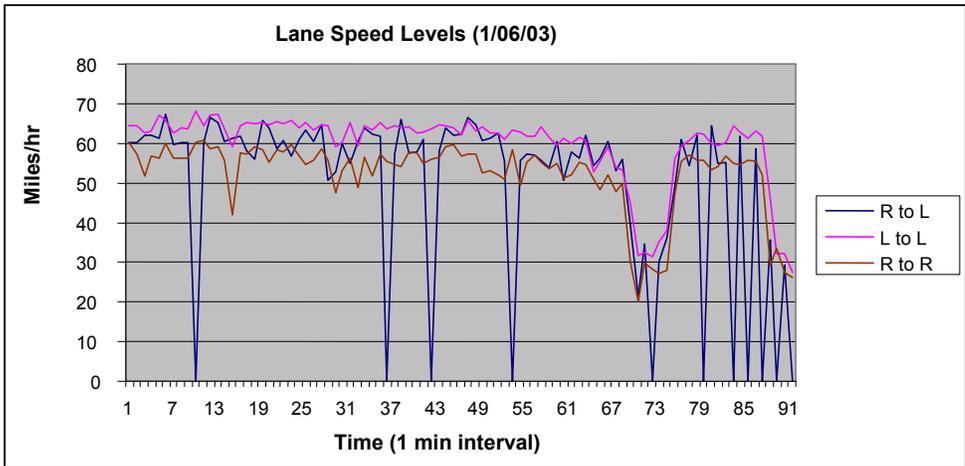
Figure 2.5 Speed levels of left-lane and lane-changing vehicles at the weaving site

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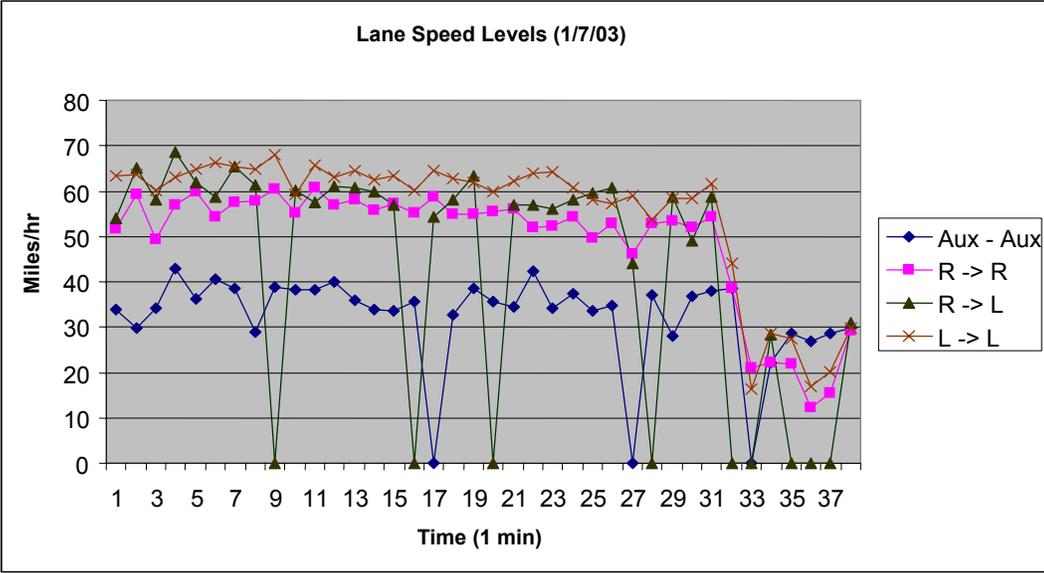
Figure 2.6 Lane speed levels on January 7, 2003
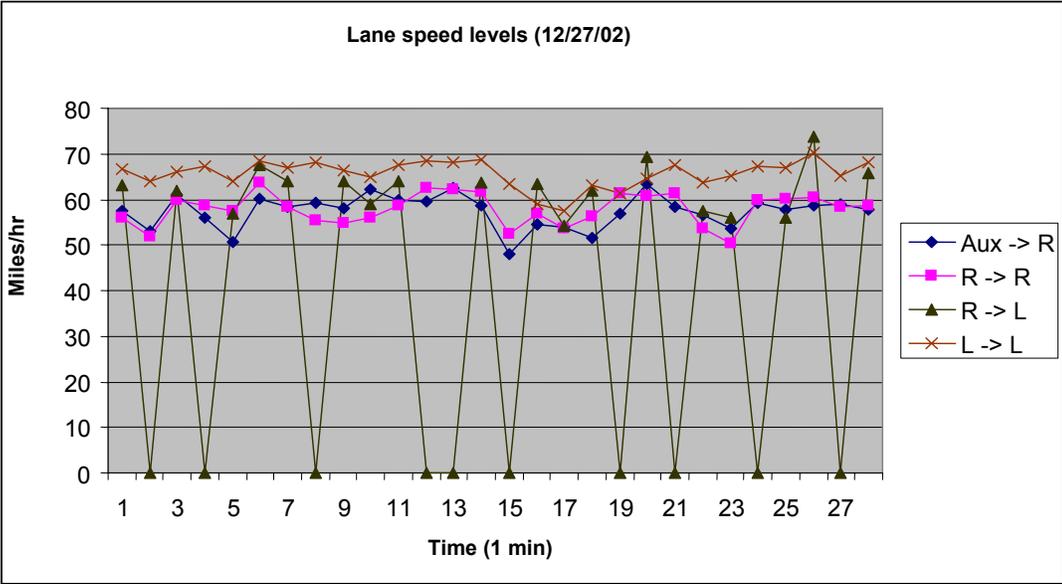
Figure 2.7 Lane speed levels on December 27, 2002
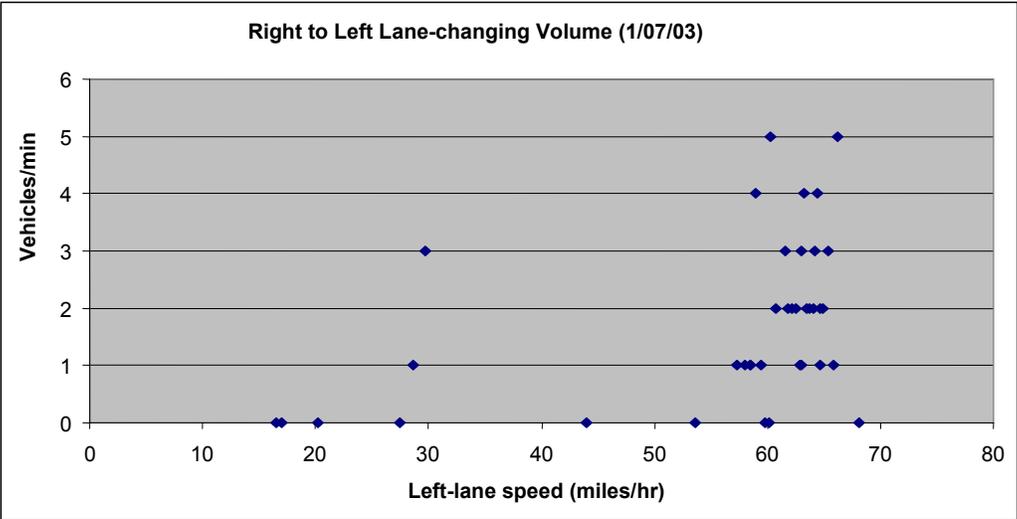
Figure 2.8 Right to left lane-changing volume vs. left-lane speed (1/07/03)
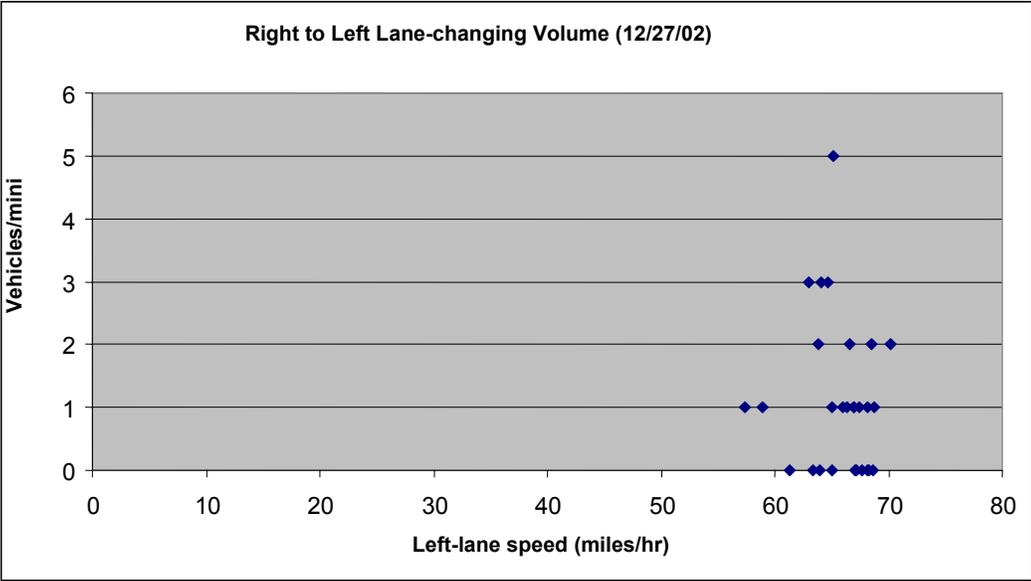
Figure 2.9 Right to left lane-changing volume vs. left-lane speed (12/27/02)

2. 2 Characteristics of Traffic Behavior at Consecutive Weaving Sections

This section summarizes the observed traffic behavior of drivers changing lanes at the sample weaving sites in the Twin Cities metro freeway network. The following two types of freeway segments shown in Figure 2.10 represent two different types of double weaving sections commonly found in the Twin Cities freeway network:
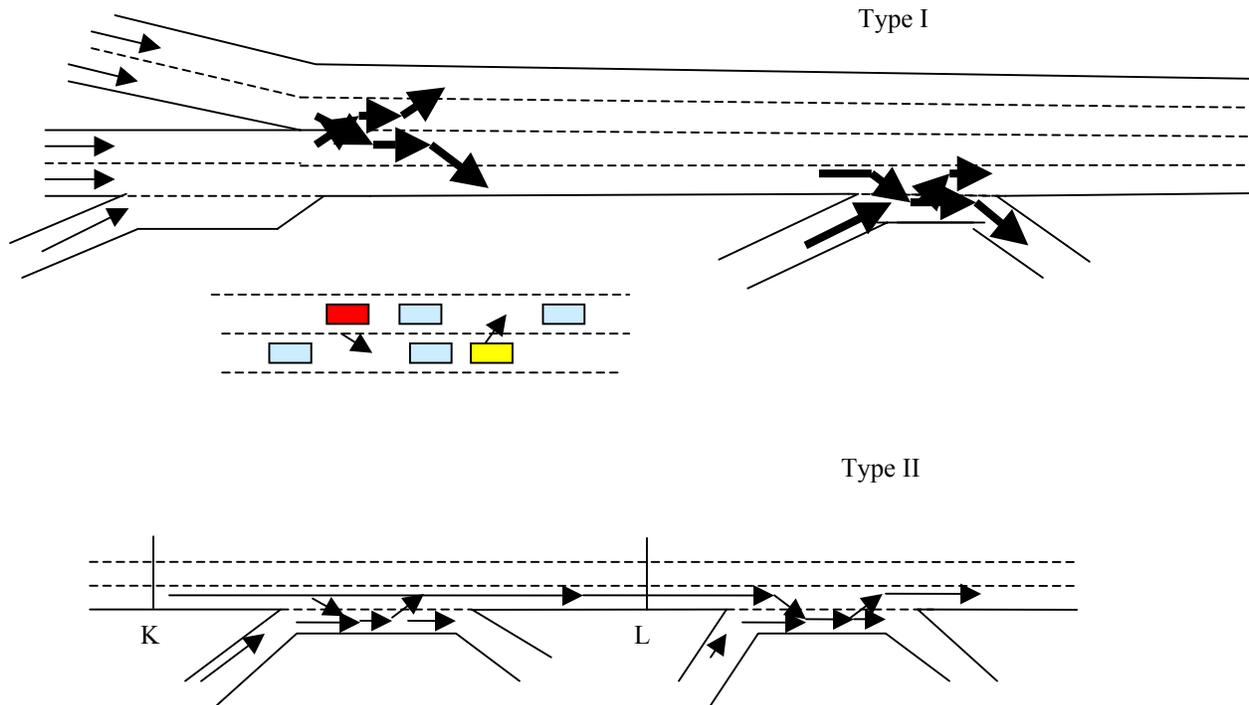
Type I

Type II

Figure 2.10   Typical types of double weaving sections

In case of Type I, most weaving happens as a sequential lane-changing process by two vehicles that need to change lanes. The first weaving usually happens as soon as two flows meet together at the first weave section, and the vehicles that need to exit at the exit ramp in the second weave section usually complete lane-changes before they reach the second weave section. The length of lane-changing area varies depending on the amount of volume in this segment. It was also observed that as the congestion in the mainline increases, the length of the lane-change zone gets shorter. The general lane-changing process of a driver in a weave section can be described as the following sequential process, where the size of an acceptable gap is a function of several factors, including the speed and relative location to the exit point for a subjective driver:

Search Gap	→	Adjust Speed	→	Change Lane	→	Adjust Headway

Acceptable Gap = f (Speed, Location, etc.)
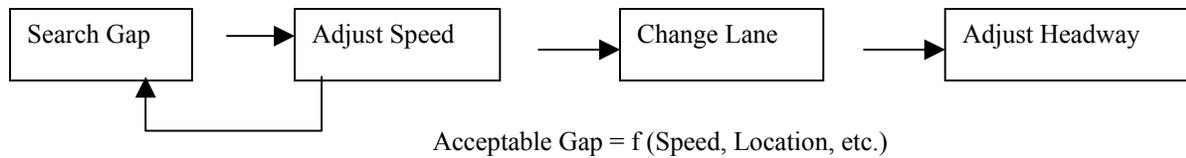
Therefore, in case of Type I, the amount of weaving volume directly affects the through capacity of the mainline and the location/range of the first weaving area, i.e., lane-changing zone, varies depending on the mainline congestion level.

Type II represents a freeway segment with two consecutive ramp-weave sections. The major characteristics of the qualitative traffic behavior observed from the 169 NB site and its video data can be described as follows:

- At the 169 NB weaving site, there is significant difference between right and left lane speed levels through time, i.e., right lane speed is consistently lower than that of the left-lane speed.

- The difference between left-lane and right-lane speed levels decreases as speed levels increase, while its variation gets larger as speed levels decrease. This indicates the possibility of modeling the effects of side friction on the left-lane flow as a function of right-lane flow conditions.

- As expected, the speed levels of merging flows within a double weaving section, i.e., auxiliary lane to right lane, and right to right lane flows, are very close to each other. Further, the speed levels of right to left lane flow and those of left to left lane flow are very similar as well.

- Very few vehicles change lanes from left to right within a double weaving section, which indicates most exit vehicles through a double weaving section have already completed lane-changes before they arrive at the beginning point of a double weaving section.

- Most lane-changing within a double weaving section happens from right to left lane, i.e., by the merging vehicles that entered a double weaving section to avoid the slow speed of the right lane.

- Most of lane-changing from right to left lane happens when the traffic condition of the left lane is relatively good, i.e., at high speed level, and there is no clear pattern between the amount of lane-changing vehicles and left-lane speed levels. This indicates that most lane-changes are discretionary, i.e., not forced lane-changes, and their effects on the merged flow is not significant.

Based on the above observation from the 169 NB and other weaving sites, the general qualitative behavior of the Type II weaving area can be summarized as follows:

- Most of the vehicles that need to exit from either the first or second exit ramp complete lane changes to the right-most lane before they reach the beginning point of the first weaving section.

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- The right-most-lane flow at the first weaving segment includes the vehicles exiting through the exit ramp at the second weaving segment. This reduces the merging capacity at the mainline portion of the first weaving segment, and therefore results in reduced weaving capacity compared to a single weaving segment, depending on the amount of vehicles exiting through the second off-ramp.

- The location K on the right-most lane right before the merge gore point of the first weaving segment would have the lowest speed level, which is affected by several factors, including the amount of merging vehicles and exit vehicle speed at the first weaving segment, the amount of exit vehicles through the second off-ramp, and speed level at L, i.e., right-most-lane before the second weaving segment.

- The low speed level at K can cause 'side friction' effects on the adjacent lanes, i.e., middle and left-most lanes, whose speed levels also decrease as a function of the speed level at K.

- The second weaving segment has normal maximum weaving capacity, i.e., one-lane through capacity, and its mainline flow after the weave segment becomes free-flow unless it is affected by the traffic conditions spilling back from downstream.

2. 3 Qualitative Analysis of Changes in Traffic Patterns and Capacities at Weaving Areas

Based on the traffic behavior analysis results from the previous section, determining the operational capacity of a Type II double weaving section, shown in the following figure, can be summarized as the issue of estimating the maximum volume that can pass the location K and L through time, i.e., the mainline locations right before each weaving segment, assuming that the volume entering from each entrance ramp can be controlled. The maximum volume at K and L can be affected by the traffic patterns at each weaving segment as follows:
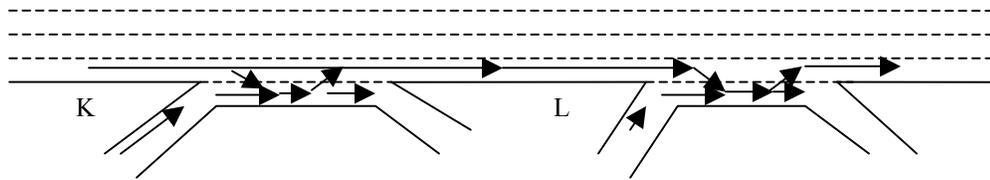
Figure 2.11 Typical configuration of Type II double weaving section

- Assuming that there is no congestion spilling back from downstream of the second weaving section, the total maximum volume that can pass the point K can be directly affected by the level of congestion at the right-most-lane. The congestion at the right-most lane causes the effects of the side friction on the adjacent lanes, whose capacity reduction varies depending on the level of congestion at the right-most lane.

- The right-most lane at K mostly contains the vehicles exiting through the two exit ramps in a double weaving section. Further, the congestion level of the right-most lane at K is directly affected by the weaving conflict at the first weaving section, which is also influenced by the congestion level at L.

- When mainline traffic at location L is congested, then both the maximum volume that can pass K and the weaving capacity of the first weaving site are directly affected by the congestion level at L.

- Since the right-most-lane flow at K, in general, also contains the exit traffic for the second exit ramp, the maximum weaving volume at the first weaving segment would be less than or equal to that of the second weaving segment, depending on the amount of the exit flow through the second off-ramp.

The above relationship involving the mainline locations before and within a double weaving segment can be best shown with the real traffic data collected from the I-694 WB site including the exit ramps to River Road and I-94. The locations of the mainline detector stations are shown in Figure 2.12.
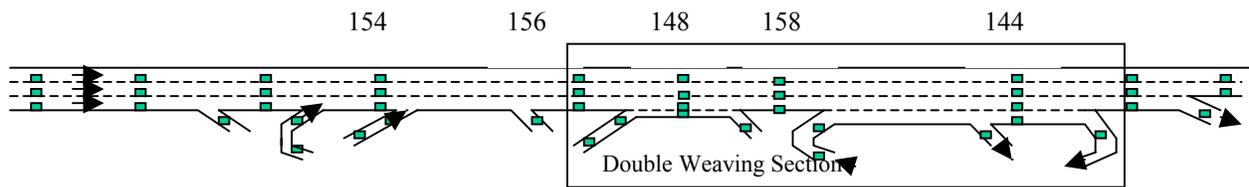
Figure 2.12 I-694 weaving site

The occupancy variations from the above mainline locations on Oct. 15, 2002, from 6:00 a.m. to 9:00 a.m., are shown in Figure 2.13.
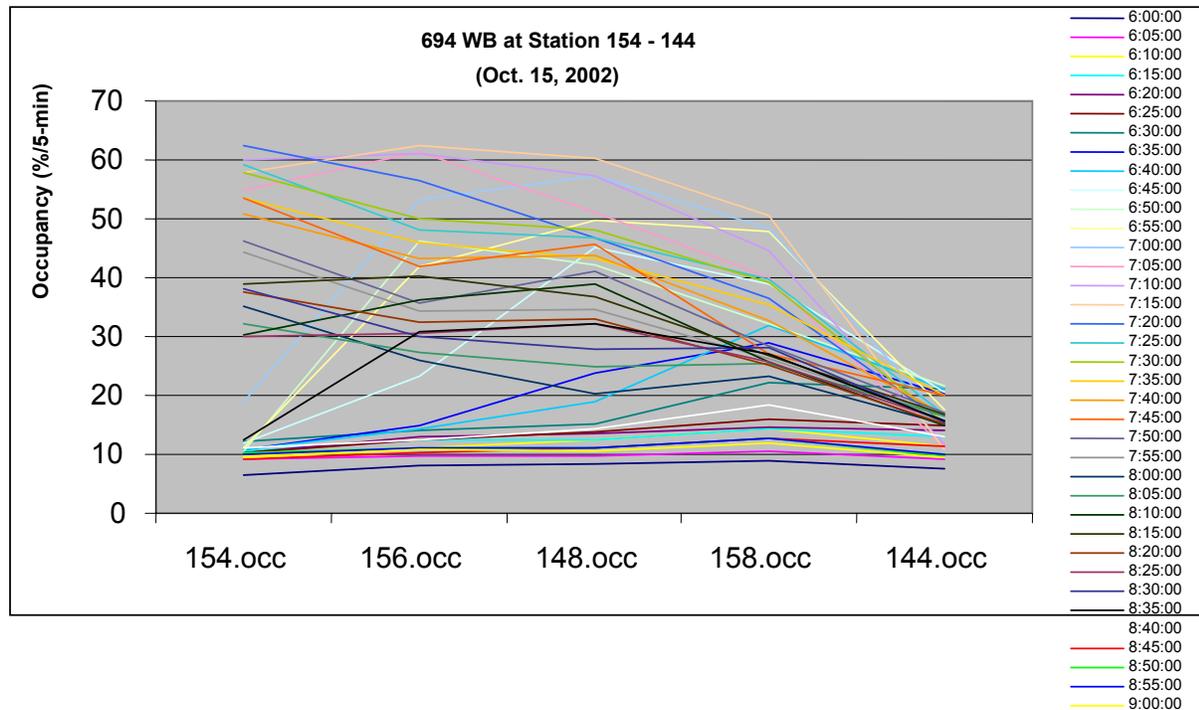
Figure 2.13 Occupancy variation through time at the I-694 weaving site

As illustrated in the above figure, the congestion on the mainline in the subject site starts from Station 158, which is located right before the beginning point of the second weaving segment, and continuously grows beyond Station 156, the location just before the starting point of the first weaving segment. It can be noted that the congestion level at Station 156 is first governed by the conflict at the first weaving site, but is quickly affected by the mainline condition at downstream caused by the second weaving site. It can be clearly seen that the congestion at this site is entirely caused by these two weaving sites, i.e., the traffic at Station 144, near the end of the second weaving segment, is almost at free-flow conditions during the entire peak period.

Figure 2.14 shows the flow variations at the right-most-lane (Detector 512 in Station 156) just before the first weaving segment, and at the first exit ramp (Detector 566) from 5:00 a.m. to 12:00 p.m. on Oct. 15, 2002, at the same weave site. Further, Figure 2.15 includes the right-most-lane before the 2nd weave section and the total exit flows through the 2nd weave section. As exhibited in these figures, the right-most-lane before the first weave carries substantially higher volume than the exit flow through the first off-ramp, while the amount of the right-most-lane volume before the 2nd weave section is close to that of the total exit flow.

Figure 2.16 compares the volume/occupancy values of right-most and middle lane flows through time at the mainline Station 158, located at the beginning point of the 2nd weave section. The quantity volume/occupancy can be considered as a pseudo speed value that can indicate the

congestion level at the data collection point. As shown in the figure, the differences between the two values get bigger as congestion increases, while during the relatively un-congested period both of them have similar values. Figure 2.17 exhibits a strong linear relationship between these two values with a positive intercept, and this indicates the possibility of modeling the effects of the side friction with volume/occupancy values.
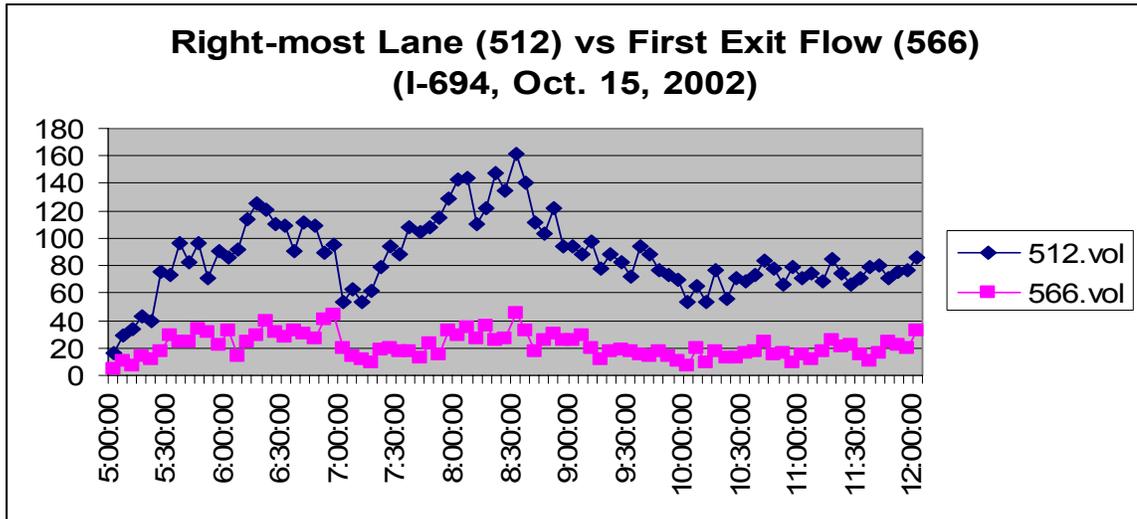
Figure 2.14 Comparison of right-most-lane and exit ramp flows in the first weave
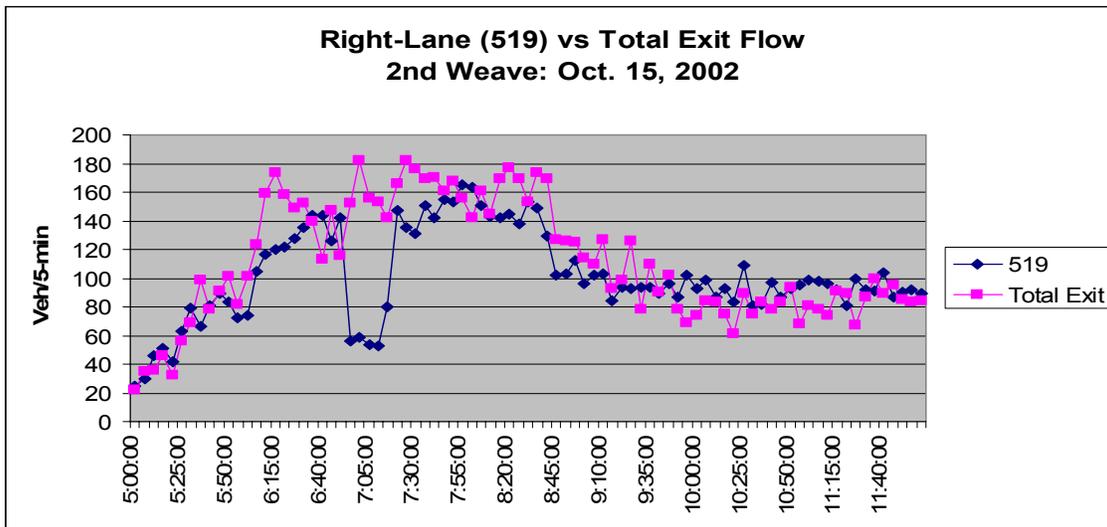
Figure 2.15 Comparison of right-most-lane and total exit flows at the second weave
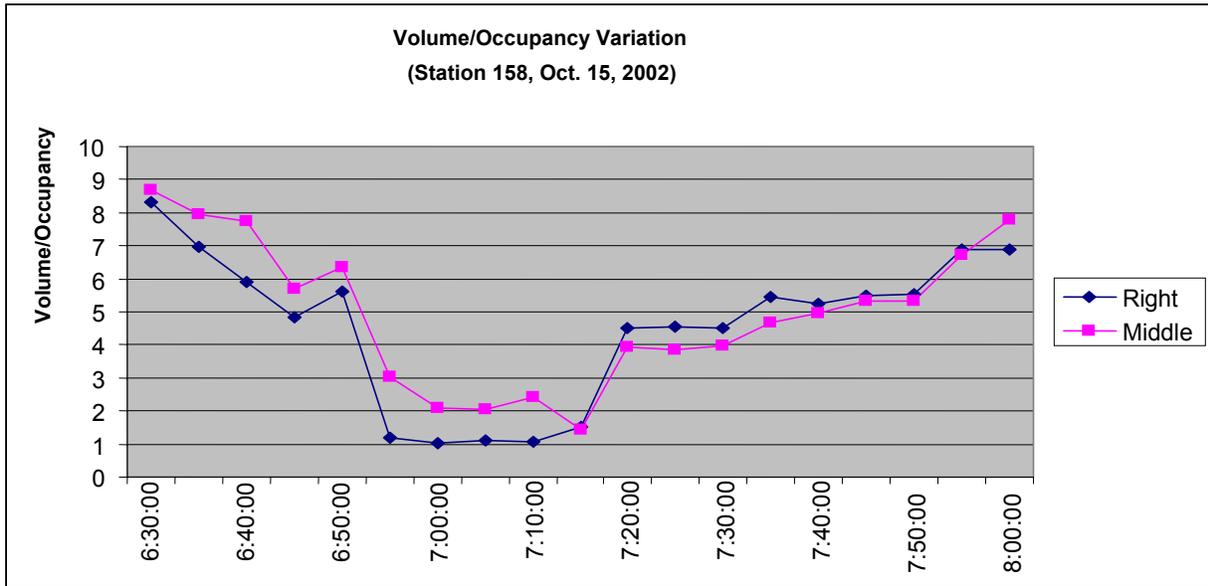
Figure 2.16 Variation of volume/occupancy values at mainline before weave section
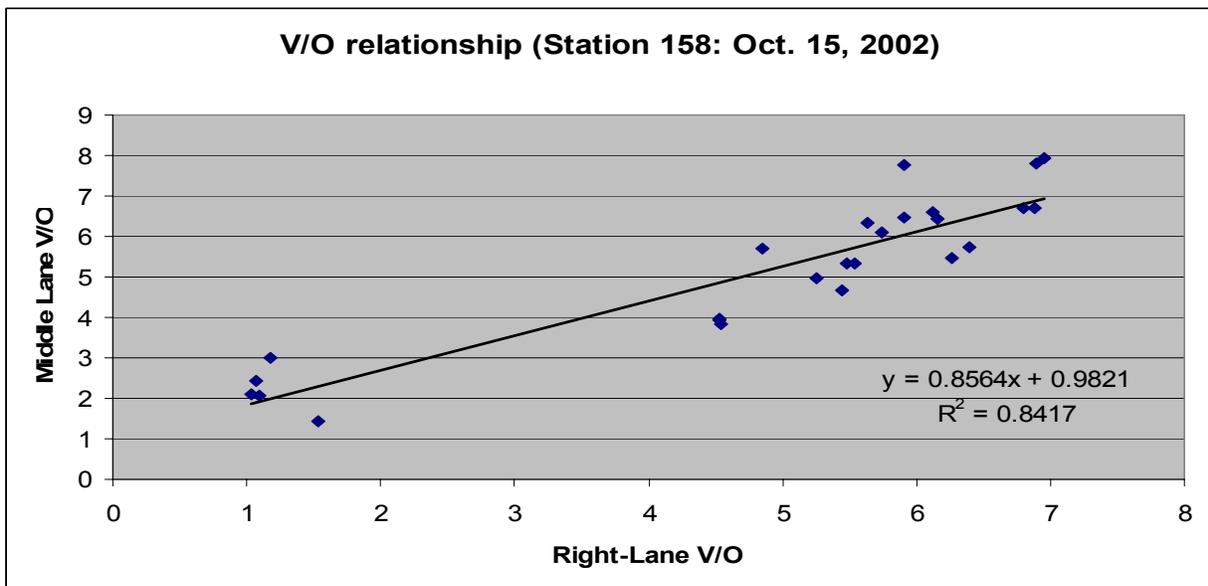
Figure 2.17 Relationship between right and middle lane volume/occupancy values

3. DEVELOPMENT AND TESTING OF ADAPTIVE ESTIMATION PROCEDURES FOR OPERATIONAL CAPACITY AT CONSECUTIVE WEAVING SECTIONS

3. 1 Overview of Adaptive Estimation Procedure

As discussed in the previous chapter, estimating the time-variant, operational weaving capacity, which is defined as the maximum total volume that can enter a given weaving section from mainline and an entrance ramp under current traffic conditions, would include the determination of the following quantities:

1) Maximum weaving volume, defined as the sum of maximum possible volumes entering and exiting through a given weaving section if all traffic in a weave section is either entering or exiting flows, i.e., sum of E and X in Figure 3.1.

2) Maximum total volume that can enter a given weaving section, i.e., the sum of right-most-main-lane flow before the weave section and the flow entering from an entrance ramp at each weave section, i.e., sum of Vr and E.

3) Maximum mainline volume at middle and left lanes before the weaving section, i.e., location K and L in Figure 3.1.
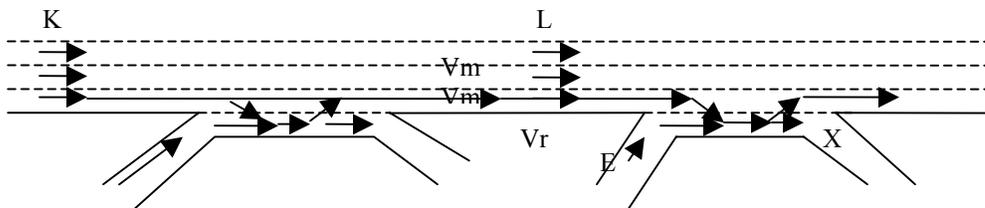
Figure 3.1 Typical example of consecutive weaving sections

In this research, the volume entering a given weave area from an entrance ramp is assumed to be controllable and an adaptive procedure to estimate the above quantities through time with given entering volumes is developed. Figure 3.2 shows the framework of the proposed procedure, which includes an adaptive identification process for model parameters with a Kalman Filter.

```
┌─────────────────────────────────────────────────┐
│ Estimate Maximum Weaving Volume for next time     │
│ interval under current traffic conditions         │
└─────────────────────────────────────────────────┘
                        │
                        ▼
┌─────────────────────────────────────────────────┐
│ Determine Maximum Total Volume that can enter a   │
│ given weaving section during next time interval   │
│ (Mainline Right Lane Flow + Entrance ramp Flow)   │
└─────────────────────────────────────────────────┘
                        │
                        ▼
┌───────────────────────────────────┐     ┌──────────────────────┐
│ Determine Maximum Right-most-lane  │◄────│ Given entrance ramp   │
│ volume and corresponding occupancy │     │ volume for next time  │
│ for next time interval             │     │ interval              │
└───────────────────────────────────┘     └──────────────────────┘
           │
           ▼
┌────────────────────────┐     ┌──────────────────────────┐
│ Identification of       │     │ Determine Expected        │
│ Volume/occupancy        │────►│ Volume/Occupancy values   │
│ Relationship for each   │     │ for adjacent mainline     │
│ lane of the mainline    │     │ lanes for next time       │
│ with V-O data up to     │     │ interval                  │
│ current time interval   │     └──────────────────────────┘
└────────────────────────┘
           │
           ▼
┌───────────────────────────────────────────────────┐
│ Determine Total Mainline Volume that can enter a    │
│ given weave area for next time interval             │
└───────────────────────────────────────────────────┘
```

Figure 3.2 Framework for Adaptive Estimation Process

First, the maximum weaving volume under the current traffic conditions is estimated for each weave segment for the next tim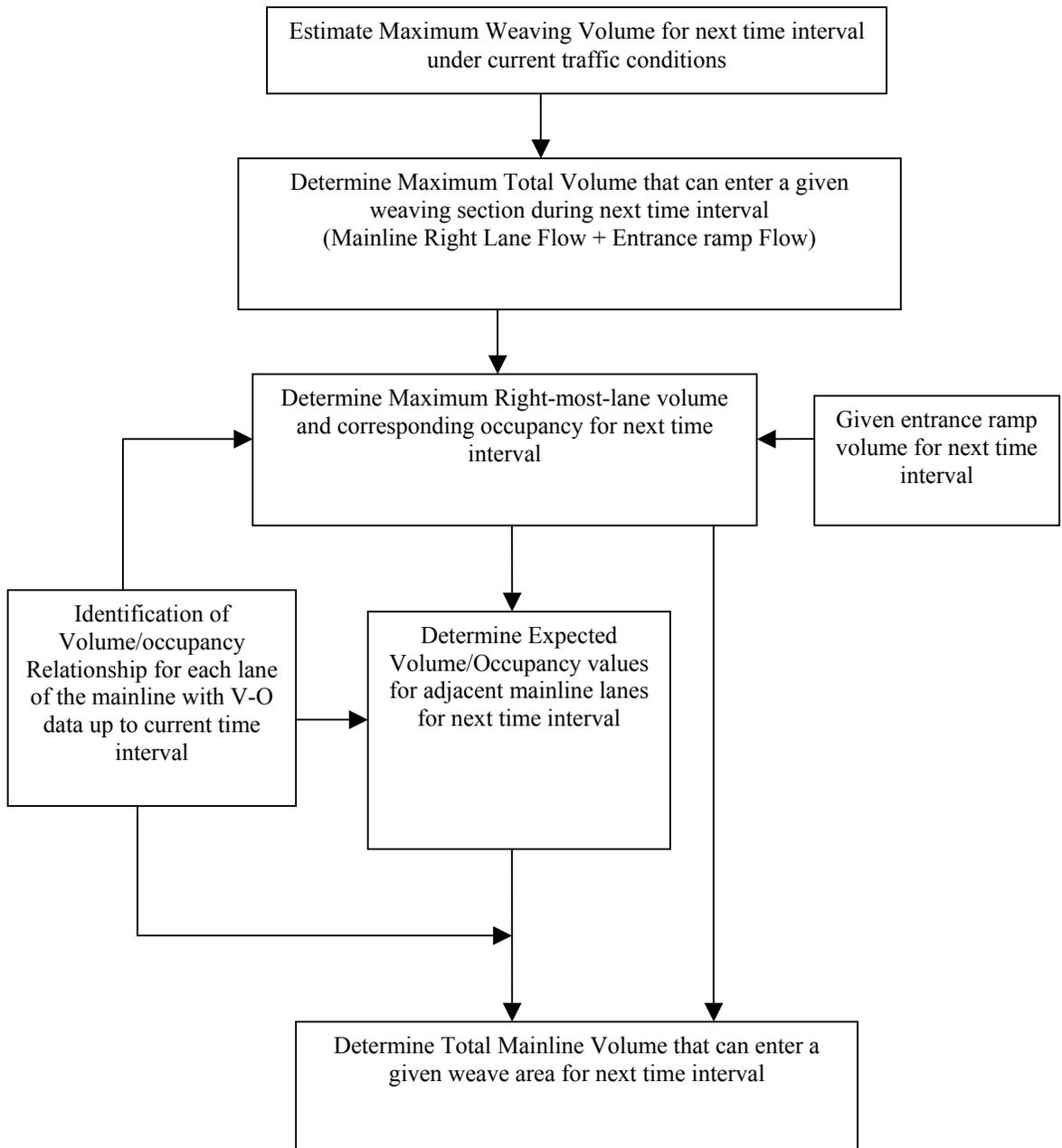e interval. This quantity denotes the maximum sum of entering and exiting volumes when all the flows on a given weaving segment consist of either merging or exiting vehicles. Based on the maximum weaving volume, the next step is to estimate the total volume that can enter a given weaving section including through vehicles by adjusting the maximum weaving volume estimated in the previous step. In this research, the volume from an entrance ramp in a weave section is assumed to be controllable through metering operations. Therefore, the maximum right-most-lane volume before a weave section can be determined as the difference between the total volume that can enter a subjective weave section and the entrance volume given for the next time interval. Once the amount of volume for the right-most-lane is estimated, its expected occupancy level can be determined from the volume/occupancy relationship being updated through time and the occupancy level of the right-most-lane at the previous time interval.

The final step is to estimate capacity of the adjacent lanes, which are directly affected by the congestion level of the right-most-lane. In this study, the effects of the side friction were modeled as a function of the volume/occupancy values of each lane. Once the expected volume/occupancy values of each adjacent lane is determined, then the maximum volume for those lanes for the next time interval can be estimated with the updated volume/occupancy relationship of each lane. One of the key elements in this procedure is the adaptive process to identify a functional relationship between volume and occupancy for each lane using the measured data up to current time interval. For this research, a Kalman Filter (Kalman, 1960) is used to update the parameters of the simplified volume/occupancy function, assuming that the time-dependent evolution of the model parameter follows a random walk process. This approach has been applied to identify the parameters of traffic prediction models in real time (Kwon, et al. 2000). The rest of this chapter summarizes the process of each step.

3. 2 Estimation of Maximum Weaving and Total Entering Volumes

This section describes the procedure to estimate the maximum total entering volume for a given weaving section, i.e., the sum of right-most-lane volume, Vr, and entrance ramp volume, E, shown in Figure 3.1. As explained in the previous chapter, it has been observed that drivers exiting through a weave segment complete their lane changes before they enter the weave area. Therefore, it can be assumed that all the flow entering a weave area from a mainline is from the right-most-lane, i.e., Vr contains both all the exit and the through volumes. First, based on the results from the previous phase of this research (Kwon, et al, 2000), the maximum possible weaving volume for a given weave section can be estimated as follows:

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

where, $Wmax,k$ = Maximum possible weaving volume for time interval k,

$Wmax$ = Maximum through volume of an auxiliary lane,

Mc,k = Merging capacity at time k <= Entrance ramp capacity (Mc)

Xc,k = Exit capacity at time k <= Exit ramp capacity (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 3.4 shows the general relationships for Mc,k and Xc,k. The previous research also developed the following procedures to estimate both merging and exit capacities at time k, Mc,k and Xc,k, using the data collected until time k-1.

For Mc,k : Merging capacity during time k　　　*For Xc,k : Exit capacity during time k*

　If Om,k-1 <= Om,cr　　　　　　　　　　　*If Ox,k-1 <= Ox,cr*

　　then Mc,k = Mc　　　　　　　　　　　　*then Xc,k = Xc*

　　　else if Om,k-2 <= Om,cr, then Mc,k = Mc,　　*else if Xc,k-2 <= Ox,cr, then Xc,k = Xc,*

　　　　else Mc,k = (Mk-1 + Mk-2) /2　　　　　*else Xc,k = (Xk-1 + Xk-2)/2*

where, Om (x),k = Occupancy measurement during time interval k at the detector located at

　　　　　　　merge (exit) area,

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

It can be noted that the maximum weaving volume estimated through the above process denotes the maximum amount of flow at a given weave section if all the flows consist of weaving traffic, i.e., either merging or diverging vehicles. Therefore, the total volume that can enter a given weave section, $W_{C,k}$, i.e., maximum sum of Vr and E for time interval t in Figure 3.1, can be modeled as follows:

$$W_{C,k} = \theta_k * Wmax,k$$

therefore, the maximum right-most-lane volume during k, Vr,max, k, can be determined as

　　　　Vr,max, k = $W_{C,k}$ - E_k

　　where, θ_k >= 1.0, E_k = Entrance ramp volume during k.

In the above formula, θ_k is the adjustment factor reflecting unknown flow patterns at a given weaving section during time interval k and can be adaptively estimated using a Kalman Filter as follows:

　　　$\theta_{k+1} = \theta_k + \gamma_k W_{T,k} = \theta_k * W_k + \sigma_k$

where, $W_{T,k}$ = Observed total volume that entered a given weave section during k,

　　　W_k = Observed total weave volume during k,

　　　γ_k , σ_k = State and observation noise vectors assumed to be white noise.

The above formulation considers that the state variable follows a random walk process. Further, the initial values for θ and the covariance matrices for state and observation noise can be calibrated using historical data collected from each weaving site. The resulting estimation procedure for θ 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 $W_{T,\,k+1}$ using updated $\theta_{k+1/k}$, and measured W_k where $\theta_{k+1/k} = \theta_{\,k/k.}$

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

4) Obtain error $e_{\,k+1}$ using measured $W_{T,\,k+1}$.

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

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

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 process tries to determine iteratively through time the unbiased estimate of state variables with the most recent prediction error and has been applied to predict traffic parameters in real time in the past (Kwon, et al., 2000). The proposed procedure was tested with the data collected from the I-35W NB weaving site at I-694 interchange shown in Figure 3.3. This site is a single weave section, which is not affected by the downstream conditions unless there is an incident. Figures 3.4-6 include the prediction results for the maximum possible volume at the right-most-lane on the mainline, Detector ID 897, approaching the weaving segment for every 5-minute interval during afternoon peak periods of 3 different days. As indicated in these figures, the proposed procedure reasonably and accurately estimates the upper boundary of the right-most-lane volume through time, resulting in the mean percentage estimation error during congested periods of approximately 11%. In particular, the prediction results indicate the adaptability of the proposed procedure to prevailing traffic conditions in predicting the maximum possible volume that can approach the weaving segment at the right-most-lane through time.
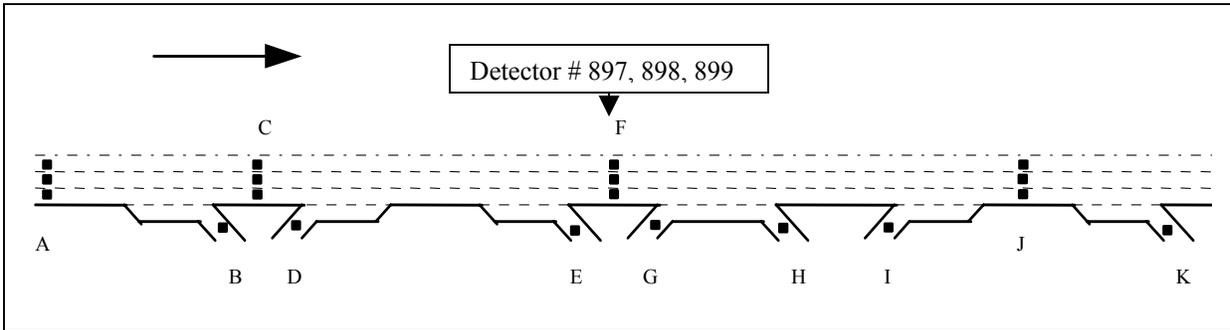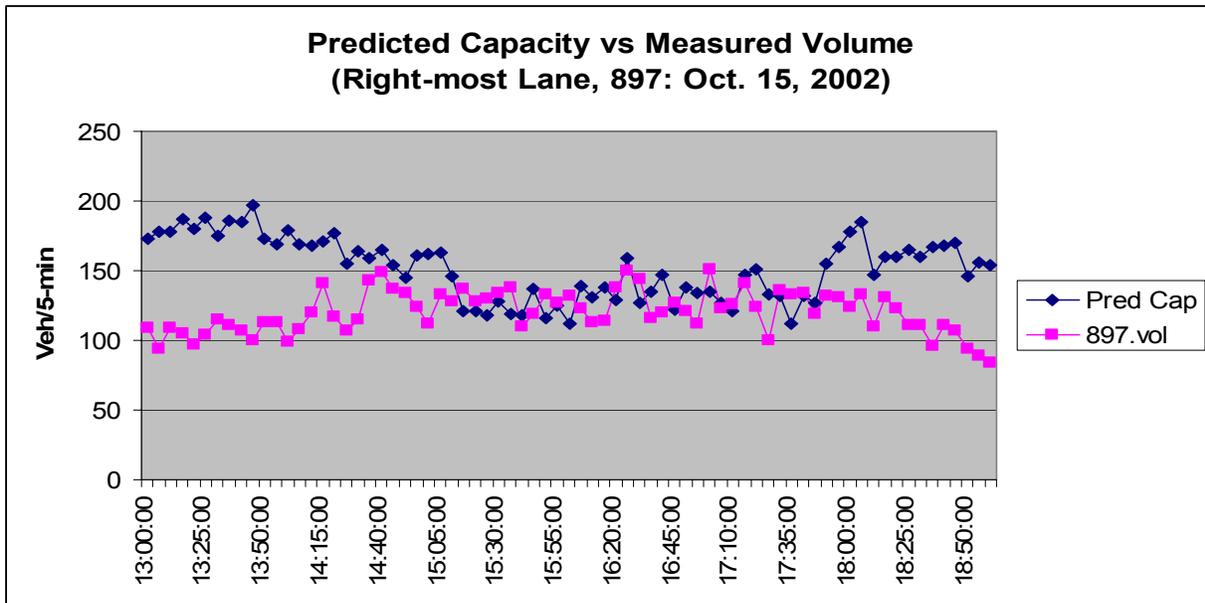
Figure 3.3 I-35 NB weaving site at I-694

Figure 3.4 Right-most-lane capacity prediction results: Oct. 15, 2002
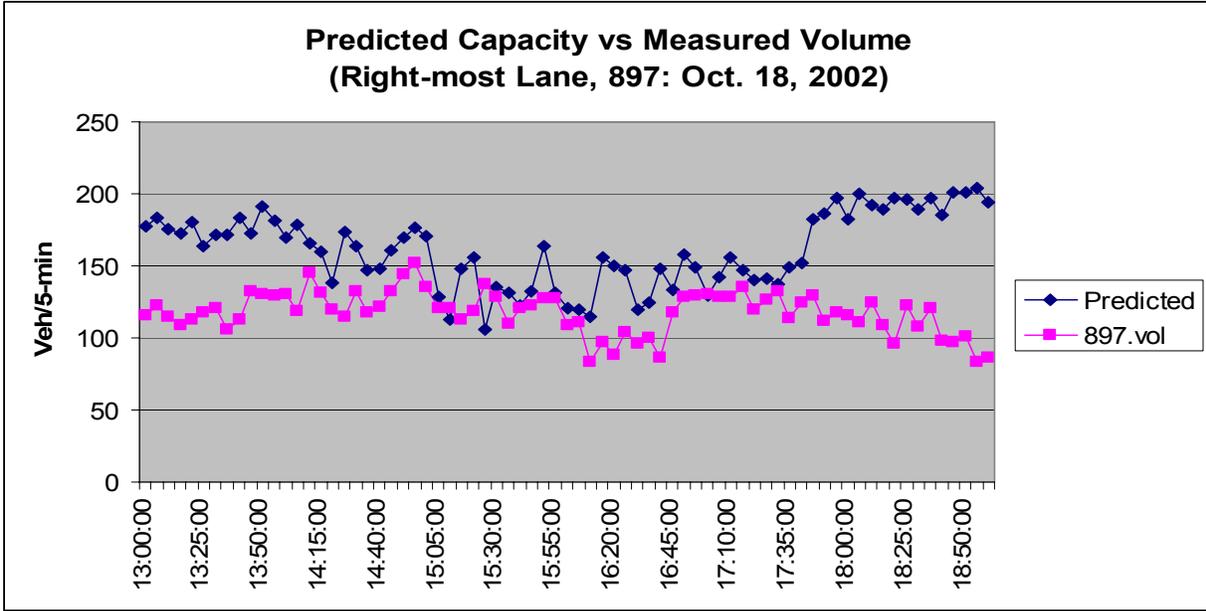
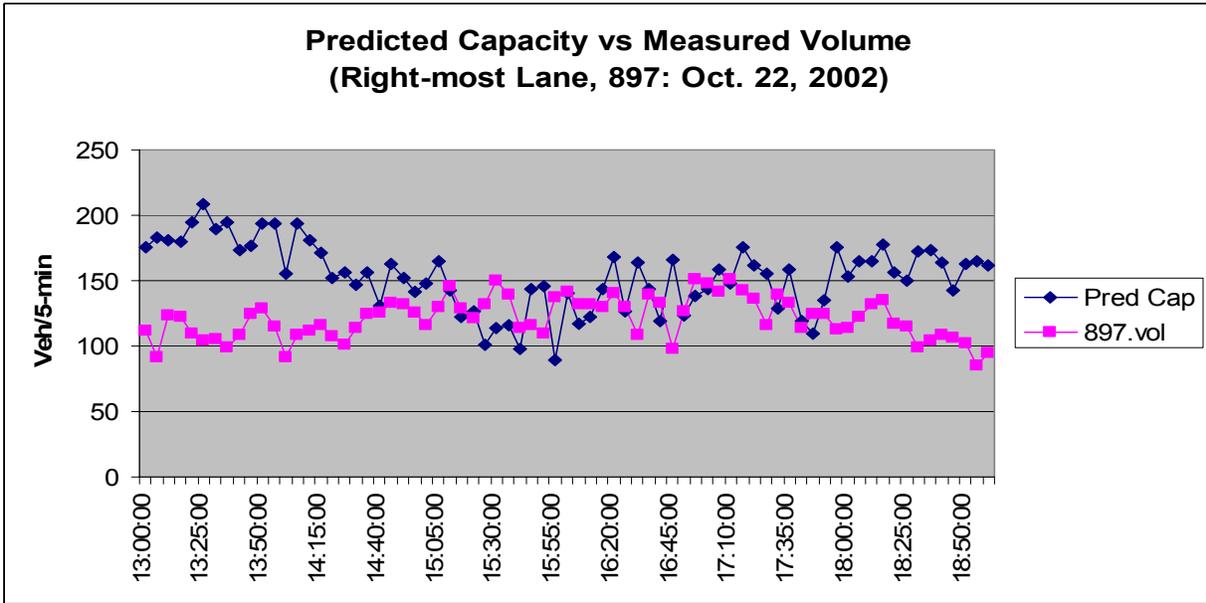Figure 3.5 Right-most-lane capacity prediction results: Oct. 18, 2002

Figure 3.6 Right-most-lane capacity prediction results: Oct. 22, 2002

3. 3 Estimation of Middle Lane Capacity in Mainline through Time

In this section, a procedure is developed to estimate the capacity of the middle lane next to the right-most-lane, i.e., V_m as shown in Figure 3.1. While the capacity of the right-most-lane before a weaving segment is directly affected by the traffic conditions at the subjective weaving area and the pattern of weaving flows, the congestion at the right-most-lane can cause 'side friction' to the middle lane flow, whose capacity can be significantly reduced depending on the level of speed at the right-most-lane. Figure 3.7 shows the variations of volume/occupancy of two lanes before the I-35W NB weaving site during an afternoon peak period. It can be noted that the difference between two lanes becomes greater as congestion increases. Further, as shown in Figures 3.8 and 3.9, there is a consistent pattern between the volume/occupancy values of right and middle lanes indicating that the middle lane traffic condition is governed by the congestion level of the right-most-lane. Figure 3.10 shows the relationship between two volume/occupancy values of right and left lanes at the 169 NB weaving site. As indicated, a strong linear pattern can be also found at this site, while the values of the linear function are different from those at the I-35W NB weaving section.
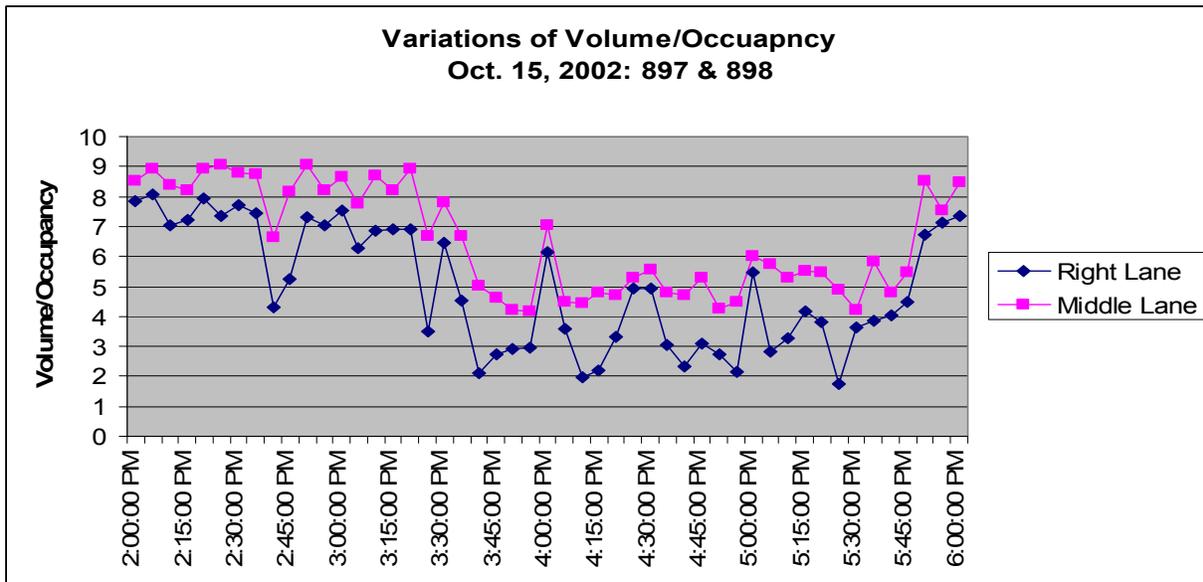

Figure 3.7 Volume/Occupancy variations through time for right and middle lanes
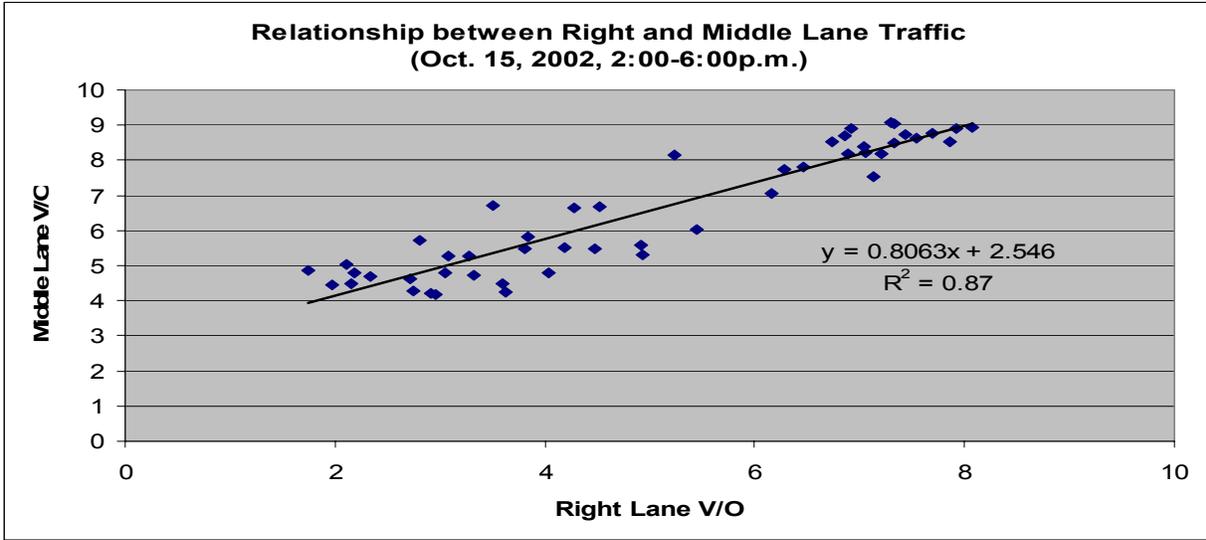
Figure 3.8 Relationship between volume/occupancy values of right and middle lanes (Oct.15)
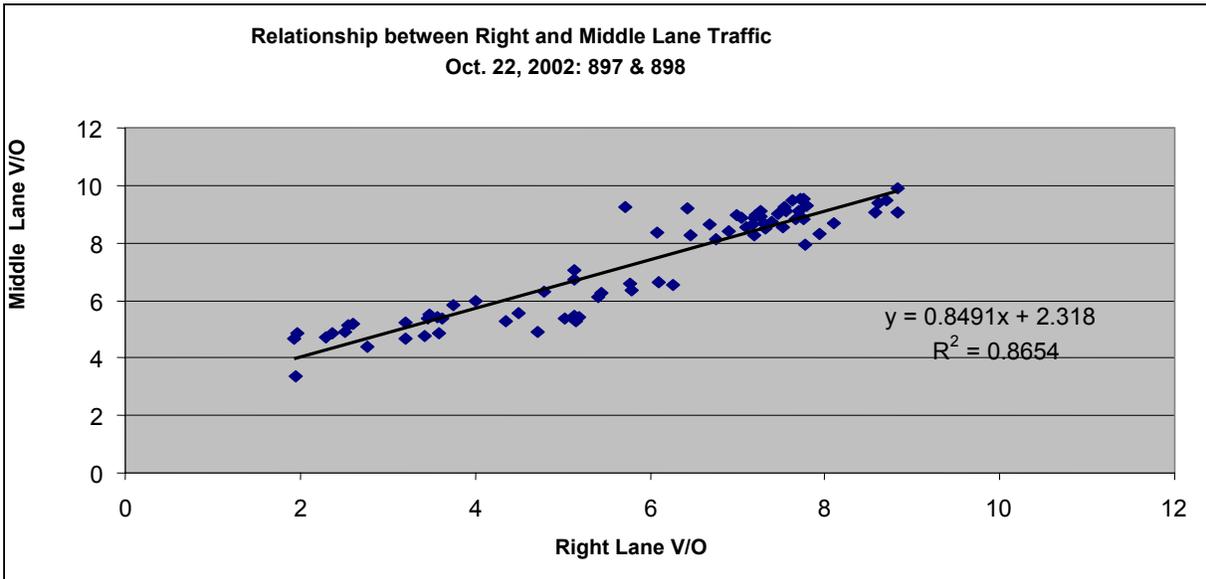

Figure 3.9 Relationship between volume/occupancy values of right and middle lanes (Oct.22)
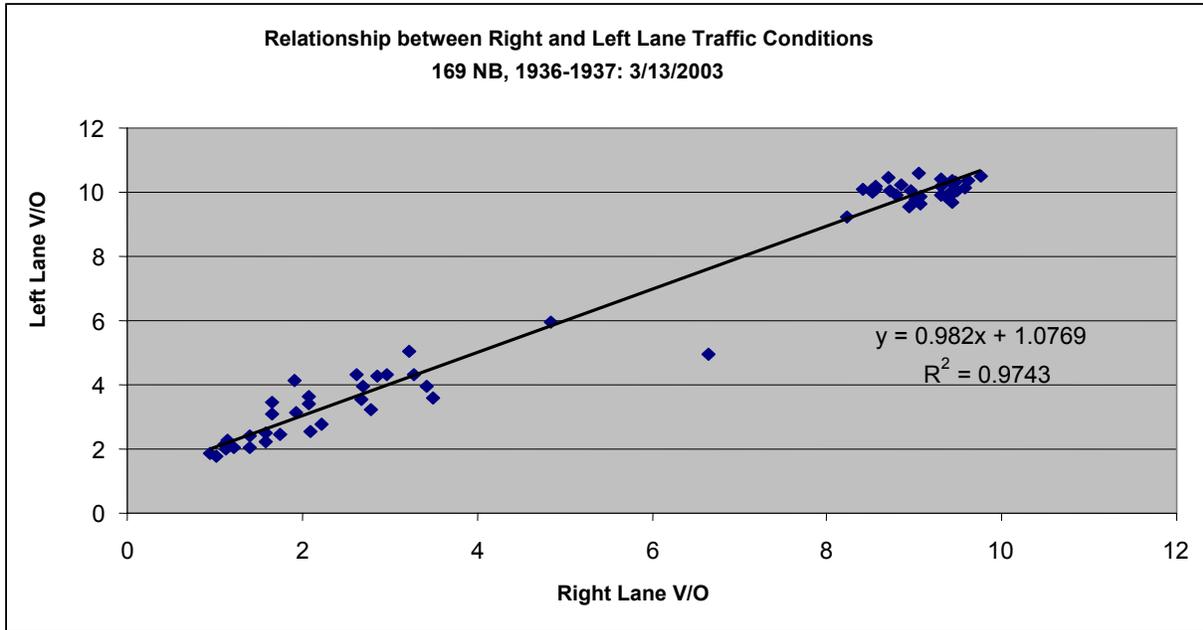
Figure 3.10 Relationship between volume/occupancy values of right and middle lanes (169 NB)

In this research, the above relationship is used to estimate the volume/occupancy value of the middle lane, $(V/O)_{m,t}$, for a given V/O value of the right-most-lane, $(V/O)_{r,t}$, before a weaving segment,

i.e., $(V/O)_{m,t} = a_t (V/O)_{r,t} + b_t$

where a_t and b_t are location-specific parameters that can be calibrated off-line or estimated in real time. In this study, constant values of a and b, calibrated off-line for each location, are used. Once the volume/occupancy value of the middle lane for time t is determined with a given v/o value of the right-most-lane, then the maximum volume of the middle lane for time t can be obtained from the volume/occupancy relationship of the middle lane as shown in Figure 3.11.

Volume

Estimated maximum
volume for a given V/O

Updated V-O
relationship with
(Ot, Vt)

Vt

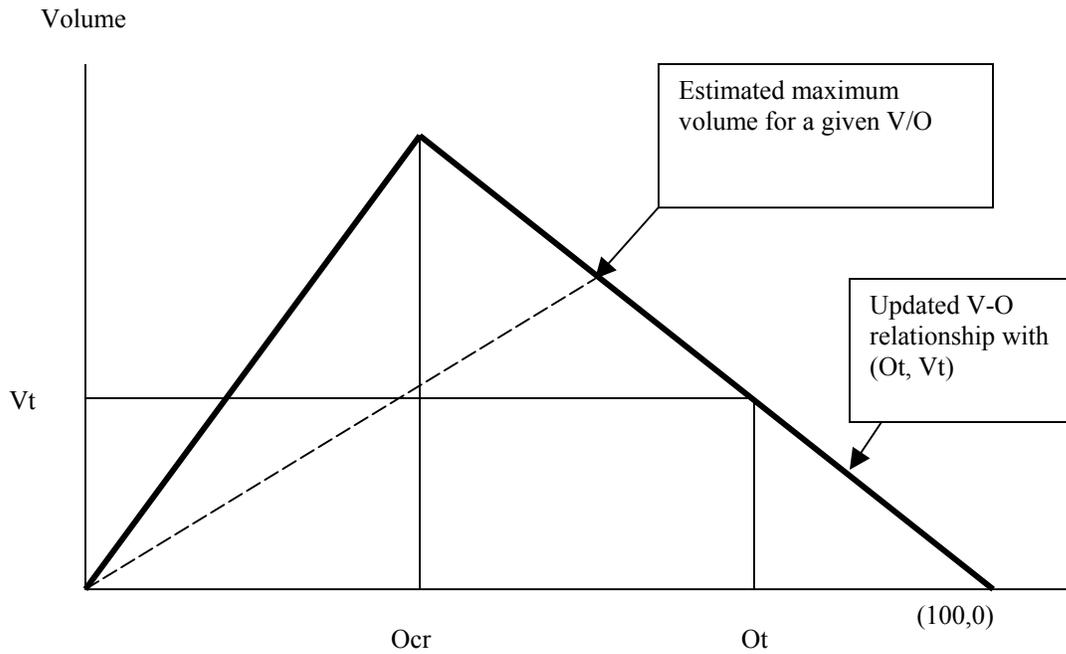Ocr   Ot

(100,0)

Figure 3.11 Simplified Volume/occupancy relationship

In this research, an adaptive procedure is developed to identify the parameter of a
simplified linear function of volume/occupancy through time using a Kalman Filter. As
illustrated in Figure 3.11, the volume/occupancy relationship for a congested region is assumed
to be a line connecting a measured data point at t, (O_t, V_t), and the jam point (100,0), i.e.,

$$\beta_{t+1} = \beta_t + w_t$$

$$O_t = \beta_t \left[(100 \ V_{t-1} - (100 - O_{t-1}) \ V_t)/V_{t-1}) \right] + \delta_t$$

For the un-congested region, i.e., Occupancy < Critical Occupancy, Ocr

$$O_t = \beta_t \left[V_t/(V_{t-1}/O_{t-1}) \right] + \delta_t$$

where, (O_t, V_t) = measured occupancy and volume values for time interval t,

β_t = adjustment factor updated in real time with a Kalman Filter,

w_t, δ_t = state and observation noise.

In the above formulation, β_t can be updated with a Kalman Filter using the same procedure described in the previous section. The above approach tries to approximate a real volume/occupancy relationship by continuously updating a simplified linear function with the data collected in real time, i.e., the above formula defines the relationship between occupancy and volume at time t based on the data measured up to t-1. Figures 3.12 and 3.13 show the test results of the above procedure with the data collected from Detector 897, located at the right-most-lane just before the I-35W NB weave site. In this testing, the linear volume/occupancy relationship for the given detector is first determined for time t with the data measured up to time t-1 with a Kalman Filter. Then using the measured volume at t, the corresponding occupancy value was estimated with the updated volume/occupancy relationship and compared with the actual measured one for every 5 minute interval. As indicated in these figures, the predicted occupancy values closely follow the measured ones resulting in the mean absolute error of 6 – 8 %.
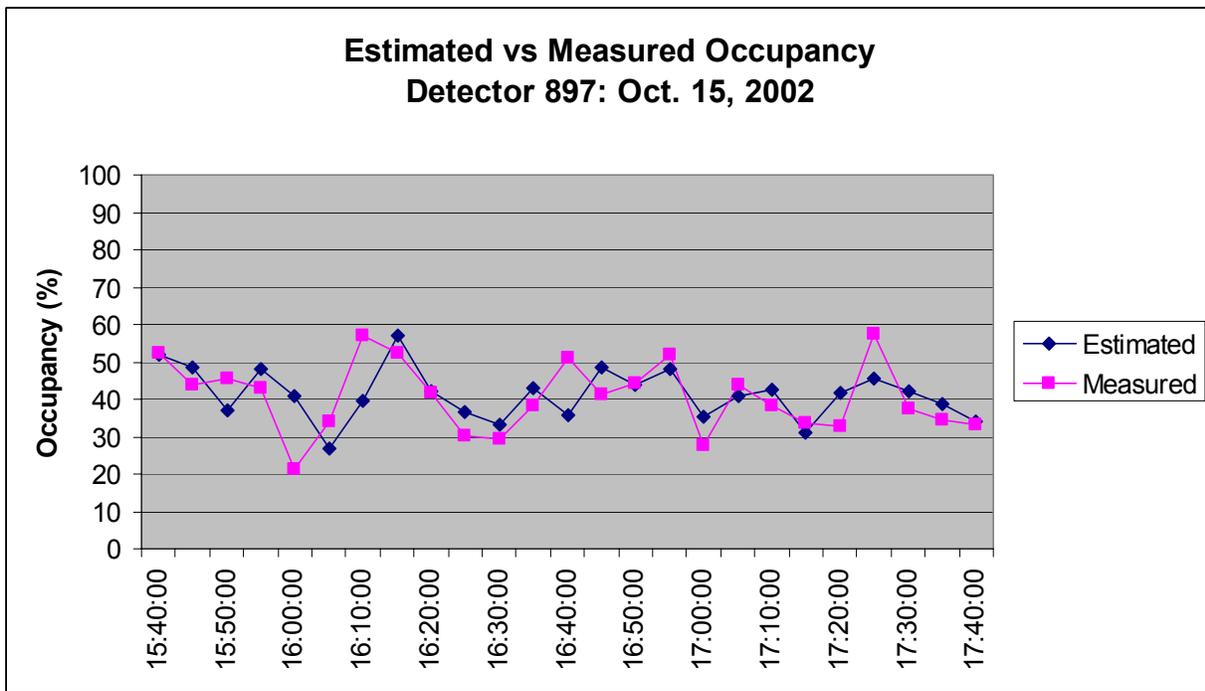

Figure 3.12 Test results of Volume/occupancy relationship identification process (Oct.15)
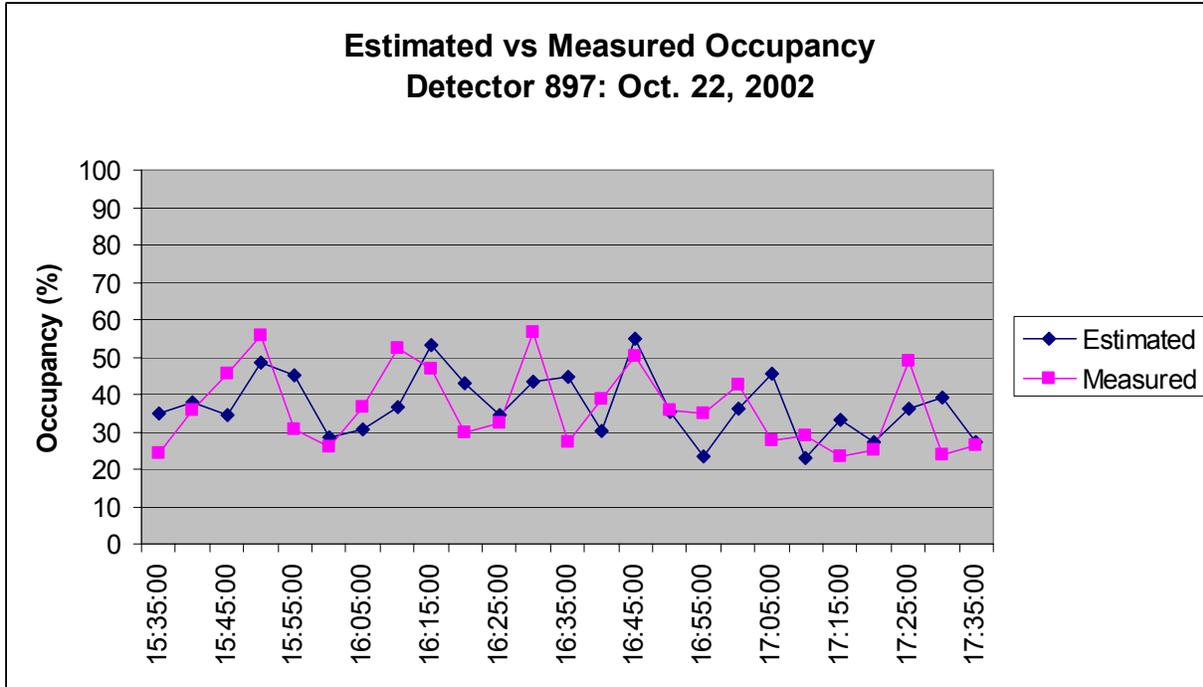
Figure 3.13 Test results of Volume/occupancy relationship identification process (Oct.22)

Once the functional V-O relationship is updated for each lane on the mainline approaching a given weaving site, and the value of V/O for the middle lane is determined for the next time interval, then the maximum volume that can be accommodated by the middle lane for next time interval can be estimated as the cross point between two lines as illustrated in Figure 3.11. The specific formula to determine the volume that corresponds to a particular V/O value in a congested region of the volume/occupancy space can be written as follows:

$$V_t = 100 \ V_{t-1} \ \alpha_t \ / \ [(100-O_{t-1})+V_{t-1}/(V/O)]$$

where, α_t is the adjustment factor for the Volume/occupancy relationship estimated with the data from t-1.

In summary, the process to estimate the maximum volume for the middle lane just before a weaving area can be described as follows:

1) Update volume/occupancy relationships of right-most and middle lanes using the measured data.

2) For the maximum right-most-lane flow estimated in the previous section, determine the corresponding occupancy value using an update volume/occupancy relationship and calculate the value of V/O.

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3) With the right-most-lane V/O value from the previous step, determine that of the middle lane using the V/O-relationship model calibrated for that location.

4) Determine the maximum volume at the middle lane for the next time interval by finding the volume on the updated V-O line for the given V/O value.

The above process was tested with the data collected from the right-most and middle lane at the I-35W NB weave site during one afternoon peak period. Figure 3.14 shows the test results of the middle lane capacity prediction compared with the measured volume through time on October 15, 2002. The mean percentage difference between estimated capacity and actual measured volume during congested periods was approximately 11%.

Testing Adaptive Estimation Procedure at 169 NB Weaving Sites

Finally, the proposed procedure was applied to the 169 NB consecutive weaving site, and both the maximum mainline volumes that the right and left lanes can accommodate through time at the beginning point of the first weave section were estimated for two afternoon peak periods in 2003. Figures 3.20 and 3.21 show the prediction results of those values along with the measured volumes for every 5 minute interval. It can be noted that the prediction results follow the change patterns in the traffic conditions at the weaving segment and determine the upper bounds of both the right-most and left-lane flows through time with reasonable accuracy. The mean percentage error of estimation during congested periods ranged from 9.5% to 10.6%.
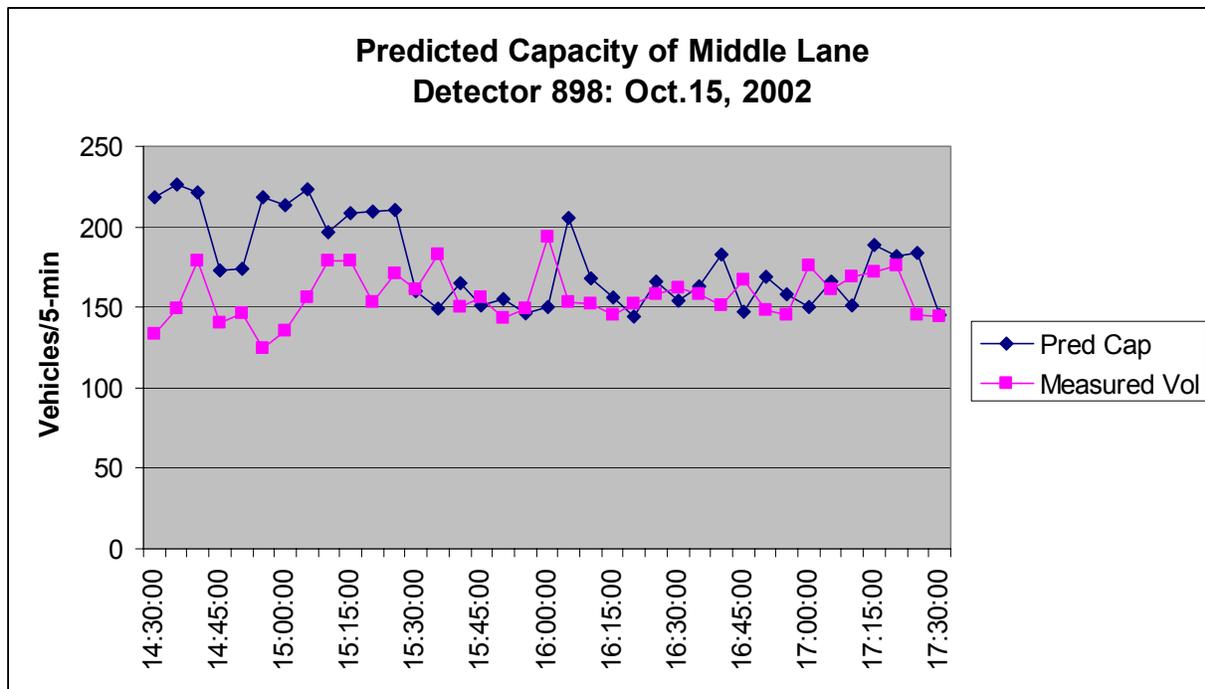

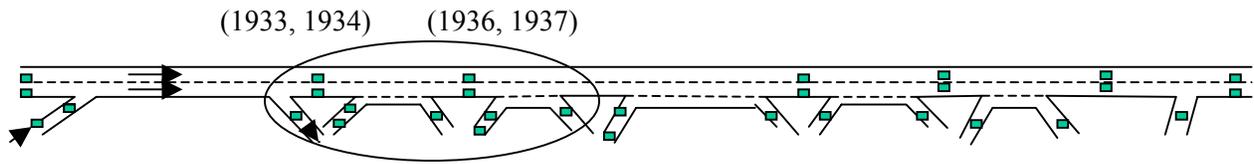Figure 3.14 Middle-lane capacity prediction results at I-35W NB weaving site
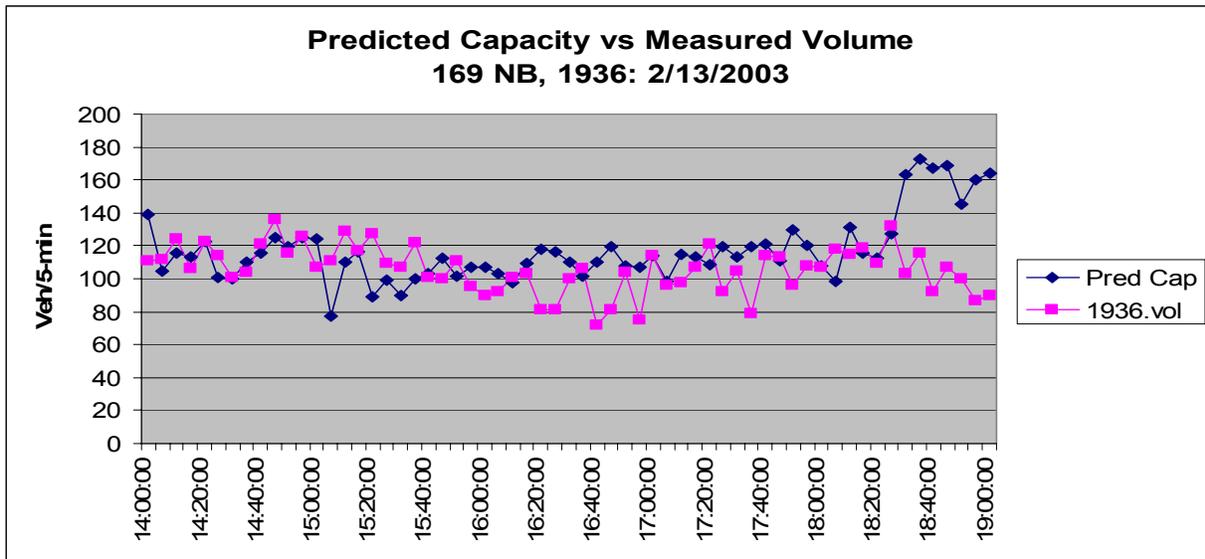
Figure 3.15 169 NB weaving site

Figure 3.16 Right-most-lane capacity estimation before 2nd weave (1936, 2/13/2003)
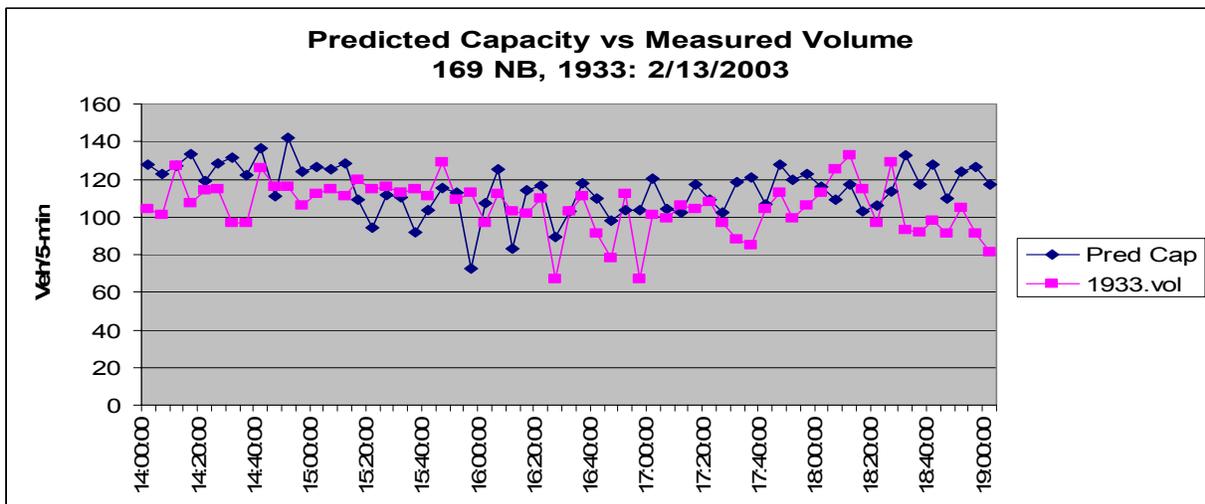

Figure 3.17 Right-most-lane capacity estimation before 1st weave (1933, 2/13/2003)
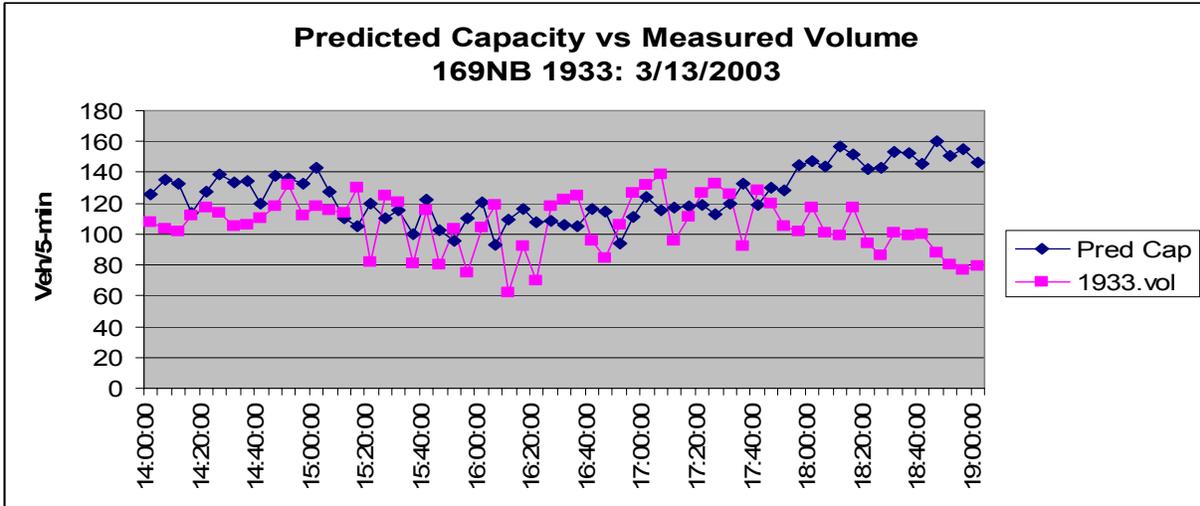
Figure 3.18 Right-most-lane capacity estimation before 1st Weave (1933, 3/13/2003)
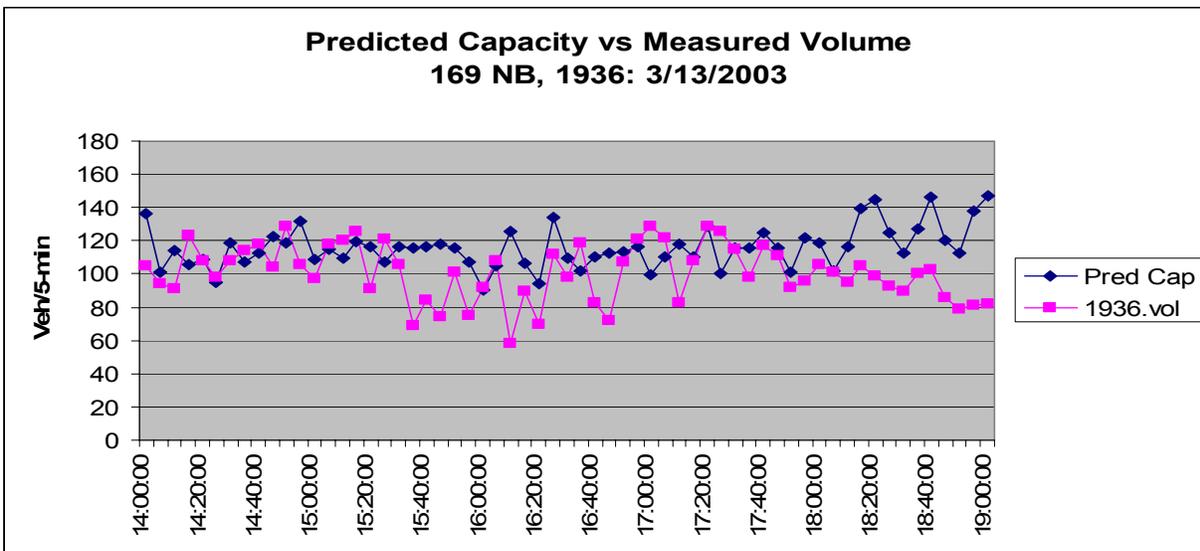

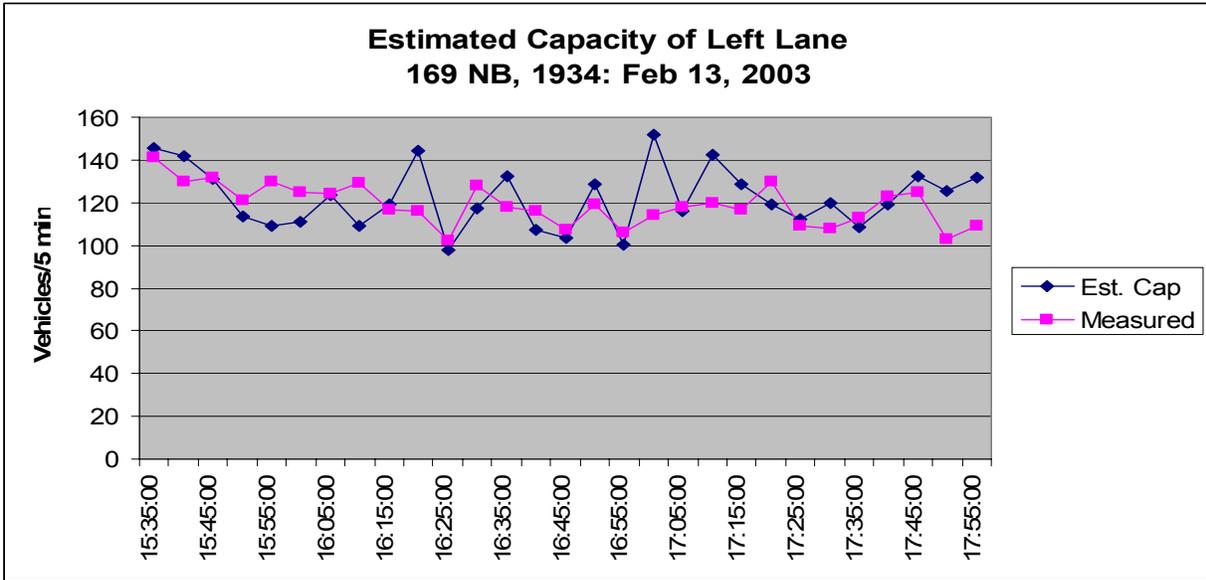Figure 3.19 Right-most-lane capacity estimation before 1st weave (1933, 3/13/2003)

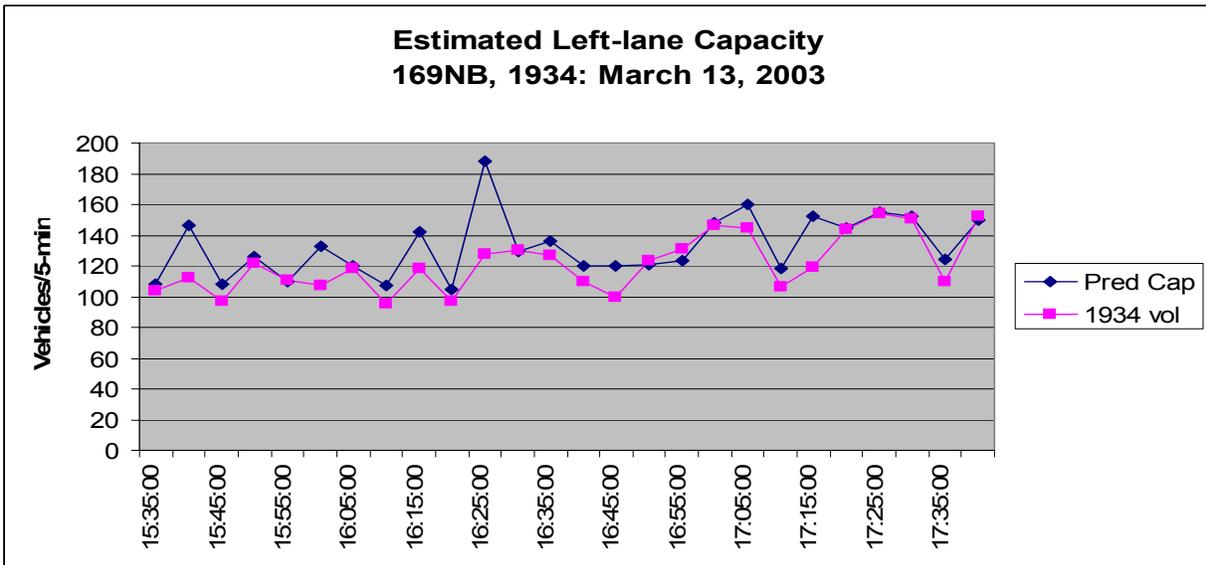Figure 3.20 Testing results of left-lane capacity: Feb 13, 2003

Figure 3.21 Testing results of left-lane capacity: March 13, 2003

4. CONCLUSIONS

Estimating the time-variant capacity reduction in freeway weaving areas has been one of the major issues in freeway operations. In particular, the complex interaction among different flows at consecutive weaving sections, which have short spacing between two weaving segments, makes those weaving sites major bottlenecks during peak periods. While there have been several research efforts to address the capacity issues in weaving areas, there is still lack of a practical on-line procedure that can be used to estimate the time-variant maximum volume that can enter given weave areas with currently available data.

In this research an adaptive procedure was developed to estimate the time-variant capacity of freeway weaving areas using commonly available data from single loop detectors. The proposed procedure explicitly addresses the effects of entrance ramp flows, which can be controlled through metering, on the maximum possible mainline volume approaching weave areas. First, the traffic behavior at several weaving sites that have consecutive weaving segments were analyzed using the loop and video data as well as visual observation. The major findings from this analysis include:

- The right-most-lane flow approaching a first weaving segment contains the vehicles exiting through the first and second exit ramps in a given consecutive weaving segment. This reduces the merging capacity at the mainline portion of the first weaving section and therefore results in a smaller weaving capacity than that of the second weaving segment. The level of capacity reduction depends on complex traffic patterns including the amount of vehicles exiting through the second off-ramp.
- The reduction of weaving capacity at the first weaving segment also results in increased congestion at the right-most-lane before the first weaving segment. The right-most-lane congestion can cause 'side friction' effects on the adjacent lanes, i.e., middle and left-most lanes, whose speed levels decrease as a function of the right-most-lane speed level. It was also found out that there existed a clear pattern between the volume/occupancy values of right-most and adjacent lanes.
- Most lane-changing within a consecutive weaving segment is discretionary and no clear pattern was found between amount of lane-changing and the capacity reduction of the merged lane.
- As in a single weave section, the maximum volume that can be accommodated by a consecutive weaving area varies through time, depending on the patterns of traffic flows as well as geometric conditions.

Based on the above findings, an adaptive estimation procedure that uses only the data from single loop detectors, i.e., volume and occupancy, was developed and tested with the real data collected from the sample sites. The test results indicate that the proposed procedure can estimate the time-variant capacity of the weaving segment in a consecutive weaving area with reasonable accuracy. In particular, the results clearly exhibit the adaptability of the proposed procedure to the prevailing traffic conditions in determining the upper boundaries of the flows entering a given weave area through time. Further, the use of the volume/occupancy ratio in determining the time-variant capacity of the adjacent lane showed promising results along with the simplified representation of volume/occupancy relationships.

The proposed capacity estimation procedure can be directly applicable in improving ramp metering operations, which currently use fixed capacity at mainline detector stations. The complex flow patterns at consecutive weaving areas, identified in this research, can also be used

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to develop better designs of freeways involving weaving segments. Future research needs to include improvement of the ramp metering algorithm to reflect time-variant capacities and continuous enhancement of adaptive estimation procedures to improve the accuracy of the procedure.

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