Proposed Analytical Technique for Estimating Capacity and Level of Service of Major Freeway Weaving Sections

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Weaving typically occurs where merging traffic movements cross over diverging movements. The prevalence of weaving areas on freeways warrants the need for analytical techniques that can reliably analyze or design these critical freeway components. However, previous research at the University of California suggested that existing analytical procedures may not predict weaving operation with a sufficient degree of reliability. Consequently, a more reliable procedure for evaluating weaving performance was developed. Unlike most existing procedures, the proposed technique evaluates traffic flow behavior in individual lanes of the weaving section. The procedure is applicable to major weaving areas, a subset of all weaving configurations. The proposed procedure predicts vehicle flow rates in critical regions within the weaving section as a function of prevailing traffic flow and geometric conditions. Predicted flows are then used to assess the capacity sufficiency and level of service of a subject weaving area. The model itself was developed using large amounts of empirical and simulation data, collected from a number of sites throughout California. Some of the more interesting traffic flow characteristics empirically observed on a single weaving site are highlighted. Moreover, the basic format of the proposed procedure is presented.

The 1985 Highway Capacity Manual (HCM) (*1*) defines weaving as "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway, without the aid of traffic control devices." For freeway facilities, a weaving section is typically formed "when a merge area is closely followed by a diverge area, or when an on-ramp is closely followed by an off-ramp and the two are joined by an auxiliary lane." Four types of traffic movements will generally travel on a freeway weaving section:

- Freeway-to-freeway traffic (a nonweaving movement),
- Freeway-to-off-ramp traffic (a weaving movement),
- On-ramp-to-freeway traffic (a weaving movement), and
- On-ramp to off-ramp traffic (a nonweaving movement).

These four traffic movements are shown in Figure 1.

Considerable lane-changing activity typically occurs on weaving sections as motorists access lanes appropriate for their destinations. Vehicular conflicts occur as weaving traffic movements are forced to cross one another and merge into nonweaving traffic streams. These intense lane-changing maneuvers often result in operational problems within the weaving area.

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RESEARCH SCOPE

An improved analytical technique for analyzing and designing freeway weaving areas has been developed. Major weaving sections were emphasized. Such weaving configurations are formed where at least three of the weaving areas' entrance and exit legs have two or more lanes. (Figure 1 shows one possible geometric configuration for a major weaving section.) This type of weaving configuration commonly occurs at freeway-to-freeway interchanges.

The proposed weaving technique is presented. In calibrating the proposed procedure, a great deal of empirical (and simulation) data were collected from numerous weaving sites in California. Space constraints prohibit presentation of all data and analysis results. Thus, in the interest of brevity, empirical observations were collected from a single weaving site. These data reveal some of the more interesting traffic flow characteristics observed in the overall study; Cassidy et al. (*2*) present greater detail.

Existing Weaving Procedures

Given the prevalence of weaving sections on freeways, and the turbulence problems often associated with weaving operation, the need exists for analytical techniques that reliably model weaving performance. A number of existing analytical procedures are available for analyzing and designing freeway weaving areas (*3–8*). These procedures typically attempt to predict the average travel speed of vehicles operating on the subject weaving section as a function of certain prevailing traffic flow and geometric conditions. However, data collected and analyzed by the Institute of Transportation Studies (ITS) at the University of California (*9–12*) and the California Department of Transportation (Caltrans) (*13*) indicate that the existing procedures cannot reliably predict operation observed on weaving areas in California. Much of these findings have been outlined by Cassidy et al. (*9*). There are several

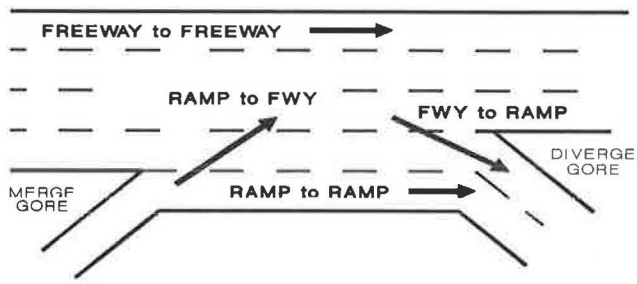

FIGURE 1 Weaving area traffic movements.

possible explanations for the deficiencies associated with the existing analytical techniques.

The procedures use aggregate traffic volumes to predict performance. That is to say, information reflecting total flow conditions operating on the subject weaving section is used to predict average travel speeds. No attempts are made to model the lane use distributions of vehicles or the lane-changing patterns of traffic within the subject weaving area.

However, the operation of freeway weaving sections may be largely influenced by what is occurring in individual lanes. Thus, operational performance can perhaps best be modeled on a lane-by-lane basis. The distribution of vehicles across available lanes and the conflicts created by weaving vehicles should be considered. Only in this way can the complex interactions occurring between weaving and nonweaving traffic streams be reliably modeled.

Input requirements for the existing procedures generally include variables that represent basic geometric design conditions of a subject weaving area. Given the influence of geometrics on traffic flow behavior, weaving procedures should perhaps consider geometrics more explicitly.

Perhaps the most significant problem associated with the existing procedures is the measure of effectiveness used. It appears that average vehicle travel speed does not reliably reflect operational quality occurring in a weaving section. Figure 2 is a scatterplot of average traffic flow per lane (V/N) versus average composite vehicle travel speed. Note that this composite speed represents a weighted average observed among weaving and nonweaving traffic movements. Data points shown in Figure 2 represent 5-min empirical observations collected from eight major freeway weaving sites in California (*14*).

Referring to Figure 2, speed appears to be rather insensitive to flow, up to V/N values of about 1,600 passenger cars per hour (pcph). Thus, average speed does not decrease with decreasing level of service (LOS) (i.e., with operational quality). Moreover, the high observed variance exhibited in Figure 2 suggests that speed is not easily predicted given aggregate flow information.

Research Approach

As a result of research efforts at ITS, a proposed procedure has been developed for analyzing and designing major freeway weaving sections. In an effort to remedy potential weaknesses in the existing weaving techniques, the proposed procedure consists of a different analytical framework. Rather than predicting the average speeds of vehicles traveling in the weaving area, the proposed technique predicts the distribution of vehicles at any location within the right-most lanes of a major weave. In other words, the proportions of each traffic movement occupying the right-hand lanes of the weaving area are estimated and used to measure operational performance. In this way, the proposed technique evaluates performance by examining traffic flow behavior in individual lanes of a subject weaving section.

By predicting the number of vehicles in individual lanes, the proposed approach models lane use. Moreover, changes in vehicle distributions (within individual lanes) over some interval of length reflect lane-changing activity. Both lane utilization and lane-changing activity can be used to reflect capacity of a given weaving area. One of the primary objectives behind this work was to identify weaving area capacity and to develop a technique to determine under which geometric and traffic flow conditions capacity is exceeded.

Lane utilization and lane changing activity also reflect motorists' perceptions concerning service quality. The proposed measure of effectiveness used in assessing weaving area level of service is discussed in a later section.

The analytical approach presented was originally developed by Moskowitz (*15*). The procedure is included in the 1965 HCM (*7*). However, the Moskowitz procedure was developed using data observed on so-called ramp weave sections. Such weaving areas are formed where a one-lane on-ramp is followed by a one-lane off-ramp and the two are joined by a

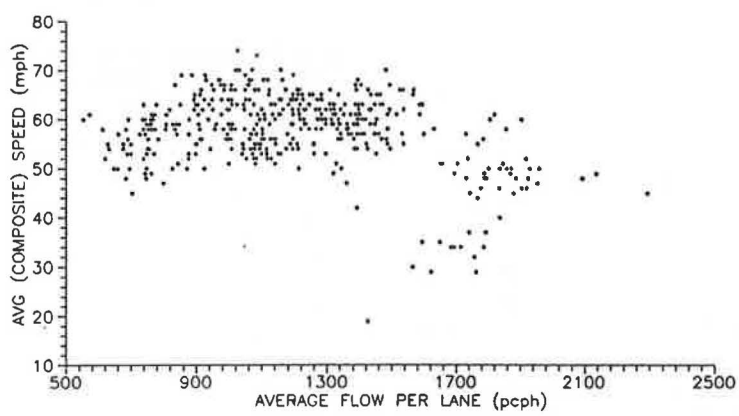

FIGURE 2 Average (composite) travel speed versus average flow per lane.

continuous auxiliary lane. (The geometric configuration of such a weaving section does not vary.)

Moreover, the Moskowitz procedure does not predict operation as a function of traffic flow conditions. The procedure was originally developed to evaluate high-flow (i.e., near-capacity) conditions. The procedure does not account for the effects of varied contributions from the four traffic movements (as shown in Figure 1).

In contrast, the proposed technique was developed to evaluate weaving operation as a function of geometric design and varying traffic flow conditions. The effects of geometric design and traffic flows are further examined in the following section.

EMPIRICAL OBSERVATIONS

To develop the proposed procedure, more than 30 hr of empirical data were collected from 9 major weaving sites in California and analyzed in considerable detail. In the interest of brevity, empirical observations from only one weaving location are presented. Data from this weaving site reflect some of the more interesting operational patterns observed on all weaving test beds.

The Weaving Test Site

Operational data presented were collected on the westbound San Bernardino Freeway, just east of Los Angeles, California. The weaving section itself is formed by a one-lane on-ramp (Garvey Avenue) followed by a two-lane off-ramp (Freeway 605 Interchange). The distance between the painted merge and diverge gore points (i.e., the ends of the painted merge and diverge areas) is 1,460 ft. The weaving site is shown in Figure 3.

Data Collection

In this research, operational data were collected using video recording. Videotaping traffic provides a permanent record of the data that can later be analyzed at various levels of detail or rechecked as necessary. A Panasonic camera model WV-3250, with a 12:1 lens, was mounted on a tripod and stationed at overcrossings immediately upstream or downstream of the subject weaving areas. The camera was positioned such that the operation of the entire weaving section could be videotaped. Once captured on video, appropriate operational data were extracted directly from the video tapes. Required data were processed through repeated viewing on a large monitor.

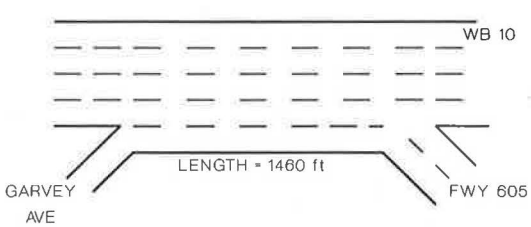

FIGURE 3 Weaving site.

All empirical data were collected by 5-min totals. Just under 5 hr of operational data (i.e., fifty-nine 5-min data points) were collected from the weaving site. These observations were collected during a.m. and p.m. peak periods and the noon off-peak period.

As previously stated, the proposed technique predicts traffic flow behavior in the rightmost portion of a subject weaving area. It is this portion of the weaving section that typically experiences the greatest turbulence because of merging and diverging traffic streams. For this reason, spatial distribution data were collected only in the weaving site's auxiliary lane (Lane 1) and the rightmost freeway lane (Lane 2).

In collecting spatial distribution data, the weaving site was divided into reference points located at fixed intervals within the weaving section's right-hand lanes. Flows from each of the four traffic movements were measured at these points. The first reference points are located 0 ft downstream of the painted merge gore point (i.e., the entrance of the weaving section). The second and third sets of reference points are located 250 and 500 ft downstream of the painted merge point, respectively. Remaining reference points are sequentially located at 500-ft intervals until the end of the weaving area (i.e., the painted diverge gore point) is reached.

Data Analysis

Freeway-to-Ramp Traffic

In an effort to evaluate the traffic flow behavior of freeway-to-ramp vehicles (in individual lanes) as a function of the location within the weaving section, scatterplots were constructed illustrating the observed percent spatial distributions of freeway-to-ramp vehicles versus the location within the weave. Figure 4 shows these spatial distributions in Lane 1 for the a.m., noon, and p.m. data. Each data point represents a 5-min empirical observation.

Figure 4 shows that these spatial distributions follow a logical pattern. For all time periods, roughly 5 percent of the freeway-to-ramp traffic travel in Lane 1 at a location 0 ft

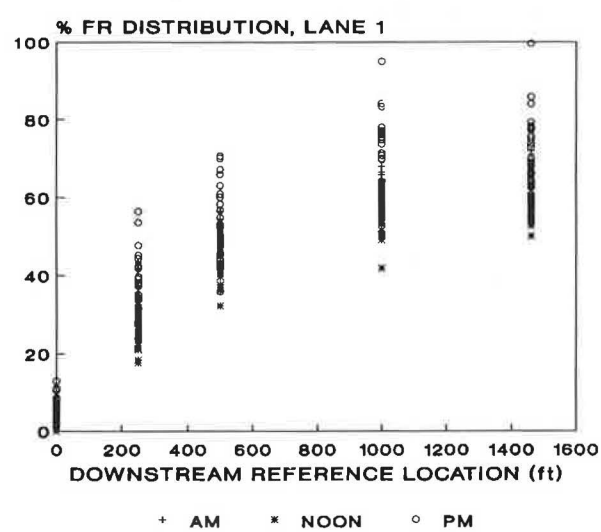

FIGURE 4 Freeway-to-ramp distributions, Lane 1.

downstream of the painted merge gore point. These vehicles perform somewhat premature lane changing by actually crossing into the painted merge gore area on executing their maneuver.

At a point 250 ft downstream of the merge gore, approximately 25 to 35 percent of the freeway-to-ramp vehicles are traveling in Lane 1. At this 250-ft location, the remaining freeway-to-ramp vehicles are traveling in Lane 2 or in median lanes.

At a point 500 ft downstream of the merge gore, about 45 to 55 percent of freeway-to-ramp traffic is traveling in Lane 1. The proportion of freeway-to-ramp vehicles traveling in Lane 1 continues to increase (slightly) at further downstream locations. Figure 4 shows how freeway-to-ramp vehicles diverge to the right as they move downstream within the weaving area.

Figure 5 shows freeway-to-ramp spatial distributions in Lane 2 as a function of the downstream location for a.m., noon, and p.m. data. The pattern appears compatible with Lane 1 flows. The proportion of freeway-to-ramp traffic in Lane 2 declines as vehicles move downstream within the weaving section.

Figures 4 and 5 indicate that the majority of lane changes made by freeway-to-ramp vehicles occur within the first 500 ft of the weaving area. Figures 4 and 5 suggest that a fair amount of scatter does exist among freeway-to-ramp observations. Much of this variance is caused by varying traffic flow conditions occurring during data collection periods.

Analysis of variance (ANOVA) tests were performed on the spatial distributions of each time period (i.e., a.m., noon, p.m.) at each reference location. At the 0.05 significance level, the null hypothesis (μa.m. = μnoon = μp.m.) could not be accepted at all but one reference location. Thus statistically significant differences exist between the distribution means of the a.m., noon, and p.m. observations.

Thus, some traffic flow parameters, or related externalities, may be contributing to differences in observed traffic flow patterns across all three time periods, as well as the variances exhibited within individual time periods. The traffic flow parameters that influence the operation of major weaving areas can therefore be determined by identifying the parameters causing scatter among the observed traffic flow patterns.

The traffic flow parameter that appears to be most clearly influencing the behavior of freeway-to-ramp vehicles on the weaving site is weaving flow rate (i.e., the sum of the freeway-to-ramp and ramp-to-freeway flow rates). Figure 6 is a scatterplot of the percent of freeway-to-ramp traffic traveling in Lane 2, at 250 ft downstream of the painted merge gore versus weaving flow. The figure indicates a downward-sloping relationship between these two variables. It suggests that as weaving flows increase, freeway-to-ramp motorists become more anxious to change lanes over shorter traveled distances (i.e., lane changes occur closer to the merge gore). Such a relationship may logically reflect motorist desires. Where weaving intensity increases, motorists may sense greater pressure in performing driving tasks. This increased feeling of pressure may encourage motorists to perform lane-change maneuvers as soon as possible. On the subject weaving site, ramp-to-freeway and ramp-to-ramp traffic operate at relatively low flow levels. Thus, these movements exhibit a preponderance of available gaps. Freeway-to-ramp motorists, wishing to perform required maneuvers as soon as possible, accept the first suitable gaps in conflicting traffic streams and are therefore able to change lanes over shorter traveled distances.

The ability of freeway-to-ramp motorists to perform lane changes in shorter distances under observed high-weaving flows is linked to the fact that freeway-to-ramp vehicles represent the predominant weaving movement on the weaving site. It was observed that on other weaving sites, where freeway-to-ramp vehicles comprise the smaller weaving movement, freeway-to-ramp motorists require greater distances to perform desired lane changes as weaving flow rates increase. Overall findings suggest that lane-changing characteristics are a function of gap availability in conflicting traffic streams.

As shown in Figure 6, the proportions of freeway-to-ramp traffic traveling in Lane 2, at 250 ft, were divided into three partitions:

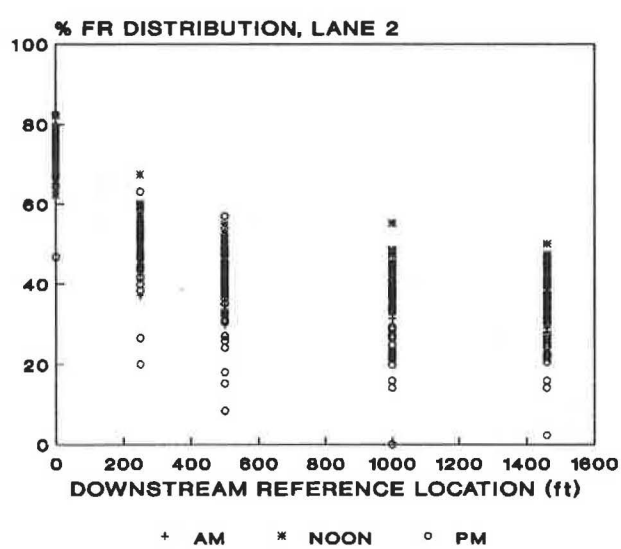

FIGURE 5 Freeway-to-ramp distributions, Lane 2.

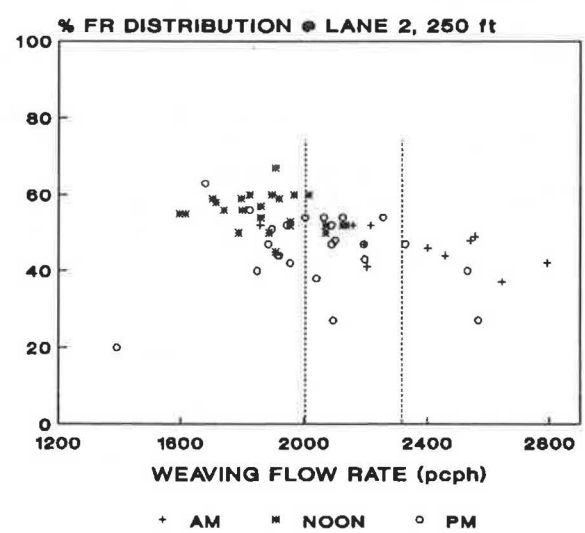

FIGURE 6 Freeway-to-ramp distributions, Lane 2, at 250 ft, versus weaving flow rate.

1. Observations where total weaving flow rates are less than 2,000 passenger cars per hour (pcph).
2. Observations where total weaving flow rates are between 2,000 and 2,300 pcph.
3. Observations where total weaving flow rates exceed 2,300 pcph.

ANOVA and difference of means (DOM) tests indicate that a.m., noon, and p.m. observations within these three partitions do not have statistically significant differences in their distribution means. Thus, three flow regimes have been identified. By partitioning the data, observations from all three time periods can be directly combined (within partitions). Similar findings occurred at other reference points within the subject weaving site.

Ramp to Freeway Traffic

Figures 7 and 8 show the spatial distributions of ramp-to-freeway traffic traveling in Lanes 1 and 2 for a.m., noon, and p.m. observations. Figure 7 shows that no ramp-to-freeway vehicles remain in Lane 1 at the downstream end of the weaving site (i.e., at 1,460 ft). This is logical given that Lane 1 of the subject weaving site is a mandatory off-ramp lane. Ramp-to-freeway vehicles must exit Lane 1 within the length of the weaving section.

Figure 8 shows that less than 100 percent of the ramp-to-freeway vehicles typically travel in Lane 2 at the downstream end of the weaving section. This merely illustrates that a portion of the ramp-to-freeway vehicles have merged from Lane 2 into the median lanes within the length of the weaving area.

The data shown in Figures 7 and 8 exhibit a high degree of scatter. These higher-observed variances are caused by two factors:

1. Ramp-to-freeway vehicles comprise the smaller weaving movement on the subject site.
2. Ramp-to-freeway vehicles are forced to change lanes using available gaps in conflicting traffic streams (i.e., freeway-to-ramp and freeway-to-freeway movements) that operate under high-flow conditions.

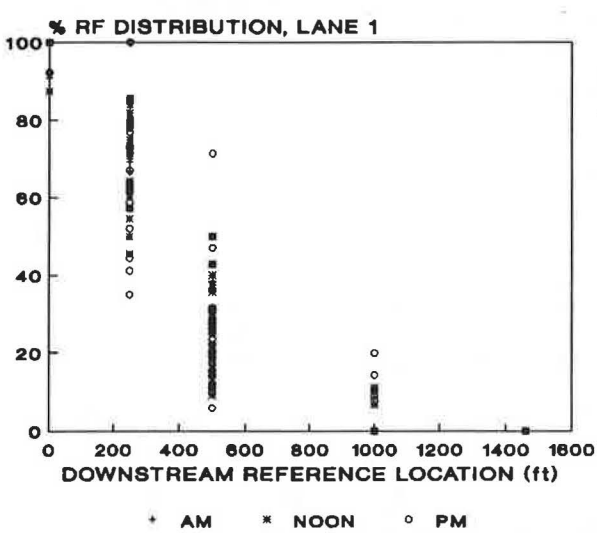

FIGURE 7 Ramp-to-freeway distributions, Lane 1.

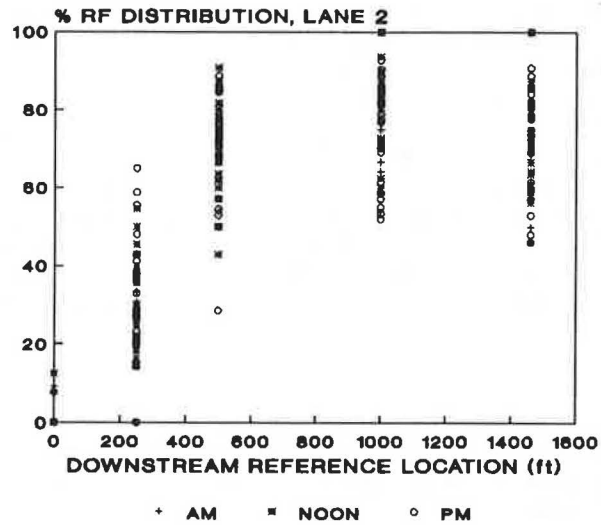

FIGURE 8 Ramp-to-freeway distributions, Lane 2.

The explanation of how these two factors contribute to higher observed variances is fairly straightforward. The lane-changing behavior of individual vehicles can be approximated as a binomial process. For example, a ramp-to-freeway vehicle traveling in Lane 1 of a weaving section will either (a) cross over a reference point located downstream in Lane 1, or (b) avoid crossing over the reference point by changing lanes.

This process can be represented by the indicator function:

$$x = \begin{cases} 1 \text{ if vehicle crosses reference point} \\ 0 \text{ if vehicle does not cross reference point} \end{cases}$$

Let x_i represent a single binomial event. The number of vehicles (in a particular traffic movement) actually crossing a given reference point, Σ_n, can be represented as

$$\Sigma_n = x_1 + x_2 + \ldots x_n$$

Represented as a proportion,

$$\Sigma_n/n = (x_1 + x_2 + \ldots x_n)/n$$

Because each binomial event x_i can be approximated as an independent identically distributed random variable,

$$\text{VAR}\ (\Sigma_n/n) = (1/n^2)\ [n * \text{VAR}\ (x)] = (1/n)\ \text{VAR}\ (x)$$

Each sample mean shown in Figures 7 and 8 can be thought of as independently identically distributed random variables. Therefore, the observed variance among sample means is

$$\text{VAR (5-min observations)} = N * \text{VAR}\ (\Sigma_n/n)$$

where N is the number of 5-min observations.

Thus, the variance among the 5-min data points is inversely proportional to n, the number of vehicles observed during the individual 5-min periods. Ramp-to-freeway flow is signifi-

cantly lower than freeway-to-ramp flow on the subject weaving site. This partially explains the higher variances exhibited in Figures 7 and 8.

The scatter among ramp-to-freeway observations on the subject site is also influenced by conflicting traffic movements. The term VAR (x) represents the variations among individual lane-changing movements. These variations are clearly a function of the gaps available to individual lane-changing vehicles.

P is defined as the probability that a lane-changing vehicle accepts a gap in the conflicting traffic streams. Recalling that lane-changing behavior can be approximated as a binomial process,

$$\text{VAR}(x) = Pq$$

where q is defined as the probability that a lane-changing vehicle will not accept a gap in conflicting traffic streams.

Therefore,

$$\text{VAR}(x) = P(1 - P)$$

Thus, VAR (x) is minimal where conflicting traffic flow rates are low ($P \rightarrow 1.0$) and where conflicting flow rates are high ($P \rightarrow 0$).

The influence of sample size and conflicting flow rates is exhibited by the freeway-to-ramp vehicles operating on the subject site. Freeway-to-ramp traffic represents the higher weaving flow traveling on the subject site. Thus, the sample size of freeway-to-ramp data is relatively large. Moreover, freeway-to-ramp vehicles perform lane changes in conflicting traffic streams of relatively low flow. The result is less variance among freeway-to-ramp observations when compared with ramp-to-freeway data.

ANOVA tests indicate that statistically significant differences do not exist between mean values of the ramp-to-freeway spatial distributions observed during the a.m., noon, and p.m. periods.

Freeway-to-Freeway Traffic

Figure 9 shows the proportional distributions of freeway-to-freeway traffic traveling in Lane 2 for a.m., noon, and p.m. observations. Freeway-to-freeway vehicles will not travel in Lane 1 as it is a mandatory exit lane.

No observed traffic flow variables appear to influence the distributions of freeway-to-freeway vehicles in Lane 2.

Ramp-to-Ramp Traffic

Figures 10 and 11 show the proportions of ramp-to-ramp traffic traveling in Lanes 1 and 2 for the a.m., noon, and p.m. data. Some lane changes are executed among ramp-to-ramp traffic, despite the fact that lane changing is not required to perform the maneuver.

Similarly to freeway-to-freeway traffic, ramp-to-ramp distributions do not appear to be influenced by variations in observed traffic flow conditions.

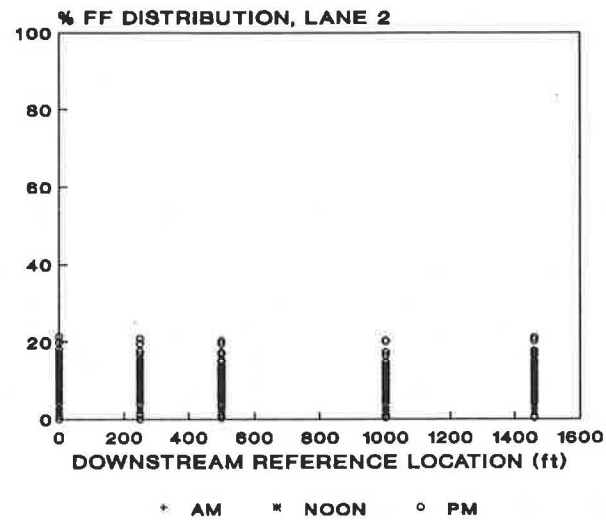

FIGURE 9 Freeway-to-freeway distributions, Lane 2.

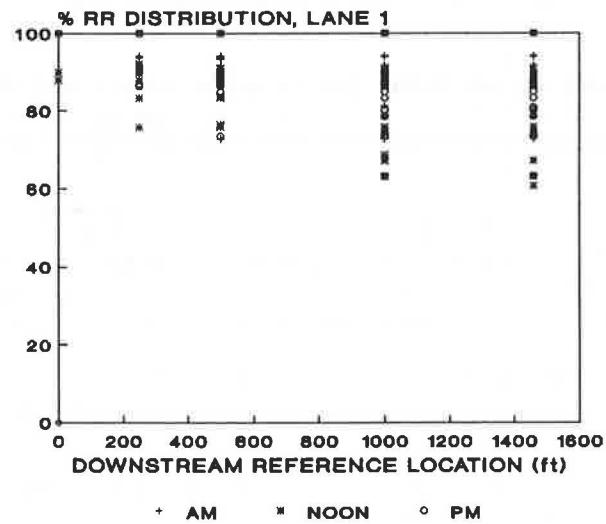

FIGURE 10 Ramp-to-ramp distributions, Lane 1.

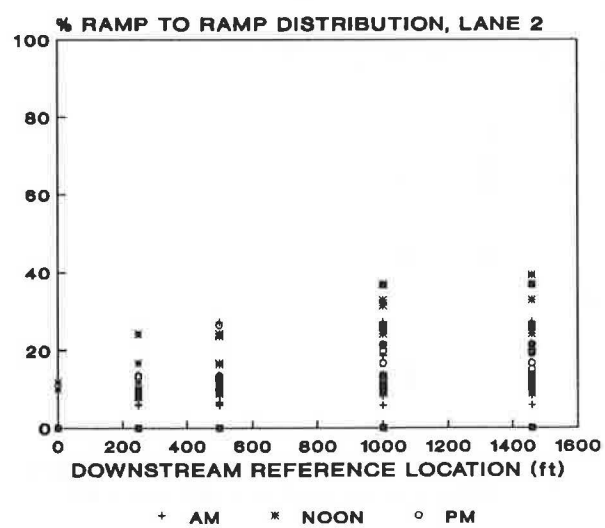

FIGURE 11 Ramp-to-ramp distributions, Lane 2.

PROPOSED WEAVING PROCEDURE

The ultimate objective of this research has been to develop an improved analytical technique for modeling traffic flow characteristics in major freeway weaving areas. The proposed procedure predicts the spatial distributions of all traffic movements within a subject weaving area as a function of the prevailing geometric design and traffic flow characteristics. Specifically, the procedure computes flow rates at user-specified reference points within the weave. Lane-changing activity is reflected in changes in flow rates of each traffic movement between sequential reference points. Flow rate and lane-changing information is then used for designing or evaluating performance of a weaving section.

The proposed technique is graphical in form. The procedure consists of a family of curves that are used to predict the spatial distributions of each traffic movement. The curves, which were developed both from empirical and from simulation data, reflect a wide range of traffic flow and geometric conditions. Curves vary in shape on the basis of factors such as the weaving area's geometric configuration, section length, and traffic flow rates. The curves represent interpolated data between mean values for sets of specific observations. The cubic spline function was used for constructing the curves.

Space constraints again dictate that only those curves calibrated from observations occurring on the single selected weaving site (shown in Figure 3) are presented. These curves are presented in Figures 12–17. Although applicable to only one specific geometric configuration, these curves show procedural format. Other sets of curves are available for other weaving configurations (*2*).

Procedural Steps

In performing the proposed procedure, the user first selects the curves appropriate for the weaving area geometric configuration. Separate graphs correspond to individual traffic movements. In many cases, appropriate curves are also selected on the basis of relevant traffic flow conditions.

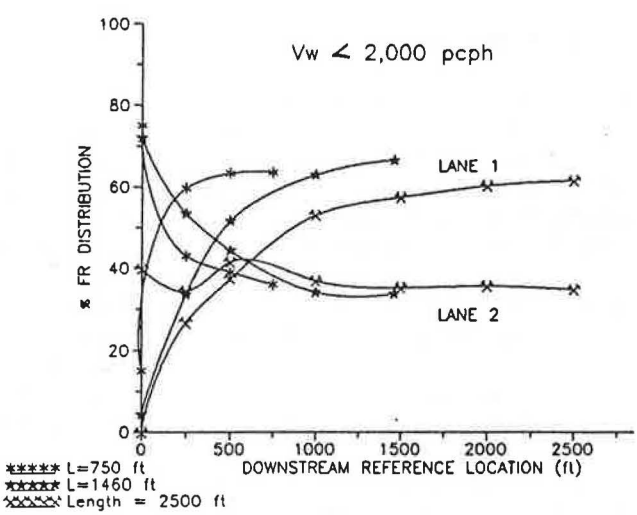

FIGURE 12 Freeway-to-ramp distributions, low weaving flow rates.

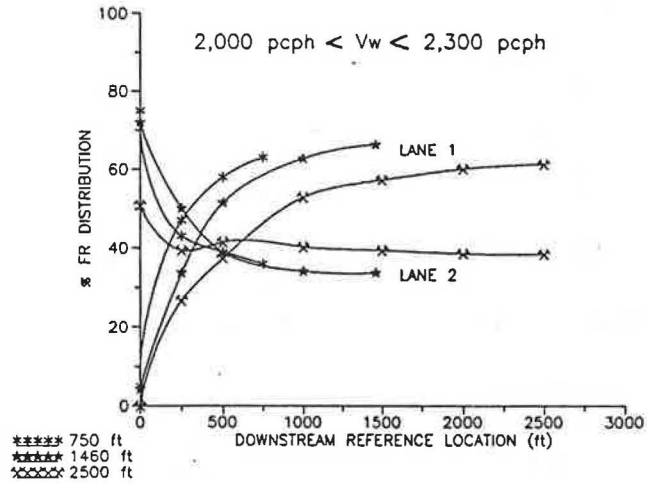

FIGURE 13 Freeway-to-ramp distributions, moderate weaving flow rates.

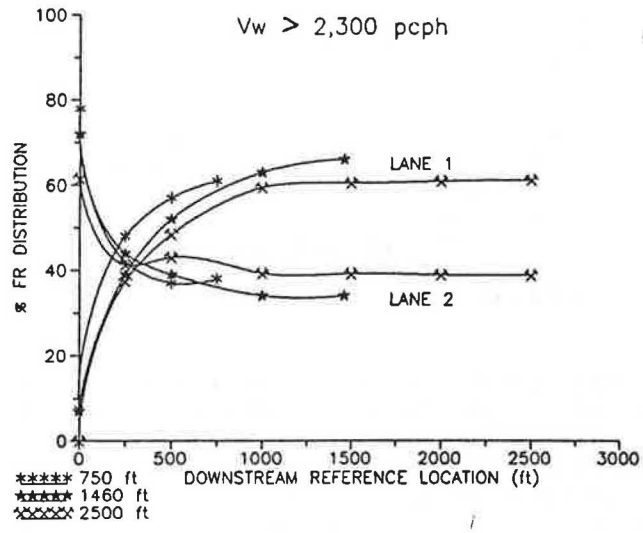

FIGURE 14 Freeway-to-ramp distributions, heavy weaving flow rates.

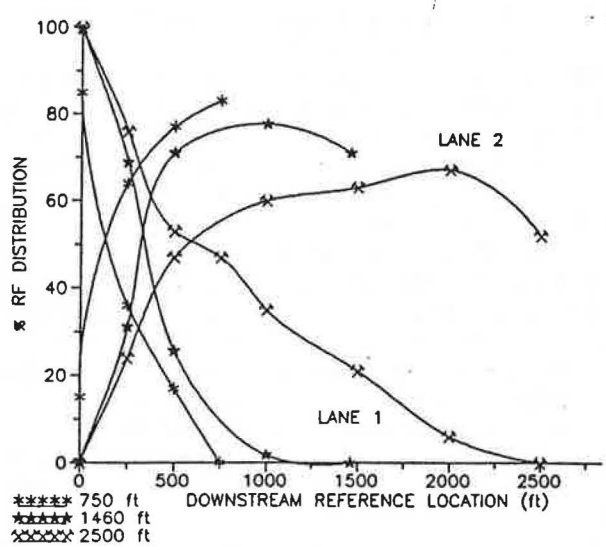

FIGURE 15 Ramp-to-freeway distributions.

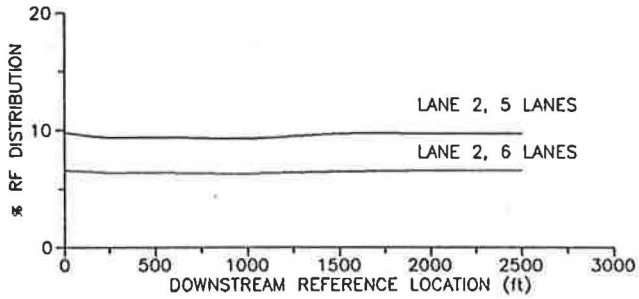

FIGURE 16 Freeway-to-freeway distributions.

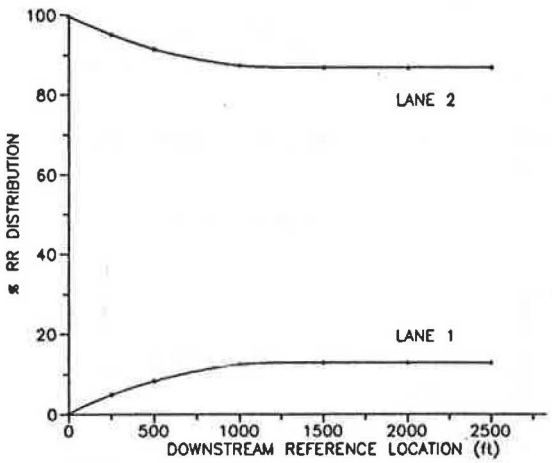

FIGURE 17 Ramp-to-ramp distributions.

Once applicable curves are selected, the user determines the reference points within the weaving area where operational performance is to be evaluated. A conservative approach would be to examine points across the entire length of a weaving section to ensure that all critical points are evaluated. Typical distance intervals between selected reference points would range from 250 to 500 ft. Reference points are located on the horizontal axis of each graph.

The user projects vertically upward from the horizontal axis until intersecting the appropriate curve on the graph. Individual curves typically represent predicted spatial distributions occurring in specific lanes on a weaving section of specific length. The user should refer to the legend in the lower left corner of the graph to determine lengths represented by each curve. Interpolation will generally be required for selecting appropriate curves.

From the intersection of the user's vertical line and the appropriate curve, the analyst projects horizontally to the left and determines the proportion of the specific movement traveling at the selected reference location. This predicted proportion is converted to a flow rate by simply multiplying by the total flow rate of the particular movement.

These tasks should be repeated for each of the four traffic movements. In this way, total flows are used in assessing LOS and in evaluating capacity sufficiency of the subject weaving area.

In Figures 12–15, the curves reflecting traffic flow behavior on 1,460-ft weaving sections were constructed using empirical data extracted from the subject weaving test site (Figure 3). Curves reflecting operation on 750- and 2,500-ft sites were constructed using calibrated simulations. Curves depicted in Figures 16 and 17 were developed using both empirical and simulation data.

Limitations of Proposed Model

The proposed model can be used for the analysis or design of simple, major freeway weaving areas. In this research, every effort was made to develop a procedure that is applicable to a wide range of weaving scenarios. Empirical and simulation data used to calibrate the proposed model reflect a wide range of traffic flow conditions. In extreme cases, however, traffic flow conditions at a subject weaving site may fall beyond the range of the calibration data set. In such cases, the reliability of the proposed model may deteriorate.

The model can be applied to a number of different weaving area geometric designs. However, the curves incorporated in the proposed model do not reflect all possible weaving site geometries. Where a weaving design not accommodated by the model is to be evaluated, traffic flow patterns may often be approximated using the model's curves that most closely match this actual weaving design.

The calibration test sites used in this research do not vary significantly in their number of lanes. Thus, the proposed model is most applicable for major weaving sections having five or six lanes within the weaving area.

This research has adopted an important simplifying assumption. Where on- and off-ramps have two lanes, each of these ramp lanes often leads to, or extends from, different directional flows on connecting facilities. Thus, the origin of on-ramp vehicles and the destination of off-ramp vehicles may, to some extent, influence presegregation and lane-changing within the weaving section. However, such considerations are beyond the scope of the proposed research. (Data collection alone precludes such considerations.) Therefore, it is assumed that lane changing influenced by such origin and destination considerations occurs on the ramp connection facility and not within the weaving section itself.

Weaving Area Capacity

A significant problem associated with weaving sections is that of determining capacity. Typically, capacity is thought of as the maximum flow of vehicles that can reasonably be expected to travel through a given facility. However, with weaving sections, the maximum number of vehicles that can traverse the facility will vary with different contributions from the four traffic movements. For example, lane-changing activity resulting from high weaving flow rates will restrict throughput capabilities within a given weaving section. Conversely, where weaving flow rates are low (i.e., little lane changing exists), weaving capacity will be relatively high. For this reason, the existing speed-prediction procedures do not directly predict weaving area capacity.

The proposed procedure defines capacity somewhat microscopically. Capacity is defined 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 lane segment (i.e., lane stripe) within the weaving area.

These capacity values were determined largely through simulation. In this research, an updated version of the INTRAS (INtegrated TRAffic Simulation) microscopic simulation model (*16–18*) was used to augment empirical data. Weaving area capacity was determined by performing repeated simulations of high traffic flow conditions. Capacity threshold values were assumed to have been exceeded when simulated conditions became so congested that a small number of weaving vehicles (i.e., 1 or 2 percent) were unable to perform desired movements.

By successfully calibrating the INTRAS model so that it reliably replicated observed conditions (including near-capacity conditions), it is believed that capacity values derived from simulation are reliable. Using simulation to extrapolate observed flow conditions simply represented the best means available for determining capacity.

The results of extensive simulation modeling indicate that capacity flow values are 2,200 pcph at any point within a weaving section. Lane-changing capacity is found to range from 1,100 to 1,200 lane changes per hour (across a single lane-line) over any 250-ft segment within the weaving area. As these capacity values represent microscopic measures, they are consistent regardless of geometric and traffic flow conditions prevailing at the weaving site.

Where application of the proposed weaving technique yields flow and lane changing values that exceed the capacity thresholds, operational breakdown is expected and the user should consider geometric modifications.

Weaving Area LOS Criteria

Another aspect of the research has been to determine an appropriate measure and criteria by which the LOS of a given weaving section can be assessed. LOS values typically reflect one of two possible perspectives:

1. The viewpoint of the system operator—in which case LOS may be expressed in measures such as productivity or volume-capacity ratio.
2. The viewpoint of the highway user—in which case LOS may be expressed in measures such as average travel speed, delay, or density.

In an effort to stay consistent with the basic philosophy behind the HCM, the measure of effectiveness for this research must be a parameter directly perceivable by users (i.e., motorists and passengers). Therefore, flow or volume-to-capacity ratio would not be suitable measures of effectiveness. Although perceivable by the user, average travel speed would also appear to be an inappropriate measure, largely because of its insensitivity to changing traffic volumes (Figure 2).

Two remaining measures perceivable by the user are

1. The rate of lane-changing activity over a given segment within a weaving area, and
2. The average density within a small segment of a weaving section.

The level of lane-changing activity does characterize the overall operational performance of a weaving area. The negative aspect of such a measure is that the number of lane changes cannot be easily field-measured. The analyst trying to quantify performance by field observation would be charged with a difficult task.

Like lane-changing activity, density might initially seem to be a difficult parameter to field-measure. Figure 18 shows that density behaves predictably relative to flow conditions. Data points shown in Figure 18 represent over 400 5-min observations collected from eight major freeway weaving areas located in California. These data, which reflect uncongested flow conditions, were collected as part of the initial ITS weaving research (*5*).

The relatively low scatter among the observations in Figure 18 suggests that density can be reliably estimated given average flow information. Thus, to field-measure density, the analyst need only count observed flow rates at a single point.

The x-axis in Figure 18 reflects average flow per lane. However, one can assume that using the curve depicted in Figure 18 to estimate density on the basis of a (predicted) point flow in a single lane represents a reasonable approximation. Thus, the curve can be used to predict density as a function of point flow rate. The resulting best-fit curve is a polynomial with three degrees of freedom (also shown in Figure 18).

The equation for this curve is

$$D = 0.42 + 0.02(V/N) - 1.19 * 10^{-5}(V/N)^2 + 5.36 * 10^{-9}(V/N)^3$$

where

D = density, passenger cars per mile per lane; and
V/N = flow per lane, pcph.

Data used to develop Figure 18 indicate that, under high-flow conditions (i.e., $V/N > 1{,}600$ pcph), average travel speed for uncongested conditions is approximately 48 mph. Data appearing to be in the congested regime (i.e., speeds below 35 mph) were not included in determining average speed under high-flow conditions. As an approximation, it was assumed that travel speed takes on a constant speed over the range of high-flow conditions (i.e., $V/N > 1{,}600$ pcph).

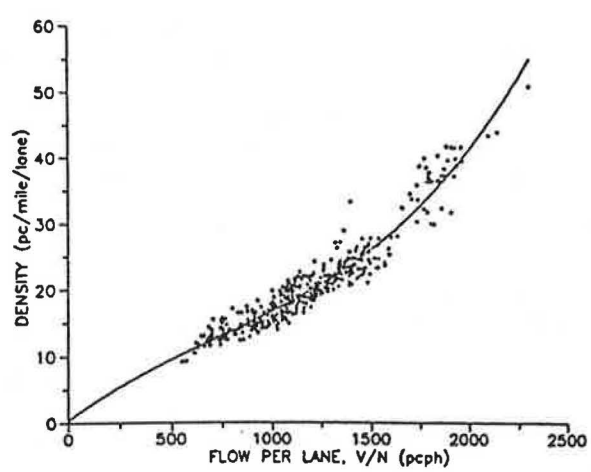

FIGURE 18 Density versus average flow per lane.

Because capacity flow conditions have been determined to be 2,200 pcph, the value of density at capacity is roughly 46 passenger cars, per mile, per lane (2,200 pcph divided by 48 mph). This value of optimum density corresponds to data shown in Figure 18.

m The 1985 HCM defines optimum density for basic freeway segments to be 67 passenger cars, per mile, per lane. It is expected that optimum densities for weaving areas would be less than those observed on straight-pipe freeway sections. Turbulence created by weaving traffic streams reduce optimum densities. Moreover, the relatively high freeway density values documented in the HCM are likely the result of overly conservative estimates of average travel speeds.

Once an optimum density value was determined, boundary conditions for the remaining LOS designations were divided evenly.

In part because of the simplicity associated with the proposed density estimating technique, average density is the suggested measure of effectiveness for assessing weaving area performance.

The proposed procedure does not automatically suggest that the lowest LOS governs for the entire weaving section. Such an approach may often lead to overly conservative LOS predictions. The proposed technique evaluates operation within relatively small lane segments of the weaving area. Traffic flows (and service qualities) vary from one segment to the next. Thus, application of the proposed technique will typically result in one or two reference points operating at the lowest relative LOS (i.e., highest relative densities) with surrounding reference points often operating at LOS values that are one or two designations higher. In estimating the overall LOS values for a given weaving area, the user is encouraged to evaluate the LOS values occurring in lane segments throughout the weaving section and determine if overall operation is acceptable. The overall LOS becomes a somewhat subjective average of the lowest LOS values occurring in a region of a weaving section. User judgment is required.

Space constraints prohibit the inclusion of example applications of the proposed technique. Example applications were provided by Cassidy et al. (*2*).

Model Validation

As part of this research, a small amount of data was collected and reserved exclusively for model validation. Thirty minutes of high-flow validation data were collected from the subject weaving site presented. These validation data represent flow conditions exceeding most or all of the calibration data. (All validation data points reflect weaving flow rates greater than 2,300 pcph.)

Figures 19 and 20 show validation results among freeway-to-ramp data. The solid curves in Figures 19 and 20 depict freeway-to-ramp spatial distributions (in Lanes 1 and 2) predicted by the proposed technique. The data points in Figures 19 and 20 represent empirical observations.

Figures 19 and 20 suggest that the proposed model predicts freeway-to-ramp flow patterns reasonably well. The same general results were observed among the remaining three vehicle movements.

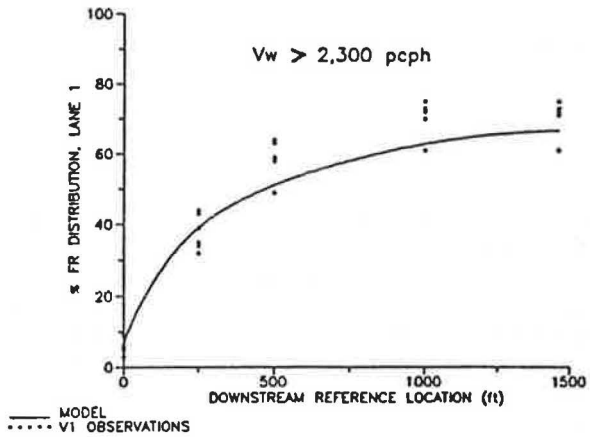

FIGURE 19 Model validation—freeway-to-ramp distributions, Lane 1.

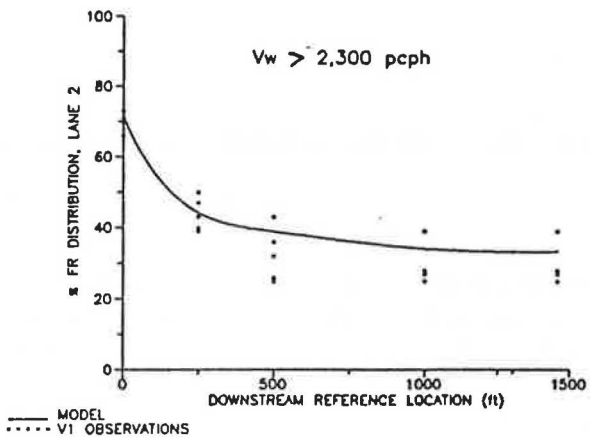

FIGURE 20 Model validation—freeway-to-ramp distributions, Lane 2.

CONCLUSIONS

An analytical technique has been developed for the design and analysis of simple, major freeway weaving sections. The research project examined traffic operation on a number of different weaving sites in California. Observations occurring on one of the weaving test locations were summarized.

Initial research (*12–14*) suggested that more reliable weaving area analysis and design procedures were needed. Currently available techniques for predicting weaving performance were found to be unreliable. The analytical technique detailed in this report is used to predict the spatial distributions of individual traffic movements at user-specified points within the weaving area. Such a technique implicitly estimates vehicle presegregation and lane-changing activity within the weave. In this way, the proposed model considers the interactions of vehicles traveling in individual lanes and operation is thereby evaluated on a more microscopic level.

Data analyses performed in this research suggest that evaluating operation in individual lanes represents a preferred approach for modeling weaving performance. Knowing key traffic flow and geometric conditions, spatial distributions of individual vehicle movements can be predicted reasonably

well. Lane utilization and lane-changing activity can be used as a measure of weaving area capacity. Moreover, these measures reflect performance of weaving areas. Thus, the proposed technique enables engineers and planners to more reliably design and analyze weaving sections.

Finally, the proposed model represents a rational and easily understood evaluation method. In simplest terms, the procedure estimates changing lane volumes as vehicles travel downstream within the weaving section. Such changing traffic flow patterns should appear intuitive to the user. In contrast, many of the (regression-based) speed prediction techniques have received significant criticism from the user community for not appearing rational.

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