Operation of Major Freeway Weaving Sections: Recent Empirical Evidence

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Weaving areas are critical elements in the operation of the freeway network, involving complex vehicle interactions. Many of the existing procedures for the design and analysis of weaving sections are based on data collected in the late 1960s and mid-1970s and may not reflect current driver/vehicle characteristics, especially in California. This paper describes what the analysis of more recently collected data has revealed. As part of a 2-year project to develop improved weaving analysis procedures, a large amount of data were collected using a video camera at eight major freeway weaving locations throughout California. Information on geometrics, volumes, and speeds of weaving and nonweaving vehicles were then extracted from the tapes, thoroughly checked, and verified with field observations. Six existing methods for the design and analysis of freeway weaving sections were then applied to all data sets. Results indicate that significant discrepancies exist between the predicted and measured average speeds of weaving and nonweaving vehicles. Several statistical analyses were performed using regression analysis and classification and regression trees, to identify basic relationships between weaving section design and traffic characteristics. Regression techniques were also employed in an effort to improve existing analysis and design procedures and to develop new performance prediction models. One important finding is that speed was insensitive to changes in geometric and traffic factors over the range of values in the data set. Overall, analyses suggest that average travel speed may not be an ideal measure of effectiveness. More research needs to be carried out to develop a more accurate procedure for designing and analyzing freeway weaving sections. Such procedures could consider measures of effectiveness other than speed. This paper also discusses the direction of possible future research.

In November 1987, research on freeway weaving sections was undertaken at the Insutute of Transportation Studies (ITS), University of California at Berkeley. The research project, entitled "Evaluation of Existing Methods for the Design and Analysis of Freeway Weaving Sections," was sponsored by the California Department of Transportation (Caltrans). The work has focused on major freeway weaving sections, such as those at or near freeway interchanges. Research was concurrently performed on ramp-weave freeway sections (*1*).

Preliminary findings of the research on major weaving sections are outlined in Skabardonis et al (*2*), which describes initial research tasks, including data collection, and findings from the application of existing weaving analysis methods to the collected data.

This paper describes efforts subsequent to Skabardonis et al. to (a) identify factors significantly influencing traffic operations on major freeway weaving sections, (b) assess the predictability of measures of effectiveness (i.e., speed and density), and (c) develop improved procedures for predicting weaving section performance.

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The purpose of this research project is to develop improved procedures for the design and analysis of major freeway weaving sections—focusing on weaving locations in the state of California. The work has had the following specific objectives: to evaluate all known existing methods used for the design and analysis of weaving sections, and to develop a new or modified methodology as needed.

BACKGROUND

The 1985 Highway Capacity Manual (HCM) (*3*) 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." Typically, a weaving section is formed by a merge area followed closely by a diverge area. Four types of traffic movements generally occur on a freeway weaving section: freeway to freeway (a nonweaving traffic stream), freeway to off-ramp (a weaving traffic stream), on-ramp to freeway (a weaving traffic stream), and on-ramp to off-ramp (a nonweaving traffic stream).

The intense lane-changing maneuvers that go on in weaving areas often present sharp operational problems.

The 1985 HCM has designated several classifications of weaving sections: a simple weaving area is formed by a single merge followed by a single diverge; a multiple weaving area is formed by one merge followed by two diverges or by two merges followed by a single diverge; a ramp-weave section is formed by a one-lane on-ramp followed closely by a one-lane off-ramp where the two are joined by a continuous auxiliary lane; and a major weaving section is formed when at least three entry and exit legs have two or more lanes.

The 1985 HCM also defines three weaving area configuration types—A, B, and C. These classifications are based on the minimum number of lane changes required by weaving vehicles as they travel through the section:

- Type A configurations require that each weaving vehicle perform one lane change in order to execute their desired movements. Ramp-weave freeway sections are typically of this configuration.

- Type B weaving areas require vehicles in one weaving traffic stream to execute one lane change, while vehicles in the other weaving traffic stream perform desired movements without changing lanes.
- Type C weaving sections require vehicles in one weaving traffic stream to perform two or more lane changes, while

vehicles in the other weaving traffic stream can perform desired maneuvers without changing lanes.

The research described in this paper focuses on simple, major freeway weaving sections but gives consideration to all three configuration types.

Initial Research Tasks

This section summarizes initial tasks performed in the early stages of the research project. A more complete description of these tasks is in Cassidy et al. (*4*) and Skabardonis et al. (*2*).

Literature Review

At the beginning of this study, a detailed literature search was performed using the ITS library and TRISNET computerized searches. Over 100 documents concerning weaving were identified. These published materials were classified into seven major categories: methods for design/analysis of freeway weaving sections, simulation models, theoretical studies, data collection, related capacity analysis, nonfreeway weaving sections, and California studies. Several researchers and practitioners were contacted to find out which methods are commonly employed and what application experience has been.

Seven existing procedures for the design and analysis of freeway weaving sections were identified through the literature search. In chronological order of development, these methods are as follows:

1. California Method (Level D Method) (*5*),
2. HCM-65 (*6*),
3. Leisch (*7,8,9*),
4. PINY (*10*),
5. JHK (*11*),
6. HCM-85 (*3*), and
7. Fazio (*12*).

The Level D Method (*5*) is used to predict the spatial distribution of vehicles operating on ramp-weave freeway sections under heavy volume conditions. The HCM-65 technique (*6*) predicts a "Quality of Flow" (and corresponding approximate travel speeds) for vehicles traveling on a subject weaving section. The remaining five procedures predict average vehicle travel speeds and typically establish a level of service designation based on those predicted speeds. With the exception of the Level D Method, all existing procedures can be applied to major freeway weaves as well as to ramp-weaves. All existing procedures can be used to evaluate proposed geometric designs for weaving sections (*2*).

Data Collection

As part of this research project, data from major freeway weaving sections in California were collected and analyzed. These data were used to evaluate the reliability of existing procedures and to calibrate new prediction models as needed.

Eight test sites were chosen for data collection. These sites were all major weaving sections, representing a wide variation of design characteristics and section configurations. Table 1 of this report describes the site locations and geometric configurations.

Following the selection of the study locations, data were collected using video recording. Videotaping traffic provides for a permanent record of the data, which can later be analyzed at various levels of detail or rechecked as necessary.

A Panasonic 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 sections so that the operation of the entire weaving section could be videotaped. Several tests proved that accurate measurements could be made using the video camera for distances up to 3,000 ft.

Six hours of video recording were made on each site to obtain a range of traffic conditions. The tapes were analyzed to obtain input data for the procedures—volumes and traffic composition—and performance measures—average speeds of weaving and nonweaving vehicles.

Information on geometrics was obtained from field measurements and checked through aerial photos and Caltrans photologs.

The data were extensively checked, and a number of floating car runs were made to verify the speeds at the weaving sections. Statistical tests were performed to check sample size requirements for speed measurements. A total of 143 data points were obtained, each representing 15-min observations at the study locations. Approximately 11 hr of additional data were excluded from further analysis because of congestion, incidents, and inclement weather occurring during the videotaping.

Evaluation of Methods

Six of the seven existing methods were applied to all test site data. The California procedure (LOS D method) was not applied because it was developed specifically for the analysis of ramp-weave freeway sections.

Table 2 presents a comparison of measured and predicted performance measures (i.e., average weaving and nonweaving speeds) for a sample of data points. Each data point listed represents 60-min observations collected at the eight test sites. As the table shows, the methods typically predict operating speeds that are lower than actual speeds. The differences between predicted and measured speeds range from −17 percent to + 64 percent for weaving traffic, and from −16 percent to +44 percent for nonweaving traffic.

Table 2 also lists mean values of the differences between field-measured and predicted average travel speeds; these average differences were computed using absolute values of the differences between measured and predicted speeds. The mean squared errors are also listed on this table. Figure 1 illustrates the differences between field-measured and average weaving speeds predicted using the 1985 HCM weaving model. Predicted average weaving speeds equal to field-measured values would be positioned directly on the diagonal line bisecting Figure 1, but these weaving speeds are all lower than their corresponding field-measured values. [See Skabardonis et al.

TABLE 1 WEAVING SECTION TEST SITES

Caltrans District	Location	Geometric Characteristics L	N	N_b	N_r	N_f	Comments
4	WB 92 Ralston onramp and 280 I/C	1400	3	2	1	2	Lane Balance Type C
4	SB 280 at 88 I/C and and Bascom offramp	1347	5	3	2	1	Lane Balance Type C
7	SB 101 at 110 I/C and Broadway offramp	792	5	3	2	2	Lane Imbalance Type A
7	NB 101 at Los Angeles onramp and 110 I/C	787	5	4	1	2	Lane Imbalance Type C
7	EB 10 605 I/C and Frazier St. offramp	1437	6	4	2	1	Lane Imbalance Type B
7	WB 10 at Garvey St. onramp and 605 I/C	1690	5	4	1	2	Lane Balance Type B
8	WB 10 15 I/C and Etiwanda onramp	1989	5	4	1	2	Lane Balance Type B
11	NB 805 at University onramp and El Cajon offramp	1371	5	4	1	2	Lane Balance Type B

Definitions:

L: length of weaving section (ft)
N: number of lanes in weaving section
Nb: number of freeway lanes approaching the weaving area
Nr: number of lanes on entrance ramp
Nf: number of lanes on exit ramp

TABLE 2 MEASURED VERSUS PREDICTED SPEEDS

CALTRANS DISTRICT	TEST SITE	FIELD MEAS: Sw	Snw	HCM-85 Sw	Snw	LEISCH Sw	Snw	JHK Sw	Snw	FAZIO Sw	Snw	PINY Sw	Snw	HCM-65 Sw
4	WB92 AM	51	55	*	*	41	59	42	38	55	31	50	50	> 40
4	WB92 NOON	53	56	29	41	44	65	48	50	60	45	55	55	> 40
4	SB280 AM	67	67	33	47	41	54	51	56	44	48	50	50	> 40
4	SB280 NOON	62	63	34	48	42	55	51	57	42	49	50	50	> 40
4	SB280 PM	60	62	31	43	36	39	49	54	34	41	*	*	40-45
7	SB101 AM	50	55	*	*	25	48	37	42	31	41	50	50	40-45
7	SB101 NOON	55	59	*	*	20	46	36	42	28	40	*	*	40-45
7	NB101 AM	44	52	*	*	24	35	34	39	38	33	*	*	30-35
7	NB101 PM	56	62	29	42	25	59	37	42	39	42	44	46	40-45
7	EB10 AM	48	56	36	50	34	59	53	58	47	51	56	56	> 40
7	EB10 NOON	54	59	34	48	32	54	52	57	45	48	56	56	> 40
7	EB10 PM	41	42	*	*	19	34	48	52	32	38	*	*	30-35
7	WB10 AM	56	59	40	40	38	40	52	56	53	47	*	*	40-45
7	WB10 NOON	63	64	43	45	42	50	54	58	56	51	45	47	> 40
7	WB10 PM	58	62	42	43	40	47	53	58	53	50	42	44	> 40
8	WB10 NOON	58	61	48	54	53	56	58	61	58	60	55	55	> 40
8	WB10 PM	64	66	47	52	50	54	57	60	58	57	54	54	> 40
11	NB805 AM	56	63	42	42	37	40	50	56	44	51	*	*	> 40
11	NB805 NOON	56	64	41	41	38	41	50	55	42	51	*	*	> 40
11	NB805 PM	52	59	41	41	38	41	50	56	45	51	*	*	> 40
avg. difference+				19	16	19	12	8	8	11	13	8	9	
mean sqrd error				432	293	420	190	96	96	188	205	112	131	

* METHOD COULD NOT BE APPLIED BECAUSE TRAFFIC AND/OR GEOMETRIC CHARACTERISTICS EXCEED LIMITS OF THE MODEL

\+ MEAN DIFFERENCE BETWEEN FIELD-MEASURED AND PREDICTED SPEEDS FOR EACH SAMPLE DATA POINT (ABSOLUTE VALUES USED TO REFLECT EACH DIFFERENCE)

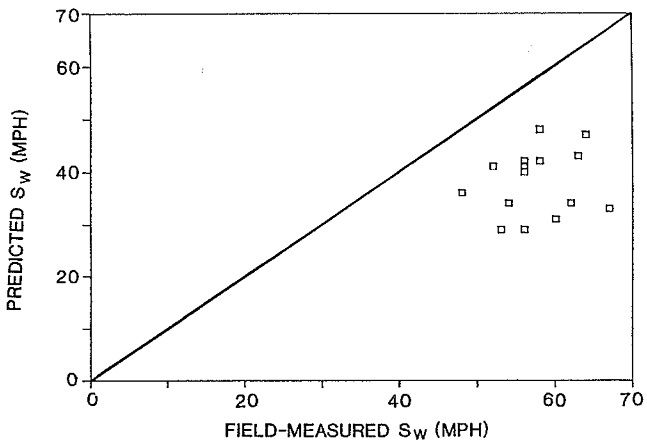

FIGURE 1 Measured versus HCM predicted weaving speeds.

(*2*) for further discussion of the existing methods' predictive value.] Overall, the existing analysis and design procedures do not appear to have strong predictive ability. Based on these findings, it was decided that new or modified procedures should be developed.

The following two sections of this paper describe efforts to calibrate stronger predictive models.

FUNDAMENTAL RELATIONSHIPS

Before attempting to calibrate predictive models, speed, flow, and density relationships were examined to lend a better understanding of operational phenomena occurring at freeway weaving sections.

Speed-Flow Relationships

Relationships between speed and volume-capacity (*v/c*) ratios were first studied. A value of 2,000 passenger cars/hr/lane (pcphpl) was used for capacity. This value represents only a rough estimate since the actual capacity of weaving sections is uncertain. However, the reasonableness of a value such as 2,000 is not important. A capacity value was used here simply to normalize volumes operating on the weaving section. The number of lanes in the weaving area, rather than an estimated capacity, could just as easily have been used.

Figure 2 illustrates speed versus *v/c* scatter plots constructed using 5-min observation data. Speeds used to construct these scatter plots were average weaving speed and average nonweaving speed. The scatter plots were developed using aggregated data from all eight test sites.

The speed versus flow diagram, constructed using nonweaving speed, does to some degree resemble a conventional speed-flow curve. However, speed appears to be insensitive to flow up to *v/c* values of about 0.8. This nondifferentiable behavior between speed and flow agrees with findings by Persaud and Hurdle (*13*) and others concerning "straight-pipe" freeway sections. Unpublished research on multilane rural highways also indicates that speed varies only slightly with increasing traffic volumes under low and moderate flow conditions.

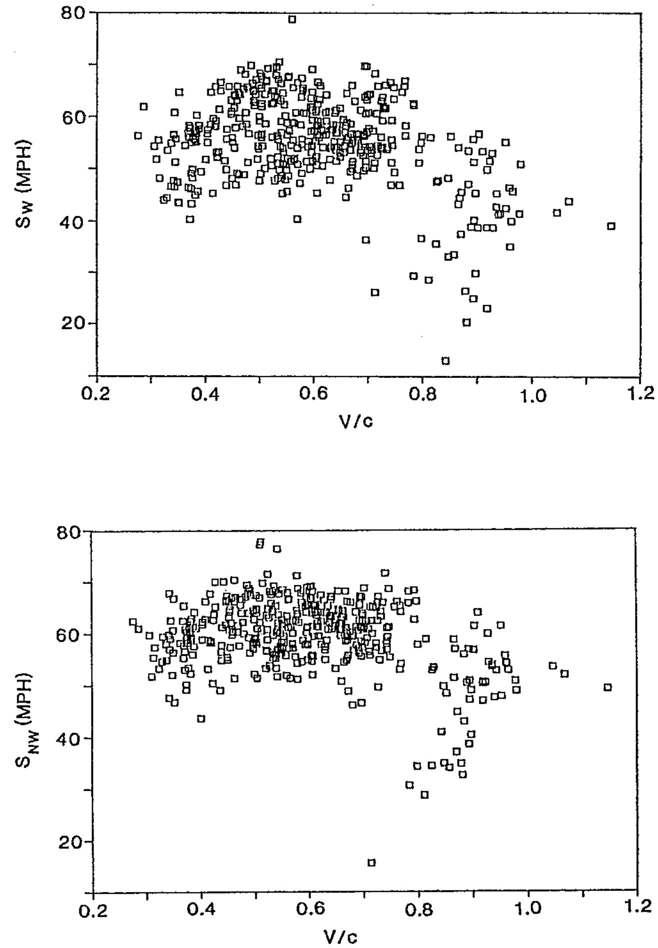

FIGURE 2 Speed versus *v/c* scatter plot.

Figure 2 illustrates the high degree of scatter among the data, which is particularly prevalent in the weaving speed versus *v/c* scatter plot. Separately grouping data by individual location or by configuration type (as defined in the 1985 HCM) did little to improve the high variance between speed and flow.

The data collected at the California test sites therefore do not indicate that obvious relationships exist between speed and flow. Indeed, the apparent insensitivity of speed under low and moderate flow conditions and the high degree of scatter among the data initially indicate that speed may not be an ideal measure of performance for weaving sections.

Density-Flow Relationships

Relationships between density and *v/c* were also examined. Average density/lane, within each weaving section, was computed by dividing total volume by a weighted average of weaving and nonweaving average speeds. Figure 3 illustrates the density-flow relationships for all eight test sites using 5-min observation data. The scatter between density-versus-flow data is significantly tighter than the speed-flow data points. This is because volume is contained in both the *x*- and *y*-axes of the density-flow scatter plot. Nonetheless, relationships between density and flow do appear to be desirable in that density is

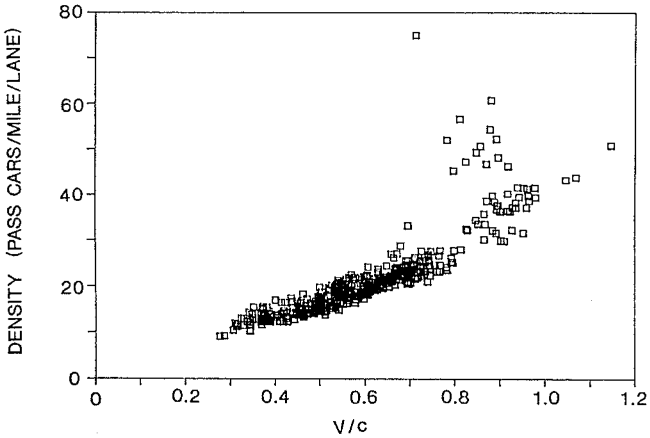

FIGURE 3 Density versus *v/c* scatter plot.

sensitive to flow, and scatter is great only under heavy flow conditions.

EMPIRICAL MODELS TO PREDICT PERFORMANCE

Analyses were performed to assess the predictability of speed and density, and to better understand factors affecting performance at weaving sections. Two types of analyses were done on the California test site data, regression analysis and classification and regression trees (CART) analysis.

Regression Analysis

Consideration was first given to recalibrating existing prediction models. For these recalibrations, the structures of the existing models were left unchanged. Regression coefficients and exponents were modified based on the data collected in this research. The models chosen to be recalibrated were the JHK model and the 1985 HCM model.

These models were selected because they were recently developed speed-based models originally calibrated using nonlinear regression techniques.

The two models differ in that the 1985 HCM model considers geometric configuration, while the JHK model does not. Also, the 1985 HCM model considers the type of operation (i.e., constrained or unconstrained) occurring within the weaving section. In constrained operation, nonweaving vehicles operate at significantly higher speeds than do weaving vehicles. In unconstrained operation, the average speeds of weaving and nonweaving vehicles typically differ by less than 5 mph.

The JHK Model

The basic structure of the JHK models for predicting average weaving and nonweaving speeds is as follows:

$$S_W = 15 + 50/[1 + (1 + V_W/L)^{B1}(V/N^{B2}/A_W]$$
$$S_{NW} = 15 + 50/[1 + (1 + V_W/L)^{B3}(V/N)^{B4}/A_{NW}] \quad (1)$$

where

$B1$, $B2$, $B3$, and $B4$ = regression exponents,
A_W and A_{NW} = regression coefficients,

and all other variables are defined in the glossary.

New exponents and coefficients were developed using the collected data, representing 5-min observations. The original JHK models were calibrated with an upper limit for weaving and nonweaving speeds of 65 mph. Thus, in recalibrating the models, data points having speeds in excess of 65 mph had to be excluded from the calibration data set.

The resulting recalibrated models were quite poor: for the weaving speed prediction model, the r^2 was 0.09 and only 0.06 for the nonweaving speed prediction model. The values for the recalibrated exponents and coefficients do not resemble those of the original JHK model. Table 3 of this report lists the original and recalibrated values for the coefficients and exponents.

The rather poor results would suggest that the models' structure does not fit the data collected at the eight California test sites.

The 1985 HCM Model

The structure of the 1985 HCM model is as follows:

$$S_W \text{ or } S_{NW} = 15 + 50/[1 + a(1 + VR)^b(V/N)^c/L^d] \quad (2)$$

where

a = regression coefficient,
b, c, and d = regression exponents,

and all other terms are defined in the glossary.

Recalibrating the HCM models was not as straightforward as recalibrating the JHK equations. The HCM equations use a greater variety of coefficients and exponents for weaving and nonweaving speeds than the JHK models.

Predicting travel speeds using the HCM equations is an iterative process. The procedure was first performed assuming unconstrained operation, and the resulting predicted speeds were then used to predict the type of operation (constrained or unconstrained) occurring on the section. If constrained operation was predicted, the equations were recalculated using constrained coefficients and exponents.

Since field-measured speeds had been determined for the test sites, these measured speeds were used to determine operation (*3*). Data were then grouped according to configuration and operation type.

Limitations in this project's database prohibited developing new coefficients and exponents for all configurations and types

TABLE 3 REGRESSION COEFFICIENTS AND EXPONENTS (JHK MODEL)

Coefficient/ Exponent	Original JHK Model	Re-Calibrated Model
Aw	7500	9.44
Anw	9000	17.32
B1	1.33	1.21
B2	1.1	-0.05
B3	1.1	0.89
B4	1.1	0.001

of operation. The 1985 HCM equations were recalibrated only for Type B weaving sections operating under unconstrained conditions and for Type C sections operating under constrained conditions. As with the JHK models, the 1985 HCM models required the exclusion of all calibration data having measured speeds greater than 65 mph.

Results from these recalibrations were not promising. For Type B sections, r^2 values were 0.25 and 0.13 for unconstrained weaving and nonweaving speed predictions, respectively. For Type C sections, r^2 values were 0.44 and 0.37 for constrained weaving and nonweaving speed models, respectively.

Recalibrated constants were not usually of the same magnitude as those of the 1985 HCM models. Table 4 lists constants for the original and for the recalibrated HCM models. Referring to Table 4, the recalibrated regression coefficient, a, approaches zero for weaving and nonweaving speed prediction models. Thus, the recalibrated HCM models invariably predict these speeds to be 65 mph. Such prediction models are not satisfactory.

The structure of the HCM models was derived from the JHK models; neither seems to fit the data gathered from the test sites.

New Speed Prediction Models

In an effort to assess the predictability of weaving and nonweaving speeds, a variety of linear regression analyses were performed using test site data. Data representing 15-min observations were used initially (15-min rates of flow were used simply as a matter of convention).

In calibrating the models, the data were aggregated in a variety of ways. Virtually all variables listed in the glossary were considered in developing proposed models. The following section highlights some of the more significant findings resulting from efforts to calibrate improved prediction methods.

Aggregating All Eight Sites

Models were first calibrated using all the data from the eight sites aggregated. The resulting model for predicting average weaving speed is as follows:

$$S_W = 47.38 - 0.01(V) + 10.38(N) - 13.46(N_b) + 0.01(V_1) + 0.01(L) + 0.01(V_2) \qquad (3)$$

The r^2 value is 0.45.

The model for predicting nonweaving speed calibrated by aggregating all eight test sites is as follows:

$$S_{NW} = 97.22 - 64.13(v/c) + 0.03\,(V_{W2}) - 40.09(WR) - 6.41(N_b) + 0.01(V_1) - 0.01(V_3) \qquad (4)$$

The r^2 value is 0.44.

The r^2 values for these equations were better than those developed from recalibrating the two existing methods, but the coefficients of determination are still rather low.

Aggregating by Configuration Type In calibrating Equations 3 and 4, efforts were made to account for weaving section configuration type; however, categorical and dummy variables proved to be statistically insignificant. Because it was thought that unspecified geometric factors might have been affecting operations, models were calibrated according to configuration type, yet aggregating data in this manner did not result in improved prediction models.

Aggregating by Number of Lanes Improved results occurred when models were calibrated by using the data from test sites with five lanes (i.e., N = 5). The two sites that did not have five lanes were excluded from the data set.

The resulting model for predicting average weaving speed is as follows:

$$S_W = 26.76 + 0.01(L) - 33.98(WR) + 67.38(VR) - 0.01(V_{W1}) + 0.002\,(V_N) + 3.58(C) + 0.005(V_3) \qquad (5)$$

where

C = categorical variable representing configuration,
1.0 = configuration Type A,
2.0 = configuration Type B, and
3.0 = configuration Type C.

The r^2 value for this model is 0.82.

The manner in which the effects of geometric configuration are accounted for in the above model is somewhat unusual. Using dummy variables would intuitively seem more appropriate; however, the linear form of the categorical variable proved to be a better model.

The model for predicting average nonweaving speed where $N = 5$ is as follows:

TABLE 4 REGRESSION COEFFICIENTS AND EXPONENTS (1985 HCM MODEL)

	HCM MODEL				RE-CALIBRATED MODEL			
	a	b	c	d	a	b	c	d
TYPE B UNCONSTRAINED:								
WEAVING	0.1	1.2	0.77	0.5	2E-10	-3.65	2.57	0.41
NONWEAVING	0.2	2	1.42	0.95	3E-24	-7.7	2.93	4.42
TYPE C UNCONSTRAINED:								
WEAVING	0.1	1.8	0.8	0.5	9E-11	65.26	1.74	2.16
NONWEAVING	0.07	1.8	1.1	0.5	1E-14	42.12	3.72	4.05

$$S_{NW} = 15.70 + 0.02(V_1) + 120.91(VR) - 0.01(V_3) + 1.84C + 0.01\,(L) - 0.01(V_{UP}) \quad (6)$$

The r^2 value for this model is 0.58.

Aggregating by Individual Site In an effort to account for site-specific factors significantly influencing the operation of each test site, regression models were calibrated for each individual site. However, no factor or group of factors significantly influenced all eight sites. Each model was unique, leading researchers to conclude that developing a model to account for all geometric and traffic factors will be difficult.

Cross-Validation Analysis All previous regression analyses were performed using resubstitution. In an attempt to obtain more reliable prediction models, a cross-validation regression with two partitions was performed.

In performing this analysis, data from the test sites were divided into two groups. Alternating data points from each of the sites were assigned to each of the two data sets. Only one of these data sets was used to calibrate weaving and nonweaving speed prediction models. The unused data set was then used for validation. Residuals were computed for each data point, and the absolute values of all residuals were totaled. The process was then alternated so that the data set previously used for validation was used to calibrate new prediction models. Again, the unused data set was used for validation, and the absolute values of all residuals were totaled.

A number of models were constructed using this method. The models ultimately selected were those yielding the smallest sum of residuals.

The resulting model for predicting average weaving speed is as follows:

$$S_W = 116 - .004(V_3)J - 125.67(VR) - 5.82(N_b) + 3.26C - 22.49(WR) \quad (7)$$

The r^2 for this model is 0.52.

The resulting model for predicting average nonweaving speed is as follows:

$$S_{NW} = 80.43 - 0.01(V) - 8.02(N_b) + 6.10(N) - 52.57(VR) + 0.01(V_{UP}) \quad (8)$$

The r^2 for this model is 0.42.

Cross-validation typically yields more reliable models than does resubstitution regression. For this research, models yielded by cross-validation analysis appear more rational than do the previously calibrated models. None of the speed-prediction models developed in this project using linear regression is ideal, however.

Density Prediction

Efforts were also made to predict average density/lane using regression techniques. Figure 3 shows that the density-versus-flow diagram behaves quite predictably. Only where flow conditions apparently approach the congested regime does high scatter among data points occur.

Prediction models were calibrated using data representing 15-min observations. A linear model was first constructed. The resulting equation is as follows:

$$d = -3.71 + 40.90\,(v/c) \quad (9)$$

The r^2 value for this model is 0.88.

Referring to Figure 3, the density-flow scatter plot forms a somewhat exponential relationship. Thus, a nonlinear model was calibrated, and the resulting model is as follows:

$$d = 35.35\,(v/c)^{1.06} \quad (10)$$

The r^2 value for this model is 0.89.

Equations 9 and 10 should be used only to predict densities in uncongested flow regions. Outlying points occurring at v/c values greater than 0.8 can best be predicted by a second nonlinear model. In this way, the density-flow curve would resemble the conventional parabolic model.

Sufficient data points have not yet been collected to calibrate a reliable density model for flow conditions in the congested region. Future efforts in this research project will involve obtaining additional data for traffic flow operating under heavy flow or near congested conditions. This data may be obtained from field studies and/or simulation.

Equations 9 and 10 were developed using ordinary least-squares regression. A weighted least-squares regression might better reflect density-flow relationships for v/c values between 0.8 and 1.0. Had weighted least-squares regression been used, regression coefficients for these equations would have been slightly larger. Nonetheless, they do represent acceptable approximations.

Analyzing 5-Minute Observations Attempts were made to develop speed and density prediction models using 5-min observation data. The obvious advantages of using 5-min flow rates are the increased number of data points and the wider range of traffic flow volumes. Statistical tests indicated that contiguous 5-min data points were independent from one another. However, efforts to calibrate models using 5-min observations did not yield improvements over 15-min models. It would seem that the higher variations occurring in the 5-min flow rates resulted in prediction difficulties.

Classification and Regression Tree Analysis

In an effort to gain deeper insights into factors influencing the operation of freeway weaving sections, the eight test sites were evaluated using CART analysis. CART is a technique and computer program developed by Breiman et al. (*14*). The methodology classifies and groups entities based on a set of measurements or characteristics by tree methodology.

The concept is to partition response variables (e.g., average weaving and nonweaving speeds) by a sequence of binary splits into terminal nodes (see Figure 4). The tree structure output provides easily understood and interpreted information regarding the main factors and interaction of factors that are significant in speed prediction.

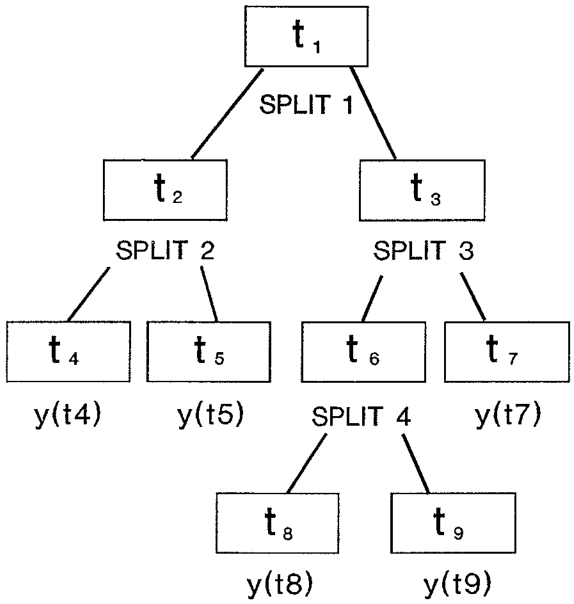

FIGURE 4 Sample CART.

Using the California test site data to develop predictive models, three issues for determining the tree predictor needed to be addressed:

1. **A way of selecting a split (or factor) at every intermediate node.** A regression tree is formed by iteratively splitting nodes. Splits are selected at every intermediate node in such a way as to maximize the decrease in resubstitution error measure. The best split of a node is the split that minimizes the weighted variance;
2. **A rule for determining when a node is terminal.** This decision is related to issues of tree pruning. It can be influenced by user-specified options in the CART program; and
3. **A rule for assigning a value $y(t)$ to every terminal node.** This is simply the average of responses of the terminal group t.

The CART program is written in standard FORTRAN and can be run on most computers in both interactive and batch modes. The program offers three options for estimation method, namely, resubstitution, test sample, and cross validation.

CART analyses were performed on data aggregated in several ways. Where sufficient numbers of data points existed, the cross-validation estimation method with two partitions was the preferred method as it tends to provide the most reliable trees. Where data were aggregated in such a way that an insufficient number of cases were available, resubstitution was used.

Speed Prediction

Attempts were first made to directly predict weaving and nonweaving speed using the CART program. Essentially all variables defined in the glossary were incorporated into the CART learning sample (i.e., input data set). Fifteen-min flow rate data from the California weaving sections were aggregated several ways.

Aggregating All Eight Sites Weaving and nonweaving speed prediction CART models were first developed by aggregating the data from all eight California test sites. The resulting CART for weaving speed prediction is illustrated in Figure 5.

Numbers in each node represent the sample size, the average value of speed, and the standard deviation (reading from left to right). In the first node, the learning sample consisted of 143 data points, with an average weaving speed of 56 mph and a standard deviation of 6.6. The first split is based on volume ratio, *VR*. Data points having *VR* values less than 0.36 are split to the left intermediate node, while data points with *VR* values greater than 0.36 are split to the right.

For the most part, the binary tree illustrated appears to follow logical splitting. There is, however, an exception. Two data points have a lower total volume which leads to lower operating speeds. This causal relationship does not seem logical. This binary tree was constructed without incorporating site-specific categorical variables. When such categorical variables were incorporated, they tended to significantly influence the splitting in the resulting CARTs. However, individual sites were split in such a way that additional insights could not be obtained.

Aggregating by Number of Lanes Somewhat improved results did occur when CARTs were constructed using data only from five-lane weaving sections in the learning sample. The two sites not having five lanes were excluded from the analysis. The resulting weaving speed binary tree is illustrated in Figure 6. The causal relationships contained in this model appear to be logical.

Aggregating by Individual Site CARTs were constructed for each individual test site in an effort to identify factors significantly influencing the operation of each weaving sec-

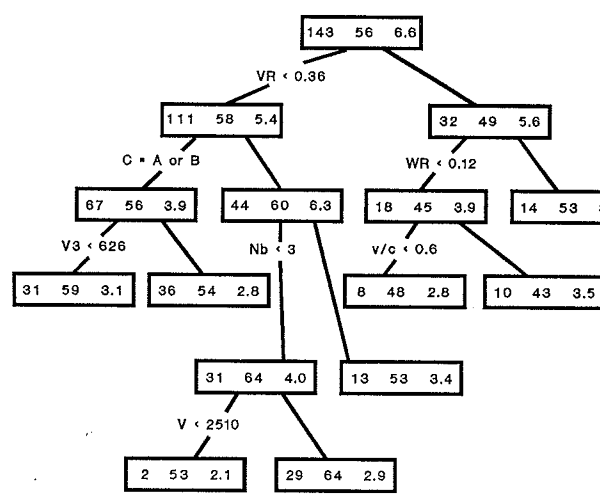

FIGURE 5 CART for weaving speed (all eight sites).

tion. Unfortunately, no single factor or group of factors seemed to dominate tree splitting.

Residual Prediction

CART analysis was also used in this research to predict speed-flow residuals. It was thought that, in the absence of flow impedance caused by weaving vehicles, traffic operating on major freeway weaving sections would exhibit conventional speed-flow relationships. Curves were constructed for speed versus *v/c* scatter plots, like the ones illustrated in Figure 2. The curves were drawn to be an envelope of the observed data points (see Figure 7).

Vertical distances between the envelope curve and each data point were considered to be the residuals. The CART program was then used to predict each residual.

It was assumed that freeway traffic on a straight-pipe section would have data points grouping closely to the envelope curve, and that perhaps factors related to the weaving phenomena (e.g., conflicts between weaving vehicles) were causing points to fall below the curve. By predicting the residuals, researchers thought, factors significantly affecting operation on the test sites might be identified.

Residual prediction was performed on the data set aggregating all eight test sites. Envelope curves and residual measurements were made for both the weaving speed versus *v/c* and the nonweaving speed versus *v/c* scatter plots. Data representing 15-min observations were used.

The resulting CART for weaving speed residual prediction is illustrated in Figure 8. The learning sample used in this analysis incorporated categorical variables representing configuration type and contains 143 data points with an average residual of 0 and a standard deviation of 5.0.

Developing residual prediction CARTs using data aggregated over numerous sites (see Figure 8) did not yield significant insights into factors influencing weaving section operation. Further efforts were also directed toward residual prediction for individual weaving sites. However, results did not appear to be extremely promising.

CONCLUSIONS

Summary of Project Findings

The objectives of the research were to evaluate existing methods for the design and analysis of major freeway weaving sections and to develop new or modified procedures as deemed appropriate. Research results determined that existing speed prediction techniques are generally not very reliable, so efforts were made to calibrate improved prediction models.

Attempts to develop new speed prediction tecdhniques have not been completely successful. Analysis indicates that travel speed is not easily predicted, given aggregate flow information and geometric characteristics. Table 5 presents a comparison between average field-measured weaving speeds and average weaving speeds predicted using newly calibrated models. It also contains a sample of the data points collected as part of

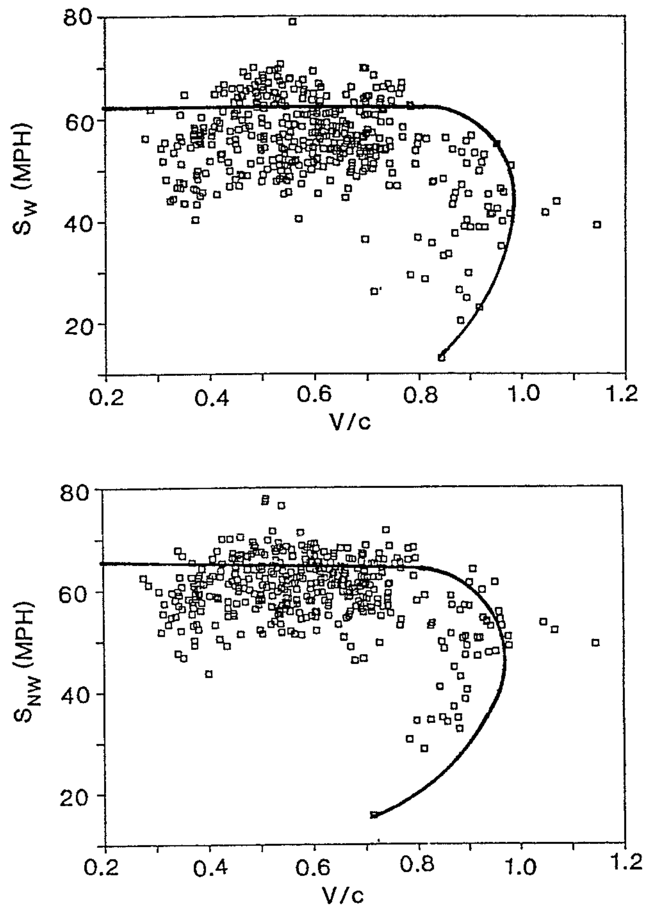

FIGURE 7 Sample envelope curves.

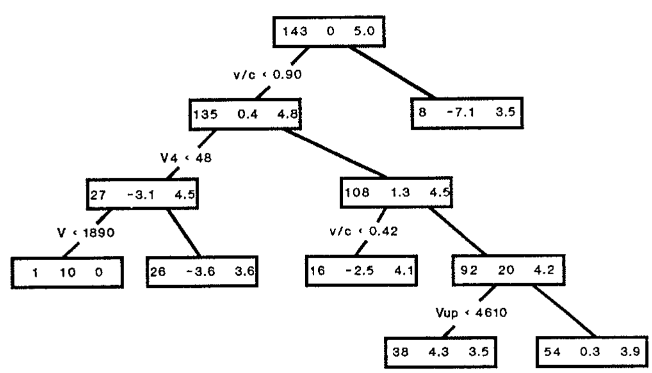

FIGURE 8 CART for weaving speed residuals (all eight sites).

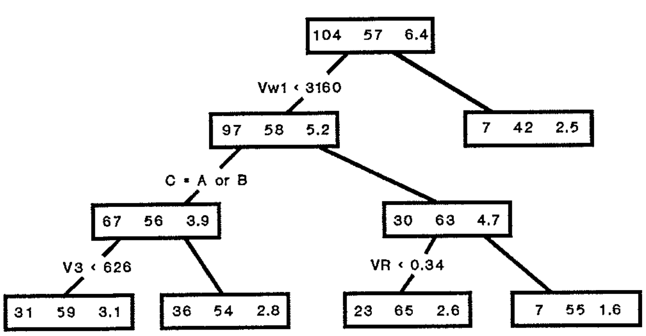

FIGURE 6 CART for weaving speed (N = 5).

the research. These data points are identical to those contained in Table 2. Each data point represents 60-min observations. Mean squared errors between field-measured and predicted weaving speeds are also listed in Table 5.

Comparing mean squared error values in Tables 2 and 5, recalibrated JHK and HCM-85 models represent improvements over their corresponding original models. This, of course, is to be expected since data used to validate recalibrated models are essentially the same data used to develop the models. As previously stated, small values for the recalibrated HCM-85 regression coefficient forced all predicted speeds to be 65 mph.

Newly developed models calibrated using regression techniques and CART may not be satisfactory. The traffic and geometric factors that most significantly affect the operation on test sites vary from location to location. Factors having the greatest overall influence on the operation of major freeway weaving sections therefore could not be identified.

Referring again to Table 5, the regression-based weaving speed prediction model calibrated with data from five-lane weaving sections (Equation 5) performed better than the regression equation calibrated with data from all eight test sites (Equation 3). As expected, the regression model calibrated using the cross-validation technique (Equation 7) seems to have the best predictive ability of all regression-based weaving speed prediction models.

It is rather surprising that the CART weaving speed model developed with data from all eight test sites (Figure 5) predicts speed better than the CART model calibrated with only from five-lane weaving sections (Figure 6). These results are opposite to those found for the regression models.

In general, none of the newly developed speed prediction models (weaving and nonweaving) seems to perform in a satisfactory manner. It should be noted that speed predictions in Table 5 were the results of input data used to calibrate the models. Had unused validation data been input to test the newly developed models, even greater prediction errors would likely occur. In addition, none of the newly developed speed prediction models readily accommodates design considerations.

Table 5 also lists average speeds predicted using the HCM's Chapter 3 method for analyzing straight-pipe freeway sections. Comparing these predicted speeds to weighted average values of observed weaving and nonweaving speeds yields relatively small prediction errors. It would seem that the HCM's Chapter 3 procedures more reliably predict average speeds on weaving sections than do the HCM's weaving analysis methods (*3*).

Analyses do indicate that average density can readily be predicted when *v/c* values are less than 0.8. These predicted densities can perhaps be used as a measure of effectiveness or incorporated as an input variable to predict speed. Preliminary evaluations do indicate that using density as an independent variable enhances speed-prediction regression models. Overall, it may be that average travel speed is not an ideal measure of effectiveness for weaving sections. The poor predictive abilities of speed-prediction models calibrated in this

TABLE 5 MEASURED VERSUS PREDICTED SPEEDS (NEWLY CALIBRATED MODELS)

CALTRANS DISTRICT	Test Site	Field Meas. Sw	Recal JHK Sw	Recal HCM Sw	EQ3 Sw	EQ5 Sw	EQ7 Sw	CART Fig 5 Sw	CART Fig 6 Sw	Field Meas. Speed	HCM Ch3 Calc. Speed
4	WB92 AM	51	58	65	52	70	55	53	65	53	58
4	WB92 NOON	53	59	65	55	58	57	53	55	55	58
4	SB280 AM	67	57	*	57	65	60	64	65	67	58
4	SB280 NOON	62	57	*	58	63	61	64	65	63	58
4	SB280 PM	60	56	*	56	62	61	64	65	61	54
7	SB101 AM	50	53	*	51	51	55	54	54	54	57
7	SB101 PM	55	52	*	49	53	51	54	54	58	56
7	NB101 AM	44	47	*	25	44	53	43	42	49	46
7	NB101 PM	56	51	*	33	54	48	53	55	60	57
7	EB10 AM	48	57	65	52	69	47	48	55	53	*
7	EB10 NOON	54	56	65	51	67	50	53	65	64	*
7	EB10 PM	41	52	65	37	64	40	43	42	42	*
7	WB10 AM	56	56	65	41	55	58	59	59	58	53
7	WN10 NOON	63	57	65	44	58	58	59	59	64	57
7	WB10 PM	58	57	65	44	59	54	59	59	61	56
8	WB10 AM	58	59	65	52	58	59	59	59	60	59
8	WB10 PM	64	59	65	51	57	57	59	59	65	59
11	NB805 AM	56	57	65	49	52	58	54	54	61	55
11	NB805 NOON	56	57	65	46	53	55	54	54	62	56
11	NB805 PM	52	57	65	48	51	56	54	54	57	56
	avg. difference+		4.4	10.4	8.5	5.6	3.9	2.2	3.6		4.5
	mean sqrd error		29	140	114	81	20	6	25		26

* METHOD COULD NOT BE APPLIED BECAUSE TRAFFIC AND/OR GEOMETRIC CHARACTERISTICS EXCEED LIMITS OF THE MODEL

\+ MEAN DIFFERENCE BETWEEN FIELD-MEASURED AND PREDICTED SPEEDS FOR EACH SAMPLE DATA POINT (ABSOLUTE VALUES USED TO REFLECT EACH DIFFERENCE) project, as well as the speed-versus-*v/c* scatter plots in Figure 2, suggest that other performance measures should perhaps be investigated.

Future Research

Additional research on major freeway weaving sections is required to develop reliable prediction methodologies.

Perhaps one reason for the inability to reliably predict operating speeds lies in the nature of the independent variables utilized. In this research, traffic characteristics were analyzed in their aggregate form; total volumes for each traffic movement (e.g., freeway to freeway, freeway to ramp, and so on) were used to predict speed. Existing design and analysis methodologies typically take this form.

However, the operation of freeway weaving sections may be largely influenced by what is occurring in individual lanes. Congestion at freeway weaving areas often occurs as a result of breakdown in a single lane. In addition, the effects of conflicting weaving vehicles might best be modeled on a lane-by-lane basis.

Preliminary findings of some research indicate that the Level D Method (*5*) can reliably predict the lane utilization rate of vehicles at ramp-weave freeway sections. Perhaps here lies the solution to reliably predicting operation on major weaving sections. If the presegregation of vehicles entering a weaving section and the lane-changing maneuvers within the section can be modeled, improved prediction methods might be developed. Fazio (*12*) developed such a model and reported improved prediction results. What is needed is additional research to refine and validate a lane-changing model that can be used to perform design tasks.

Previously collected videotaped data will be used to calibrate the proposed model. Additional calibration and validation data will be used to develop the model so that more reliable inferences can be drawn about the influences of traffic and geometric factors on traffic flow behavior in major weaving sections. Simulations may also be used to augment empirical data. In this project, simulations conducted using the INTRAS model (*15,16*) have been performed and seem to hold promise. A detailed discussion of simulation experiments performed in this research project is described in Skabardonis et al. (*17*).

GLOSSARY

The terms listed below are parameters affecting weaving area operation.

C = categorical variable representing configuration.
d = average density, in pcph/mi/lane.
L = length of weaving area (ft).
N = total number of lanes in the weaving area.
N_b = number of freeway lanes approaching the weaving area.
S_{NW} = average running speed of nonweaving vehicles in the weaving area, in mph.
S_W = average running speed of weaving vehicles in the weaving area, in mph.
V = total flow rate in weaving area, in pcph.
V_1 = total flow rate of the freeway to freeway traffic stream, in pcph.
V_2 = total flow rate of the freeway to off-ramp traffic stream, in pcph.
V_3 = total flow rate of the on-ramp to freeway traffic stream, in pcph.
V_4 = total flow rate of the on-ramp to off-ramp traffic stream, in pcph.
v/c = volume-to-capacity ratio (assume c = 2000 pcphpl).
V_{NW} = total non-weaving flow rate in the weaving area, in pcph ($V_{NW} = V_1 + V_4$).
VR = volume ratio, V_W/V.
V_W = total weaving flow rate in the weaving area, in pcph ($V_W = V_{W1} + V_{W2}$).
V_{W1} = weaving flow rate for the larger of the two weaving flows, in pcph.
V_{W2} = weaving flow rate for the smaller of the two weaving flows, in pcph.
V_{UP} = total upstream flow rate, in pcph ($V_{UP} = V_1 + V_2$).
WR = weaving ratio, V_{W2}/V_W.

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