distributional assumptions on the model errors. The standard assumptions are that the dependent variable is normally distributed and that the errors are independent and have homogeneous variances.

In this study, the possible consequences of overlooking the distributional assumptions about the error variances have been examined. The results of this limited study suggest that nonconstancy of the error variances (heteroscedasticity) may result in regression models that substantially underestimate left-turn departure headways. It is hoped that the discussion relating to model estimation and validation will encourage others to address these basic issues in the literature.

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Freeway Weaving Sections: Comparison and Refinement of Design and Operations Analysis Procedures

JOSEPH FAZIO AND NAGUI M. ROUPHAIL

Weaving sections represent the common right-of-way that occurs when two or more crossing freeway traffic streams are traveling in the same general direction. In conjunction with the development of the 1985 *Highway Capacity Manual* (HCM), several procedures have evolved for the purpose of updating, revising, and replacing the 1965 HCM procedure for design and operations analysis of freeway weaving sections. The objectives of this paper are twofold: to present and review the latest three weaving procedures available to highway and traffic engineers, and to propose specific refinements to a simple weaving section procedure to account for the lane distribution of traffic upstream of the weaving section. These adjustments primarily involve the development of a lane-shift variable, which represents the average amount of peak-period passenger car lane shifts occurring under a given geometric configuration and prevailing traffic volumes. Statistical testing of the refined procedure against the three procedures at more than 50 sites nationwide indicated that the proposed procedure tends to predict observed average running weaving and nonweaving speeds more closely than do the other procedures in most cases.

A weaving section represents the physical space along a freeway where two (simple weaving) or more (multiple weaving) traffic streams traveling in the same general direction cross each other. Four basic movements are serviced in a simple weaving section, two weaving and two nonweaving (outer flows), as indicated in Figure 1*a*. Weaving traffic originating from the freeway mainline is denoted V_2 and nonweaving traffic is denoted V_1. Weaving traffic originating from the minor approach or entrance ramp is denoted V_3 and nonweaving traffic is denoted V_4. The length of a weaving section *(L)* and the number of lanes *(N)* are the two design parameters that dictate the mode of traffic operation to be expected, as illustrated in Figure 1*b*. (Note in this figure that N_b is the basic

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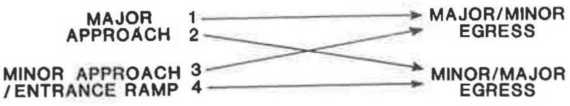
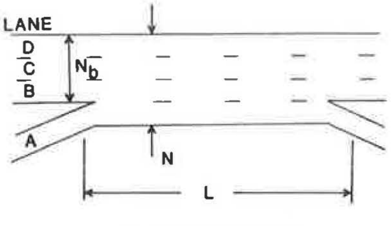


a) MOVEMENT IDENTIFICATION



b) CONFIGURATION

FIGURE 1 Simple freeway weaving section: movement identification and configuration.

number of lanes on a major approach to a weaving section. The number of lanes entering the weaving section from the minor approach or entrance ramp is denoted N_r.) As L or N decreases, drivers must execute their lane changes in a relatively short space, thus resulting in a general decrease in speed and level of service (LOS) for all traffic. In addition, lane changes originating from the outer lanes (i.e., median lane on the main approach and shoulder lane on the minor approach) will tend to create increased disruption to traffic operations in the weaving section compared with the situation resulting from a presegregated traffic stream, when weaving traffic is essentially confined to the boundary lanes between the two traffic streams.

Design procedures for weaving sections are aimed at determining the minimum length and number of lanes in the weaving section needed to meet a prespecified LOS in the analysis period. Operations analysis involves the determination of LOS and average running speeds for an existing weaving section.

BACKGROUND

One of the earliest weaving procedures for the design and operations analysis of weaving sections for the nation's first freeways appeared in the 1950 *Highway Capacity Manual (1)*. The development of this procedure was based on field data collected at six weaving sites. In 1957, the 1950 HCM procedure was updated with additional field data *(2)*. A major data collection effort was undertaken by the Bureau of Public Roads in 1963, which resulted in a new weaving analysis procedure in the 1965 HCM *(3)*. This method has been widely used during the past two decades and constitutes the current state of practice for design and analysis of weaving sections.

In an effort to keep abreast of changes in traffic composition and characteristics that took place since the Bureau of Public Roads data were collected, Project 3-15, Weaving Area Operations Study, was initiated in 1969 through the National Cooperative Highway Research Program *(4)*. This study, conducted by the Polytechnic Institute of New York (PINY), included field data collection at 17 northeastern sites. The results of Project 3-15 ultimately led to an interim weaving procedure published in 1980 *(5)*. In an independent effort, a nomographic weaving procedure initially published in 1979 *(6)*, was also included in the *Interim Materials for Highway Capacity;* this procedure was further modified in 1984 [see Leisch *(7)*]. Recently, the FHWA, U.S. Department of Transportation, initiated a study to evaluate the two procedures; the study resulted in yet another procedure for analyzing weaving sections [see JHK *(8)*]. Based on the conclusions of the JHK report, the PINY procedure was revised and eventually adopted as the weaving procedure for the 1985 HCM *(9)*. Since that time, both the Leisch and JHK procedures have undergone further revisions.

The procedures reviewed in this paper are the 1985 HCM (PINY) procedure, the revised JHK procedure (based on weaving study memoranda by W. Reilly and P Johnson, JHK and Associates, November 1984), and revised Leisch procedure (based on information letter from J. Leisch of J. Leisch and Associates, February 1985).

COMPARISON OF WEAVING ANALYSIS PROCEDURES

Tables 1 and 2 give summaries of the input requirements and output obtained for each of the three procedures. Of the three weaving procedures, the JHK procedure is the simplest to use.

TABLE 1 COMPARISON OF INPUT REQUIREMENTS FOR THREE WEAVING PROCEDURES

Method	Configuration	N_b	N	L	V	V_W	V_{W2}	V_4
JHK			X	X	X	X		X
Leisch	X	X	X	X	X	X	X	
1985 HCM	X		X	X	X	X	X	

Note: N = number of lanes within weaving section, L = length of the weaving section measured from the point at which the entrance gore is 2 ft wide to the point at which the exit gore is 12 ft wide, V = total volume of traffic in the weaving section = $V_1 + V_2 + V_3 + V_4$, V_1 = volume of nonweaving traffic stream originating from the major approach to the weaving section, V_2 = volume of weaving traffic stream originating from the major approach to the weaving section, V_3 = volume of weaving traffic stream originating from the entrance ramp or minor approach to the weaving section,V_4 = volume of nonweaving traffic stream originating from the entrance ramp or minor approach to the weaving section, V_W = volume of weaving traffic in the weaving section = $V_2 + V_3$, and V_{W2} = volume of smaller of the two weaving traffic streams [min (V_2, V_3)].

In essence, this procedure utilizes two equations for average running speeds, one for weaving, and the other for nonweaving traffic, in Equations 1 and 2:

$$S_W = 15 + \left[50/\left(1 + \{2{,}000[1 + (V_4/V)]^{2.7}\ [1 + (V_W/V)]^{0.9} \times [V/(QN)]^{0.6}/L^{1.8}\}\right)\right] \tag{1}$$

$$S_{NW} = 15 + \left[50/\left(1 + \{100\ [1 + (V_4/V)]^{5.4} \times [1 + (V_W/V)]^{1.8}\ [V/(QN)]^{0.9}/L^{1.8}\}\right)\right] \tag{2}$$

where Q is the heavy vehicle factor, and the other variables are as defined in Tables 1 and 2.

To use the JHK equations, hourly volumes must be adjusted to passenger car equivalents via the heavy vehicle factor *(Q)*.

TABLE 2 COMPARISON OF OUTPUT GENERATED BY THREE WEAVING PROCEDURES

Method	S_W	S_{NW}	S	LOS_W	LOS_{NW}	LOS_T	N_W	SF	Operation Mode
JHK	X	X		X	X				
Leisch	X		X	X		X		X	
1985 HCM	X	X		X	X		X		X

Note: S_W = average running speed of weaving traffic in the weaving section (mph), S_{NW} = average running speed of nonweaving traffic in the weaving section (mph), S = average running speed of all traffic in the weaving section (mph), LOS_W = level of service for weaving traffic, LOS_{NW} = level of service for nonweaving traffic, LOS_T = level of service for all traffic within the weaving section, N_W = theoretical number of lanes used by weaving traffic in the weaving section, and SF = service flow (pcphpl).

After the average running weaving and nonweaving speeds are calculated from Equations 1 and 2, weaving and nonweaving levels of service are read out from appropriate tables.

The Leisch procedure is nomograph-oriented, as shown in Figure 2. [Note in Figure 2 that R is the weaving ratio (V_{w2}/V_w). All other variables are defined elsewhere in the paper.] Two nomographs are used for one-sided weaving sections and two for two-sided sections. Configuration is accounted for in the procedure by *(a)* categorizing the weaving section as one sided or two sided, *(b)* specifying the presence or absence of lane balance (lane balance occurs when the combined number of exit lanes on the freeway and ramp is one more than the number of lanes on the freeway within the weaving section), and *(c)* providing for an approximate reduction in traffic speeds when the section configuration is concomitant with an excessive amount of lane shifts. Peak-hour factor values are built into the procedure, thus requiring no adjustments for peak-hour flow, except for vehicle composition. The procedure derives the average running speed for weaving traffic and overall average running speed within the weaving section. Also determined by the procedure are service flow [service volume in passenger cars per hour per lane (pcphpl)], weaving intensity factor *(k)*, LOS_W, and LOS_T, as defined in Table 2.

The 1985 HCM weaving procedure uses the following equation to estimate average running weaving and nonweaving speeds.

$$S_W \text{ or } S_{NW} = 15 + \left[50/(1 + \{a\,[1 + (V_W/V)^b \times (V/N)^c/L^d\})\right] \qquad (3)$$

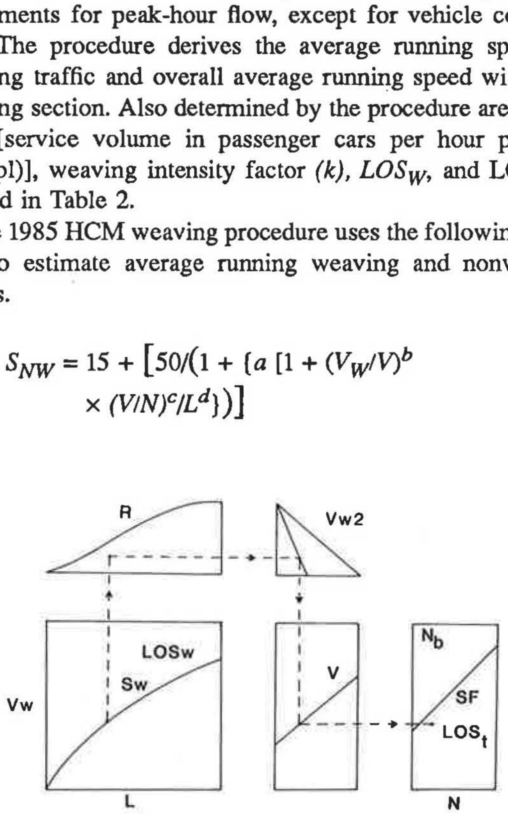


FIGURE 2 Leisch procedure: nomograph outline.

where *a, b, c* and *d* are calibration constants based on section configuration and type of operation. The method categorizes weaving sections into Types A, B, and C as a function of the minimum number of lane shifts performed by a driver in each of the two weaving traffic streams, as indicated in the HCM Weaving Chapter (*9*, Table 4-1).

A key element in the HCM procedure is whether traffic operation is constrained or unconstrained. This is determined by comparing the number of lanes required for unconstrained operation, N_W, with the theoretical value N_W (Max) [see HCM Table 4-4 *(9)*]. Weaving and nonweaving speeds are then determined from Equation 3 based on configuration type and operation mode for the section under consideration. Finally, two levels of service are determined separately for weaving and nonweaving traffic [see HCM Table 4-6 *(9)*].

Another important aspect of all procedures is the range of operating conditions in which a solution can be found. Inherent limitations in the procedures include section geometry [i.e., maximum values for *L*, *N*, or N_b, section capacity V_W, *SF*, weaving frequencies *VR* (where *VR* is volume ratio = V_W/V), R (where R is weaving ratio = V_{W2}/V_W), and running speeds S_W, S_{NW}]. A comparison of the three procedures in that respect is given in Table 3.

LANE SHIFT CONCEPT

A noticeable difference between the JHK and HCM procedures is that the latter introduces the configuration of the weaving section into the speed equation *(9)*. The parameters *a, b, c,* and *d* in the HCM method are determined in part from the minimum number of lane shifts required by a driver in each of the weaving streams (as indicated in HCM Table 4-1), thus implying that weaving traffic is completely segregated on entering the weaving section.

Field measurements collected recently indicate that weaving traffic is not fully segregated on entering the weaving section (based on information letter from Eric Ruehr, JHK and Associates, October 1984). For $N_B = 2$, it was found that an average of 93.4 percent of Movement 2 traffic entered by way of Lane B (Figures 1*a* and 1*b*), while 6.6 percent entered via Lane C. For $N_B \geq 3$, only 90.5 percent of Movement 2 traffic entered the weaving section by way of Lane B, with almost 10 percent of all traffic arriving in Lanes C and D. A negligible percentage of vehicles arrive in the outer lanes E, F, and so forth. A summary

TABLE 3 COMPARISON OF PROCEDURE LIMITATIONS

Procedure	Parameter	Limitation	Comments
Leisch	S_{Wi}	~ ≤ 55 mph	Initial average running speed of weaving traffic out of realm of weaving
	S_{Wf}	~ ≤ 55 mph	Same as above, for final weaving speed
	SF	~ 2000 pcphpl	Service flow beyond nomograph boundary
JHK	S_W	15 mph < S_W < 65 mph	Outside the realm of weaving
	S_{NW}	15 mph < S_{NW} < 65 mph	
	L	≤ 4,000 ft	
1985 HCM	V_W	Type A, 1,800 pcph Type B, 3,000 pcph Type C, 3,000 pcph	Weaving section capacity
	V/N	1,900 pcph (A, B, C)	Lane capacity
	VR	Type A: N = 2, 1.00 N = 3, 0.45 N = 4, 0.35 N = 5, 0.22 Type B: 0.80 Type C: 0.50	Volume ratio limits
	R	Type A: 0.50 Type B: 0.50 Type C: 0.40	Weaving ratio limits
	L	Type A: 2,000 ft	Length out of realm of weaving
		Types B and C: 2,500 ft	
	S_W	15 < S_W < 65	
	S_{NW}	15 < S_{NW} < 65	

of the observed distribution of Movement 2 vehicles is given in Table 4.

As a logical extension of the results just given, an index was developed that takes into account the interaction of the following

- Weaving volumes V_2 and V_3,
- Distribution of V_2 and V_3 across lanes, and
- The minimum number of lane shifts by lane of entry.

A lane shift multiplier has been developed that represents the minimum number of lane shifts that must be executed by the driver of a weaving vehicle from his lane of origin to the closest destination lane. This parameter can be determined directly from a sketch of the existing or proposed weaving section. Two examples, with balanced and imbalanced sections, which demonstrate the computation of the lane shift multipliers *A*, *B*, *C*, and *D* are shown in Figures 3*a* and 3*b*, respectively. Note the following in Figure 3:

A = lane shift multiplier for entering lane A (LS/veh);
B = lane shift multiplier for entering lane B (LS/veh);
C = lane shift multiplier for entering lane C (LS/veh);
D = lane shift multiplier for entering lane D (LS/veh);

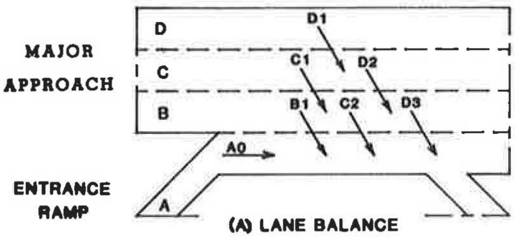
TABLE 4 OBSERVED LANE DISTRIBUTION OF TRAFFIC UPSTREAM OF WEAVING SECTIONS

JHK Site No.	Percent Movement 2 Traffic in Indicated Lane[a]				
	$N_b = 2$		$N_b = 3$		
	B	C	B	C	D
1			93.1	6.9	0.0
2	97.0	3.0			
3	89.7	10.3			
4[b]			91.1	8.4	0.5
			95.1	4.5	0.0
			88.3	9.2	2.5
5[b]			84.3	14.4	1.3
			92.2	6.8	1.0
			88.8	9.4	1.8
Avg	93.4	6.6	90.5	8.5	1.0

Source: Information letter from Eric Ruehr, JHK and Associates, October 1984.

[a] See Figure 1 for lane designation.
[b] Multiple observations per site.

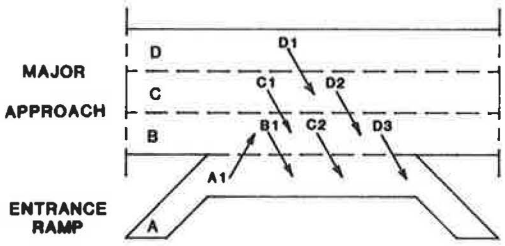
From the previous analysis, the total number of peak-hour lane shifts performed in the weaving section can be calculated. When adjusted for variations in vehicle and driver population, peak-hour factor (PHF), and lateral clearances, the resulting index, termed passenger car lane shifts per hour (pcLSph) provides a means for integrating several operating parameters of the weaving section into a single variable. The index also avoids the artificial designation of weaving sections into Type A, B, and so forth; rather, it provides the traffic engineer with a single numeric value that is indicative of the level of maneuvering difficulty encountered by all drivers in the weaving section.



(A) LANE BALANCE

LANE SHIFT MULTIPLIERS (LS/veh.):

A=0, B=1, C=2, D=3



(B) LANE IMBALANCE

LANE SHIFT MULTIPLIERS (LS/veh.):

A=1, B=1, C=2, D=3

FIGURE 3 Examples of determining lane shift multipliers.

Equations for determining the lane shift index are given in Table 5 for different configurations of weaving sections. Note the following in Table 5:

LS = average number of lane shifts performed by the drivers of weaving vehicles = $LS_2 + LS_3$ [passenger car lane shifts per hour (pcLSph)];
LS_2 = average number of lane shifts performed by the drivers of the Movement 2 vehicles (pcLSph); and
LS_3 = average amount of lane shifts performed by the drivers of the Movement 3 vehicles (pcLSph).

Initial testing of the lane shift index consisted of a correlation analysis between the index and average running weaving and nonweaving speeds observed at six sites comprising a total of 12 cases. Examination of the data indicated an inverse relationship between the two parameters, as suspected. Further testing pertaining to the form of the variable indicated that LS/L and LS_3/V correlated well with average running weaving speeds, whereas LS_3/LS correlated well with average running nonweaving speeds. The resulting speed models, which represent an extension of the JHK and 1985 HCM models, are expressed by the following equations:

$$S_W = 15 + \Big\{50/\big[\big(1 + \{[1 + (V_3 + V_4)/V]^{3.045}\ (V/N)^{0.605} \times (LS/L)^{0.902}\}\big)/75.959\ [1 + (LS_3/V)]^{3.94}\big]\Big\} \tag{4}$$

and

$$S_{NW} = 15 + \Big\{50/\big[1 + (\{[1 + (V_4/V)]^{5.08}\ [1 + (V_W/V)]^{2.019} \times (V/N)^{1.523}\}/\{60.995\ [1 + (LS_3/LS)]^{0.916}\ L^{1.07}\})\big]\Big\} \tag{5}$$

It should be noted that the calibration data set for the speed models consisted of 56 cases, including 35 sites from the Bureau of Public Roads study *(3)* and 6 from the JHK study [Reilly and Johnson *(8)*, and weaving study memoranda by Reilly and Johnson, JHK and Associates, November 1984].

PRELIMINARY MODEL EVALUATION

To determine that the proposed speed models are an improvement over other procedures available, a comparison with the JHK models was performed. This task required the recalibration of the JHK models using the set of 56 data points mentioned in the previous section. After both models were calibrated, they were utilized to predict average weaving and nonweaving speeds in 11 validation cases [Reilly and Johnson *(8)*, and weaving study memoranda by Reilly and Johnson, JHK and Associates, November 1984]. A simple regression model between field and predicted average running speeds was developed to test the predictive power of each model. The results are presented in Table 6. As can be observed, the proposed model exhibited higher correlations with observed weaving speeds compared with the recalibrated JHK model. Both models exhibited modest correlations with average nonweaving speeds; the JHK procedure had a slight edge over the proposed model.

COMPARISON OF THE FOUR PROCEDURES

The proposed model has been expanded to a step-by-step procedure for the design and operations analysis of simple weaving sections. Details of the procedure may be found elsewhere *(10)*. In addition, an interactive, microcomputer-based program has been developed that performs all of the calculations necessary to carry out the four procedures described in this paper *(11)*. A set of 67 cases representing the full data base available to the research staff was processed

TABLE 5 LANE SHIFT INDEX EQUATIONS

N_b	LS_2	LS_3
1	$V_2B/(PHF * f_{HV} * f_W * fp)$	$V_3\ A/(PHF*f_{HV} * f_W * f_p)$
2	$(0.934V_2B + 0.066V_2C)/(PHF * f_{HV} * f_W * fp)$	$V_3A/(PHF*f_{HV}*f_W*fp)$
≥ 3	$(0.905V_2B + 0.085V_2C + 0.010V_2D)/(PHF * f_{HV} * f_W * fp)$	$V_3A/(PHF*f_{HV} * f_W * f_p)$

Note: f_{HV} = heavy vehicle adjustment factor; f_W = lateral clearance adjustment factor; fp = driver propulation adjustment factor; and all other variables are as defined in the text or previous tables.

TABLE 6 FIELD VERSUS PREDICTED SPEEDS: RESULTS OF TWO MODELS

	Data Set Type			
	Calibration[a]		Validation[b]	
Parameter	JHK[c]	Proposed Model	JHK	Proposed Model
Weaving speeds				
r[d]	0.62	0.74	0.56	0.65
Slope	0.90	0.89	0.62	0.63
Intercept	3.50	3.90	12.20	13.30
Nonweaving speeds				
r	0.53	0.55	0.46	0.40
Slope	0.80	0.79	0.82	0.66
Intercept	7.20	7.70	8.80	16.60

[a] 56 cases.
[b] 11 cases.
[c] Recalibrated model.
[d] Correlation coefficient.

through the microcomputer program [Reilly and Johnson *(8)*, and weaving study memoranda by Reilly and Johnson, JHK and Associates, November 1984]. A detailed breakdown of the study sites is given in Table 7.

A comparative summary of the results obtained is given in Table 8. As can be observed, the proposed procedure produced the highest correlation with field weaving ($r = 0.72$) and nonweaving speeds ($r = 0.53$). In contrast, the HCM procedure ranked last in correlation with weaving ($r = 0.56$) as well as nonweaving speeds ($r = 0.31$). The JHK and Leisch procedures yielded almost identical correlations for both speeds. Furthermore, the proposed procedure produced the lowest intercept (for perfect correlation, intercept approaches zero) and second highest slope (for perfect correlation, slope approaches unity) compared with the other three procedures.

An assessment of the applicability of each procedure, is presented in Table 9. In this table, the number of sites for which a solution could not be found as a result of inherent operational limitations in each procedure (given in Table 3) is listed for each procedure. Of the 67 cases making up the data base, the 1985 HCM procedure could only be applied to 39 cases. It appears that the limitation on weaving section capacity of 1,800 pcph for Type A configuration and 3,000 pcph for Types B and C resulted in the rejection of many sites in the data base. It is interesting to note that a solution that disregards these limitations produces an estimate of speeds that is in close agreement with some of the field observations.

To confirm that the majority of invalid cases are indeed reflective of the HCM weaving capacity limitations and not due to site anomalies such as excessive length and or number of lanes, the frequencies of all Type A sections were compared with the frequencies of those invalid Type A configuration cases in which V_W exceeded 1,800 pcph. The comparisons were made with respect to length (Figure 4) and number of lanes within the weaving sections (Figure 5). In both instances, the invalid case frequencies closely parallel all Type A frequencies; in other words, the frequencies of invalid cases did not progressively increase as length or number of lanes increased. Similar patterns were observed were observed when the frequencies of Types B and C configurations were compared. No such limitation problems were encountered with the other pro-

TABLE 7 GEOGRAPHICAL DISTRIBUTION OF STUDY SITES

Location	No. of Cases[a]	Method(s) That Used Case(s) for Calibration[b]	No. of Sites
Arlington, Virginia	2 A	L, H, P	2
	1 A	L	
Atlanta, Georgia	1 B	J, P	2
	1 B	L, J	
Boston, Massachusetts	1 A		1
Chicago, Illinois	13 A	L, H, P	14
	1 B	L, J	
	1 A	L	
Gowanus Expressway, New York	1 A		1
Long Island, New York	4 A	L, H, P	3
Los Angeles, California	6 A	L, H, P	6
New York, New York	8 A	L, H, P	5
	1 A		
San Diego, California	2 A		2
San Francisco, California	8 A	L, H, P	9
	9 B	J, P	
Washington, D.C.	3 A	L, H, P	5
	2 B	J, P	
White Plains, New York	1 A		1
Yonkers, New York	1 A		1
Total	67		52

Source: Reilly and Johnson *(8)* and weaving study memoranda by Reilly and Johnson, JHK and Associates, November 1984.

[a] A = pre-1970 data and B = post-1970 data.
[b] L = Leisch weaving procedure, H = 1985 HCM weaving procedure, J = JHK weaving procedure, and P = proposed weaving procedure.

TABLE 8 SUMMARY EVALUATION OF FIELD VERSUS METHOD AVERAGE RUNNING SPEEDS

	Weaving Speed (mph)						Nonweaving Speed (mph)					
Method	r	Slope	Intercept (mph)	Standard Deviation Field (mph)	Standard Deviation Method (mph)	Absolute Mean Difference (mph)	r	Slope	Intercept (mph)	Standard Deviation Field (mph)	Standard Deviation Method (mph)	Absolute Mean Difference (mph)
Proposed	0.72	0.84	5.4	9.7	8.4	5.4	0.53	0.79	8.2	11.6	7.8	7.9
JHK	0.62	0.65	10.4	10.0	9.6	5.9	0.48	0.60	13.6	11.8	9.4	8.6
Leisch[a]	0.63	0.85	7.7	9.6	7.1	5.7	0.48	0.72	10.5	11.4	7.7	8.4
1985 HCM	0.56	0.82	7.3	7.9	5.3	4.7	0.31	0.42	24.7	11.0	8.0	8.7

[a] Nonweaving speeds in this procedure cannot be directly estimated. Observed nonweaving speeds are correlated with overall speeds, as recommended by the author.

TABLE 9 SUMMARY EVALUATION OF METHOD APPLICABILITY

			No. of Invalid Cases Due To[a]								
Method	No of Cases	No. of Valid Cases	$V_W >$ 1,800 pcph	$SF >$ 2,000 pcphpl	$VR > 0.22$	$V_W >$ 3,000 pcph	Out of Realm[b]	$R > 0.4$	$L >$ 2,500 ft	4,000 ft	$VR > 0.5$
Leisch	67	65	–	1	–	–	1	–	–	–	–
JHK	67	63	–	–	–	–	–	–	–	4	–
1985 HCM[c]	67	39	9	–	1	9	–	1	6	–	2
Proposed[c]	67	67	–	–	–	–	–	–	–	–	–

[a] In which at least one constraint was violated.
[b] Considered to be beyond the realm of weaving.
[c] Based on 5-min peak flow rates.

cedures: the JHK procedure was applicable in 63 cases, the Leisch procedure in 65 cases, and the proposed procedure in all 67 cases making up the data base.

FINAL NOTE ON THE ANALYSIS PERIOD

Although the decision to calibrate speed models based on hourly or peak flow rates is highly controversial, a simple rule exists when the final models are to be tested: follow the appropriate input requirements stipulated by the method.

In this study, hourly volumes were not adjusted for peak periods in either the Leisch or JHK procedure; the former procedure automatically performs PHF adjustments in the nomographs, whereas the latter does not consider any automatic peak-period adjustments. The proposed procedure and HCM procedure require peak-period adjustments for 5- and 15-min peak flow rates, respectively.

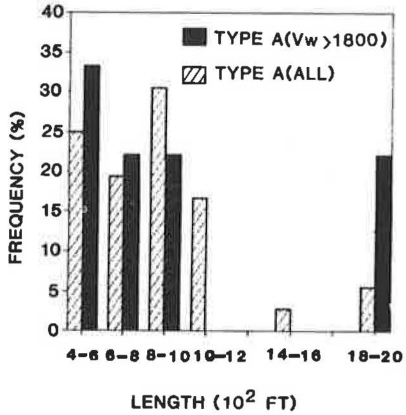


FIGURE 4 Distribution of section length: rejected HCM cases ($V_W >$ 1,800 pcph) versus all Type A.

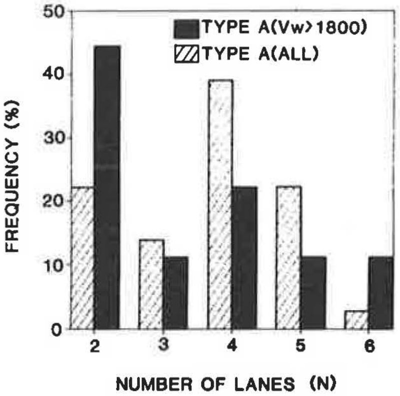


FIGURE 5 Distribution of No. of lanes: rejected HCM cases ($V_W >$ 1,800 pcph) versus all Type A.

However, due to the lack of 15-min data, both procedures were tested based on 5-min peak flow rates. Although it is anticipated that some cases may no longer be invalid under the 15-min assumption, results indicated that the majority of cases that were rejected under the original test ($V_W >$ 1,800 pcph for Type A, $V_W >$ 3,000 pcph for Types B and C) remain invalid even when a PHF of 1.0 is assumed (12 out of 18 cases). The true number of rejected cases will probably range between 12 and 18. Even in the absence of such information, it is evident from Equation 3 that PHF (in the term V/N) does not signifi-

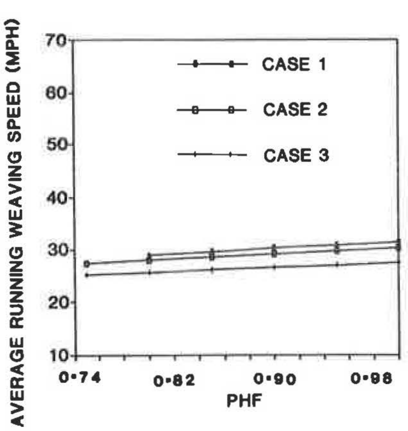


FIGURE 6 Sensitivity of HCM average weaving speed to peak-hour factor for $N = 2$.

cantly affect the operation of the weaving section. Results for three cases from the data base plotted in Figures 6 and 7 for N = 2 (the most critical value for PHF) indicate little variation in predicted weaving and nonweaving speeds in response to variations in the peak-hour factor.

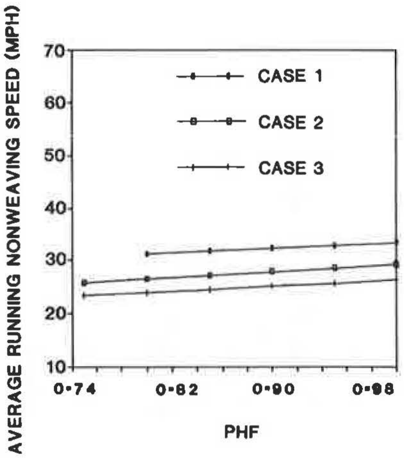


FIGURE 7 Sensitivity of HCM average nonweaving speed to peak-hour factor for $N = 2$.

CONCLUSIONS AND RECOMMENDATIONS

This study was designed to investigate several freeway weaving analysis procedures that were contemplated for the 1985 HCM. It has resulted in the development of a weaving procedure that is superior in predicting weaving and nonweaving speeds compared with existing procedures. The following conclusions are offered.

- The total number of lane shifts required by drivers in weaving sections affects both weaving and nonweaving speeds. Negative correlations between speeds and lane shifts were observed in the field.
- The inclusion of lane shift as an independent variable in average running weaving and nonweaving speed models enhanced the predictive ability of the models considerably. When compared with the latest procedures developed by JHK, Leisch, and the 1985 HCM (PINY), the proposed models yielded the highest correlations with field weaving and nonweaving speeds.
- The 1985 HCM procedure appears to be severely limited in its application; more than 41 percent of all cases analyzed in this study did not meet the constraints stipulated by the method. The majority of the cases failed to satisfy the constraints on weaving section capacity; a majority of these cases would still have been rejected even if hourly rates had been used instead of peak 5-min flow rates. A lower bound on the proportion of rejected cases is estimated at 33 percent in this study.

Considerable research remains to be done in the area of freeway weaving sections design and analysis. Four recommendations follow.

- Fundamental work on vehicle dynamics in freeway weaving sections is needed. The procedures described in this paper are primarily empirical (data based) and do not capture the essence of vehicle interaction and its impact on average weaving and nonweaving speeds. Microscopic simulation modeling, using INTRAS *(12)* or a similar package is recommended as a cost-effective tool for conducting such analyses.
- A persistent problem throughout this study was the inadequate sample size of new (post-1970) field data. The reliability of empirical procedures can be greatly enhanced with additional data points for both calibration and validation purposes.
- Although the weaving procedure proposed in this paper has yielded superior results compared with the other three procedures, it is recommended that all four procedures be tested to solve the same problem. The final design decision must still rest with the engineer, who may select the procedure yielding the most conservative design, average out all the results, and so forth. The interactive, microcomputer program developed in this study greatly simplifies this task *(14)*.
- There is great need to tie in the safety characteristics of weaving sections (i.e., accident frequencies, type, location, and so forth) to the design and operations analysis procedures. This may result in defining lower bounds on section length and number of lanes based on accident experience.

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A Comparison of the 1985 *Highway Capacity Manual* and the Signal Operations Analysis Package 84

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The primary objective of this paper is to determine if the signalized intersection procedure as described in Chapter 9 of the 1985 *Highway Capacity Manual* (HCM) will give results consistent with the microcomputer version of the Signalized Operations Analysis Package 84 (SOAP 84). Each procedure was used to analyze the intersection in Chapter 9, Calculation 3, of the 1985 HCM. Average stopped delay was calculated for the intersection by each method and was used as the basis for comparing the 1985 HCM and SOAP 84. For through movements and protected–restricted left turns, the two procedures produced similar results for calculating stop delay, X ratios, and effective green ratios. However, for the results to be consistent, the saturation flow as calculated by the HCM method must be used in SOAP 84 as the capacity (saturation flow) for through movements and the protected–restricted left turns. For protected–permissive and unprotected left turns, the two methods produce significantly different results.

Described is an effort to compare the microcomputer version of SOAP 84 with the methodology in Chapter 9, Signalized Intersections, of the 1985 *Highway Capacity Manual* (HCM).

The Signal Operations Analysis Package (SOAP 84) is a computerized method for developing control plans and evaluating the operations of individual signalized intersections. As the basis for the comparison between SOAP 84 and the 1985 HCM, delay will be calculated by each method. SOAP 84 determines average delay, which includes delay incurred during deceleration and acceleration as well as stop delay. The 1985 HCM calculates average stop delay as the basis for determining level of service. To make a comparison between the two methods, average delay will be converted to average stop delay by using the following formula *(1)*:

$$\text{Average delay}/1.3 = \text{average stop delay} \tag{1}$$

As the first step in the analysis, Calculation 3: Operational Analysis of a Multiphase Actuated Signal from Chapter 9 of

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