Development of Weaving Area Analysis Procedures for the 1985 *Highway Capacity Manual*

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The development history of the procedures included in Chapter 4 of the 1985 *Highway Capacity Manual* for the analysis and design of freeway weaving areas is reviewed. Noting the studies and efforts providing input, the final development of procedures under the National Cooperative Highway Research Program Project 3-28B is detailed. The merging of the weaving and nonweaving speed prediction algorithm developed by JHK & Associates with the concepts of weaving configuration and type of operation, developed by the Transportation Training and Research Center of the Polytechnic University is explained. A comparative analysis is conducted indicating the superior accuracy of the final procedure to its predecessors.

The development of the weaving area analysis procedures of the 1985 *Highway Capacity Manual (1)* (HCM) was perhaps the most difficult of all the methods and procedures included in the manual. This was true despite the fact that weaving areas were better researched and had more significant data bases available than any other facility type. The reason for this incongruity is that various researchers took radically different approaches to the analysis of weaving areas, making several different procedures available for consideration by the Highway Capacity and Quality of Service Committee of TRB. Because the approaches taken were fundamentally different, the various procedures led to vastly differing results in some cases.

THREE WEAVING PROCEDURES

The Polytechnic Method

Three procedures for weaving area analysis were developed during the period from 1972 to 1984. The first was developed by the Polytechnic Institute of New York (now Polytechnic University) as part of an ongoing research program sponsored by both the National Cooperative Highway Research Program (NCHRP) and FHWA. The NCHRP-sponsored "Weaving Area Operations Study" led to the analysis of a 1963 data base collected by the then Bureau of Public Roads, and the collection of additional data from 1972 to 1973. A new analysis methodology was proposed and published in *NCHRP Report 159 (2)*. The key feature of the proposed methodology was that the geometric configuration of lanes in the weaving area was a major determinant of operating quality.

However, the methodology presented in the report was difficult to use and comprehend. Presented as a complex two-part nomograph, the method was not widely used. As part of the "Freeway Capacity Analysis Procedures" study sponsored by FHWA in 1976 to 1978 *(3, 4)*, Polytechnic University's weaving procedure was reformatted and revised to provide for easier use and understanding. This revised procedure was published in TRB's *Circular 212: Interim Materials on Highway Capacity (5)*.

The Leisch Method

In 1979, Jack Leisch presented the Highway Capacity and Quality of Service Committee with a second weaving procedure that he had developed independently using data from both the 1963 and 1973 studies. The Leisch procedure was similar in structure to the 1965 HCM method, and used two nomographs for all solutions. Although the procedure was undocumented, it was published in *Circular 212* in the hope that users would compare the two methods and comment on which was more accurate. FHWA later provided support to update and document the procedure *(6)*.

Thus, *Circular 212* was published with two weaving procedures yielding substantially different results in many cases. Commentary from users, however, did little to resolve the issue of which procedure was more accurate.

The JHK Method

In response to the outcome of Leisch's work, FHWA sponsored an additional effort from 1983 through 1984 to compare the two procedures, and to make recommendations for a procedure to be included in the 1985 HCM. This study was conducted by JHK & Associates *(7)*.

The JHK study concluded that neither of the two methods in *Circular 212* adequately described weaving area operations. The study proposed a more simplified method consisting of two equations, one for the prediction of the average speed of weaving vehicles, and one for the prediction of the average speed of nonweaving vehicles. The method proposed, however, had three basic differences from previous methods:

1. The method used hourly volume data. This was consistent with the Leisch method and at variance with Polytechnic University's method, which used 15- and 18-min flow rates. It was noted that most materials in the new (1985) HCM, and certainly all materials for uninterrupted flow, used rates of flow during peak 15-min periods as the basis for analysis.
2. The concept of configuration, central to both the Polytechnic University and Leisch procedures (although in different ways), was eliminated.

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3. The concept of constrained and unconstrained operation, central to the Polytechnic procedure, was eliminated.

RESOLVING THE ISSUES

In late 1984, the Highway Capacity and Quality of Service Committee had before it three different weaving area analysis procedures, all producing different results in many cases. Furthermore, comparative accuracy analyses were clouded by the difference in input data and output results, that is, hourly volumes and average speeds over a full hour versus flow rate for 15-min intervals and average speeds during those 15-min intervals. The committee commissioned the NCHRP Project 3-28B team to do the following:

1. Retain the basic form of the speed prediction equations calibrated by JHK & Associates,
2. Recalibrate the procedure using 15-min rates of flow and speed, and
3. Reintroduce the concepts of configuration and constrained versus unconstrained operation into the procedure.

This effort took place in late 1984, and the revised procedure was presented to and approved by the Highway Capacity and Quality of Service Committee in January 1985.

The concept of the revised method was to calibrate JHK-type equations for the prediction of weaving and nonweaving vehicle speeds in weaving areas for three basic types of configuration and for constrained and unconstrained operations. This led to a need for 12 calibrated equations.

The calibration effort used 18- and 15-min data from 45 experiments from the 1963 and 1973 studies. Data in this form was not available from the later JHK data collection effort.

DEVELOPING THE 1985 HCM METHODOLOGY

In accordance with recommendations in the JHK final report, sites longer than 1,500 ft (for ramp weaves) and 2,500 ft (for major weaves) were eliminated from the data base. The 207 resulting data points each consisted of rates of flow for each weaving and nonweaving movement in the segment, the average travel speed of each movement, and a complete geometric description of the site. The data were stratified by configuration type and by constrained or unconstrained operation, creating six categories. Within each category, equations predicting the average speed of weaving and nonweaving vehicles were calibrated.

Because the general form of the equation desired (the JHK format) was known, regressions were easily organized and performed. However, the initial calibration attempt using regression led to unsatisfactory results. R-squared values ranged from 0.40 to 0.85, with many in a clearly unsatisfactory range. Moreover, the resulting equations did not always display logical or reasonable sensitivity trends. When equations for various configuration types, as well as for unconstrained and constrained operation, were compared, the results were also illogical in many cases. These difficulties were primarily due to the concentration of data in small regions of the defined matrix of variables.

Recognizing the overwhelming importance of the sensitivity of results to the variables of configuration and type of operation, regression results were modified on a trial-and-error basis, forcing appropriate sensitivities to occur. Key aspects of this analysis were as follows:

1. All weaving and nonweaving speed prediction equations were restricted to the general form suggested by JHK & Associates

$$S_w \text{ or } S_{nw} = 15 + \frac{50}{1 + a\,(1 + VR)^b\,(v/N)^c/L^d} \tag{1}$$

where

a,b,c,d = constants of calibration;
VR = volume ratio, that is, the ratio of weaving flow rate to total flow rate in the section;
v = total flow rate in the weaving section in passenger cars per hour (pcph);
N = number of lanes in the weaving section; and
L = length of the weaving section in feet.

2. Constrained operation should produce higher nonweaving speeds and lower weaving speeds than corresponding unconstrained cases.
3. For high values of *VR*, major weaves should produce higher weaving speeds and lower nonweaving speeds than corresponding ramp-weaves.
4. Type C weaves should have lower nonweaving and weaving speeds than corresponding Type B weaves because of the increased lane-changing required by Type C configurations. As weaving volume increases, this difference should increase.

Complete descriptions and definitions of configuration types are given in the 1985 HCM. Type A, B, and C weaving configurations are defined in terms of the number of lane changes which must be made to successfully complete each weaving maneuver.

Adjustment of the original regression equations in the manner described resulted in a system of equations that *(a)* displayed all of the appropriate sensitivities, and *(b)* predicted both average weaving and nonweaving speeds more accurately than any available method at the time of the 1985 HCM publication. The equations are given in Table 1 (*1*, see Table 4-3).

Because the equations calibrated require a differentiation between constrained and unconstrained operation, a method was needed to make this distinction. The methodology developed was to assume unconstrained operation, computing the weaving and nonweaving speeds that would result. Using several equations calibrated for the Polytechnic University procedure in *Circular 212*, the number of lanes required by weaving vehicles to achieve these speeds could be estimated and compared to maximum values achievable for each configuration type. The equations and maximum values are given in Table 2 (*1*, see Table 4-4).

Maximum values of N_w, the number of lanes used by weaving vehicles during unconstrained operation, were obtained by

TABLE 1 ALGORITHMS FOR PREDICTING WEAVING AND NONWEAVING SPEEDS IN THE 1985 HCM (*1*, Table 4-3)

GENERAL FORM:

$$S_w \text{ or } S_{nw} = 15 + \frac{50}{1 + \mathrm{a}\,(1 + VR)^{\mathrm{b}}\,(v/N)^{\mathrm{c}}/L^{\mathrm{d}}}$$

TYPE OF CONFIGURATION	CONSTANTS FOR WEAVING SPEED, S_w				CONSTANTS FOR NONWEAVING SPEED, S_{nw}			
	a	b	c	d	a	b	c	d
TYPE A								
Unconstrained	0.226	2.2	1.00	0.90	0.020	4.0	1.30	1.00
Constrained	0.280	2.2	1.00	0.90	0.020	4.0	0.88	0.60
TYPE B								
Unconstrained	0.100	1.2	0.77	0.50	0.020	2.0	1.42	0.95
Constrained	0.160	1.2	0.77	0.50	0.015	2.0	1.30	0.90
TYPE C								
Unconstrained	0.100	1.8	0.80	0.50	0.015	1.8	1.10	0.50
Constrained	0.100	2.0	0.85	0.50	0.013	1.6	1.00	0.50

review of the data base. When the calibrated equations shown were used to predict the required values of N_w, use of the proposed maximums resulted in a correct determination of the type of operation in over 90 percent of all cases. Thus, if the number of weaving lanes required for unconstrained operation is more than the maximum value that can be achieved, the operation is constrained.

Maximum values for key variables in weaving areas are given in Table 4-5 of the 1985 HCM. Most of these were observed from the data base, and many were the subject of considerable discussion in the Highway Capacity and Quality of Service Committee. Weaving capacity (the highest total weaving flow rates that can be handled in weaving areas) was established as 1,800 pcph for Type A configurations, and as 3,000 pcph for Types B and C. The maximum total flow per lane in a weaving section was established as 1,900 passenger cars per hour per lane (pcphpl), in recognition of the turbulence that exists in weaving areas. It was felt that a capacity of 2,000 pcphpl was unlikely in such turbulent areas. Moreover, none of the 207 data cases had flow rates in excess of this, despite the fact that many were obviously operating at or near capacity. Maximum values of volume ratio (VR) and weaving ratio (R) were similarly established.

The most controversial limitation of weaving areas is the maximum length provision of Table 4-5 in the 1985 HCM. This has always been a controversial issue. The Leisch method of *Circular 212* shows weaving lengths up to 8,000 ft, as does the 1965 HCM. None of the available data, however, extends far beyond the 3,000-ft range. The issue is clear: At what length does a weaving area begin to operate as isolated merge and diverge areas with basic freeway operation in between? The answer, however, is not as clear. For Type B and C configurations, data for long sites in the 3,000- to 3,600-ft range provides some insight. For these cases, when the weaving methodology was used to predict average speeds, results were less accurate than if the facilities were treated as basic freeway sections. Thus, the maximum length of section qualifying for analysis as a weaving area was set at 2,500 ft for Type B and C configurations and at 2,000 ft for Type A sections. The limits reflected the limits of the data base, and judgment, based on a limited amount of data, reflected the fact that beyond these lengths operations were basically isolated, merging and diverging rather than weaving.

VALIDATING THE PROCEDURE

To verify the accuracy of the calibrated procedure, all 207 data samples were tested by comparing the calibrated procedure with the unrevised JHK procedure. The methods in *Circular*

TABLE 2 DETERMINING TYPE OF OPERATION IN THE 1985 HCM (*1*, Table 4-4)

TYPE OF CONFIGURATION	NO. OF LANES REQ'D FOR UNCONSTRAINED OPERATION, N_w	MAX. NO. OF WEAVING LANES, N_w (max)
Type A	$2.19\ N\ VR^{0.571}\ L_H^{0.234}/S_w^{0.438}$	1.4
Type B	$N\ \{0.085 + 0.703\ VR + (234.8/L) - 0.018(S_{nw} - S_w)\}$	3.5
Type C	$N\ \{0.761 - 0.011\ L_H - 0.005(S_{nw} - S_w) + 0.047\ VR\}$	3.0 [b]

[a] All variables are as defined in Table 4-2.

[b] For 2-sided weaving areas, *all* freeway lanes may be used as weaving lanes.

NOTE: When $N_w \leq N_w$ (max), operation is unconstrained.
When $N_w > N_w$ (max), operation is constrained.

212 were not tested because the JHK study had already shown them to be inferior to the unrevised JHK approach. Although the use of the same data for both calibration and validation does not constitute a formal validation, the comparison of results does document the fact that the HCM procedure further improves the accuracy of the unrevised JHK method.

The results of these comparisons are shown in Figures 2-2 through 2-4 in the 1985 HCM. For all types of configurations, the calibrated procedure produces more correct speed predictions (within 3 mph of actual speed) and reduces the magnitude of errors where they occur. The improvement in accuracy is most noticeable for Type B configurations, and is generally better in the prediction of weaving speeds than in the prediction of nonweaving speeds (See Figures 1–3).

The larger errors obtained with the calibrated procedure primarily result from erroneous identification of constrained versus unconstrained operation.

Although 15-min data from the JHK study were not available for study at the time the weaving methodology was being finalized, the calibrated equations were tested against hourly data samples published in the JHK final report. The results of this analysis are given in Table 3.

For most of the cases, the results using the HCM procedure are reasonable. Cases 106 and 107 result in significant underpredictions of both weaving and nonweaving speeds. Both cases involve a site with heavy traffic flows in the range of 1,700 to 1,850 pcphpl. Even on a basic freeway section, the 1985 HCM would not predict speeds as high as those indicated. This site appears to represent unusually high speeds. Despite the difficulties in comparing predictions based on rates of flow during 15-min intervals with hourly data samples, the calibrated procedure appears to work acceptably with not only the 1963 and 1973 data bases (with which it was calibrated), but the 1983 JHK data base as well.

This method was, therefore, adopted by the Highway Capacity and Quality of Service Committee for the following reasons:

1. The method is consistent with other uninterrupted flow techniques of the 1985 HCM, that is, it is based on flow rates during a 15-min interval;
2. The method is computationally straightforward, using a simple algorithm developed by JHK & Associates;
3. The method retains the logical framework of the JHK equations, while reflecting the important concepts of configuration and type of operation;
4. The method is demonstrably more accurate in predicting

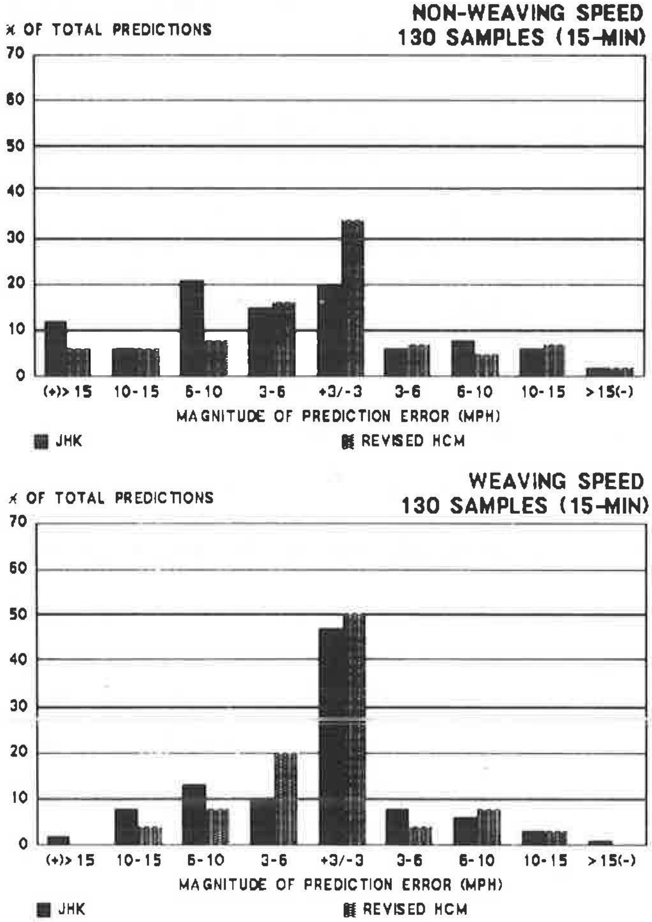

FIGURE 1 Comparative accuracy of weaving area analysis methodologies for Type A configurations.

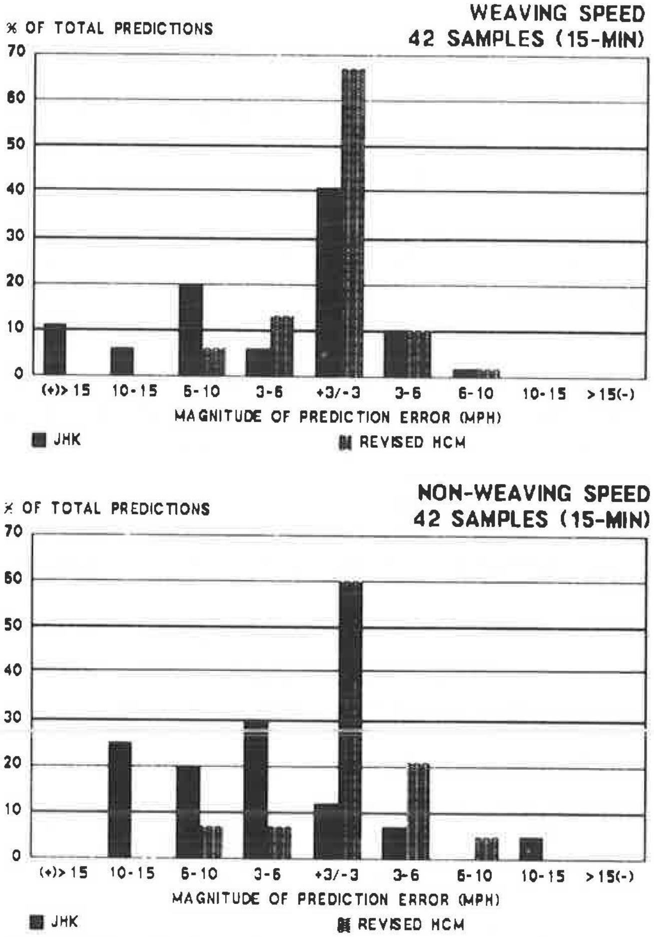

FIGURE 2 Comparative accuracy of weaving area analysis methodologies for Type B configurations.

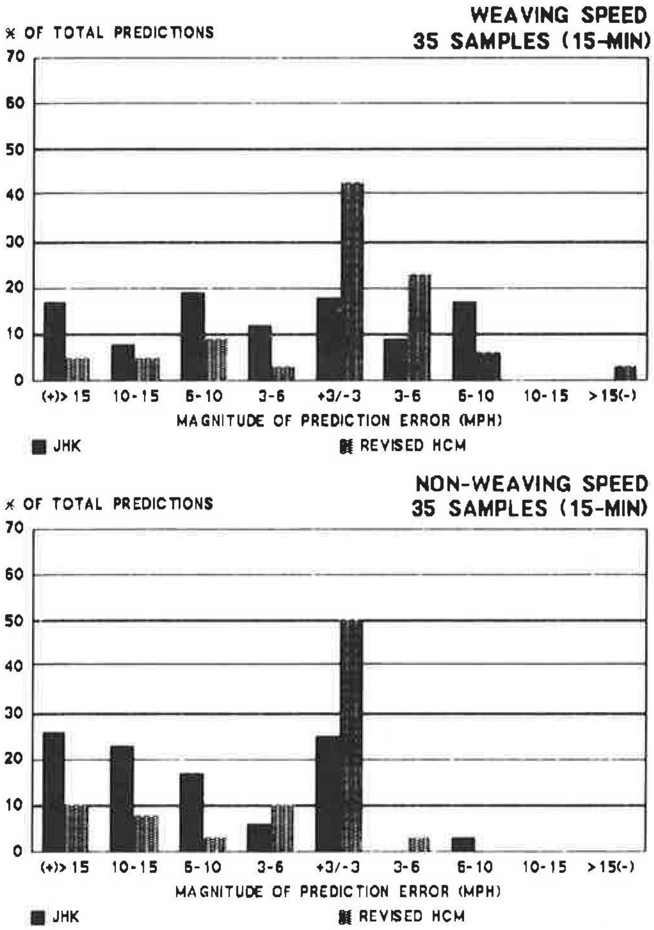

FIGURE 3 Comparative accuracy of weaving area analysis methodologies for Type C configurations.

average speeds of weaving and nonweaving vehicles than other methods available at the time of the 1985 HCM publication; and

5. The method eliminates the need for iterative computations, as are needed in the Polytechnic University procedure described in *Circular 212*.

There is one disadvantage to the 1985 HCM methodology with respect to the Polytechnic procedure in *Circular 212*. The HCM method makes the constrained versus unconstrained operation comparison a zero-to-one decision. Operation is either constrained or unconstrained. The Polytechnic University technique recognizes degrees of constraint by incorporating actual values of N_w into the speed prediction algorithm. Thus, the largest errors using the 1985 HCM method will occur in cases that are "borderline constrained," that is, the type of operation is close to the dividing boundary. This loss of precision is more than outweighed by the computational simplicity and improved overall accuracy of the 1985 HCM method.

TABLE 3 HCM WEAVING METHOD APPLIED TO HOURLY JHK DATA

	Weaving Speed (mph)		Nonweaving Speed (mph)	
JHK Case No.	Actual	Computed	Actual	Computed
101	40.9	43.3	43.9	44.7
102	42.3	47.8	51.5	56.6
103	44.4	48.7	47.6	57.1
104	47.3	49.9	54.9	57.9
105	45.5	41.0	43.8	40.7
106	51.7	42.9	59.7	44.0
107	55.5	43.9	62.8	45.9
111	36.1	38.2	46.9	36.6
112	44.5	42.4	43.8	42.6

LEVEL OF SERVICE CRITERIA

The final determination of the Highway Capacity and Quality of Service Committee was the establishment of the level of service criteria given in Table 4 (*1*, see Table 4-6).

For any given level of service, weaving vehicles are expected to travel somewhat slower than nonweaving vehicles because of the relative difficulty of the weaving maneuver. However, the difference between weaving and nonweaving speeds lessens as the level of service worsens because all vehicles are affected by congestion. Weaving vehicles occasionally travel faster than nonweaving vehicles, which occurs under congested conditions where nonweaving vehicles often segregate to outer lanes to avoid weaving turbulence. Sometimes, this segregation results in slower speeds in outer lanes than in weaving lanes. When this occurs, the level of service for weaving vehicles may be better than the level of service for nonweaving vehicles.

The boundary between levels of service E and F is more complicated. Two values are given in Table 4. Thirty miles per hour is the normal boundary for freeways, and also applies to weaving areas. However, the characteristic of the weaving equations calibrated is to slightly overpredict low speeds and to slightly underpredict high speeds. The equations are bounded at 65 and 15 mph. To adjust for this characteristic, a 35-mph boundary is used for comparison to computed speeds, while a 30-mph boundary is retained for comparison with field-measured speeds.

SUBSEQUENT WORK

The publication of the 1985 HCM has not dispelled the interest of researchers in furthering the state of the art of weaving area analysis.

TABLE 4 LEVEL OF SERVICE CRITERIA FOR WEAVING AREAS IN THE 1985 HCM (*1*, Table 4-6)

LEVEL OF SERVICE	MIN. AVG. WEAVING SPEED, S_w (MPH)	MIN. AVG. NONWEAVING SPEED, S_{nw} (MPH)
A	55	60
B	50	54
C	45	48
D	40	42
E	35/30[a]	35/30[a]
F	< 35/30[a]	< 35/30[a]

[a] The 35-mph boundary for LOS E/F is used when comparing to computed speeds using the equations of Table 4-3. The 30-mph boundary is used for comparison to field-measured speeds.

A 1985 master's thesis by Joseph Fazio of the University of Illinois at Chicago *(8)* resulted in the development of a most interesting concept. Rather than categorizing weaving sections by configuration type, regression equations were developed to predict the number of lane shifts that would be made by weaving vehicles in the section, based on the number of lanes in the section, and the relative positioning of entry and exit lanes. The number of lane shifts is then used as an explicit parameter in the equations for prediction of average weaving vehicle and nonweaving vehicle speeds. For a small data base, this approach was shown to be more accurate in predicting speeds than the 1985 HCM formulation.

Leisch further revised his methodology in 1985, which has been included in a comprehensive comparison of all weaving analysis methods (including the 1965 HCM) using a new data base being conducted by the Institute for Transportation Studies at the University of California, Berkeley. The study is sponsored by the California Department of Transportation and will include data only from California sites.

SUMMARY AND CONCLUSIONS

The study of weaving areas is an analytically complex subject, reflecting the complexity of operations in these intense turbulence areas. The state of knowledge about weaving area operations has improved markedly since the early 1960s through the active research of several different organizations and individuals.

At the point of the publication of the 1985 HCM, three alternative methods were available to the Highway Capacity and Quality of Service Committee, with no clear comparison as to which was the most accurate. In accord with the wishes of the committee, the 1985 HCM method was developed by taking key conceptual and analytic ideas from each of the available methodologies. The development of the resulting method is documented here. The method is shown to be more accurate than its predecessors in the prediction of weaving and nonweaving speeds for the data base available in 1984.

However, research in the subject continues. New and valuable ideas have been developed, and continue to be developed as various studies progress. It was a wise decision to publish the 1985 HCM as a loose-leaf document that can be updated on a chapter-by-chapter basis. If new concepts and models of weaving area operations can be shown to be more accurate than the 1985 HCM over a broad range of data from various regions of the United States, they can be incorporated into an updated chapter. In the meantime, the 1985 HCM provides a valuable and accurate analysis tool for weaving areas and represents significant conceptual and analytic improvement over the 1965 HCM.

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