WEAVING AREA OPERATIONS STUDY: ANALYSIS AND RECOMMENDATIONS

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Work has been completed on the first major phase of a study of the operations of weaving areas aimed at analyzing and evaluating the weaving section procedures of the 1965 Highway Capacity Manual; developing a study program that will lead to improved techniques for the analysis and design of weaving sections; and implementation of the study program to achieve the improved techniques. A hitherto unused data base of weaving section operations was available for analysis. Data collected in 1963 by the Bureau of Public Roads were restructured for computer analysis. New programs were written, and existing programs were extended and applied. In this phase, several analyses were conducted: the internal structure of the weaving capacity procedure, accuracy of the weaving and ramp capacity procedures, consistency of these procedures in specifying level of service, and specific aspects of the two ramp capacity procedures such as accuracy of lane 1 volumes. Results of these analyses indicate that quite frequently the predicted level of service differs from the actual level of service. For basic weaves and ramp weaves, the current weaving capacity procedure is as likely to show poorer as it is better levels of service. When applied to major weaves, however, it tends to predict poorer levels of service than actually occur. For ramp weave cases, the weaving capacity method produces more accurate estimates of levels of service than does either of the ramp capacity procedures, both of which tend to predict better levels of service than those actually experienced in the field. On the basis of these analyses, a reconstitution of the weaving procedure that would be applied to both major weave and auxiliary lane-ramp weave cases is recommended. A data program was specified that would enable calibration of the recommended procedure.

•IN RECENT YEARS, urban freeway design and analysis have been an area of much interest. As such, that segment of the 1965 Highway Capacity Manual (1) dealing with problems of weaving and ramps has taken on particular significance.

In 1969, the National Cooperative Highway Research Program (NCHRP) authorized a project to analyze and evaluate the weaving area procedures presented in the Manual. That project is now in progress. This paper presents some of the prime analyses done in the first major phase of the project, the resultant recommendations, and some work in progress. This reporting corresponds to the following three defined project objectives:

1. To analyze and evaluate the weaving area procedures of the Manual by using currently (1969) available field data;
2. To develop a study program that will lead to improved techniques for the analysis and design of weaving sections; and
3. To implement the study program so as to achieve the improved techniques.

The third objective was defined by the addition of continuation phases to effect the implementation. A final report (2) on the analysis and study program is available on loan from NCHRP.

Reference is made herein to the three weaving procedures discussed in the Manual. Procedure 1 is a direct analysis of simple weaving sections, procedure 2 is the regression-based approach with nomographs, and procedure 3 is the vehicle-distribution-profile approach. The Manual recommends procedure 2 for ramp cases at levels of service A to C and procedure 3 for ramp cases at level of service D. Although not specifically recommended, procedure 3 is often applied to cases at level of service E.

There are no other recent studies on this immediate topic that utilize a broad data base, but there are studies that investigate or extend particular aspects of weaving behavior, such as the analysis of three-segment multiple weaves (3) or a study of alternate striping on a test facility (4). Another is an extensive performance study of a ramp-weave configuration during two phases of reconstruction and the base condition (5). Data were collected by aerial photography. Significant improvements in travel times and reductions in internal queuing were observed as the configuration was altered, increasing the effective weaving potential within essentially fixed dimensions. There are also important related studies of lane changing (6, 7), lane distribution profiles near entrances and exits (8), and vehicle behavior out of the vicinity of ramps (9), all of which may be of assistance in the continuing study.

DATA AND TOOLS AVAILABLE

Content and Form of Data Bases

Two major data bases were available for use in this study. The first resulted from the urban weaving area capacity study conducted by the Bureau of Public Roads in 1963 at some 40 different locations in the eastern, midwestern, and far western portions of the United States. A total of 58 experiments were conducted by use of the "lights-on" survey technique. About 70 percent of the experiments were of simple weaving sections, whereas the remainder were of multiple-weaving configurations. Subsequent to the initiation of the weaving area operation study, BPR provided data for seven additional experiments conducted around the Washington, D.C., area as pilot tests for the 1963 national survey.

The data provided for each experiment included volumes by type and by lane for each entrance and exit leg. Traffic volume counts were made for 5 out of every 6 min for periods of about 2 hours. Samples of vehicle travel times through the weaving section were taken as well. In addition, relevant geometric information was provided. The data were available only in handwritten form.

The second data base, also supplied by BPR, was the sets of values used to develop the regression curves in the Highway Capacity Manual. This information was provided in the form of punched cards.

Of the two data bases available, the former was the more valuable because it provided information on physical configurations that could be analyzed by both weaving and ramp procedures and because it was "new" data—that is, it had not been used in the development of the Manual and was expected to be extremely useful in the conduct of the study.

The thrust of the first phase research was the analysis of simple weaves, of which 908, 6-min samples were available, with 11,000 travel time measures. These were structured for computer manipulation and punched on cards. Figure 1 shows the leg and lane codes used.

Tools Available and Developed

Two programs that were of considerable use were in existence at the initiation of the project. They are the weaving and ramp capacity programs developed at the Institute of Transportation and Traffic Engineering (10, 11). Before these programs were used, they were carefully reviewed and, where applicable, modified and extended to provide additional power in analysis. Some of these modifications and extensions in the weaving capacity program included the option of using either the service volumes contained in the Manual or a set of exogenously entered values, alteration of Table 7.1 of the Manual, and addition of a test of "out of the realm of weaving." In the ramp capacity program the use of truck equivalency factors on ramp grades was incorporated.

In addition to these existing programs, a battery of new programs was developed for manipulation and analysis of the data. These included programs to read in and adjust 6-min volumes, to calculate through and weaving movements by type by 6-min periods, and to compute a variety of volume characteristics for the peak hours of each experiment. Programs were also developed to compute (for each 6-min sample) space and time mean speeds by movement. As an added output of these programs, arrays were created and put on magnetic tape that contained, for each 6-min period, the weaving and through volumes by type as well as several "speed" statistics such as number of samples, sums of travel times, and sums of squares of travel times for the through and weaving movements. These arrays served as the input to other programs created to perform sensitivity and accuracy analyses as well as to the development of a new formulation for the weaving analysis and design methodology.

AREAS OF ANALYSIS

To accomplish the first project objective, the analysis and evaluation of existing procedures, we conducted several analyses, which involved the following:

1. The internal structure of the weaving procedure (procedure 1),
2. The accuracy of each of the procedures, based on both peak-hour and short-term (6-min) data,
3. The consistency of the three procedures in specifying level of service, and
4. Specific aspects of procedures 2 and 3, such as accuracy of lane 1 volumes.

Internal Structure of the Weaving Procedure

A number of analyses were undertaken to determine the viability and rationality of procedure 1. These analyses included an examination of the specified service criteria for clarity and internal consistency and an examination of the development of the weaving chart, with consideration of a recalibration thereof. The principal results of these analyses were as follows.

1. An adequate description of the operating characteristics of a weaving section requires the specification of both a level of service and a quality of flow.
2. The relationships among speed, level of service, and quality of flow are not clearly specified by the Manual, which leads to confusion in interpretation.
3. Quality of flow and level of service are not functionally dependent on each other. The consistent relationship suggested by the Manual does not exist.
4. Separate level of service standards for weaving and nonweaving vehicles would seem to produce a more accurate description of weaving section service characteristics.
5. Geometric configuration may be a vital design factor.
6. The development of the weaving chart was based on sparse data. The k-values utilized as expansion factors were rationalized and not supported by data.
7. The range of k-values exceeds the Manual specification of 1.0 to 3.0.
8. The k-values do not relate to total weaving volume V_{wo} [measured in passenger cars per hour (pcph)] and section length L as depicted in the weaving chart. Constant k-curves do not exist as suggested in the Manual.
9. Should a valid expansion exist, it appears to be more complex, involving several parameters, than that used in the Manual, in which only the minor weaving volume V_{w2} is expanded.

Description of Service Characteristics—Although it is not clearly stated, the use of the Manual procedure requires the specification of both a level of service and a quality of flow. Consider the equation for the width of a weaving section:

$$N = [V_T + (k - 1)V_{w2}]/SV \tag{1}$$

where

N = number of lanes in section,
V_T = total volume in section,

k = expansion factor,
V_{w2} = minor weaving volume, and
SV = service volume.

The length of the weaving section and the k-value used in the width equation are determined by entering the weaving chart with a specified weaving volume (in pcph) and quality of flow. SV is selected from Table 9.1 in the Manual (for freeways) and is dependent on a specified level of service.

Most properly, quality of flow relates to the speed of weaving vehicles alone. Level of service describes the speed of all vehicles combined. Neither of these can adequately describe the operating characteristics of a weaving area. Inasmuch as quality of flow relates only to weaving vehicles, it may not be used alone to describe a section containing both weaving and nonweaving vehicles. Level of service treats collectively two flows with often widely differing characteristics and effectively conceals such differences. Only when both are specified is a complete picture drawn. Even this, however, produces an awkward, indistinct description.

Speed Criteria—There are several problem areas that create a degree of confusion in the speed-service relationships detailed in the Manual. The first of these involves the use of operating speed as a criterion. Strictly defined, operating speed is the maximum speed at which a car may travel under prevailing traffic and roadway conditions without at any time exceeding the design speed. Most properly, this parameter is measured with a test vehicle observing sample vehicles. From such a sample speed distribution, such items as 85th percentile speed, median speed, and space mean speed may be determined. None of these corresponds directly to operating speed, although they may be used to estimate it. Of greater importance is the fact that such sample data were used to calibrate Manual procedures and were collected in the 1963 urban weaving area capacity study. It is of extreme importance that sample data be accurately segregated into specified service standard categories. Some of the analyses reported herein required such stratification by service categories. For these analyses, space mean speed rather than operating speed was used.

The stated speed criteria are ambiguous to a large degree. The specification of quality of flows I and II states that speeds of 50 mph or more and 45 to 50 mph respectively "are attainable." Whether these speeds refer to all vehicles, weaving vehicles, or nonweaving vehicles is not clear. It is assumed that only weaving vehicles are included, as criteria for quality of flows III, IV, and V (40 to 45, 30 to 35, and <30 mph respectively) specifically refer only to these.

Level of service criteria are similarly unclear, with the Manual suggesting that speeds in weaving sections for a given level of service be 5 to 10 mph lower than those on similar sections of open highway. Open highway standards are taken from Table 9.1 of the Manual (for freeways) or corresponding tables. Because these tables refer to the average speed of all vehicles, it is assumed that all vehicles are included in the application of adjusted standards to weaving areas.

Also of concern is the discontinuity in both level of service and quality of flow criteria for speeds of 35 to 40 mph. Several of the analyses reported herein required determinations of level of service and quality of flow, so standards were adjusted to provide continuous boundaries. For level of service in weaving areas, 10 mph was deducted from open highway standards. The standards used are given in Table 1.

Quality of Flow and Level of Service Relationships—Table 7.3 of the Manual details a relationship between level of service and quality of flow, which is presumed to be consistent. However, when we consider the parameters that determine each, it can be seen that no consistent dependence exists. Analytically, quality of flow as determined by the weaving chart depends on the weaving volume and the length of the segment. Level of service depends on the service volume, which is found by dividing the total expanded volume by the number of lanes. Although these parameters are loosely related, it can be seen that specification of a quality of flow does not automatically yield a level of service or vice versa. The full range of quality of flow-level of service combinations is theoretically feasible, and conditions actually occurring are not restricted to those combinations shown in Table 7.3 of the Manual.

These observations are supported by data from the 1963 BPR study. If actual qualities of flow and levels of service are identified by sample speeds, 15 of 45 experiments reveal combinations not indicated in the Manual. Because the space mean speed (SMS) of all vehicles numerically includes the SMS of weaving vehicles, even those experiments that conform to the Manual may be more indicative of a computational dependence on rather than a real interrelationship between flows.

The unrestricted nature of the level of service-quality of flow relationship can be seen in both analysis and design. Consider, for example, a weaving configuration long enough to be "out of the realm of weaving." Such a section may conceivably operate at quality of flow I as analytically determined by V_{we} and L but will experience the full range of levels of service based on total volume fluctuations. Because of the great length of such a section, weaving volumes may never be high enough to deteriorate the quality of flow. Although analytic determinants may indicate, for example, quality of flow I and level of service D, the high weaving speeds predicted for quality of flow I will not be achieved, as total volumes restrict the entire operation to level of service D.

In design, a similar situation is encountered. When the width equation $N = [V_T + (k - 1)V_{w2}]/SV$ yields fractional results, additional length may be provided to reduce N to the nearest whole number. In this way, a more economical design is achieved. However, as the length is increased, a better quality of service is attained. Level of service, on the other hand, remains unchanged.

It can be seen that the analytic relationship between level of service and quality of flow is unrestricted. In the use of these measures in analysis, it is necessary to determine which of the two measures gives a more realistic description of operations. In general, this will be the "worse case," as in the example above where quality of flow I could not actually be achieved due to the low level of service. In design, because the general design level of service for a given facility is of primary interest, the quality of flow for weaving areas should be as good as or better than the design level of service.

A Recommended Descriptor of Service—It was pointed out that no functional analytic relationship exists between quality of flow and level of service. It was also stated that actually occurring values do not conform to the relationship predicted by the Manual and that the inclusion of all vehicle speeds in the level of service description may mask significant differences between weaving and nonweaving flows. Such differences often occur, and, because they do, it would appear that separate levels of service for weaving and nonweaving vehicles would be more descriptive of actual operating conditions.

Geometric Effects—It is valuable to investigate why drastic differences in weaving and nonweaving speeds occur in some cases and not in others. It would appear that geometric configuration is a major factor. Data given in Table 2 illustrate that speed differences occur most often on ramp-weave sections and that the differences are generally larger than those observed for other configurations. In the ramp-weave configuration, weaving vehicles are more or less restricted to the auxiliary lane and the shoulder lane regardless of the total number of lanes provided. Additional lanes in ramp-weave sections will be used primarily by nonweaving vehicles. Where total width is excessive, weaving vehicles may operate at low speeds in two lanes while outer flows travel at considerably higher speeds in other lanes. Major weaves, which vary widely with configuration, are generally not as restrictive. This is shown in Figure 2.

The number of lanes actually occupied by weaving vehicles was computed for each experiment from the 1963 study data. In no ramp-weave case was 2.0 exceeded, whereas in the majority of major weave cases weaving vehicles occupied more than 2.0 lanes. This result supports the hypothesis, but it cannot be viewed as conclusive because the major weave cases entailed generally higher weaving volumes than ramp-weave cases and would normally be expected to occupy more lanes. However, this result, coupled with the frequent occurrence of speed differences in ramp-weave cases, indicates that the hypothesis has merit.

Thus, the Manual procedure of computing total lane requirements may be misleading. Lane requirements for weaving and nonweaving flows should be separately computed so that a configuration allowing appropriate lane use may be designed.

Development of the Weaving Chart—The original data and rationale behind the weaving chart have not been documented and are not available for study. However, certain facts concerning the development of the chart are known and may be commented on.

Figure 1. Standard coding for weaving data.

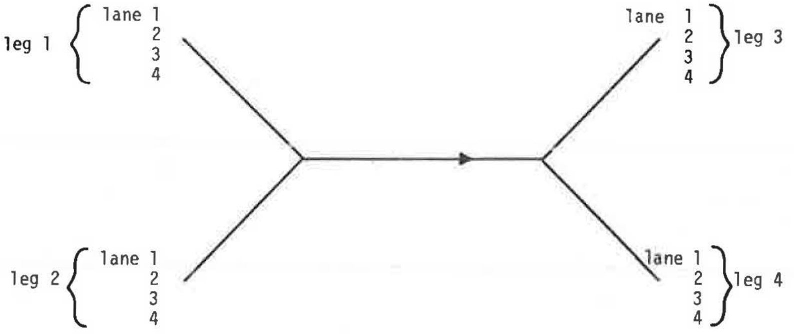


Table 1. Service criteria.

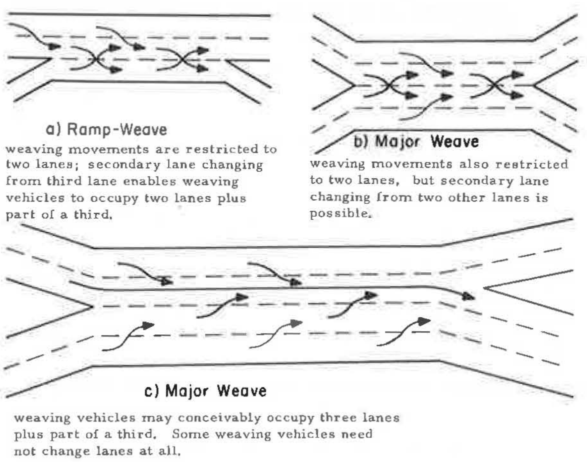
Level of Service	SMS of All Vehicles On Freeways	SMS of All Vehicles In Weaving Areas	Quality of Flow	SMS of Weaving Vehicles
A	≥60	≥50	I	≥50
B	55 to 60	45 to 50	II	45 to 50
C	50 to 55	40 to 45	III	37.5 to 45
D	37.5 to 50	27.5 to 40	IV	30 to 37.5
E	30 to 37.5	20 to 27.5	V	<30
F	<30	<20		

Table 2. Nonweaving vehicles having SMS different from those of weaving vehicles.

SMS (mph)	Number of Vehicles RA Section[a]	Number of Vehicles M and CD Sections[b]	Number of Vehicles All Sections
>5	1	2	3
±5	10	17	27
5 to 10	0	4	4
10 to 15	2	1	3–
>15	4	0	4

[a]Ramp weave with auxiliary lane formed between consecutive on- and off-ramps.
[b]Major weave with at least three legs having more than two lanes and weaving sections on collector-distributor roadway.

Figure 2. Weaving movements as affected by configuration.



a) Ramp-Weave
weaving movements are restricted to two lanes; secondary lane changing from third lane enables weaving vehicles to occupy two lanes plus part of a third.

b) Major Weave
weaving movements also restricted to two lanes, but secondary lane changing from two other lanes is possible.

c) Major Weave
weaving vehicles may conceivably occupy three lanes plus part of a third. Some weaving vehicles need not change lanes at all.

The original weaving chart of the 1950 Highway Capacity Manual involved three plots on a V_{we} versus L field: one for maximum possible capacity, one for 30-mph operating speed, and one for 40 mph. These three curves were based on field data and were adjusted slightly in 1957 (12). These three curves became curves III, IV, and V in the 1965 Manual. The original equation for width was similar to the present one but contained a constant expansion factor of 3.0 rather than a variable k based on V_{we} and L. The 3.0 expansion factor was rationalized on the basis of approximate gap size necessary to execute a weaving maneuver and not on observed data. By the time the 1965 Manual was being formulated, limited amounts of data permitted estimation of curve I for "out of the realm of weaving." For this curve, the expansion factor was logically 1.0. This left the problem of providing a smooth expansion transition from 1.0 below curve I to 3.0 above curve III. The intermediate curves of the 1965 Manual are the result of a constructed transition.

Therefore, whereas the length-weaving volume relationships depicted by curves I, III, IV, and V of the 1965 Manual weaving chart are based on limited amounts of data, the k-factor expansion mechanism has not been subjected to calibration.

The Range of k-Values—Freeway experiments of the BPR study were used to calibrate and verify the constant k-curves of the weaving chart. With the use of the width equation, with all values except k known, k may be computed as

$$k = [N(SV)/V_{w2}] + [1 - (V_T)/(V_{w2})] \tag{2}$$

where the terms are as defined. Service volume is given in Table 9.1 of the Manual for each level of service as identified by the SMS of all vehicles (the speed criteria of Table 1 are used).

A problem arises in that only integer values of N are observed, whereas in design fractional values may be obtained. Thus, an error from rounding off results, causing inflated values of k to appear. These errors arise, however, because SV is treated as a step function, with one value for a range of speeds. In actuality, all lanes are used. If a fractional part of a lane has been added to the design computation, speeds slightly higher than the minimum for the level of service used will result. Therefore, if the values of speed detailed in Table 1 and the SV values of Table 9.1 in the Manual are viewed as threshold values and a straight-line interpolation between values is used, a value of SV based on the exact observed speed may be selected and the round-off error eliminated.

If step function SV values are used, it is possible to compute the maximum round-off error for each experiment (2). The analysis presented is more easily manipulated and interpreted. This was done, and k-values were computed. For 16 ramp-weave cases, k took on 3 values above 3.0 and 4 below 1.0. Of 19 major weaves, 8 values were significantly above 3.0, and one was below 1.0.

Values below 1.0 are disturbing, inasmuch as it does not seem feasible that a vehicle among V_{w2} is equivalent to less than 1.0 other vehicle and certainly does not occupy negative space. Such values may be the result of unusual geometric conditions, such as sharp loop ramps, that exist at one of the sub-1.0 experiments or extra wide lanes that exist at another. In this latter case, a 72-ft roadway was striped for 5 lanes although vehicles had room to form 6. Sampling errors may have also influenced these values.

Despite this concern, the upper limit of 3.0 has most certainly been shown to be false, inasmuch as 11 of 26 computed k-factors are beyond this limit. The calibration does not, however, clearly indicate or suggest any other upper limit on k.

The Relationship of k to V_{we} and L—The k-factors were plotted on the V_{we} versus L field (Fig. 3) in an attempt to reestablish the constant k-curves of the 1965 Manual weaving chart. The plot clearly shows that no such constant k-curves exist and that the relationship among k, V_{we}, and L is not as is depicted in the Manual.

The Expansion Concept—Before we discarded the basic idea of an equivalence expansion mechanism, a number of possible alternatives were examined. Two additional sets of expansion factors k_{V_w} and $k_{V_{w1}}$ were computed based on expansion of the entire weaving volume V_w and the larger weaving volume V_{w1}. These were plotted on the V_{we}

versus L field, and, as in the case of the k-factors, no constant value curves were formed. However, all three expansion constants, k, k_{V_w}, and $k_{V_{w1}}$, exhibited promising correlations when plotted versus the ratios V_w/V_T and V_{w2}/V_{w1}. Although not conclusive, these results suggest two things about the true expansion mechanism: Expansion of both V_{w2} and V_{w1}, perhaps individually in an additive fashion, should be considered; and the expansion value seems to depend on both the percentage of weaving vehicles in the traffic stream and the split between V_{w1} and V_{w2}. A predictive mechanism for k, therefore, should involve both parameters. It is concluded that a valid expansion model would be far more complex than that used in the 1965 Manual. The data at hand are not sufficient to investigate possible forms. Because of the difficulties involved in collecting such data and the difficulties involved in formulating such a model, it appears that development of a design procedure that does not directly involve equivalence expansion would be advisable.

Analysis of the Accuracy of Manual Procedures

It was decided, where possible, to test the accuracy of all three procedures in predicting actual levels of service.

A problem immediately arises because the speed-level of service relationships that must be used to identify field levels of service differ in Chapters 7 and 8 of the Manual. Procedures 2 and 3, from Chapter 8, use the relationships of Table 9.1 directly, whereas procedure 1, from Chapter 7, specifies a deduction of an ambiguous 5 to 10 mph from these standards. In the internal analysis of the weaving procedure 1, the authors used the 10-mph deduction for consistency. For accuracy, a number of alternatives were tested, including one suggested by a principal in the development of Chapter 7 of the Manual. Results indicated that this latter specification correlated best to predicted levels of service; therefore, only results for this case are reported. The speed-level of service relationships used in the accuracy analysis are given in Table 3.

The problem that in the Manual level of service C means different standards depending on the procedure used must be kept in mind when the results of the accuracy analyses are considered. The analysis considered basic weaving sections (in which all traffic weaves), ramp-weave cases, and major weave cases separately. Only in the case of ramp weaves may all three procedures be applied and compared. Only procedure 1 is used in other cases. Data from the 1963 BPR study were utilized for both peak-hour data and individual 6-min periods. The results of the analysis are given in Table 4.

The following conclusions may be drawn from these results:

1. The accuracy of level of service predictions by procedure 1 is highest for basic weaving sections, followed by ramp weaves and major weaves. Accuracy of the procedure is generally poor, inasmuch as less than a third of all experiments were accurately predicted. Use of operating speed would have further degraded the accuracy.
2. For basic weaves and ramp weaves, the majority of errors are by a single level of service, with no trend toward being poorer or better than actual values for procedure 1. When applied to major weaves, procedure 1 tends to predict levels of service poorer than those that actually occur.
3. Although the Manual recommends the use of procedures 2 or 3 for ramp-weave cases, procedure 1 produces more accurate estimates of level of service.
4. Level of service predictions for ramp-weave cases by procedures 2 and 3 tend to be better than actual field conditions.

The accuracy of procedures 2 and 3 as regards ramp-weave cases was further investigated. These procedures depend on the prediction of lane 1 volumes in advance of ramps. Accordingly, lane 1 volumes were computed by procedures 2 and 3 immediately in advance of the on-ramp and were compared to actual volumes. Although the Manual recommends procedure 2 for cases of levels of service A to C and procedure 3 for levels of service D and E, both methods were applied to all experiments where possible.

The accuracy of procedure 2 for levels of service A to C is shown in Figure 4. Differences between computed and observed ranged from 6 to 24 percent with an average difference of 15 percent. The sample size, however, was only 4, and definitive conclusions may not be reached.

Figure 3. Computed k-factors on a weaving chart.

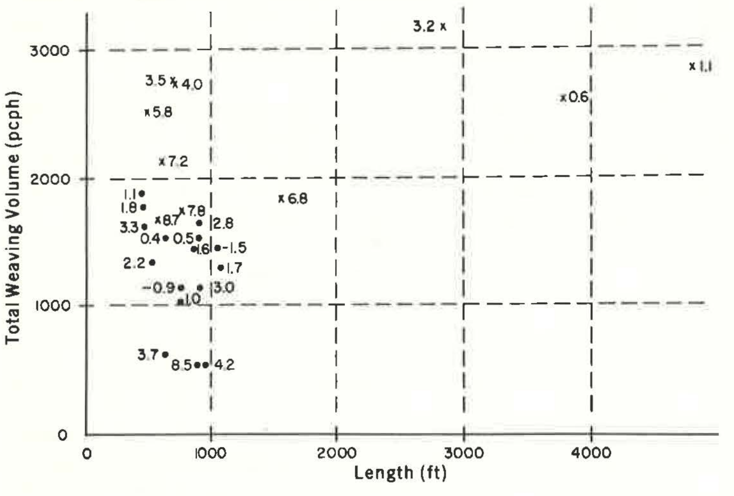


Table 3. Service criteria for accuracy analysis.

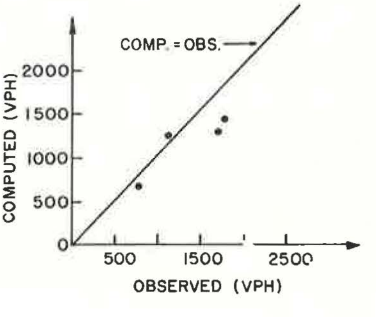
Level of Service	SMS of All Vehicles: Procedures 2 and 3	SMS of All Vehicles: Procedure 1	Level of Service	SMS of All Vehicles: Procedures 2 and 3	SMS of All Vehicles: Procedure 1
A	≥60	≥50	D	37.5 to 50	25 to 37.5
B	55 to 60	45 to 50	E	30 to 37.5	15 to 25
C	50 to 55	37.5 to 45	F	≤30	≤15

Table 4. Percentage of difference between actual and predicted levels of service.

Procedure	Weave Section	Sample Period	Level of Service: Same	1 Level Better	1 Level Poorer	>1 Level Better	>1 Level Poorer
1	Basic	Peak-hour[a]	50	16	16		16
		6-min	30	34	17	8	11
	Major	Peak-hour	27		69	4	
		6-min	21	7	43	4	25
	Ramp	Peak-hour[b]	35	23	35	7	
2	Ramp	Peak-hour[b]	23	41	12	24	
3	Ramp	Peak-hour[b]	20	40		40	

[a]Sample size only six experiments.
[b]Six-min data not shown for brevity; results are similar.

Figure 4. Computed versus observed lane 1 volume for levels of service A to C, procedure 2, peak-hour data.



Twenty experiments were determined to be in levels of service D and E. When lane 1 volumes were computed by procedure 3, the differences between observed and computed values ranged from 1 to 70 percent with an average of 25 percent. As shown in Figure 5, most errors involve computed values lower than actual values, a serious condition that may result in inadequate designs.

Thirteen of the 20 levels of service D and E cases were also examined by procedure 2. Differences between observed and computed lane 1 volumes ranged from 1 to 43 percent, with an average of 17 percent, a distinct improvement over procedure 3 results (Fig. 6). Despite the Manual specification of procedure 3 for these cases, lane 1 volumes were more accurately predicted by procedure 2 in 10 of 13 cases.

It should be noted that procedure 3 most properly applies only to level of service D. It is prescribed for checking a given ramp-weave segment or ramp to see whether it meets the requirements for the high-volume threshhold of level D. The accuracy analyses referenced herein did in fact do this. When the criteria for level D are not met, level E was assumed. The method was extended to include a check against Table 8.1 (of the Manual) level E checkpoint values to determine whether a level F condition was indicated.

These results show that procedure 2 produces more accurate levels of service predictions than procedure 3 for ramp-weave cases with auxiliary lanes, even for cases of levels of service D and E. Six-min data were used to further examine the accuracy of procedure 2 for all levels of service. An average difference between observed and computed lane 1 volumes of 19 percent was obtained. A general trend toward decreasing accuracy as length of the section increases was noted. The angle of approach at on-ramps was also investigated, but results indicated that it had little effect on the accuracy of lane 1 volume predictions in the normal range of 1 to 6 deg.

The accuracy of Figure 8.22 of the Manual, which predicts the percentage of trucks in lane 1, was also tested. Differences between observed and actual values ranged from 1 to 37 percent with an average of 13 percent. Particularly in the case of eight-lane freeways, the results predicted by the Manual are markedly different from a regression line fit to the actual data. This is shown in Figure 7. Although the differences noted for four- and six-lane freeways are not as drastic, Figure 8.22 of the Manual does not appear to accurately represent the relationship between freeway volume and percentage of trucks in lane 1.

Consistency of Procedures 1, 2, and 3 in Specification of Level of Service

The consistency of the three procedures in specifying levels of service was examined by comparing predictions for ramp-weave cases of the 1963 BPR study. To obtain a comparison over a wider range of levels of service, we constructed and analyzed a range of cases. The results of the analysis indicate that procedure 1 yields level of service estimates poorer than procedures 2 and 3 for relatively short or wide sections and better levels of service than procedures 2 and 3 for longer, narrower sections. These general results, however, must be viewed in light of the fact that level of service criteria differ for procedure 1 and procedures 2 and 3. Because of this problem, the results of the accuracy analyses must be viewed as the more meaningful.

Adjustments to Current Manual Procedures

The results of the analyses reported earlier point out the need for a new weaving methodology. Work is progressing along these lines and is described later. An improved algorithm is being developed; several modifications in the use of current procedures can improve their accuracy.

1. Level of service criteria for procedure 1 (Manual, Chapter 7) have been shown to be unclear. The accuracy analysis showed that the following standards resulted in the best correlation to predicted values of the alternatives tested. It is therefore recommended that the level of service criteria given in Table 5 be adopted. (Note that in this table space mean speed rather than operating speed is used as a correlate.)
2. The quality of flow-level of service combinations shown in Manual Table 7.3 suggest that these are the only feasible combinations. This has been shown to be weak,

in both actual cases, based on observed speeds, and analytically, in the case of predicted values based on known volumes and geometric factors. In design, a quality of flow that will not interfere with the maintenance of the design level of service under design hour volumes must be selected. In analysis, prediction of incompatible level of service and quality of flow indicates that the poorer condition will most likely prevail. Because design level of service for an entire facility is of primary importance, the level of service should be the controlling measure in well-planned sections.

3. Geometric configuration appears to have a marked effect on the operation of a weaving section. Certain configurations have been shown to restrict weaving vehicles to a portion of the roadway, regardless of total width. For this reason, lane requirements for weaving and nonweaving vehicles should be separately computed and considered for suitability. The Manual width equation may be modified:

$$N_w = N_{weaving} = (V_{w1} + kV_{w2})/SV$$

$$N_{nw_1} = N_{nonweaving_1} = (V_{o1}/SV)\ N_{nw_2} = N_{nonweaving_2} = (V_{o2}/SV)$$

where

V_{wi} = weaving volume i,
V_{oi} = outer volume i,
SV = service volume,
k = expansion factor,

and N_j designates number of lanes (which may be fractional) for purpose j. Note that N_{nw_1} and N_{nw_2} are computed separately and must be provided on opposite sides of the weaving lanes. In this way, a configuration that provides an adequate number of total lanes and that permits weaving vehicles to use the required number of lanes may be designed. The Manual specifies that ramp-weave sections with auxiliary lanes should be treated as suggested in the procedures given in the Manual, Chapter 8. The accuracy analysis has shown that the Chapter 7 weaving procedure is more accurate in these cases despite its weakness. It is therefore recommended, as an interim measure, that such cases be analyzed according to Chapter 7 and not Chapter 8. Service criteria outlined in the first item apply.

RECOMMENDATIONS

On the basis of the analyses conducted in the first major phase, it was recommended that the weaving procedure be reconstituted, that it incorporate both major weave and auxiliary lane cases, and that it be macroscopic in approach. It is further recommended that lane balance and geometric capability be explicitly considered to be of prime importance in the procedure. Given that values of certain macroscopic variables are computed (weaving width N_w and length L specifically), it is essential that the configuration be such that these may in fact be provided. Conversely, the specification of a configuration effectively determines the range of N_w that is realizable in a given length. As evidenced by Gafarin (5), a change of configuration within fixed dimensions can significantly affect the weaving capability. Configuration as it influences weaving is a subject of on-going research.

To realize these general recommendations, we specified a study program. The prime points of that program are as follows.

1. Further data efforts in regard to weaving sections should be devoted to three areas: collection of the data for the calibration of the reconstituted procedure, collection of some detailed supplemental data to enhance the engineer's understanding of the basic mechanisms of weaving, and synthesis of existing data banks and research related to weaving.

2. The principal data collection effort should be devoted to the calibration of the reconstituted procedure at levels of service B and C particularly, the existing base having little such data, and over those lengths not well represented in the existing base, even at levels of service D and E.

3. The speed measure used in the reconstituted procedure should be space mean speed as is the case with the AASHO policies, with travel time samples used to estimate SMS.
4. The data collection generally should be done by ground-based time-lapse photography, with filming done for 4 to 6 consecutive hours so as to observe not only the various levels of service but also the transitions from one to another.
5. Based on the data collected, the model for the weaving design-analysis procedure should be revised and calibrated as necessary.

This study program has been accepted by NCHRP, and it is now being executed.

It should be noted that some work has been done on the form and equations of the reconstituted procedure (2). This is an outline of probable structure and is not suitable for promulgation at this time. It does, however, propose (a) explicit consideration of the section configuration in its calibration and use, (b) a particular mathematical form involving weaving parameters (volume, length, width, and minor-to-total weaving ratio), (c) functional constraints on length-width combinations and on minimum length, and (d) an investigation of the number and range of plateaus (levels of service) that exist in a weaving situation.

The research under way is considering a full range of section lengths, including rather short sections. These will provide some important basic knowledge of weaving intersections and a basis for the analysis of existing sections. They may also provide information for a design of last resort in some urban areas, but it will be most important that these not be able to be interpreted as desirable design.

CONDUCT OF DATA BASE PHASE

As part of the study program, it was specified that data would be collected at 16 major weave or ramp-weave sites and at one multiple-weave configuration. All data are to be of the recommended 4 to 6 hours' duration, with the possible exception of the multiple weave, the duration of which is to be controlled by cost. All sites are located in the northeast United States, no discernible variation with geography having been observed in the existing data base.

In general, data are to be collected by fixed-position time-lapse photography. A limited number of sites (the longer major weaves) may require a hybrid collection mode that includes input-output license plate recording and tracing vehicles by calibrated camera from a vantage point that would not permit fixed-camera photography.

The fixed-position camera system for sites visible by one camera is generally a 16-mm Beaulieu time-lapse camera with a 200-ft magazine, intervalometer, and a 50-mm Angenieux zoom lens with a split-image adaptation. This adaptation permits a calibrated timer to be shown on the film. For sites that require two cameras for adequate coverage, a super-8 Minolta (Autopak 806) is used as the second camera. This camera is also equipped with intervalometer, zoom lens, and split-image adaptation. Sample photographs of two sites are shown in Figures 8 and 9. These are two 990-ft major weaves on the Cross-Bronx Expressway near the George Washington Bridge in New York City and a 700-ft ramp weave on the Kensington Expressway in Buffalo, New York, respectively. The first site was filmed with the super-8 system, which was backing up the 16-mm system on that site. The calibrated timer is clearly in view in both cases.

The data are being reduced by teams of two who either observe and trace each vehicle (or a sample thereof) or count volumes and then trace vehicles for travel time samples, depending on the type of site and its outer flows. An L&W photo data analyzer model 224-A is being used for 16-mm films, and a Kodak model MFS-8 super-8 stop-action projector is being used for the super-8 films. The calibrated timer is read and recorded appropriately. All data are recorded on forms from which keypunching can easily be done. Keypunched data are checked for common recording and punching errors by special computer programs.

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Figure 5. Computed versus observed lane 1 volumes for levels of service D and E, procedure 3, peak-hour data.

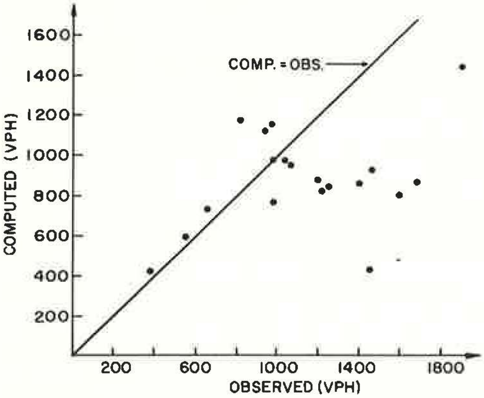

Figure 6. Computed versus observed lane 1 volume for levels of service D and E, procedure 2, peak-hour data.

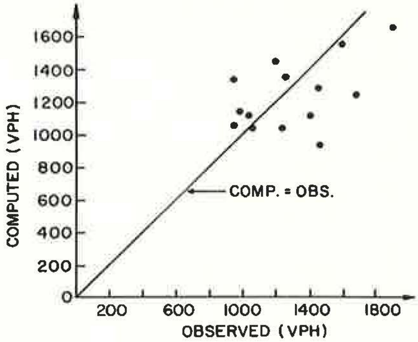

Figure 7. Eight-lane freeway (all experiments).

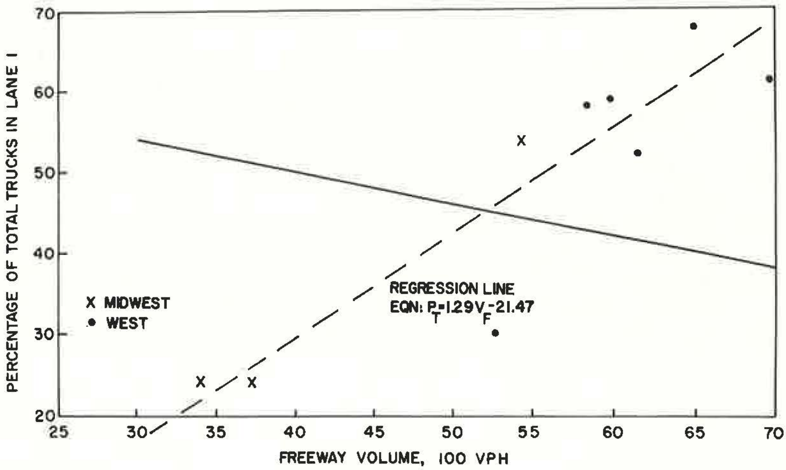

Table 5. Recommended interim service criteria.

Level of Service	SMS of All Vehicles	Level of Service	SMS of All Vehicles
A	≥50	D	25 to 37.5
B	45 to 50	E	15 to 25
C	37.5 to 45	F	≤15

Figure 8. Data taken on Cross-Bronx Expressway, New York City.

Figure 9. Data taken on Kensington Expressway, Buffalo.

drawn from a National Cooperative Highway Research Program project. The opinions and findings expressed or implied in this paper are those of the authors and not necessarily those of the Highway Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, or the individual states participating in the National Cooperative Highway Research Program.

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DISCUSSION

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During the several years that have elapsed since the 1965 Highway Capacity Manual was published, I have had the opportunity to work extensively with the procedures recommended for computing the service volumes and levels of service for ramp junctions and weaving sections. This involvement has been primarily as a user and as an instructor in several workshops and seminars aimed at teaching the use of the Manual. Therefore, I have reviewed and would like to comment on the paper prepared by Pignataro and his associates from the viewpoint of a user and not a theoretician.

To the average technical employee of a highway engineering organization, be it a government agency or a consulting firm, the two main criteria for judging an analysis or computation procedure are the following: Is it straightforward and easy to understand and use; and are the answers derived sufficiently accurate to satisfy the requirements of the overall project involved? The technical employee making the analysis is not usually interested in the theoretical basis for the procedure and, generally, does not have the time to analyze the underlying principles even if he is interested. With these thoughts in mind, I would like to comment on a few of what I consider to be the major findings, conclusions, and recommendations of the paper.

A substantial portion of the paper is devoted to an analysis of the internal structure of the weaving procedure described in Chapter 7 of the Manual to determine the viability and rationality of the procedure. Of the nine major conclusions reached as a result of this analysis, only one would appear to be of major concern to the user.

The paper indicates that the relationships among speed, level of service, and quality of flow are not clearly specified by the Highway Capacity Manual. Of major concern is the use of the "operating speed" to define the quality of flow and indirectly the level of service. The fact that the operating speed is not a directly measurable quantity has led to problems of not only analysis of weaving sections but also the free flow analysis of freeway, expressway, and two-lane highway sections. The use of a measurable parameter such as the space mean speed would certainly eliminate much of the confusion that has been generated through the use of the term "operating speed."

The discontinuity in level of service and quality of flow criteria at speeds of 35 to 40 mph, which exists in both Chapter 7 and Chapter 9 of the Manual, have also been of concern to many users. Although the discontinuity has not led to any particular user problems, it has resulted in a certain amount of apprehension by some users who then question the creditability of the whole procedure.

The results of the analysis of the accuracy of the three weaving procedures should certainly be encouraging and welcomed by most persons involved in analyzing weaving sections. I believe that the vast majority of organizations and individuals involved in the analysis of weaving sections are using the Chapter 7 procedure for analysis of all types of weaving sections of all levels of service. Although the basic decision to disregard the recommendations of the Manual were, I believe, based on the complexity of the procedures described in the chapter on ramps, the conclusion that procedure 1 produces more accurate estimates of service level although the Manual recommends the use of procedures 2 or 3 for ramp-weave cases supports the decision.

The results of the accuracy analysis are also encouraging from a second point of view. The Chapter 7 procedure accurately predicted the level of service in 50 percent of the basic weaving section experiments and was within one level of service in 80 percent of the cases. For ramp-weave sections and major weaves, the Chapter 7 weaving procedure came within one level of predicting the actual level of service in over 90 percent of the cases analyzed. Because the actual level of service was determined by calculating the space mean speed of all vehicles, it is possible that a number of the cases that the Chapter 7 procedure predicted as being one level of service too high or too low missed the mark by only 1 or 2 mph. If this is the case, I believe that the results are even more encouraging than might be believed at first glance.

As a result of the various analyses made, the paper recommends several modifications in the current procedures. Table 5 includes recommended service criteria utilizing the space mean speed of all vehicles rather than the operating speed, eliminates the discontinuity at speeds of 35 to 40 mph discussed earlier, and should close the creditability gap that exists in the minds of some people. The use of space mean speed rather than operating speed should increase the usefulness of the procedure as a tool for evaluating operations on existing roadways.

The second recommendation contains guidelines for resolving the limited relationship between level of service and quality of flow specified in Table 7.3 of the Manual. This recommendation is relatively obvious and is, I believe, being followed by most individuals involved in analyzing weaving sections.

The paper also recommends that the number of lanes required for weaving vehicles be calculated separately from the number of lanes required for nonweaving vehicles. Whereas the total number of lanes thus calculated is identical to the number calculated by using the Chapter 7 weaving procedure, the analyst will be better able to visualize the need for the lanes, the geometric configuration required, and how the section of roadway will operate. Properly utilized, this information could result in improved geometric designs; improperly used, the design would be the same as would result by utilizing the Chapter 7 procedure without modification.

The final recommendation is that the Highway Capacity Manual Chapter 7 weaving procedure be used to analyze ramp-weave sections with auxiliary lanes in place of the Chapter 8 procedures. As was previously indicated, most organizations are currently following the Chapter 7 procedure, and this recommendation tends to support their action.

In summary, I heartily support all four adjustments to the Highway Capacity Manual procedure and believe that they would be an improvement over the Manual when judged by the user's criteria of simplicity and accuracy.

AUTHORS' CLOSURE

The authors are pleased that Sullivan found the paper satisfying and thank him for his detailed attention in the review. We offer only a few comments on his discussion.

It is agreed that the average user of a computation procedure would not be concerned with its theoretical aspects in day-to-day applications, nor should he be. He should, however, satisfy himself at some time that it is a sound and rational procedure. Moreover, those providing him with the procedure as a tool should ensure this. This is the intent of our analysis of internal structure.

The possibility that a significant number of cases were out of the computed (by the Manual) level of service by only 1 or 2 mph was considered and was not a significant occurrence. The general problem of level of service in a weaving section by speed or volume categorization or both, however, is a substantial one and is being considered in the continuing project research. In particular, the redefinition of the number and boundaries of levels within a weaving section and the existence of a critical region in which speed performance is not simply related to volume and geometrics are being considered.

The fact that separate computation of the lanes required on each side for nonweaving vehicles is numerically identical to the existing Chapter 7 procedure is quite true. Sullivan correctly points out, more clearly than the original text, that the advantage is in properly assessing the requisite configuration.