CONFIGURATION, DESIGN, AND ANALYSIS OF WEAVING SECTIONS

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The paper discusses and illustrates the effect that lane configuration can have on weaving-section operations, specifically, how lane utilization may be substantially controlled by configuration. Data from the 1963 urban weaving-area capacity study are used to quantify these effects. Further illustration is given through the use of lane-transition matrices to model gross weaving movements under various configurations. The paper concludes that the weaving procedure in the Highway Capacity Manual leads to inadequate results because of the failure to differentiate between weaving and nonweaving lane requirements. That procedure is modified to take this into account and to avoid the design of sections with a proper total number of lanes. The modified procedure yields a configuration that prohibits proportional use of those lanes by weaving and nonweaving traffic.

•EXISTING PROCEDURES for the design and analysis of weaving sections as specified in the Highway Capacity Manual (1) have been shown to be inaccurate in the prediction of level of service (2). Some of the inaccuracies can be traced to ambiguities in the specification of service standards and to the basic inaccuracy of the k-factor equivalence expansion mechansim of the HCM weaving procedure (1, ch. 7; 3, 4).

Another, possibly more basic cause of the observed inaccuracies lies in the fact that lane configuration is not considered as a parameter in the design-analysis procedure.

CONFIGURATION AS A FACTOR IN WEAVING DESIGN AND ANALYSIS

Lane configuration is a tremendously important factor that can have a drastic effect on lane utilization by component flows, the number of lane changes required to complete a weaving movement, relative speeds of component flows, and other operational factors.

Leisch (5) demonstrated the benefits of certain configurations in meeting varied or changing demand patterns. Leisch also showed how configuration changes can reduce total lane changing in a weaving section (2). The effect of configuration improvements is also adequately demonstrated in the results of the Ward-Fairmount weaving study (6), in which increased vehicle speeds for similar volumes were accomplished largely through configuration changes. (The Ward-Fairmount study is treated later in this paper.)

Of principal concern to the designer or analyst is the effect of configuration on actual or potential lane utilization. The HCM procedure results in a computation for N, the number of total lanes in the weaving section. No explicit distinction is made between lanes needed for weaving and those for outer flows. Figure 1 shows how lane configuration can substantially limit the number of lanes used by weaving flows, regardless of the total number of lanes provided. Three weaving sections of equal length are shown, and configuration differences are seen to drastically affect potential lane utilization.

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A ramp-weave section is a weaving section formed by consecutive on- and off-ramps joined by an auxiliary lane. A major weave section is one in which three or more entry and exit legs have two or more lanes, forming either a major fork, a major merge point, or both.

All weaving movements in a ramp-weave section must take place in shoulder and auxiliary lanes (Fig. 1a). Secondary lane-changing movements are possible from the center lane; the extent to which the center lane may be used for secondary lane changing is primarily related to the length provided. Based on these considerations, it is seen that weaving vehicles could occupy at best two full lanes. Partial occupation of the center lane would be more than offset by through vehicles using the shoulder lane, as indicated by the HCM. Therefore, although it seems possible to have weaving vehicles occupy two full lanes, a reasonable maximum of one full lane plus a substantial proportion of a second might be more appropriate.

The major weave section shown in Figure 1b is similar to a ramp-weave section, and, again, weaving movements are restricted primarily to two lanes, although secondary lane movements may take place from either of two outside lanes. Once again, it appears feasible for weaving vehicles to occupy two full lanes, perhaps a little more, depending on the extent of the outer flows.

The geometry of a major weave section, however, can be slightly altered to effect a significant change in possible lane use, as shown in Figure 1c.

In this configuration, a vehicle can make a weaving movement without changing lanes. Weaving movements can be made with a single lane change (as is usually the case) from either of two additional lanes. Therefore, with this configuration it is feasible for weaving vehicles to occupy three full lanes and possibly part of another. In addition, it would be expected that a weaving movement requiring no lane change would be more efficient than one requiring a lane change.

The configurations shown in Figure 1 indicate the possible effect of lane configuration on effective utility of weaving section lanes. The HCM methodology does not consider this vital aspect. It is apparent that simply providing the proper total number of lanes is not sufficient to guarantee the predicted operating characteristics. Lane arrangement may be such that the use of the lanes by weaving and nonweaving flows is not in proportion to the relative flows, resulting in part of the roadway being underutilized while another portion is overutilized.

Because lane arrangement depends heavily on the design of entry and exit legs, any design procedure should seriously consider this element as an integral part of the weaving area. In many cases it might be preferable to add lanes to exit or entry roadways rather than completely reconstruct a poorly operating weaving area.

The effects of lane configuration may be demonstrated and supported by (a) examination of flow speeds and lane utilization from a study of urban weaving areas and (b) use of lane-change transition matrices.

Relative Speeds and Lane Use

A 1963 study of urban weaving-area capacity (2) conducted by the Bureau of Public Roads showed that, in most cases, the speed of weaving vehicles and the speed of nonweaving vehicles are within 5 mph of each other. Table 1 gives the speeds of weaving and nonweaving vehicles obtained in the study. This is to be reasonably expected, for, in many weaving situations, weaving and nonweaving vehicles must share the same lanes. This has the effect of creating more or less uniform flow throughout the section.

In some cases, however, the roadway is wide enough to allow weaving and nonweaving flows to substantially isolate. In such instances, the effect of weaving flows on nonweaving flows is minimal, and large differences in speed might be observed. As indicated in Table 1, such differences most often occur on ramp-weave facilities with auxiliary lanes, where nonweaving vehicles may separate to the outer lanes. The geometry and lane configuration of a ramp-weave site restrict weaving vehicles to primarily the shoulder and auxiliary lanes. On major weave facilities, however, weaving flows tend to be dominant. If multilane entry and exit legs exist, weaving vehicles may occupy the major portion of the roadway. The higher speeds of nonweaving vehicles in the ramp-weave case indicate that weaving flows would expand into the outer lanes if the lane configuration and length permitted it. In terms of balanced use of roadway space, such situations indicate an underutilization of outer lanes and congestion in weaving lanes.

It appears that, in the cases of wide speed differentials, weaving vehicles are restricted to the limited portions of the roadway as a result of lane configuration. This can be verified by considering the relative number of lanes that are occupied by weaving and nonweaving vehicles in each experiment.

The appropriate service volume for each experiment is determined from HCM Table 9.1 on the basis of observed speeds and is adjusted by using standard correction factors for lane widths and percentage of trucks. The volume of nonweaving vehicles is then divided by this adjusted service volume to obtain an estimate of the number of lanes occupied by nonweaving vehicles. The number of weaving lanes is then the total number of lanes minus the number of nonweaving lanes. These computations are given in Table 2. Note that in no instance does the number of lanes occupied by weaving vehicles in a ramp-weave section exceed 2.0 (maximum of 1.75). In several major weaves, however, more than 2.0 lanes were occupied. The distinctive lane configuration of ramp-weave sections restricts all weaving movements to essentially two lanes: the shoulder lane and the auxiliary lane. Major weave sections, which have widely variable configurations, permit easy use of more than two lanes by weaving traffic.

It must be admitted that the data in Table 2 are not conclusive, if considered alone. The major weave sections generally have higher weaving volumes than the ramp-weave sections shown and would normally be expected to have a larger portion of the roadway taken up by weaving vehicles. However, the results given in Table 1 indicate that wide speed differentials between weaving and outer flows most often occur on ramp-weave sections. This clearly indicates that additional roadway space was available to weaving vehicles had some exterior constraint not prevented them from making use of it. Although such speed differentials also occur on major weave facilities, they occur less frequently and the differences tend to be smaller.

Note that all of the major weaves of Tables 1 and 2 are of the type shown in Figure 1c. These observed results strongly support the lane utilization effects of configuration hypothesized herein.

Lane-Change Transition Matrices and Configuration

The effects of configuration on weaving-area performance may also be analytically demonstrated by using a matrix of lane-changing probabilities similar to those developed by Worrall and colleagues (7, 8) and Drew (9). The following is a brief development of the lane-changing matrix presented by Worrall, Bullen, and Gur (8).

Assume that there is a probability $p(r)_{ij}$ of a vehicle making a lane change in the rth segment of length L from lane i to lane j, where L is defined such that only one lane change per segment is possible. The following m × m matrix of values describing the probability of all lane-changing movements in segment r may be constructed:

$$P(r) = \begin{bmatrix} p(r)_{11} & p(r)_{12} & \dots & p(r)_{1m} \\ p(r)_{21} & p(r)_{22} & \dots & p(r)_{2m} \\ \vdots & & & \\ p(r)_{m1} & p(r)_{m2} & \dots & p(r)_{mm} \end{bmatrix}$$

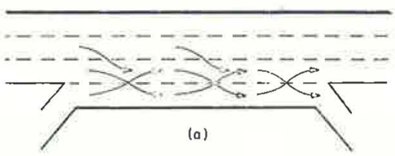
Figure 2 shows the physical interpretation of $p(r)_{ij}$. If the probable lane distribution of vehicles at the entrance of segment r is described by a vector

$$A = [a_1 \ a_2 \ a_3 \ \dots \ a_m]$$

and the probable lane distribution at the end segment r is described by another vector

$$B = [b_1 \ b_2 \ b_3 \ \dots \ b_m]$$

Figure 1. Weaving movements in (a) a ramp-weave section and (b) and (c) two major weave section configurations.



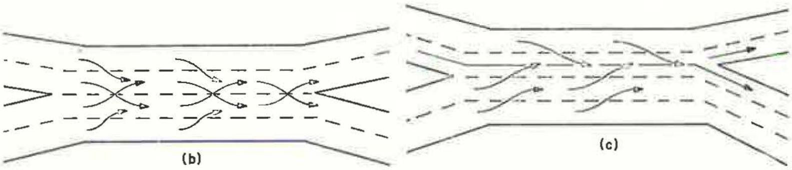


Table 1. Relation of space mean speed of nonweaving vehicle to weaving vehicle speed.

Type	>5 mph Less	±5 mph	5 to 10 mph More	10 to 15 mph More	>15 mph More
Ramp weave with auxiliary lane	1	10	0	2	4
Major weave and collector-distributor	2	17	4	1	0
All	3	27	4	3	4

Table 2. Number of freeway lanes occupied by weaving and nonweaving vehicles.

Type	No.	1 Nonweaving Vol.	2 Weaving Vol.	3 Nonweaving SV	4 Total Lanes	5 = 1/3 Nonweaving Lanes	6 = 4 - 5 Weaving Lanes
Ramp weaves	3	3,986	1,098	1,765	4	2.25	1.75
	7	3,374	1,666	1,460	4	2.30	1.70
	8	3,157	1,775	1,265	4	2.49	1.51
	9	4,572	1,526	1,804	4	2.53	1.47
	11	5,008	1,354	1,485	5	3.54	0.55
	12	5,918	638	—[a]	5	—	—
	14	6,222	627	—[a]	5	—	—
	16	5,719	940	—[a]	5	—	—
	17	3,897	1,112	1,302	4	2.97	1.03
	18	2,487	951	1,085	4	2.45	1.55
	21	4,220	539	1,582	4	2.65	1.35
	28	5,096	1,366	1,455	5	3.50	1.50
	29	1,806	1,434	1,480	3	1.33	1.67
	30	2,030	1,108	—[a]	3	—	—
	32	3,902	1,300	—[a]	4	—	—
	33	6,133	1,252	1,582	5	3.92	1.08
	34	2,706	1,131	980	4	2.76	1.24
Major weaves	4	4,649	2,486	1,840	4	2.53	1.47
	13	4,555	2,974	—[a]	5	—	—
	23	3,478	2,502	1,570	5	2.20	2.80
	24	2,019	2,293	1,420	5	2.12	2.88
	49	2,933	2,166	—[a]	4	—	—
	50	2,814	2,238	—[a]	4	—	—
	51	1,913	1,678	1,470	4	1.30	2.70
	52	2,182	2,453	1,508	4	1.45	2.55
	53	792	1,823	1,400	4	0.57	3.43
	54	631	1,767	1,425	3	0.44	2.56
	60	2,384	2,859	1,718	—[b]	—	—
	61	2,170	1,970	—[a]	—[b]	—	—
	63	1,598	2,564	1,620	3	0.97	2.03
	64	3,100	3,014	—[a]	—[b]	—	—
	65	2,465	1,651	1,440	—[b]	—	—

[a]Level of service F prevails; service volume variable. [b]Not available.

then

$$B = A \times P(r)$$

where m = the number of lanes in the section under study.

The Worrall study concerned normal lane changing, but was adapted to fit other situations. It may be restated as lane changing dictated only by driver choice and not necessitated by the need to complete a merging, diverging, or weaving maneuver. Under the latter circumstances, lane changing may be considered a random event, P(r) should be the same for all r, and the lane distribution after a segment of highway of any given length can be stated as

$$B = A \times P^N$$

where N is the number of segments of length L in the section under consideration. Further, under stable flow, the number of lane changes from i to j will be equal to the number of lane changes from j to i, and the lane distribution will remain constant.

It should be noted that the segment length L, which permits only a single lane change, may vary based on speed and possibly volume factors. This is a refinement not addressed by Worrall. Limited data collected by Worrall suggested that a segment length of 250 ft satisfactorily met all requirements under all observed flow conditions.

Transition matrices may be applied to weaving or ramp situations by the separate consideration of flow components and the appropriate use of absorbing elements in the array. An absorbing element is one that does not allow transitions out of the lane. This is convenient and allows the prediction of lane changes only in the direction of interest (weaving vehicles are assumed not to make any reverse lane changes). Separate lane-changing matrices are used for each component flow.

Consider, for example, the four-lane weaving section of Figure 3. It is possible to consider separate lane-changing matrices for weaving movements AY and BX. Absorbing states in the two matrices are set such that only lane changes in the direction of the weave are permitted. This simplifying assumption is well-founded in observed lane-changing behavior.

It is assumed that the values for p_{ij} are constant. Although it might be expected that p varies depending on conditions such as relative volumes and segment of the weaving section, an investigation into the nature of these probabilities (2) showed that p does indeed tend to be constant.

The lane-changing matrices for movements BX and AY are given by

$$P_{BX} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ p & (1-p) & 0 & 0 \\ 0 & p & (1-p) & 0 \\ 0 & 0 & p & (1-p) \end{bmatrix}$$

and

$$P_{AY} = \begin{bmatrix} (1-p) & p & 0 & 0 \\ 0 & (1-p) & p & 0 \\ 0 & 0 & (1-p) & p \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

If vectors α and β are defined as the distribution of weaving vehicles at the entrance and exit of the weaving section respectively, then

$$\alpha_{BX} = [0 \quad 0 \quad \alpha_3 \quad \alpha_4]$$

$$\alpha_{AY} = [\alpha_1 \ \ \alpha_2 \ \ 0 \ \ 0]$$

$$\beta = [\beta_1 \ \ \beta_2 \ \ \beta_3 \ \ \beta_4]$$

It is seen that

$$\beta = \alpha \times P^N$$

The vector β includes the possibility of unsuccessful weaving movements. For example, for movement BX, $\beta_1 + \beta_2$ represents the percentage of successful weaves, that is, those that completed lane changes into one of the lanes of their desired exit leg. $\beta_3 + \beta_4$ represents the percentage of unsuccessful weaves. The unsuccessful weave will most likely force its way into the proper lane at the last moment, creating a serious traffic disturbance. It may be argued, therefore, that the total number of unsuccessful or "forced" weaves is an indicator of the quality of service being provided.

For the purpose of illustration, four configurations of a four-lane weaving section of constant length are shown in Figure 4. This procedure may be applied to other configurations, with some simplifying assumptions:

1. Weaving vehicles entering on a given leg will be evenly distributed among the lanes of that leg;
2. Illustrative computations will assume that movement BX is of primary importance;
3. The section under consideration will be 1,500 ft long, an average length for such configurations;
4. The unit segment length L will be 250 ft, the length determined by Worrall for most freeway conditions (N = 6); and
5. The value of p will be varied, and comparative results will be studied.

Now, the four configurations of Figure 4 may be compared.

For the configuration shown in Figure 4a,

$$\alpha_{BX} = [0 \ \ 0 \ \ 0.5 \ \ 0.5]$$

$$\beta_{BX} = [\beta_1 \ \ \beta_2 \ \ \beta_3 \ \ \beta_4]$$

The probability of a successful weave $PR_{BX} = \beta_1 + \beta_2$ or $1 - (\beta_3 + \beta_4)$.

For the configuration shown in Figure 4b,

$$\alpha_{BX} = [0 \ \ 0 \ \ 0.5 \ \ 0.5]$$

$$\beta_{BX} = [\beta_1 \ \ \beta_2 \ \ \beta_3 \ \ \beta_4]$$

$$PR_{BX} = \beta_1 + \beta_2 + \beta_3 \ \text{ or } \ 1 - \beta_4$$

For the configuration shown in Figure 4c,

$$\alpha_{BX} = [0 \ \ 0.33 \ \ 0.33 \ \ 0.33]$$

$$\beta_{BX} = [\beta_1 \ \ \beta_2 \ \ \beta_3 \ \ \beta_4]$$

$$PR_{BX} = \beta_1 + \beta_2 \ \text{ or } \ 1 - (\beta_3 + \beta_4)$$

For the configuration shown in Figure 4d,

$$\alpha_{BX} = [0 \ \ 0.33 \ \ 0.33 \ \ 0.33]$$

$$\beta_{BX} = [\beta_1 \ \ \beta_2 \ \ \beta_3 \ \ \beta_4]$$

$$PR_{BX} = \beta_1 + \beta_2 + \beta_3 \ \text{ or } \ 1 - \beta_4$$

In general, if $\alpha = [\alpha_1 \ \alpha_2 \ \alpha_3 \ \alpha_4]$ and P^N_{BX} is computed, then

$$[\beta_1 \ \beta_2 \ \beta_3 \ \beta_4] = [\alpha_1 \ \alpha_2 \ \alpha_3 \ \alpha_4] \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 - (1-p)^N & (1-p)^N & 0 & 0 \\ R_1 & R_2 & (1-p)^N & 0 \\ R_3 & R_4 & N_p(1-p)^{N-1} & (1-p)^N \end{bmatrix}$$

Computing the elements β_1, β_2, β_3, and β_4 and substituting in the equations for PR_{BX} yield the results given below. These are plotted for various values of p as shown in Figure 5.

Configuration	PR_{BX}
A	$1 - (1-p)^6 - 0.5\,[6p\,(1-p)^5]$
B	$1 - 0.5\,(1-p)^6$
C	$1 - 0.66\,(1-p)^6 - 0.33\,[6p\,(1-p)^5]$
D	$1 - 0.33\,(1-p)^6$

For a given value of p, it is apparent that the most efficient configuration for movement BX is D, followed by B, C, and A in that order. This was to be expected. Note that configuration D has two lanes in which weaving movements may take place without a lane change, thus providing two through lanes for weaving vehicles. Both configurations B and C provide one through lane for weaving vehicles, B by splitting a lane at the diverge and C by combining one at the merge. Because the merging maneuver entails greater friction than the diverge maneuver, B would be expected to be more efficient, although the analysis does not take this factor into account. The configuration shown in Figure 4a, which requires a lane change for every weaving movement, is the least efficient.

These results confirm and reinforce the hypothesis on lane utilization presented herein. Configuration D allows a greater portion of its width to be used by weaving vehicles than each of the other configurations, with B and C allowing greater utilization than A.

It is clear that the advantage of one configuration over the other decreases as p increases. Configuration, then, becomes increasingly important as p decreases.

Conclusions on Configuration

Lane configuration has been shown to be a factor of great importance in weaving-area operations, particularly influencing lane utilization. The hypothesized restriction effects have been illustrated and verified by observations of actual data and by analysis.

As a result, several major conclusions regarding lane configuration may be offered.

1. Certain configurations restrict weaving vehicles to a portion of the roadway. Lanes beyond this portion may be used only by nonweaving vehicles, and width improvements will not affect weaving flows. It is therefore imperative that any design analysis procedure differentiate between weaving and nonweaving lane requirements, permitting a design reflecting the proper relative positioning of each.
2. Lane configuration is greatly affected by entry and exit lane arrangements. Therefore, design of these elements should be included in any design procedure.
3. The large difference in weaving and nonweaving vehicle speeds observed on many ramp-weave sections reflects the restrictive nature of this type of configuration and results in underutilization of outer lanes and congestion in weaving lanes.
4. There appear to be a maximum number of lanes that can be used by weaving vehicles for any given configuration. A summary of apparent maximum values of lane utilization is given in Table 3.
5. Configurations allowing some weaving movements to take place without a lane change will operate more efficiently than configurations that require lane changes for a weaving movement, given similar volumes and equal lengths and total number of lanes.

Figure 2. Lane-changing probability.

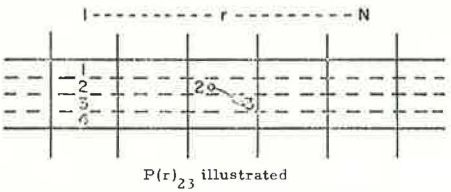


Figure 3. Four-lane weaving section.

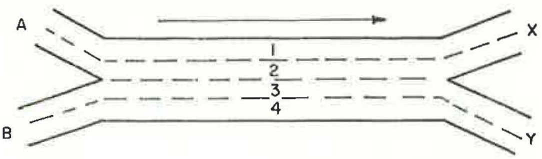


Figure 4. Alternative weaving configurations.

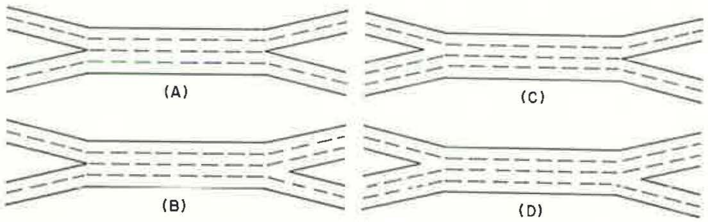
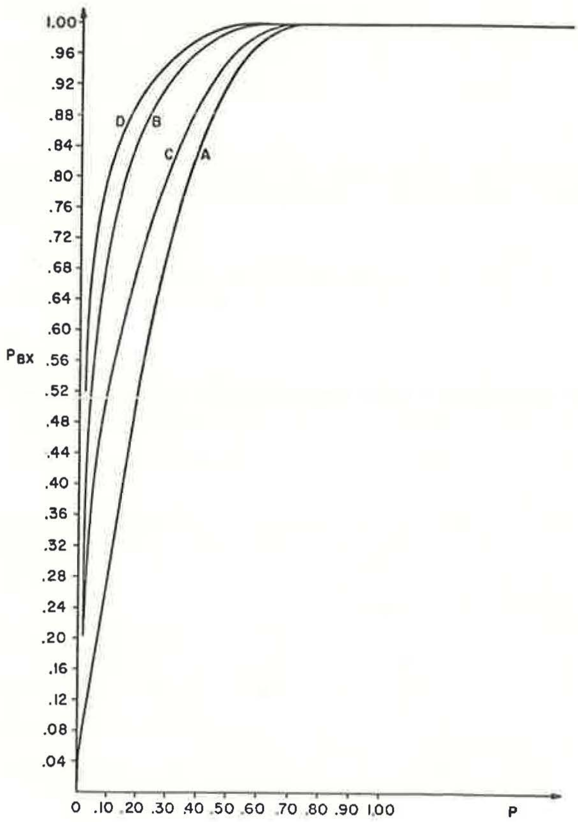


Figure 5. Comparison of configurations for various values of P for movement BX.



Use of Configuration in Weaving Design-Analysis

A procedure for design and analysis of weaving sections based on the configuration concepts presented here and on a new algorithm relating the principal weaving parameters of weaving volume, weaving ratio, and others to the design parameters of length and width (for weaving vehicles) is being developed at this writing (2). However, the results and concepts presented can be used to modify current HCM procedures to produce both results.

Principally, the HCM equation for width should be separated into its component parts. Thus,

$$N = \frac{V_T + (k - 1)\, V_{w2}}{SV}$$

becomes

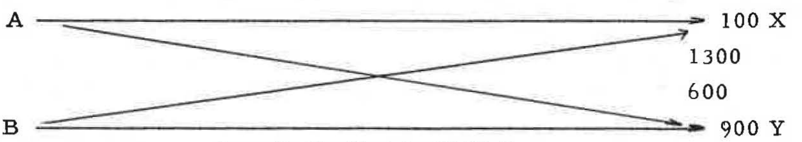
$$N_{01} = \frac{V_{01}}{SV}$$

$$N_w = \frac{V_{w1} + k\, V_{w2}}{SV}$$

$$N_{02} = \frac{V_{02}}{SV}$$

In design, this procedure gives the opportunity to examine what type of configuration is needed for a particular section and to determine the total number of lanes.

If the number of lanes required just for weaving vehicles is 2.3, a configuration requiring all weaving vehicles to make a lane change will not be adequate. Table 4 shows that such configurations limit weaving vehicles to 2.0 lanes at best. Thus, a configuration allowing the major weaving movement to proceed without a lane change is needed, and a lane dividing to two lanes at the diverge or two lanes merging to one at the merge point will be used, preferably the former. Consider the following design example:



Let A = 1 lane, leg B = 2 lanes, leg X = 1 lane, and leg Y = 2 lanes. These may be subject to change.

Design for level of service C with a peak-hour factor = 0.91. All volumes are in passenger car equivalents.

From HCM Table 9.1, SV = 2,750/2 = 1,350 passenger cars/hour/lane. For level of service C, quality of flow = II or III (HCM Table 7.3). From HCM Figure 7.4, for V_{we} = 2,200, L = 2,000, and k = 2.95, quality of flow = III (acceptable). Now,

$$V_{01} = 100/1{,}350 = 0.07$$

$$V_w = \frac{1{,}200 + 2.95\,(600)}{1{,}350} = 2.20$$

$$V_{02} = 900/1{,}350 = \underline{0.67}$$

$$2.94 \text{ or } 3 \text{ lanes}$$

The use of the HCM equation directly would have merely yielded the total of three lanes, and a weaving section would have been designed (Fig. 6). However, if the requirement that $V_w = 2.2$ is considered, this configuration, which requires that all weaving vehicles execute a lane change, will not be adequate. Weaving vehicles will be restricted to less than 2 lanes, most likely 1.8 or so inasmuch as this is really a left-hand ramp-weave (Table 4), and will experience less than level of service C. The major outer flow will experience a better level of service. This design would produce an unbalanced operation.

If the configuration is altered by adding a lane to exit X, an adequate design with the same N and L is achieved (Fig. 7). Obviously, the ability to add a lane at the exit must be weighed against the necessity to drop the lane later. However, often downstream ramps or volume fluctuations make the addition and later dropping of a lane feasible. It may be economically more feasible than providing a full interchange where a weaving design may be otherwise inadequate.

The Ward-Fairmount Study: A Case Study

The Ward-Fairmount study (6) graphically illustrated the effect of lane configuration on weaving-area operations. The section of I-8 in San Diego between Ward and Fairmount Avenues habitually experienced level of service F breakdown flow. Through two successive improvements—(a) adding a lane to the off-ramp at Fairmount Avenue, thereby creating a through lane for one weaving flow, and (b) breaking up the on-ramp into two successive on-ramps—improvements in flow were accomplished.

Although the total length of the weaving section was also increased, a major portion of the improvement in conditions was attributable to the configurational changes made.

The configurations, as well as flows, for the before, intermediate, and after conditions are shown in Figure 8. Travel times, delays, and level of service are also included.

Both the HCM and the analysis procedure being developed as part of the weaving-area operations study were used to predict the study results. As previously noted, this latter procedure is based on the configuration concepts presented herein. Approximate procedures for the after conditions are used, inasmuch as flows are not broken down by on-ramp for the multiple-weave case.

It is interesting to note that the HCM weaving procedure, when applied to the Ward-Fairmount study, predicts level of service D or E for both the before and intermediate configurations, and level of service E for the after configuration. This is clearly in conflict with the actual levels of service F, E, and D observed. The HCM procedure does not permit proper analysis of essentially unbalanced conditions, where, because of configurational constraints on lane use, weaving flows may be congested while outer flows move freely.

The procedure based on configuration and a new algorithm permits such an analysis. When applied to the Ward-Fairmount case (4), the before configuration was shown to have level of service F for weaving flows, while outer flows operated at level of service C. The intermediate condition was shown to provide balanced level of service E operation for all flows because a through lane was provided for weaving. An approximate analysis provided estimates of slightly improved balanced operation in the after case, but still in level of service E. These results clearly reflect the actual conditions observed.

SUMMARY AND RECOMMENDATIONS

The central theme of this paper has been the overwhelming importance of lane configuration as a weaving design-analysis parameter.

Data have been analyzed to show the effect of this element on the use of roadway width by weaving vehicles, particularly how poor design of lane configuration may restrict weaving vehicles to small portions of the roadway. Analytic treatment demonstrated how configurations may be altered to improve the performance of a weaving section wtihout changing length or width.

This has resulted in the development of a design-analysis procedure for weaving sections incorporating configuration as a primary element as part of the weaving-area operations study. The procedure uses new equations for weaving requirements. Because of their interim nature, they are not published here.

Table 3. Maximum utilization factors.

Configuration	Maximum No. of Lanes Occupied by Weaving Vehicles: Theoretical	Observed
Ramp weave	2.00	1.75
Major weave with no weaving movements without lane change	2.00+	–
Major weave with at least one weaving movement without a lane change	3.00+	3.43

Figure 6. Weaving section design using HCM equations.

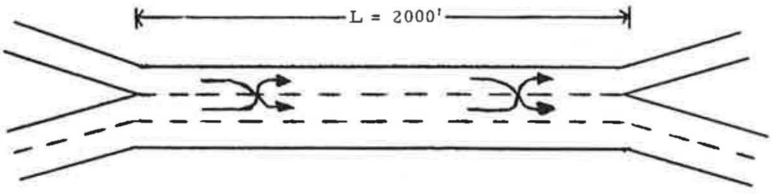


Figure 7. Weaving section design using modified HCM equations.

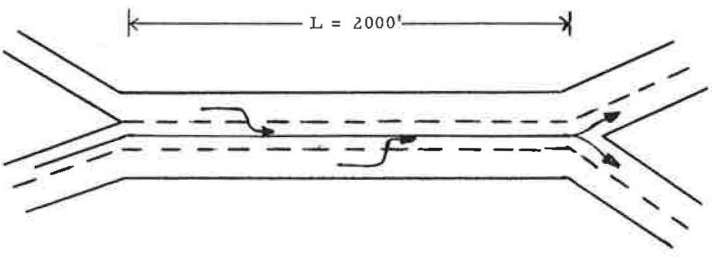
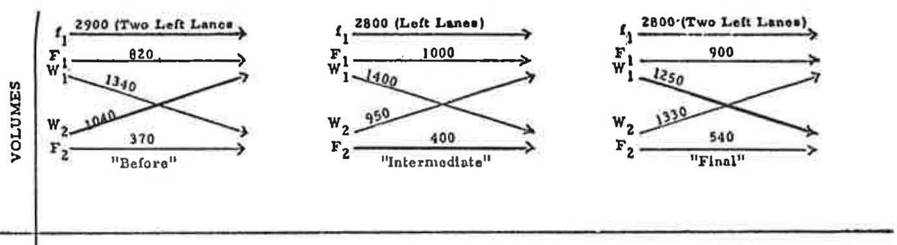


Figure 8. Before, intermediate, and final data for Ward-Fairmount study.



QUALITY OF FLOW

	TRAVEL TIMES: Average (seconds)	Standard Deviation (seconds)	Improvement %	AVERAGE NO. OF VEHICLES IN QUEUE	DELAY: Average (seconds)	Reduction %	AVERAGE SPEED (MPH)	OVERALL LEVEL OF SERVICE
"Before"	63	10	--	15	19	--	28	F
"Intermediate"	54	11	14	10	10	47	33	E
"Final"	44	2	19	2	0	100	41	D

COMPARATIVE RESULTS

(Travel through 2642' study section during peak hour)

The principles presented, however, have been used to modify the existing HCM procedure to include the element of lane configuration, and the use of the modified procedure has been illustrated.

It should be remembered that internal inaccuracies of the HCM procedure are not corrected by this modified procedure, although improved design due to the inclusion of lane configuration as a design element will result.

The procedure being developed under the weaving-area operation study for design-analysis of weaving sections permits a sensitivity to factors not included by existing methods. It will be possible, with consideration of lane configuration, to predict and understand the basic causes of unbalanced roadway use and the markedly different operating conditions for the several flow components. More importantly, such designs can be avoided. Lane configuration may be utilized to accomplish more efficient use of roadway space and balanced operation in which all flows experience similar operating conditions.

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