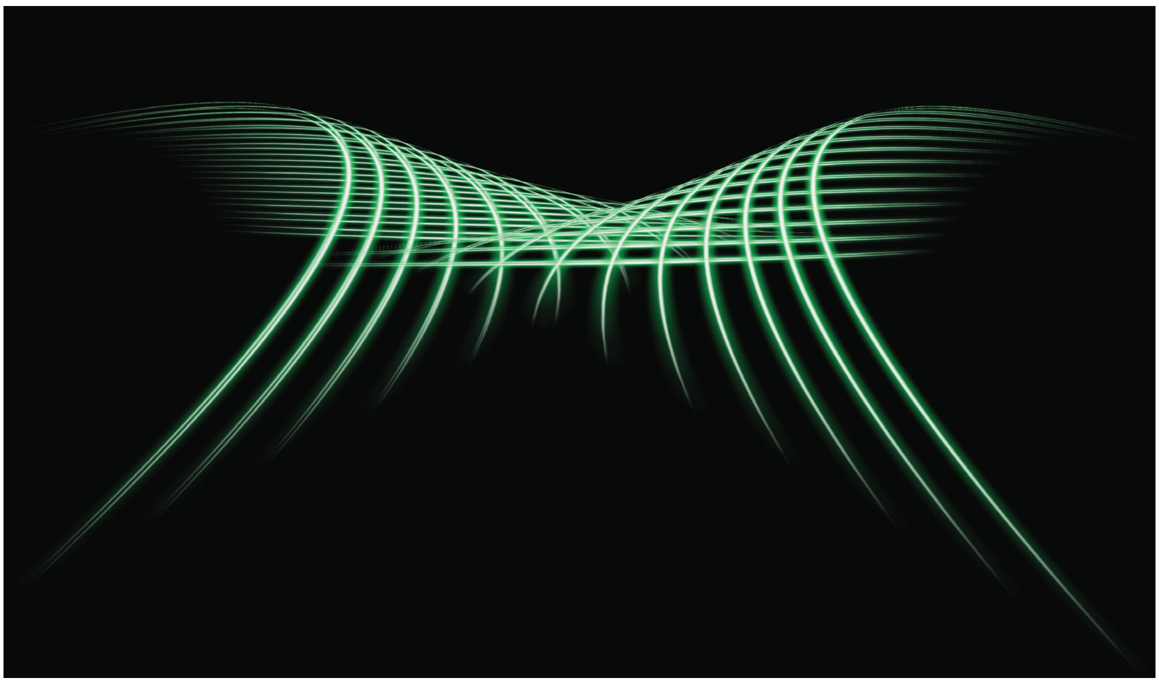
HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 12

FREEWAY WEAVING SEGMENTS

TRANSPORTATION RESEARCH BOARD
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HCM2010

HIGHWAY CAPACITY MANUAL

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CHAPTER 12
FREEWAY WEAVING SEGMENTS

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LIST OF EXHIBITS

1. INTRODUCTION

Weaving is generally defined as the crossing of two or more traffic streams traveling in the same direction along a significant length of highway without the aid of traffic control devices (except for guide signs). Thus, weaving segments are formed when merge segments are closely followed by diverge segments. "Closely" implies that there is not sufficient distance between the merge and diverge segments for them to operate independently.

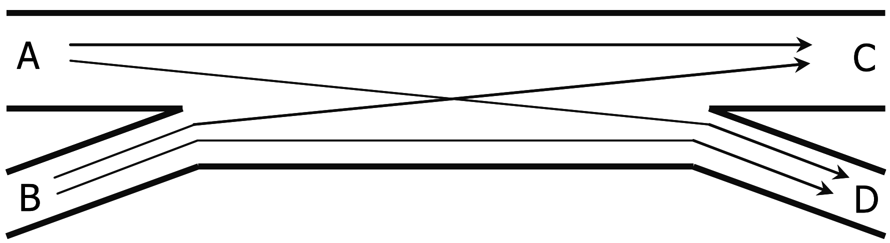
Three geometric characteristics affect a weaving segment's operating characteristics: length, width, and configuration. All have an impact on the critical lane-changing activity, which is the unique operating feature of a weaving segment. **Chapter 12, Freeway Weaving Segments,** provides a methodology for analyzing the operation of weaving segments based on these characteristics as well as a segment's free-flow speed (FFS) and the demand flow rates for each movement within a weaving segment (e.g., ramp to freeway or ramp to ramp). This chapter describes how the methodology can be applied to planning, operations, and design applications and provides examples of these applications.

2. WEAVING SEGMENT CHARACTERISTICS

OVERVIEW

Exhibit 12-1 illustrates a freeway weaving segment. On entry and exit roadways, or *legs*, vehicles traveling from Leg A to Leg D must cross the path of vehicles traveling from Leg B to Leg C. Flows A–D and B–C are, therefore, referred to as *weaving movements*. Flows A–C and B–D may also exist, but as they are not required to cross the path of any other flow, they are referred to as *nonweaving movements*.

Exhibit 12-1
Formation of a Weaving Segment



Traffic in a weaving segment experiences more lane-changing turbulence than is normally present on basic freeway segments.

Weaving segments require intense lane-changing maneuvers as drivers must access lanes appropriate to their desired exit leg. Therefore, traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic freeway segments. This additional turbulence presents operational problems and design requirements, which are addressed by this chapter's methodology.

A weaving segment's geometry affects its operating characteristics.

Three geometric characteristics affect a weaving segment's operating characteristics:

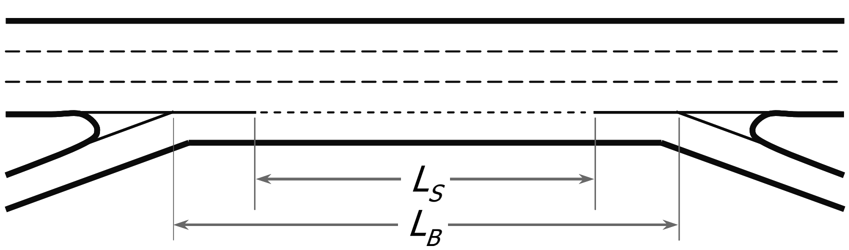
- Length,
- Width, and
- Configuration.

Length is the distance between the merge and diverge that form the weaving segment. *Width* refers to the number of lanes within the weaving segment. *Configuration* is defined by the way entry and exit lanes are aligned. All have an impact on the critical lane-changing activity, which is the unique operating feature of a weaving segment.

LENGTH OF A WEAVING SEGMENT

The two measures of weaving segment length that are relevant to this chapter's methodology are illustrated in Exhibit 12-2.

Exhibit 12-2
Measuring the Length of a Weaving Segment



The lengths illustrated are defined as follows:

L_S = short length, the distance in feet between the end points of any barrier markings (solid white lines) that prohibit or discourage lane changing.

L_B = base length, the distance in feet between points in the respective gore areas where the left edge of the ramp-traveled way and the right edge of the freeway-traveled way meet.

Neither of these definitions is the same as those used in previous editions of the *Highway Capacity Manual* (HCM). The definitions used throughout the HCM2000 were historically tied to the specifics of the design of loop ramps in a cloverleaf interchange at a time when most weaving segments were part of such interchanges. Modern weaving segments occur in a wide range of situations and designs, and a more general definition of length is appropriate.

This methodology includes several equations that include the length of the weaving segment. In all cases, these equations use the short length L_S. This is not to suggest that lane changing in a weaving segment is restricted to this length. Some lane changing takes place over solid white lines and even painted gore areas. Nevertheless, research has shown that the short length is a better predictor of operating characteristics within the weaving segment than either the base length or the length as defined in HCM2000 and previous editions.

The weaving segment length used in the methodology is defined by the distance between barrier markings. Where no markings exist, the length is defined by the distance between where the left edge of the ramp-traveled way and the right edge of the freeway-traveled way meet.

For weaving segments in which no solid white lines are used, the two lengths illustrated in Exhibit 12-2 are the same, that is, $L_S = L_B$. In dealing with future designs in which the details of markings are unknown, a default value should be based on the general marking policy of the operating agency. At the time this methodology was developed, where solid white lines were provided, L_S was equal to $0.77 \times L_B$ on average for the available data.

The estimated speeds and densities, however, apply over the base length L_B. Some evidence also indicates that these speeds and densities may apply to the 500 ft of freeway upstream of the merge and downstream of the diverge because of presegregation of movements in each case.

The weaving segment length strongly influences lane-changing intensity. For any given demand situation, longer segments allow weaving motorists more time and space to execute their lane changes. This reduces the density of lane changing and, therefore, turbulence. Lengthening a weaving segment both increases its capacity and improves its operation (assuming a constant demand).

Under constant demand conditions, making a weaving segment longer increases its capacity and improves its operation.

WIDTH OF A WEAVING SEGMENT

The width of a weaving segment is measured as the number of continuous lanes within the segment, that is, the number of continuous lanes between the entry and exit gore areas. Acceleration or deceleration lanes that extend partially into the weaving segment are not included in this count.

The number of continuous lanes between gore areas within a weaving segment defines its width.

While additional lanes provide more space for both weaving and nonweaving vehicles, they encourage additional optional lane-changing activity. Thus, while reducing overall densities, additional lanes can increase lane-changing activity and intensity. In most cases, however, the number of lanes in the weaving segment is controlled by the number of lanes on the entry and exit legs and the intended configuration.

CONFIGURATION OF A WEAVING SEGMENT

Configuration of a weaving segment refers to the way that entry and exit lanes are linked. The configuration determines how many lane changes a weaving driver must make to complete the weaving maneuver successfully. The following sections use a great deal of terminology to describe configurations; this terminology should be clearly understood.

One-Sided and Two-Sided Weaving Segments

One-sided weaving segments require no more than two lane changes to complete a weaving maneuver.

Most weaving segments are one-sided. In general, this means that the ramps defining the entry to and exit from the weaving segment are on the same side of the freeway—either both on the right (most common) or both on the left. The methodology of this chapter was developed for one-sided weaving segments; however, guidelines are given for applying the methodology to two-sided weaving segments.

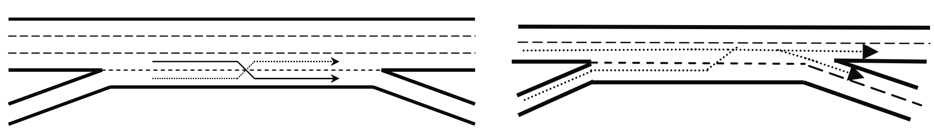
Two-sided weaving segments require three or more lane changes to complete a weaving maneuver or have a single-lane on-ramp closely followed by a single-lane off-ramp on the opposite side of the freeway.

One- and two-sided weaving segments are defined as follows:

- A *one-sided weaving segment* is one in which no weaving maneuvers require more than two lane changes to be completed successfully.
- A *two-sided weaving segment* is one in which at least one weaving maneuver requires three or more lane changes to be completed successfully or in which a single-lane on-ramp is closely followed by a single-lane off-ramp on the opposite side of the freeway.

Exhibit 12-3 illustrates two examples of one-sided weaving segments.

Exhibit 12-3
One-Sided Weaving Segments Illustrated

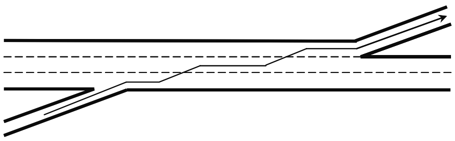


(a) One-Sided Ramp Weave (b) One-Sided Major Weave

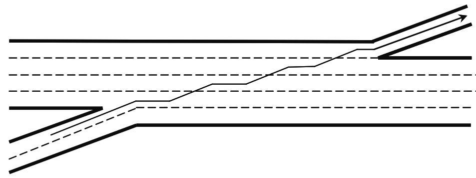
Exhibit 12-3(a) shows a typical one-sided weaving segment formed by a one-lane, right-side on-ramp followed closely by a one-lane, right-side off-ramp. The two are connected by a continuous freeway auxiliary lane. Every weaving vehicle must make one lane change as illustrated, and the lane-changing turbulence caused is clearly focused on the right side of the freeway. Exhibit 12-3(b) shows another one-sided weaving segment in which the off-ramp has two lanes. One weaving movement (ramp to freeway) requires one lane change. The other (freeway to ramp) can be made without making a lane change. Again, lane-changing turbulence is focused on the right side of the freeway.

Exhibit 12-4 contains two examples of two-sided weaving segments.

Exhibit 12-4
Two-Sided Weaving Segments Illustrated



(a) Two-Sided Weaving Section with Single-Lane Ramps



(b) Two-Sided Weaving Section with Three Lane Changes

Exhibit 12-4(a) is the most common form of a two-sided weave. A one-lane, right-side on-ramp is closely followed by a one-lane, left-side off-ramp (or vice versa). Although the ramp-to-ramp weaving movement requires only two lane changes, this movement is still classified as a two-sided weave because the geometry of the through movement on the freeway technically qualifies as a weaving flow.

Exhibit 12-4(b) is a less typical case in which one of the ramps has multiple lanes. Because the ramp-to-ramp weaving movement must execute three lane changes, it is also classified as a two-sided weaving segment.

Ramp-Weave Versus Major Weave Segments

Exhibit 12-3 can also be used to illustrate the difference between a ramp-weaving segment and a major weaving segment. Exhibit 12-3(a) shows a typical ramp-weaving segment, formed by a one-lane on-ramp closely followed by a one-lane off-ramp, connected by a continuous freeway auxiliary lane. The unique feature of the ramp-weave configuration is that all weaving drivers must execute a lane change across the lane line separating the freeway auxiliary lane from the right lane of the freeway mainline.

One-sided configurations without a continuous auxiliary lane connecting an on-ramp to a closely following off-ramp are treated as isolated ramp junctions (Chapter 13) and not as weaving segments.

It is important to note that the case of a one-lane on-ramp closely followed by a one-lane off-ramp (on the same side of the freeway), but not connected by a continuous freeway auxiliary lane, is not considered to be a weaving configuration. Such cases are treated as isolated merge and diverge segments by using the methodology described in Chapter 13. The distance between the on-ramp and the off-ramp is not a factor in this determination.

Exhibit 12-3(b) shows a typical major weaving segment. A major weaving segment is formed when three or more entry or exit legs have multiple lanes.

Numerical Measures of Configuration

Three numerical descriptors of a weaving segment characterize its configuration:

"Minimum number of lane changes" assumes vehicles position themselves when entering and exiting to make the least number of lane changes possible.

LC_{RF} = minimum number of lane changes that a ramp-to-freeway weaving vehicle must make to complete the ramp-to-freeway movement successfully.

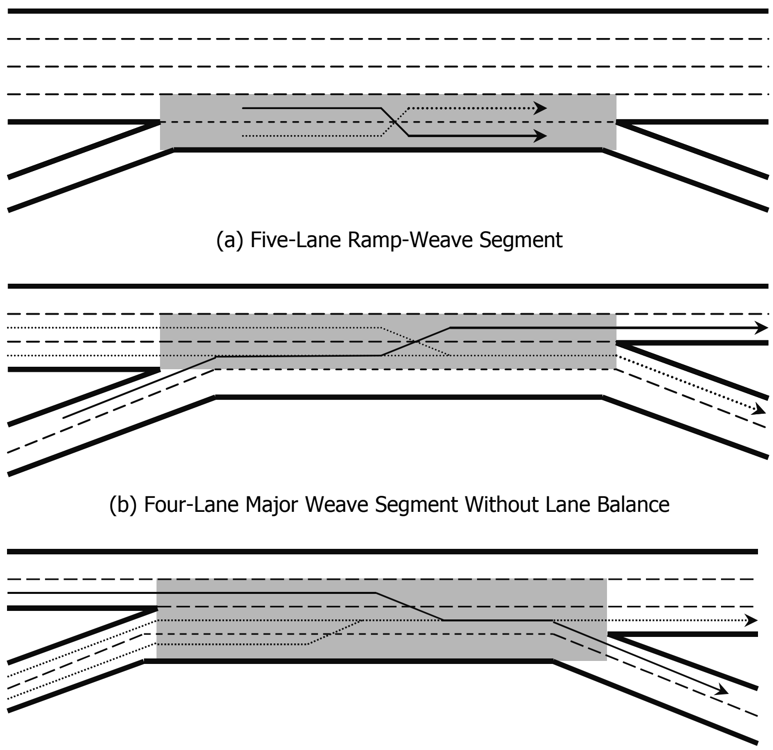
LC_{FR} = minimum number of lane changes that a freeway-to-ramp weaving vehicle must make to complete the freeway-to-ramp movement successfully.

N_{WL} = number of lanes from which a weaving maneuver may be completed with one lane change or no lane changes.

These definitions apply directly to one-sided weaving segments in which the ramp-to-freeway and freeway-to-ramp movements are the weaving movements. Different definitions apply to two-sided weaving segments. Exhibit 12-5 illustrates how these values are determined for one-sided weaving segments.

The values of LC_{RF} and LC_{FR} are found by assuming that every weaving vehicle enters the segment in the lane closest to its desired exit leg and leaves the segment in the lane closest to its entry leg.

Exhibit 12-5
Configuration Parameters Illustrated



(a) Five-Lane Ramp-Weave Segment

(b) Four-Lane Major Weave Segment Without Lane Balance

(c) Four-Lane Major Weave Segment With Lane Balance

Exhibit 12-5(a) is a five-lane ramp-weave configuration. If a weaving driver wishes to exit on the off-ramp and enters the segment on the rightmost freeway lane (the lane closest to the off-ramp), the driver must make a single lane change to enter the freeway auxiliary lane and leave via the off-ramp. Thus, for this case, $LC_{FR} = 1$. A weaving driver entering the freeway via the on-ramp has no choice but to enter on the freeway auxiliary lane. The driver must then make a single lane change from the freeway auxiliary lane to the rightmost lane of the freeway (the lane closest to the entry leg). Thus, $LC_{RF} = 1$ as well.

Lane balance within a weaving segment provides operational flexibility.

Exhibit 12-5(b) and Exhibit 12-5(c) are both major weaving configurations consisting of four lanes. They differ only in the configuration of their entry and exit gore areas. One has lane balance, while the other does not. Lane balance exists when the number of lanes leaving a diverge segment is one more than the number of lanes entering it.

Exhibit 12-5(b) is not typical. It is used here only to demonstrate the concept of lane balance in a major weaving segment. Five lanes approach the entry to the segment and four lanes leave it; four lanes approach the exit from the segment and four lanes leave it. Because of this configuration, vehicles approaching the exit gore must already be in an appropriate lane for their intended exit leg.

In Exhibit 12-5(b), the ramp-to-freeway weaving movement (right to left) requires at least one lane change. A vehicle can enter the segment on the leftmost ramp lane (the lane closest to the desired exit) and make a single lane change to exit on the rightmost lane of the continuing freeway. LC_{RF} for this case is 1. The freeway-to-ramp weaving movement can be made without any lane changes. A vehicle can enter on the rightmost lane of the freeway and leave on the leftmost lane of the ramp without executing a lane change. For this case, $LC_{FR} = 0$.

The exit junction in Exhibit 12-5(c) has lane balance: four lanes approach the exit from the segment and five lanes leave it. This is a desirable feature that provides some operational flexibility. One lane—in this case, the second lane from the right—splits at the exit. A vehicle approaching in this lane can take either exit leg without making a lane change. This is a useful configuration in cases in which the split of exiting traffic varies over a typical day. The capacity provided by the splitting lane can be used as needed by vehicles destined for either exit leg.

In Exhibit 12-5(c), the ramp-to-freeway movement can be made without a lane change, while the freeway-to-ramp movement requires a single lane change. For this case, $LC_{RF} = 0$ and $LC_{FR} = 1$.

In Exhibit 12-5(a), there are only two lanes from which a weaving movement may be made with no more than one lane change. Weaving vehicles may enter the segment in the freeway auxiliary lane (ramp-to-freeway vehicles) and in the rightmost freeway lane (freeway-to-ramp vehicles) and may execute a weaving maneuver with a single lane change. Although freeway-to-ramp vehicles may enter the segment on the outer freeway lanes, they would have to make more than one lane change to access the off-ramp. Thus, for this case, $N_{WL} = 2$.

In Exhibit 12-5(b), weaving vehicles entering the segment in the leftmost lane of the on-ramp or the rightmost lane of the freeway are forced to merge into a single lane. From this lane, the freeway-to-ramp movement can be made with no lane changes, while the ramp-to-freeway movement requires one lane change. Because the movements have merged into a single lane, this counts as one lane from which weaving movements can be made with one or fewer lane changes. Freeway-to-ramp vehicles, however, may also enter the segment on the center lane of the freeway and make a single lane change (as shown) to execute their desired maneuver. Thus, for this case, N_{WL} is once again 2.

Lane balance creates more flexibility in Exhibit 12-5(c). Ramp-to-freeway vehicles may enter on either of the two lanes of the on-ramp and complete a weaving maneuver with either one or no lane changes. Freeway-to-ramp vehicles may enter on the rightmost freeway lane and also weave with a single lane change. In this case, $N_{WL} = 3$.

In all one-sided weaving segments, the number of lanes from which weaving maneuvers may be made with one or no lane changes is either two or three. No other values are possible. Segments with $N_{WL} = 3$ generally exist in major weaving segments with lane balance at the exit gore.

Special Case: Two-Sided Weaving Segments

Only the ramp-to-ramp movement is considered to be a weaving flow in a two-sided weaving segment.

The parameters defining the impact of configuration apply only to one-sided weaving segments. In a two-sided weaving segment, neither the ramp-to-freeway nor the freeway-to-ramp movements weave. While the through freeway movement in a two-sided weaving segment might be functionally thought of as weaving, it is the dominant movement in the segment and does not behave as a weaving movement. Thus, in two-sided weaving segments, only the ramp-to-ramp movement is considered to be a weaving flow. This introduces two specific changes to the methodology:

1. Instead of LC_{RF} and LC_{FR} being needed to characterize weaving behavior, a value of LC_{RR} (the minimum number of lane changes that must be made by a ramp-to-ramp vehicle) is needed. In Exhibit 12-4(a), $LC_{RR} = 2$, while in Exhibit 12-4(b), $LC_{RR} = 3$.
2. In all cases of two-sided weaving, the value of N_{WL} is set to 0 by definition.

With these two modifications, the methodology outlined for one-sided weaving segments may be applied to two-sided weaving segments as well.

3. METHODOLOGY

The methodology presented in this chapter was developed as part of National Cooperative Highway Research Program (NCHRP) Project 3-75, *Analysis of Freeway Weaving Sections* (*1*). Elements of this methodology have also been adapted from earlier studies and earlier editions of this manual (*2–9*).

LIMITATIONS OF THE METHODOLOGY

The methodology of this chapter does not specifically address the following subjects (without modifications by the analyst):

- Special lanes, such as high-occupancy vehicle lanes, within the weaving segment;
- Ramp metering on entrance ramps forming part of the weaving segment;
- Specific operating conditions when oversaturated conditions exist;
- Effects of speed limit enforcement practices on weaving segment operations;
- Effects of intelligent transportation system technologies on weaving segment operations;
- Weaving segments on arterials or other urban streets, including one-way frontage roads;
- Effects of downstream congestion or upstream demand starvation on the analysis segment; or
- Multiple weaving segments.

The last subject has been included in previous versions of this manual. Multiple weaving segments must now be divided into appropriate merge, diverge, and simple weaving segments for analysis.

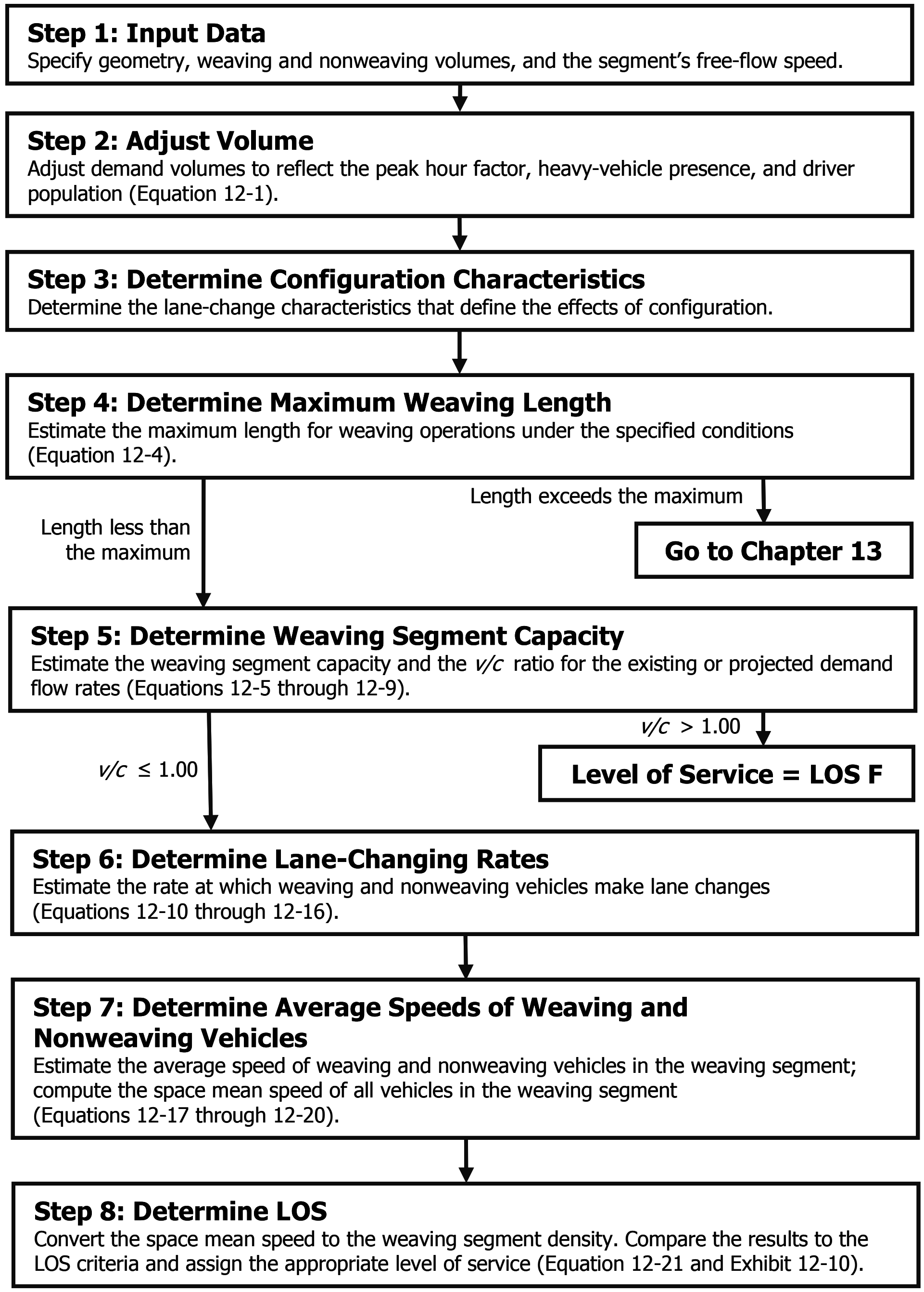
Multiple weaving segments must be divided into merge, diverge, and simple weaving segments for analysis.

OVERVIEW OF THE METHODOLOGY

Exhibit 12-6 is a flowchart illustrating the basic steps that define the methodology for analyzing freeway weaving segments. The methodology uses several types of predictive algorithms, all of which are based on a mix of theoretical and regression models. These models include the following:

- Models that predict the total rate of lane changing taking place in the weaving segment. This is a direct measure of turbulence in the traffic stream caused by the presence of weaving movements.
- Models to predict the average speed of weaving and nonweaving vehicles in a weaving segment under stable operating conditions, that is, not operating at Level of Service (LOS) F.
- Models to predict the capacity of a weaving segment under both ideal and prevailing conditions.
- A model to estimate the maximum length over which weaving operations can be said to exist.

Exhibit 12-6
Weaving Methodology Flowchart



If the potential weaving segment is longer than the value given by Equation 12-4, it is treated as isolated merging and diverging ramp junctions by using the procedures of Chapter 13.

LOS F exists in a weaving segment when demand exceeds capacity.

PARAMETERS DESCRIBING A WEAVING SEGMENT

Several parameters describing weaving segments have already been introduced and defined. Exhibit 12-7 illustrates all variables that must be specified as input variables and defines those that will be used within or as outputs of the methodology. Some of these apply only to one-sided weaving segments. Exhibit 12-8 lists those variables that are different when applied to two-sided weaving segments.

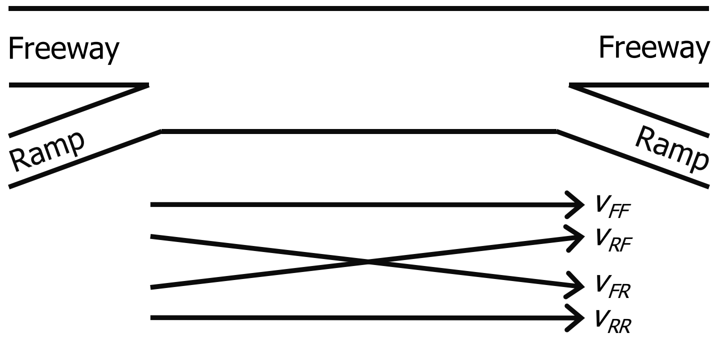


Exhibit 12-7
Weaving Variables for One-Sided Weaving Segments

v_{FF} = freeway-to-freeway demand flow rate in the weaving segment in passenger cars per hour (pc/h);

v_{RF} = ramp-to-freeway demand flow rate in the weaving segment (pc/h);

v_{FR} = freeway-to-ramp demand flow rate in the weaving segment (pc/h);

v_{RR} = ramp-to-ramp demand flow rate in the weaving segment (pc/h);

v_W = weaving demand flow rate in the weaving segment (pc/h), $v_W = v_{RF} + v_{FR}$;

v_{NW} = nonweaving demand flow rate in the weaving segment (pc/h), $v_{NW} = v_{FF} + v_{RR}$;

v = total demand flow rate in the weaving segment (pc/h), $v = v_W + v_{NW}$;

VR = volume ratio, v_W/v;

N = number of lanes within the weaving section;

N_{WL} = number of lanes from which a weaving maneuver may be made with one or no lane changes (see Exhibit 12-5);

S_W = average speed of weaving vehicles within the weaving segment (mi/h);

S_{NW} = average speed of nonweaving vehicles within the weaving segment (mi/h);

S = average speed of all vehicles within the weaving segment (mi/h);

FFS = free-flow speed of the weaving segment (mi/h);

D = average density of all vehicles within the weaving segment in passenger cars per mile per lane (pc/mi/ln);

W = weaving intensity factor;

L_S = length of the weaving segment (ft), based on the short length definition of Exhibit 12-2;

LC_{RF} = minimum number of lane changes that must be made by a single weaving vehicle moving from the on-ramp to the freeway (see Exhibit 12-5);

LC_{FR} = minimum number of lane changes that must be made by a single weaving vehicle moving from the freeway to the off-ramp;

LC_{MIN} = minimum rate of lane changing that must exist for all weaving vehicles to complete their weaving maneuvers successfully, in lane changes per hour (lc/h), $LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR})$;

LC_W = total rate of lane changing by weaving vehicles within the weaving segment (lc/h);

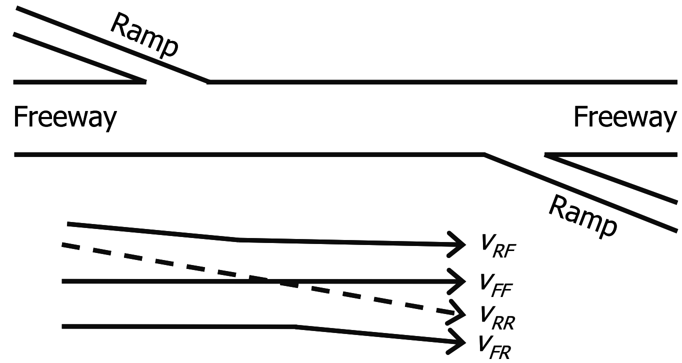
LC_{NW} = total rate of lane changing by nonweaving vehicles within the weaving segment (lc/h);

LC_{ALL} = total rate of lane changing of all vehicles within the weaving segment (lc/h), $LC_{ALL} = LC_W + LC_{NW}$;

ID = interchange density, the number of interchanges within ±3 mi of the center of the subject weaving segment divided by 6, in interchanges per mile (int/mi); and

I_{LC} = lane-changing intensity, LC_{ALL}/L_S, in lane changes per foot (lc/ft).

Exhibit 12-8
Weaving Variables for a Two-Sided Weaving Segment



The through freeway movement is not considered to be weaving in a two-sided weaving segment.

All variables are defined as in Exhibit 12-7, except for the following variables relating to flow designations and lane-changing variables:

v_W = total weaving demand flow rate within the weaving segment (pc/h), $v_W = v_{RR}$;

v_{NW} = total nonweaving demand flow rate within the weaving segment (pc/h), $v_{NW} = v_{FR} + v_{RF} + v_{FF}$;

LC_{RR} = minimum number of lane changes that must be made by one ramp-to-ramp vehicle to complete a weaving maneuver; and

LC_{MIN} = minimum rate of lane changing that must exist for all weaving vehicles to complete their weaving maneuvers successfully (lc/h), $LC_{MIN} = LC_{RR} \times v_{RR}$.

The principal difference between one-sided and two-sided weaving segments is the relative positioning of the movements within the segment. In a two-sided weaving segment, the ramp-to-freeway and freeway-to-ramp vehicles do not weave. In a one-sided segment, they execute the weaving movements. In a two-sided weaving segment, the ramp-to-ramp vehicles must cross the path of freeway-to-freeway vehicles. Both could be taken to be weaving movements. In reality, the through freeway movement is not weaving in that vehicles do not need to change lanes and generally do not shift lane position in response to a desired exit leg.

Thus, in two-sided weaving segments, only the ramp-to-ramp flow is considered to be weaving. The lane-changing parameters reflect this change in the way weaving flows are viewed. Thus, the minimum rate of lane changing that weaving vehicles must maintain to complete all desired weaving maneuvers successfully is also related only to the ramp-to-ramp movement.

The methodology uses demand flow rates for the peak 15 min in passenger cars per hour.

The definitions for flow all refer to *demand flow rate*. This means that for existing cases, the demand should be based on *arrival flows*. For future cases, forecasting techniques will generally produce a *demand volume* or *demand flow rate*. All of the methodology's algorithms use demand expressed as flow rates in the peak 15 min of the design (or analysis) hour, in equivalent passenger car units.

COMPUTATIONAL PROCEDURES

Each of the major procedural steps noted in Exhibit 12-6 is discussed in detail in the sections that follow.

Step 1: Input Data

The methodology for weaving segments is structured for operational analysis usage, that is, given a known or specified geometric design and traffic demand characteristics, the methodology is used to estimate the LOS that is expected to exist.

Design and preliminary engineering are generally conducted in terms of comparative analyses of various design proposals. This is a good approach, given that the range of widths, lengths, and configurations in any given case is constrained by a number of factors. Length is constrained by the location of the crossing arteries that determine the location of interchanges and ramps. Width is constrained by the number of lanes on entry and exit legs and usually involves no more than two choices. Configuration is also the result of the number of lanes on entry and exit legs as well as the number of lanes within the segment. Changing the configuration usually involves adding a lane to one of the entry or exit legs, or both, to create different linkages.

For analysis, the geometry of the weaving segment must be fully defined. This includes the number of lanes, lane widths, shoulder clearances, the details of entry and exit gore area designs (including markings), the existence and extent of barrier lines, and the length of the segment. A sketch of the weaving segment should be drawn with all appropriate dimensions shown.

Traffic demands are usually expressed as peak hour volumes under prevailing conditions. If flow rates have been directly observed in the field, the flow rates for the worst 15-min period in the peak hour may be substituted. In this case, the peak hour factor (PHF) is implicitly 1.00.

Step 2: Adjust Volume

All equations in this chapter use flow rates under equivalent ideal conditions as input variables. Thus, demand volumes and flow rates under prevailing conditions must be converted to their ideal equivalents by using Equation 12-1:

$$v_i = \frac{V_i}{PHF \times f_{HV} \times f_p}$$

Equation 12-1

where

v_i = flow rate i under ideal conditions (pc/h);

V_i = hourly volume for flow i under prevailing conditions in vehicles per hour (veh/h);

PHF = peak hour factor;

f_{HV} = adjustment factor for heavy-vehicle presence; and

f_p = adjustment factor for driver population; the subscript for the type of flow i can take on the following values:

FF = freeway to freeway;

FR = freeway to ramp;

RF = ramp to freeway;

RR = ramp to ramp;

$_W$ = weaving; and

$_{NW}$ = nonweaving.

Factors f_{HV} and f_p are taken from Chapter 11, Basic Freeway Segments.

If flow rates for a 15-min period have been provided as inputs, the PHF is taken to be 1.00 in this computation. If hourly volumes are converted by using a PHF other than 1.00, there is an implicit assumption that all four component flows in the weaving segment peak during the same 15-min period of the hour. This is rarely true in the field; however, such an analysis represents a worst-case scenario.

Once demand flow rates have been established, it may be convenient to construct a weaving diagram similar to those illustrated in Exhibit 12-7 (for one-sided weaving segments) and Exhibit 12-8 (for two-sided weaving segments).

Step 3: Determine Configuration Characteristics

Several key parameters characterize the configuration of a weaving segment. These are descriptive of the segment and will be used as key variables in subsequent steps of the methodology:

LC_{MIN} = minimum rate at which weaving vehicles must change lanes to complete all weaving maneuvers successfully (lc/h); and

N_{WL} = number of lanes from which weaving maneuvers may be made with either one or no lane changes.

How these values are determined depends on whether the segment under study is a one-sided or two-sided weaving segment.

One-Sided Weaving Segments

The determination of key variables in one-sided weaving segments is illustrated in Exhibit 12-7. In one-sided segments, the two weaving movements are the ramp-to-freeway and freeway-to-ramp flows. As shown in Exhibit 12-7, the following values are established:

LC_{RF} = minimum number of lane changes that must be made by one ramp-to-freeway vehicle to execute the desired maneuver successfully, and

LC_{FR} = minimum number of lane changes that must be made by one freeway-to-ramp vehicle to execute the desired maneuver successfully.

LC_{MIN} for one-sided weaving segments is given by Equation 12-2:

Equation 12-2

$$LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR})$$

For one-sided weaving segments, the value of N_{WL} is either 2 or 3. The determination is made by a review of the geometric design and the configuration of the segment, as illustrated in Exhibit 12-5.

Two-Sided Weaving Segments

The determination of key variables in two-sided weaving segments is illustrated in Exhibit 12-8. The unique feature of two-sided weaving segments is that only the ramp-to-ramp flow is functionally weaving. From Exhibit 12-8, the following value is established:

LC_{RR} = minimum number of lane changes that must be made by one ramp-to-ramp vehicle to execute the desired maneuver successfully.

LC_{MIN} for two-sided weaving segments is given by Equation 12-3:

Equation 12-3

$$LC_{MIN} = LC_{RR} \times v_{RR}$$

For two-sided weaving segments, the value of N_{WL} is always 0 by definition.

Step 4: Determine Maximum Weaving Length

The maximum length of a weaving segment, L_{MAX}, is based on the distance beyond which additional length does not add to capacity.

The concept of maximum length of a weaving segment is critical to the methodology. Strictly defined, *maximum length* is the length at which weaving turbulence no longer has an impact on operations within the segment, or alternatively, on the capacity of the weaving segment.

Unfortunately, depending on the selected definition, these measures can be quite different. Weaving turbulence will have an impact on operations (i.e., weaving and nonweaving vehicle speeds) for distances far in excess of those defined by when the capacity of the segment is no longer affected by weaving.

This methodology uses the second definition (based on the equivalence of capacity). If the operational definition were used, the methodology would produce capacity estimates in excess of those for a similar basic freeway segment, which is illogical. The maximum length of a weaving segment (in feet) is computed from Equation 12-4:

Equation 12-4

$$L_{MAX} = \left[5{,}728(1 + VR)^{1.6}\right] - \left[1{,}566 N_{WL}\right]$$

where L_{MAX} is the maximum weaving segment length (using the short length definition) and other variables are as previously defined.

As VR increases, it is expected that the influence of weaving turbulence would extend for longer distances. All values of N_{WL} are either 0 (two-sided weaving segments) or 2 or 3 (one-sided weaving segments). Having more lanes from which easy weaving lane changes can be made reduces turbulence, which in turn reduces the distance over which such turbulence affects segment capacity.

Exhibit 12-9 illustrates the sensitivity of maximum length to both VR and N_{WL}. As expected, VR has a significant impact on maximum length, as does the configuration, as indicated by N_{WL}. While the maximum lengths shown can compute to very high numbers, the highest results are well outside the calibration range of the equation (limited to about 2,800 ft), and many of the situations are improbable. Values of VR on segments with N_{WL} = 2.0 lanes rarely rise above the range of 0.40 to 0.50. While values of VR above 0.70 are technically feasible on segments with N_{WL} = 3.0 lanes, they are rare.

While the extreme values in Exhibit 12-9 are not practical, it is clear that the maximum length of weaving segments can rise to 6,000 ft or more. Furthermore, the maximum length can vary over time, as VR is not a constant throughout every demand period of the day.

Exhibit 12-9
Variation of Weaving Length Versus Volume Ratio and Number of Weaving Lanes (ft)

VR	Number of Weaving Lanes N_{WL} = 2	N_{WL} = 3
0.1	3,540	1,974
0.2	4,536	2,970
0.3	5,584	4,018
0.4	6,681	5,115
0.5	7,826	6,260
0.6	9,019	7,453
0.7	10,256	8,690
0.8	11,538	9,972

If the length of the segment is greater than L_{MAX}, it should be analyzed as separate merge and diverge ramp junctions by using the methodology in Chapter 13. Any portion falling outside the influence of the merge and diverge segments is treated as a basic freeway segment.

The value of L_{MAX} is used to determine whether continued analysis of the configuration as a weaving segment is justified:

- If $L_S < L_{MAX}$, continue to Step 5; or
- If $L_S \geq L_{MAX}$, analyze the merge and diverge junctions as separate segments by using the methodology in Chapter 13.

If the segment is too long to be considered a weaving segment, then the merge and diverge areas are treated separately. Any distance between the two falling outside the influence areas of the merge and diverge segments would be considered to be a basic freeway segment and would be analyzed accordingly.

Step 5: Determine Weaving Segment Capacity

A weaving segment's capacity is controlled by either (a) the average vehicle density reaching 43 pc/mi/ln or (b) the weaving demand flow rate exceeding a value that depends on the number of weaving lanes.

The capacity of a weaving segment is controlled by one of two conditions:

- Breakdown of a weaving segment is expected to occur when the average density of all vehicles in the segment reaches 43 pc/mi/ln; or
- Breakdown of a weaving segment is expected to occur when the total weaving demand flow rate exceeds
  - 2,400 pc/h for cases in which N_{WL} = 2 lanes, or
  - 3,500 pc/h for cases in which N_{WL} = 3 lanes.

The first criterion is based on the criteria listed in Chapter 11, Basic Freeway Segments, which state that freeway breakdowns occur at a density of 45 pc/mi/ln. Given the additional turbulence in a weaving segment, breakdown is expected to occur at slightly lower densities.

The second criterion recognizes that there is a practical limit to how many vehicles can actually cross each other's path without causing serious operational failures. The existence of a third lane from which weaving maneuvers can be made with two or fewer lane changes in effect spreads the impacts of turbulence across segment lanes and allows for higher weaving flows.

For two-sided weaving segments (N_{WL} = 0 lanes), no limiting value on weaving flow rate is proposed. The analysis of two-sided weaving segments is approximate with this methodology, and a density sufficient to cause a breakdown is generally reached at relatively low weaving flow rates.

Weaving Segment Capacity Determined by Density

The capacity of a weaving segment, based on reaching a density of 43 pc/mi/ln, is estimated by using Equation 12-5:

$$c_{IWL} = c_{IFL} - \left[438.2(1+VR)^{1.6}\right] + \left[0.0765L_S\right] + \left[119.8N_{WL}\right]$$

Equation 12-5

where

c_{IWL} = capacity of the weaving segment under equivalent ideal conditions, per lane (pc/h/ln), and

c_{IFL} = capacity of a basic freeway segment with the same FFS as the weaving segment under equivalent ideal conditions, per lane (pc/h/ln).

All other variables are as previously defined.

The model describes the capacity of a weaving segment in terms of the difference between the capacity of a basic freeway segment and the capacity of a weaving segment with the same FFS. Capacity decreases with *VR*, which is logical. It increases as length and number of weaving lanes N_{WL} increase. These are also logical trends, as both increasing length and a larger number of weaving lanes reduce the intensity of turbulence.

Arithmetically, it is possible to get a result in which c_{IWL} is greater than c_{IFL}. In practical terms, this will never occur. The maximum length algorithm of Step 4 was found by setting the two values equal. Thus, weaving analyses would only be undertaken in cases in which c_{IWL} is less than c_{IFL}.

The value of c_{IWL} must now be converted to a total capacity under prevailing conditions by using Equation 12-6:

$$c_W = c_{IWL} N f_{HV} f_p$$

Equation 12-6

where c_W is the capacity of the weaving segment under prevailing conditions in vehicles per hour. As with all capacities, it is stated as a flow rate for a 15-min analysis period.

Weaving Segment Capacity Determined by Weaving Demand Flows

The capacity of a weaving segment, as controlled by the maximum weaving flow rates noted previously, is found from Equation 12-7:

$$c_{IW} = \frac{2{,}400}{VR} \quad \text{for } N_{WL} = 2 \text{ lanes}$$

$$c_{IW} = \frac{3{,}500}{VR} \quad \text{for } N_{WL} = 3 \text{ lanes}$$

Equation 12-7

where c_{IW} is the capacity of all lanes in the weaving segment under ideal conditions in passenger cars per hour, and all other variables are as previously defined. This value must be converted to prevailing conditions by using Equation 12-8:

$$c_W = c_{IW} f_{HV} f_p$$

Equation 12-8

Final Determination of Capacity

The final capacity is the smaller of the two estimates of Equation 12-6 and Equation 12-8. With capacity determined, a *v*/*c* ratio for the weaving segment may be computed from Equation 12-9:

Equation 12-9

$$v/c = \frac{v f_{HV} f_p}{c_W}$$

Adjustment factors are used because the total demand flow rate, v, is stated for equivalent ideal conditions, while c_W is stated for prevailing conditions.

Level of Service F

LOS F occurs when demand exceeds capacity.

If v/c is greater than 1.00, demand exceeds capacity, and the segment is expected to fail, that is, have a LOS of F. If this occurs, the analysis is terminated, and LOS F is assigned. At LOS F, it is expected that queues will form within the segment, possibly extending upstream beyond the weaving segment itself. Queuing on the on-ramps that are part of the weaving segment would also be expected. Where LOS F is found to exist, the analyst is urged to use the methodology of Chapter 10, Freeway Facilities, to analyze the impacts of this on upstream and downstream segments during the analysis period and over time.

Step 6: Determine Lane-Changing Rates

The equivalent hourly rate at which weaving and nonweaving vehicles make lane changes within the weaving segment is a direct measure of turbulence. It is also a key determinant of speeds and densities within the segment, which ultimately determine the existing or anticipated LOS.

It should be noted that the lane-changing rates estimated are in terms of equivalent *passenger-car lane changes*. It is assumed that heavy-vehicle lane changes create more turbulence than passenger-car lane changes.

Three types of lane changes can be made within a weaving segment:

- *Required lane changes made by weaving vehicles*: These lane changes must be made to complete a weaving maneuver and are restricted to the physical area of the weaving segment. In Step 3, the rate at which such lane changes are made by weaving vehicles, LC_{MIN}, was determined.
- *Optional lane changes made by weaving vehicles*: These lane changes are not necessary to weave successfully. They involve weaving drivers who choose to enter the weaving segment in the outer lanes of either the freeway or ramp (assuming it has more than one lane), leave the weaving segment in an outer lane, or both. Such drivers make additional lane changes beyond those absolutely required by their weaving maneuver.
- *Optional lane changes made by nonweaving vehicles*: Nonweaving vehicles may also make lane changes within the weaving segment, but neither the configuration nor their desired origin and destination would require such lane changes. Lane changes by nonweaving vehicles are always made because the driver chooses that option.

While LC_{MIN} can be computed from the weaving configuration and the demand flow rates, additional optional lane changes made by both weaving and nonweaving vehicles add to turbulence and must be estimated by using regression-based models.

Estimating the Total Lane-Changing Rate for Weaving Vehicles

The model for predicting the total lane-changing rate for weaving vehicles is of the form LC_{MIN} plus an algorithm that predicts the additional optional lane-changing rate. These are combined so that the total lane-changing rate for weaving vehicles, including both required and optional lane changes, is as shown in Equation 12-10:

$$LC_W = LC_{MIN} + 0.39\left[(L_s - 300)^{0.5} N^2 (1 + ID)^{0.8}\right]$$

Equation 12-10

where

LC_W = equivalent hourly rate at which weaving vehicles make lane changes within the weaving segment (lc/h);

LC_{MIN} = minimum equivalent hourly rate at which weaving vehicles must make lane changes within the weaving segment to complete all weaving maneuvers successfully (lc/h);

L_S = length of the weaving segment, using the short length definition (ft) (300 ft is the minimum value);

N = number of lanes within the weaving segment; and

ID = interchange density (int/mi).

Equation 12-10 has several interesting characteristics. The term L_S – 300 implies that for weaving segments of 300 ft (or shorter), weaving vehicles only make necessary lane changes, that is, $LC_W = LC_{MIN}$. While shorter weaving segments would be an aberration, they do occasionally occur. In using Equation 12-10, however, a length of 300 ft is used for all lengths less than or equal to 300 ft.

This model is also unique in that it is the first use of interchange density in a model not involving determination of the FFS. In this edition of the HCM, however, FFS is partially based on total ramp density rather than interchange density. The two measures are, of course, related to the type of interchange involved. A full cloverleaf interchange has four ramps, while a diamond interchange has two ramps. Care must be taken when determining the value of *total ramp density* and *interchange density*, as they are different numbers.

The algorithm uses the term 1 + ID because the value of ID may be either more than or less than 1.00, and the power term would not act consistently on the result. In determining interchange density for a weaving segment, a distance of 3 mi upstream and 3 mi downstream of the midpoint of the weaving segment is used. The number of interchanges within the 6-mi range defined above is counted and divided by 6 to determine the interchange density. The subject weaving segment should be counted as one interchange in this computation. For additional discussion of total ramp density, consult Chapter 11.

The basic sensitivities of this model are reasonable. Weaving-vehicle lane changing increases as the length and width of the weaving segment increase. A longer, wider weaving segment simply provides more opportunities for weaving vehicles to execute lane changes. Lane changing also increases as interchange density increases. Higher interchange densities mean that there are more reasons for drivers to make optional lane changes based upon their entry or exit at a nearby interchange.

Estimating the Lane-Changing Rate for Nonweaving Vehicles

No nonweaving driver *must* make a lane change within the confines of a weaving segment. All nonweaving vehicle lane changes are, therefore, optional. These are more difficult to predict than weaving lane changes, as the motivation for nonweaving lane changes varies widely and may not always be obvious. Such lane changes may be made to avoid turbulence, to be better positioned for a subsequent maneuver, or simply to achieve a higher average speed.

The research leading to this methodology (*10*) revealed several discontinuities in the lane-changing behavior of nonweaving vehicles within weaving segments. To identify the areas of discontinuity and to develop an estimation model for these areas, it was necessary to define a "nonweaving vehicle index," I_{NW}, as given in Equation 12-11:

Equation 12-11

$$I_{NW} = \frac{L_S \times ID \times v_{NW}}{10{,}000}$$

This index is a measure of the tendency of conditions to induce unusually large nonweaving vehicle lane-changing rates. Large nonweaving flow rates, high interchange densities, and long weaving lengths seem to produce situations in which nonweaving lane-changing rates are unusually elevated.

Two models are used to predict the rate at which nonweaving vehicles change lanes in weaving segments. The first, Equation 12-12, covers the majority of cases, that is, cases for which normal lane-changing characteristics are expected. This is the case when I_{NW} is less than or equal to 1,300:

Equation 12-12

$$LC_{NW1} = (0.206 v_{NW}) + (0.542 L_s) - (192.6 N)$$

where LC_{NW1} is the rate of lane changing per hour. The equation shows logical trends in that nonweaving lane changes increase with both nonweaving flow rate and segment length. Less expected is that nonweaving lane changing *decreases* with increasing number of lanes. This trend is statistically very strong and likely indicates more presegregation of flows in wider weaving segments. Arithmetically, Equation 12-12 can produce a negative result. Thus, the minimum value must be externally set at 0.

The second model applies to a small number of cases in which the combination of high nonweaving demand flow, high interchange density, and long segment length produce extraordinarily high nonweaving lane-changing rates. Equation 12-13 is used in cases for which I_{NW} is greater than or equal to 1,950:

Equation 12-13

$$LC_{NW2} = 2{,}135 + 0.223(v_{NW} - 2{,}000)$$

where LC_{NW2} is the lane-changing rate per hour, and all other variables are as previously defined.

Unfortunately, Equation 12-12 and Equation 12-13 are discontinuous and cover discontinuous ranges of I_{NW}. If the nonweaving index is between 1,300 and

1,950, a straight interpolation between the values of LC_{NW1} and LC_{NW2} is used as shown in Equation 12-14:

$$LC_{NW3} = LC_{NW1} + \left(LC_{NW2} - LC_{NW1}\right)\left(\frac{I_{NW} - 1{,}300}{650}\right)$$

Equation 12-14

where LC_{NW3} is the lane-changing rate per hour, and all other variables are as previously defined. Equation 12-14 only works for cases in which LC_{NW1} is less than LC_{NW2}. In the vast majority of cases, this will be true (unless the weaving length is longer than the maximum length estimated in Step 4). In the rare case when it is not true, LC_{NW2} is used.

Equation 12-15 summarizes this in a more precise way:

$$\begin{aligned} &\text{If } I_{NW} \le 1{,}300: && LC_{NW} = LC_{NW1} \\ &\text{If } I_{NW} \ge 1{,}950: && LC_{NW} = LC_{NW2} \\ &\text{If } 1{,}300 < I_{NW} < 1{,}950: && LC_{NW} = LC_{NW3} \\ &\text{If } LC_{NW1} \ge LC_{NW2}: && LC_{NW} = LC_{NW2} \end{aligned}$$

Equation 12-15

Total Lane-Changing Rate

The total lane-changing rate LC_{ALL} of all vehicles in the weaving segment, in lane changes per hour, is computed from Equation 12-16:

$$LC_{ALL} = LC_W + LC_{NW}$$

Equation 12-16

Step 7: Determine Average Speeds of Weaving and Nonweaving Vehicles in Weaving Segment

The heart of this methodology is the estimation of the average speeds of weaving and nonweaving vehicles in the weaving segment. These speeds are estimated separately because they are affected by different factors, and they can be significantly different from each other.

The speeds of weaving and nonweaving vehicles will be combined to find a space mean speed of all vehicles in the segment. This will then be converted to a density, which will determine the LOS.

Average Speed of Weaving Vehicles

The algorithm for predicting the average speed of weaving vehicles in a weaving segment may be generally stated as shown in Equation 12-17:

$$S_W = S_{MIN} + \left(\frac{S_{MAX} - S_{MIN}}{1 + W}\right)$$

Equation 12-17

where

S_W = average speed of weaving vehicles within the weaving segment (mi/h),

S_{MIN} = minimum average speed of weaving vehicles expected in a weaving segment (mi/h),

S_{MAX} = maximum average speed of weaving vehicles expected in a weaving segment (mi/h), and

W = weaving intensity factor.

The form of the model is logical and constrains the results to a reasonable range defined by the minimum and maximum speed expectations. The term $1 + W$ accommodates a weaving intensity factor that can be more or less than 1.0.

For this methodology, the minimum expected speed is taken to be 15 mi/h, and the maximum expected speed is the FFS. As with all analyses, the FFS is best observed in the field, either on the subject facility or a similar facility. When measured, the FFS should be observed within the weaving segment.

In situations that require the FFS to be estimated, the model described in Chapter 11, Basic Freeway Segments, is used. The average speed of weaving vehicles within the weaving segment is estimated by using Equation 12-18 and Equation 12-19:

Equation 12-18

$$S_W = 15 + \left(\frac{FFS - 15}{1 + W} \right)$$

Equation 12-19

$$W = 0.226 \left(\frac{LC_{ALL}}{L_S} \right)^{0.789}$$

Note that weaving intensity is based on the total lane-changing rate within the weaving segment. More specifically, it is based on the hourly rate of lane changes per foot of weaving length. This might be thought of as a measure of the density of lane changes. In addition, the lane-changing rate itself depends on many demand and physical factors related to the design of the segment.

Average Speed of Nonweaving Vehicles

The average speed of nonweaving vehicles in a weaving segment is estimated by using Equation 12-20:

Equation 12-20

$$S_{NW} = FFS - (0.0072\, LC_{MIN}) - \left(0.0048 \frac{v}{N} \right)$$

Equation 12-20 treats nonweaving speed as a reduction from FFS. As would be expected, the speed is reduced as v/N increases. More interesting is the appearance of LC_{MIN} in the equation. LC_{MIN} is a measure of minimal weaving turbulence, assuming that weaving vehicles make only necessary lane changes. It depends on both the configuration of the weaving segment and weaving demand flow rates. Thus, nonweaving speeds decrease as weaving turbulence increases.

Average Speed of All Vehicles

The space mean speed of all vehicles in the weaving segment is computed by using Equation 12-21:

Equation 12-21

$$S = \frac{v_W + v_{NW}}{\left(\frac{v_W}{S_W} \right) + \left(\frac{v_{NW}}{S_{NW}} \right)}$$

Step 8: Determine LOS

The LOS in a weaving segment, as in all freeway analysis, is related to the density in the segment. Exhibit 12-10 provides LOS criteria for weaving segments on freeways, collector–distributor (C-D) roadways, and multilane highways. This methodology was developed for freeway weaving segments, although an isolated C-D roadway was included in its development. The methodology may be applied to weaving segments on uninterrupted segments of multilane surface facilities, although its use in such cases is approximate.

LOS can be determined for weaving segments on freeways, multilane highways, and C-D roadways.

Exhibit 12-10
LOS for Weaving Segments

LOS	Density (pc/mi/ln) Freeway Weaving Segments	Density (pc/mi/ln) Weaving Segments on Multilane Highways or C-D Roadways
A	0–10	0–12
B	>10–20	>12–24
C	>20–28	>24–32
D	>28–35	>32–36
E	>35	>36
F	Demand exceeds capacity	

The boundary between stable and unstable flow—the boundary between levels of service E and F—occurs when the demand flow rate exceeds the capacity of the segment, as described in Step 5. The threshold densities for other levels of service were set relative to the criteria for basic freeway segments (or multilane highways). In general, density thresholds in weaving segments are somewhat higher than those for similar basic freeway segments (or multilane highways). It is believed that drivers will tolerate higher densities in an area where lane-changing turbulence is expected than on basic segments.

To apply density criteria, the average speed of all vehicles, computed in Step 7, must be converted to density by using Equation 12-22.

$$D = \frac{\left(\frac{v}{N}\right)}{S}$$

Equation 12-22

where D is density in passenger cars per mile per lane and all other variables are as previously defined.

SPECIAL CASES

Multiple Weaving Segments

When a series of closely spaced merge and diverge areas creates overlapping weaving movements (between different merge–diverge pairs) that share the same segment of a roadway, a multiple weaving segment is created. In earlier editions of the HCM, a specific application of the weaving methodology for two-segment multiple weaving segments was included. While it was a logical extension of the methodology, it did not address cases in which three or more sets of weaving movements overlapped, nor was it well-supported by field data.

Multiple weaving segments should be analyzed as separate merge, diverge, and simple weaving segments, as appropriate.

Multiple weaving segments should be segregated into separate merge, diverge, and simple weaving segments, with each segment appropriately analyzed by using this chapter's methodology or that of Chapter 13, Freeway Merge and Diverge Segments. Chapter 11, Basic Freeway Segments, contains information relative to the process of identifying appropriate segments for analysis.

C-D Roadways

The methodology applies approximately to C-D roadways, but its use may produce an overly negative view of operations.

A common design practice often results in weaving movements that occur on C-D roadways that are part of a freeway interchange. The methodology of this chapter may be approximately applied to such segments. The FFS used must be appropriate to the C-D roadway. It would have to be measured on an existing or similar C-D roadway, as the predictive methodology of FFS given in Chapter 11 does not apply to such roadways. It is less clear that the LOS criteria of Exhibit 12-10 are appropriate. Many C-D roadways operate at lower speeds and higher densities than on basic segments, and the criteria of Exhibit 12-10 may produce an inappropriately negative view of operations on a C-D roadway.

If the measured FFS of a C-D roadway is high (greater than or equal to 50 mi/h), the results of analysis can be expected to be reasonably accurate. At lower FFS values, results would be more approximate.

Multilane Highways

Multilane highway weaving segments may be analyzed with this methodology, except in the vicinity of signalized intersections.

Weaving segments may occur on surface multilane highways. As long as such segments are a sufficient distance away from signalized intersections—so that platoon movements are not an issue—the methodology of this chapter may be approximately applied.

Arterial Weaving

No generally accepted analysis methodologies currently exist for arterial weaving movements.

The methodology of this chapter does not apply to weaving segments on arterials. Arterial weaving is strongly affected by the proximity and timing of signals along the arterial. At the present time, there are no generally accepted analytic methodologies for analyzing weaving movements on arterials.

4. APPLICATIONS

The methodology of this chapter is most often used to estimate the capacity and LOS of freeway weaving segments. The steps are most easily applied in the operational analysis mode, that is, all traffic and roadway conditions are specified, and a solution for the capacity (and *v/c* ratio) is found along with an expected LOS. Other types of analysis, however, are possible.

DEFAULT VALUES

An NCHRP report (*10*) provides a comprehensive presentation of potential default values for uninterrupted-flow facilities. Default values for freeways are summarized in Chapter 10, Freeway Facilities. These defaults cover the key characteristics of PHF and percentage of heavy vehicles. Recommendations are based on geographical region, population, and time of day. All general freeway default values may be applied to the analysis of weaving segments in the absence of field data or projected conditions.

There are many specific variables related to weaving segments. It is, therefore, virtually impossible to specify default values of such characteristics as length, width, configuration, and balance of weaving and nonweaving flows. Weaving segments are a detail of the freeway design and should therefore be treated only with the specific characteristics of the segment known or projected. Small changes in some of these variables can and do yield significant changes in the analysis results.

TYPES OF ANALYSIS

The methodology of this chapter can be used in three types of analysis: operational, design, and planning and preliminary engineering.

Operational Analysis

The methodology of this chapter is most easily applied in the operational analysis mode. In this application, all weaving demands and geometric characteristics are known, and the output of the analysis is the expected LOS and the capacity of the segment. Secondary outputs include the average speed of component flows, the overall density in the segment, and measures of lane-changing activity.

Design Analysis

Design analysis is best accomplished by iterative operational analyses on a small number of candidate designs.

In design applications, the desired output is the length, width, and configuration of a weaving segment that will sustain a target LOS for given demand flows. This application is best accomplished by iterative operational analyses on a small number of candidate designs.

Generally, there is not a great deal of flexibility in establishing the length and width of a segment, and only limited flexibility in potential configurations. The location of intersecting facilities places logical limitations on the length of the weaving segment. The number of entry and exit lanes on ramps and the freeway itself limits the number of lanes to, at most, two choices. The entry and exit design of ramps and the freeway facility also produces a configuration that can generally only be altered by adding or subtracting a lane from an entry or exit roadway. Thus, iterative analyses of candidate designs are relatively easy to pursue, particularly with the use of HCM-replicating software.

Planning and Preliminary Engineering

Planning and preliminary engineering applications generally have the same desired outputs as design applications: the geometric design of a weaving segment that can sustain a target LOS for specified demand flows.

In the planning and preliminary design phase, however, demand flows are generally stated as average annual daily traffic (AADT) statistics that must be converted to directional design hour volumes. A number of variables may be unknown (e.g., PHF and percentage of heavy vehicles); these may be replaced by default values.

Service Flow Rates, Service Volumes, and Daily Service Volumes

This manual defines three sets of values that are related to LOS boundary conditions:

SF_i = service flow rate for LOS *i* (veh/h),

SV_i = service volume for LOS *i* (veh/h), and

DSV_i = daily service volume for LOS *i* (veh/day).

The *service flow rate* is the maximum rate of flow (for a 15-min interval) that can be accommodated on a segment while maintaining all operational criteria for LOS *i* under prevailing roadway and traffic conditions. The *service volume* is the maximum hourly volume that can be accommodated on a segment while maintaining all operational criteria for LOS *i* during the worst 15 min of the hour under prevailing roadway and traffic conditions. The *daily service volume* is the maximum AADT that can be accommodated on a segment while maintaining all operational criteria for LOS *i* during the worst 15 min of the peak hour under prevailing roadway and traffic conditions. The service flow rate and service volume are unidirectional values, while the daily service volume is a total two-way volume. In the context of a weaving section, the daily service volume is highly approximate, as it is rare that both directions of a freeway have a weaving segment with similar geometry.

In general, service flow rates are initially computed for ideal conditions and are then converted to prevailing conditions by using Equation 12-23 and the appropriate adjustment factors from Chapter 11, Basic Freeway Segments:

Equation 12-23

$$SF_i = SFI_i \times f_{HV} \times f_p$$

where

SFI_i = service flow rate under ideal conditions (pc/h),

f_{HV} = adjustment factor for heavy-vehicle presence (Chapter 11), and

f_p = adjustment factor for driver population (Chapter 11).

The methodology of this chapter is used to determine the values of ideal service flow rate (*SFI*) for the specific weaving segment under study. The capacity of the segment is equivalent to the ideal service flow rate for LOS E. For other levels of service, the total flow rates required to produce threshold densities (Exhibit 12-10) are found. This is an iterative procedure in which all other characteristics are held constant. Iterative analyses are conducted until the defining densities are produced.

Once the ideal service flow rates are determined, service flow rates under prevailing conditions are computed by using Equation 12-23. These can be converted to hourly service volumes *SV* by using Equation 12-24. Service volumes can then be converted to daily service volumes *DSV* by using Equation 12-25.

$$SV_i = SF_i \times PHF$$

Equation 12-24

$$DSV_i = \frac{SV_i}{K \times D}$$

Equation 12-25

where

K = proportion of AADT occurring during the peak hour, and

D = proportion of traffic in the peak direction.

All other variables are as previously defined.

Example Problem 5 illustrates the computation of service flow rates, service volumes, and daily service volumes for a specific weaving segment.

USE OF ALTERNATIVE TOOLS

General guidance for the use of alternative traffic analysis tools for capacity and LOS analysis is provided in Chapter 6, HCM and Alternative Analysis Tools. This section contains specific guidance for the application of alternative tools to the analysis of freeway weaving segments. Additional information on this topic, including supplemental example problems, may be found in Chapter 27, Freeway Weaving: Supplemental, located in Volume 4.

Strengths of the HCM Procedure

The procedures in this chapter were developed from extensive research supported by a significant quantity of field data. They have evolved over a number of years and represent a body of expert consensus. Most alternative tools will not include the level of detail present in this methodology concerning the weaving configuration and balance of weaving demand flows.

Specific strengths of the HCM procedure include

- Providing capacity estimates for specific weaving configurations as a function of various input parameters, which current simulators do not provide directly (and in some cases may require as an input);
- Considering geometric characteristics (such as lane widths) in more detail than most simulation algorithms;

- Producing a single deterministic estimate of LOS, which is important for some purposes, such as development impact reviews; and
- Generating reproducible results with a small commitment of resources (including calibration) from a precisely documented methodology.

Limitations of the HCM Procedures That Might Be Addressed by Alternative Tools

Weaving segments can be analyzed by using a variety of stochastic and deterministic simulation tools that address freeways. These tools can be very useful in analyzing the extent of congestion when there are failures within the simulated facility range and when interaction with other freeway segments and other facilities is present.

The limitations stated earlier in this chapter may be addressed by using available simulation tools. The following conditions, which are beyond the scope of this chapter, are treated explicitly by simulation tools:

- *Managed lanes within the weaving segment.* These lanes are typically modeled explicitly by simulation; for example, when one or more weaving movements are regulated by using pavement markings, signage, physical longitudinal barriers, or some combination of these.
- *Ramp metering on entrance ramps forming part of the weaving segment.* These features are also modeled explicitly by many tools.
- *Specific operating conditions when oversaturated conditions exist.* In this case, it is necessary to ensure that both the spatial and the temporal boundaries of the analysis extend beyond the congested operation.
- *Effects of intelligent transportation system technologies on weaving segment operations.* Some intelligent transportation system features such as dynamic message signs are offered by a few simulation tools. Some features are modeled explicitly by simulation; others may be approximated by using assumptions (e.g., by modifying origin–destination demands by time interval).
- *Multiple weaving segments.* Multiple weaving segments were removed from this edition of the manual. They may be addressed to some extent by the procedures given in Chapter 10 for freeway facilities. Complex combinations of weaving segments may be analyzed more effectively by simulation tools, although such analyses might require extensive calibration of origin–destination characteristics.

Because of the interactions between adjacent freeway segments, alternative tools will find their principal application to freeways containing weaving segments at the facility level and not to isolated freeway weaving segments.

Additional Features and Performance Measures Available from Alternative Tools

This chapter provides a methodology for estimating the speed and density in a weaving segment given traffic demands from both the weaving and the nonweaving movements. Capacity estimates and maximum weaving lengths are also produced. Alternative tools offer additional performance measures including delay, stops, queue lengths, fuel consumption, pollution, and operating costs.

In addition to offering more performance measures, alternative tools can identify specific point problems that could be overlooked in a segment-level analysis.

As with most other procedural chapters in this manual, simulation outputs, especially graphics-based presentations, can provide details on point problems that might otherwise go unnoticed with a macroscopic analysis that yields only segment-level measures. The effect of queuing caused by capacity constraints on the exit ramp of a weaving segment, including difficulty in making the required lane changes, is a good example of a situation that can benefit from the increased insight offered by a microscopic model. An example of the effect of exit ramp queue backup is presented in Chapter 27, Freeway Weaving: Supplemental.

Development of HCM-Compatible Performance Measures Using Alternative Tools

When using alternative tools, the analyst must be careful to note the definitions of simulation outputs. The principal measures involved in the performance analysis of weaving segments are speed and delay. These terms are generally defined in the same manner by alternative tools; however, there are subtle differences among tools that often make it difficult to apply HCM criteria directly to the outputs of other tools. Performance measure comparisons are discussed in more detail in Chapter 7, Interpreting HCM and Alternative Tool Results.

Conceptual Differences Between the HCM and Simulation Modeling That Preclude Direct Comparison of Results

Conceptual differences between the HCM and stochastic simulation models make direct comparison difficult for weaving segments. The HCM uses a set of deterministic equations developed and calibrated with field data. Simulation models treat each vehicle as a separate object to be propagated through the system. The physical and behavioral characteristics of drivers and vehicles in the HCM are represented in deterministic equations that compute passenger car equivalences, lane-changing rates, maximum weaving lengths, capacity, speed, and density. Simulation models apply the characteristics to each driver and vehicle, and these characteristics produce interactions between vehicles, the sum total of which determines the performance measures for a weaving segment.

Direct comparison of the numerical outputs from the HCM and alternative tools can be misleading.

One good example of the difference between microscopic and macroscopic modeling is how trucks are entered into the models. The HCM uses a conversion factor that increases the demand volumes to reflect the proportion of trucks. Simulation models deal with trucks explicitly by assigning more sluggish characteristics to each of them. The result is that HCM capacities, densities, and so forth are expressed in equivalent passenger car units, whereas the corresponding simulation values are represented by actual vehicles.

The HCM methodology estimates the speeds of weaving and nonweaving traffic streams, and on the basis of these estimates it determines the density within the weaving segment. Simulators that provide outputs on a link-by-link basis do not differentiate between weaving and nonweaving movements within a given link; thus, comparing these (intermediate) results to other tools would be somewhat difficult.

For a given set of inputs, simulation tools should produce answers that are similar to each other and to the HCM. Although most differences should be reconcilable through calibration and identification of point problems within a segment, precise numerical agreement is not generally a reasonable expectation.

Sample Calculations Illustrating Alternative Tool Applications

Supplemental computational examples illustrating the use of alternative tools are included in Chapter 27 of Volume 4.

Chapter 27, Freeway Weaving: Supplemental, contains three examples that illustrate the application of alternative tools to freeway weaving segments. All of the problems are based on Example Problem 1 presented later in this chapter. Three questions are addressed by using a typical simulation tool:

1. Can the weaving segment capacity be estimated realistically by simulation by varying the demand volumes up to and beyond capacity?
2. How does the demand affect the performance in terms of speed and density in the weaving segment when the default model parameters are used for vehicle and behavioral characteristics?
3. How would the queue backup from a signal at the end of the off-ramp affect the weaving operation?

5. EXAMPLE PROBLEMS

Exhibit 12-11
List of Example Problems

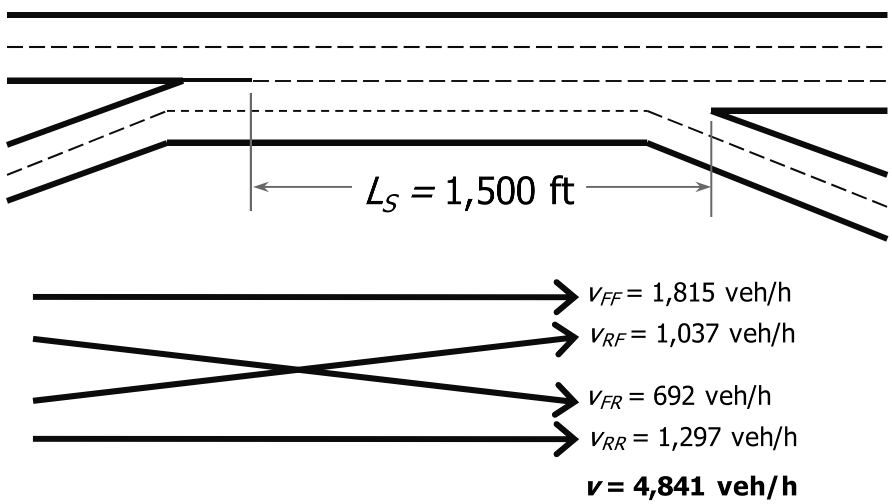
Example Problem	Description	Application
1	LOS of a major weaving segment	Operational Analysis
2	LOS of a ramp-weaving segment	Operational Analysis
3	LOS of a two-sided weaving segment	Operational Analysis
4	Design of a major weaving segment for a desired LOS	Design
5	Service volume table construction	Service Volumes

EXAMPLE PROBLEM 1: LOS OF A MAJOR WEAVING SEGMENT

The Weaving Segment

The subject of this operational analysis is a major weaving segment on an urban freeway, as shown in Exhibit 12-12.

Exhibit 12-12
Major Weaving Segment for Example Problem 1



What is the LOS and capacity of the weaving segment shown in Exhibit 12-12?

The Facts

In addition to the information contained in Exhibit 12-12, the following characteristics of the weaving segment are known:

PHF = 0.91 (for all movements);

Heavy vehicles = 10% trucks, 0% recreational vehicles (RVs) (all movements);

Driver population = regular commuters;

FFS = 65 mi/h;

c_{IFL} = 2,350 pc/h/ln (for FFS = 65 mi/h);

ID = 0.8 int/mi; and

Terrain = level.

Comments

Chapter 11, Basic Freeway Segments, must be consulted to find appropriate values for the heavy-vehicle adjustment factor f_{HV} and the driver population adjustment factor f_p.

All input parameters have been specified, so default values are not needed. Demand volumes are given in vehicles per hour under prevailing conditions. These must be converted to passenger cars per hour under equivalent ideal conditions for use in equations of the methodology. The length of the segment must be compared with the maximum length for weaving analysis to determine whether the methodology of this chapter is applicable. The capacity of the weaving segment is estimated and compared with the total demand flow to determine whether LOS F exists. Lane-changing rates are estimated to allow speed estimates to be made for weaving and nonweaving flows. An average overall speed and density are computed and compared with the criteria of Exhibit 12-10 to determine LOS.

Step 1: Input Data

All inputs have been specified in Exhibit 12-12 and the Facts section of the problem statement.

Step 2: Adjust Volume

Equation 12-1 is used to convert the four component demand volumes to flow rates under equivalent ideal conditions. Chapter 11 is consulted to obtain a value of E_T (1.5 for level terrain) and f_p (1.00 for regular commuters). The heavy-vehicle adjustment factor is computed as

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_{RV}(E_{RV} - 1)} = \frac{1}{1 + 0.10(1.5 - 1)} = 0.952$$

Equation 12-1 is now used to convert all demand volumes:

$$v = \frac{V}{PHF \times f_{HV} \times f_p}$$

$$v_{FF} = \frac{1{,}815}{0.91 \times 0.952 \times 1} = 2{,}094 \text{ pc/h}$$

$$v_{FR} = \frac{692}{0.91 \times 0.952 \times 1} = 798 \text{ pc/h}$$

$$v_{RF} = \frac{1{,}037}{0.91 \times 0.952 \times 1} = 1{,}197 \text{ pc/h}$$

$$v_{RR} = \frac{1{,}297}{0.91 \times 0.952 \times 1} = 1{,}497 \text{ pc/h}$$

Then

$$v_W = 798 + 1{,}197 = 1{,}995 \text{ pc/h}$$

$$v_{NW} = 2{,}094 + 1{,}497 = 3{,}591 \text{ pc/h}$$

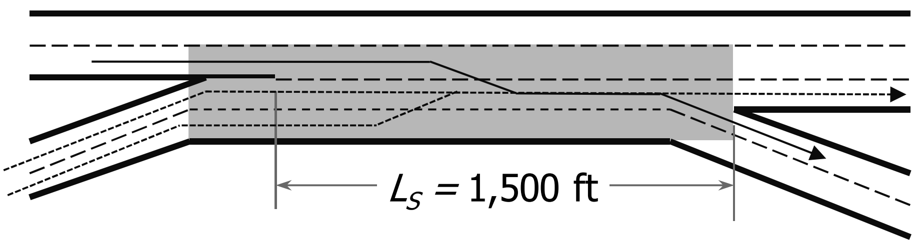
$$v = 1{,}995 + 3{,}591 = 5{,}586 \text{ pc/h}$$

$$VR = \frac{1{,}995}{5{,}586} = 0.357$$

Step 3: Determine Configuration Characteristics

The configuration is examined to determine the values of LC_{RF}, LC_{FR}, and N_{WL}. These determinations are illustrated in Exhibit 12-13. From these values, the minimum number of lane changes by weaving vehicles, LC_{MIN}, is then computed by using Equation 12-2.

Exhibit 12-13
Determination of Configuration Variables for Example Problem 1



From Exhibit 12-13, it can be seen that ramp-to-freeway vehicles can execute their weaving maneuver without making a lane change (if they so desire). Thus, $LC_{RF} = 0$. Freeway-to-ramp vehicles must make at least one lane change to complete their desired maneuver. Thus, $LC_{FR} = 1$. If optional lane changes are considered, weaving movements can be accomplished with one or no lane changes from both entering ramp lanes and from the rightmost freeway lane. Thus, $N_{WL} = 3$. Equation 12-2 can now be employed:

$$LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR}) = (0 \times 1197) + (1 \times 798) = 798 \text{ lc/h}$$

Step 4: Determine Maximum Weaving Length

The maximum length over which weaving movements may exist is determined by Equation 12-4. The determination is case specific, and the result is valid only for the case under consideration:

$$L_{MAX} = \left[5728(1 + VR)^{1.6}\right] - \left[1566 N_{WL}\right]$$

$$L_{MAX} = \left[5728(1 + 0.357)^{1.6}\right] - \left[1566 \times 3\right] = 4{,}639 \text{ ft}$$

As the maximum length is significantly greater than the actual segment length of 1,500 ft, weaving operations do exist, and the analysis may continue with the weaving analysis methodology.

Step 5: Determine Weaving Segment Capacity

Capacity may be controlled by one of two factors: operations reaching a maximum density of 43 pc/mi/ln or by the weaving demand flow rate reaching

3,500 pc/h (for a weaving segment with N_{WL} = 3). Equation 12-5 through Equation 12-8 are used to make these determinations.

Capacity Controlled by Density

$$c_{IWL} = c_{IFL} - \left[438.2(1+VR)^{1.6}\right] + \left[0.0765L_s\right] + \left[119.8N_{WL}\right]$$

$$c_{IWL} = 2{,}350 - \left[438.2(1+0.357)^{1.6}\right] + \left[0.0765 \times 1{,}500\right] + \left[119.8 \times 3\right]$$

$$c_{IWL} = 2{,}110 \text{ pc/h/ln}$$

$$c_W = c_{IWL} N f_{HV} f_p = 2{,}110 \times 4 \times 0.952 \times 1 = 8{,}038 \text{ veh/h}$$

Capacity Controlled by Maximum Weaving Flow Rate

$$c_{IW} = \frac{3{,}500}{VR} = \frac{3{,}500}{0.357} = 9{,}800 \text{ pc/h}$$

$$c_W = c_{IW} f_{HV} f_p = 9{,}800 \times 0.952 \times 1 = 9{,}333 \text{ veh/h}$$

Note that the methodology computes the capacity controlled by density in passenger cars per hour per lane, while the capacity controlled by maximum weaving flow rate is computed in passenger cars per hour. After conversion, however, both are in units of vehicles per hour.

The controlling value is the smaller of these, or 8,038 veh/h. As the total demand flow rate is only 5,320 veh/h, the capacity is clearly sufficient, and this situation will not result in LOS F.

Step 6: Determine Lane-Changing Rates

Equation 12-10 through Equation 12-15 are used to estimate the lane-changing rates of weaving and nonweaving vehicles in the weaving segment. In turn, these will be used to estimate weaving and nonweaving vehicle speeds.

Weaving Vehicle Lane-Changing Rate

$$LC_W = LC_{MIN} + 0.39\left[(L_s - 300)^{0.5}\left(N^2\right)(1+ID)^{0.8}\right]$$

$$LC_W = 798 + 0.39\left[(1{,}500 - 300)^{0.5} 4^2 (1+0.8)^{0.8}\right] = 1{,}144 \text{ lc/h}$$

Nonweaving Vehicle Lane-Changing Rate

$$I_{NW} = \frac{L_S ID v_{NW}}{10{,}000} = \frac{1{,}500 \times 0.8 \times 3{,}591}{10{,}000} = 431 < 1{,}300$$

$$LC_{NW} = \left(0.206 v_{NW}\right) + \left(0.542 L_S\right) - \left(192.6N\right)$$

$$LC_{NW} = (0.206 \times 3{,}591) + (0.542 \times 1{,}500) - (192.6 \times 4) = 782 \text{ lc/h}$$

Total Lane-Changing Rate

$$LC_{ALL} = LC_W + LC_{NW} = 1{,}144 + 782 = 1{,}926 \text{ lc/h}$$

Step 7: Determine Average Speeds of Weaving and Nonweaving Vehicles

The average speeds of weaving and nonweaving vehicles are computed from Equation 12-18 through Equation 12-20:

$$W = 0.226\left(\frac{LC_{ALL}}{L_S}\right)^{0.789} = 0.226\left(\frac{1{,}926}{1{,}500}\right)^{0.789} = 0.275$$

Then

$$S_W = 15 + \left(\frac{FFS - 15}{1 + W}\right) = 15 + \left(\frac{65 - 15}{1 + 0.275}\right) = 54.2 \text{ mi/h}$$

and

$$S_{NW} = FFS - (0.0072 LC_{MIN}) - \left(0.0048\frac{v}{N}\right)$$

$$S_{NW} = 65 - (0.0072 \times 798) - \left(0.0048 \times \frac{5{,}586}{4}\right) = 52.5 \text{ mi/h}$$

Equation 12-21 is now used to compute the average speed of all vehicles in the segment:

$$S = \frac{v_{NW} + v_W}{\left(\frac{v_{NW}}{S_{NW}}\right) + \left(\frac{v_W}{S_W}\right)} = \frac{3{,}591 + 1{,}995}{\left(\frac{3{,}591}{52.5}\right) + \left(\frac{1{,}995}{54.2}\right)} = 53.1 \text{ mi/h}$$

Step 8: Determine LOS

Equation 12-22 is used to convert the average speed of all vehicles in the segment to an average density:

$$D = \frac{\left(\frac{v}{N}\right)}{S} = \frac{\left(\frac{5{,}586}{4}\right)}{53.1} = 26.3 \text{ pc/mi/ln}$$

The resulting density of 26.3 pc/mi/ln is compared with the LOS criteria of Exhibit 12-10. The LOS is C, as the density is within the specified range of 20 to 28 pc/h/ln for that level.

Discussion

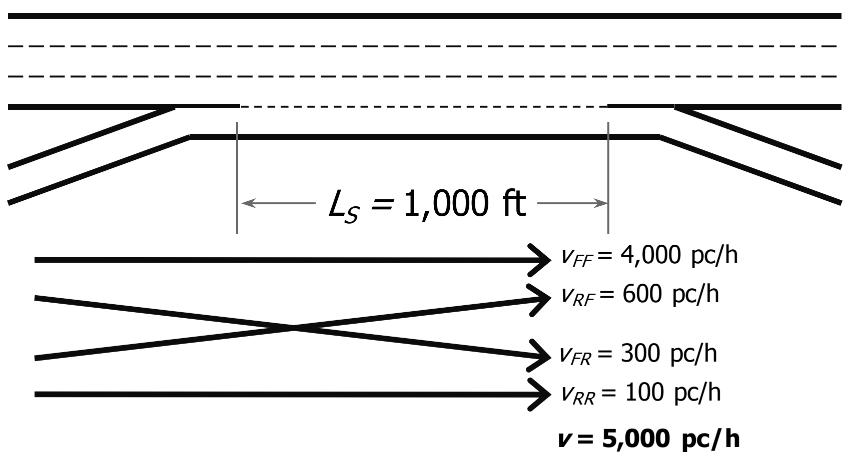
As indicated by the results, this weaving segment operates at LOS C, with an average speed of 53.1 mi/h for all vehicles. Weaving vehicles travel a bit faster than nonweaving vehicles, primarily because the configuration favors weaving vehicles, allowing many weaving maneuvers to be made without making a lane change. The demand flow rate of 4,841 veh/h is considerably less than the capacity of the segment, 8,038 veh/h. In other words, demand can grow significantly before reaching the capacity of the segment.

EXAMPLE PROBLEM 2: LOS OF A RAMP-WEAVING SEGMENT

The Weaving Segment

The weaving segment that is the subject of this operational analysis is shown in Exhibit 12-14. It is a typical ramp-weave segment.

Exhibit 12-14
Ramp-Weave Segment for Example Problem 2



What is the capacity of the weaving segment of Exhibit 12-14, and at what LOS is it expected to operate with the demand flow rates as shown?

The Facts

In addition to the information given in Exhibit 12-14, the following facts are known about the subject weaving segment:

PHF = 1.00 (demands stated as flow rates);

Heavy vehicles = 0% trucks, 0% RVs (demands given as passenger car equivalents);

Driver population = regular commuters;

FFS = 75 mi/h;

c_{IFL} = 2,400 pc/h/ln (for FFS = 75 mi/h);

ID = 1.0 int/mi; and

Terrain = level.

Comments

Because the demands have been specified as flow rates in passenger cars per hour under equivalent ideal conditions, Chapter 11 does not have to be consulted to obtain appropriate adjustment factors.

Several of the computational steps related to converting demand volumes to flow rates under equivalent ideal conditions are trivial, as demands are already specified in that form. Lane-changing characteristics will be estimated. The maximum length for weaving operations in this case will be estimated and compared with the actual length of the segment. The capacity of the segment will be estimated and compared with the demand to determine whether LOS F exists. If it does not, component flow speeds will be estimated and averaged. A density will be estimated and compared with the criteria of Exhibit 12-10 to determine the expected LOS.

Step 1: Input Data

All input data are stated in Exhibit 12-14 and the Facts section.

Step 2: Adjust Volume

Because all demands are stated as flow rates in passenger cars per hour under equivalent ideal conditions, no further conversions are necessary. Key volume parameters are as follows:

$$v_{FF} = 4{,}000 \text{ pc/h}$$

$$v_{FR} = 600 \text{ pc/h}$$

$$v_{RF} = 300 \text{ pc/h}$$

$$v_{RR} = 100 \text{ pc/h}$$

$$v_W = 600 + 300 = 900 \text{ pc/h}$$

$$v_{NW} = 4{,}000 + 100 = 4{,}100 \text{ pc/h}$$

$$v = 4{,}100 + 900 = 5{,}000 \text{ pc/h}$$

$$VR = \frac{900}{5{,}000} = 0.180$$

Step 3: Determine Configuration Characteristics

The configuration is examined to determine the values of LC_{RF}, LC_{FR}, and N_{WL}. These determinations are illustrated in Exhibit 12-15. From these values, the minimum number of lane changes by weaving vehicles LC_{MIN} is then computed by using Equation 12-2.

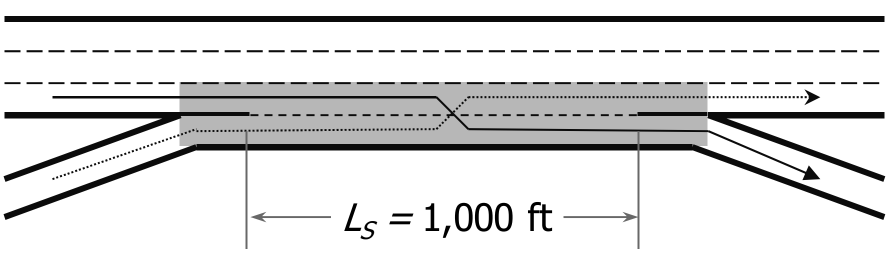


Exhibit 12-15
Configuration Characteristics for Example Problem 2

From Exhibit 12-15, it is clear that all ramp-to-freeway vehicles must make at least one lane change ($LC_{RF} = 1$), and all freeway-to-ramp vehicles must make at least one lane change ($LC_{FR} = 1$). It is also clear that a weaving maneuver can only be completed with a single lane change from the right lane of the freeway or the auxiliary lane ($N_{WL} = 2$). Then, by using Equation 12-2, LC_{MIN} is computed as

$$LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR})$$

$$LC_{MIN} = (1 \times 600) + (1 \times 300) = 900 \text{ lc/h}$$

Step 4: Determine Maximum Weaving Length

The maximum length over which weaving operations may exist for the segment described is found by using Equation 12-4:

$$L_{MAX} = \left[5{,}728(1+VR)^{1.6}\right] - \left[1{,}566 N_{WL}\right]$$

$$L_{MAX} = \left[5{,}728(1+0.180)^{1.6}\right] - \left[1{,}566 \times 2\right] = 4{,}333 \text{ ft} > 1{,}000 \text{ ft}$$

As the maximum length for weaving operations significantly exceeds the actual length, this is a weaving segment, and the analysis continues.

Step 5: Determine Weaving Segment Capacity

The capacity of the weaving segment is controlled by one of two limiting factors: density reaches 43 pc/mi/ln or weaving demand reaches 2,400 pc/h for the configuration of Exhibit 12-15.

Capacity Limited by Density

The capacity limited by reaching a density of 43 pc/mi/ln is estimated by using Equation 12-5 and Equation 12-6:

$$c_{IWL} = c_{IFL} - \left[438.2(1+VR)^{1.6}\right] + \left[0.0765 L_s\right] + \left[119.8 N_{WL}\right]$$

$$c_{IWL} = 2{,}400 - \left[438.2(1+0.180)^{1.6}\right] + \left[0.0765 \times 1{,}000\right] + \left[119.8 \times 2\right]$$

$$c_{IWL} = 2{,}145 \text{ pc/h/ln}$$

$$c_W = c_{IWL} \times N \times f_{HV} \times f_p = 2{,}145 \times 4 \times 1 \times 1 = 8{,}580 \text{ pc/h}$$

Capacity Limited by Weaving Demand Flow

The capacity limited by the weaving demand flow is estimated by using Equation 12-7 and Equation 12-8:

$$c_{IW} = \frac{2{,}400}{VR} = \frac{2{,}400}{0.180} = 13{,}333 \text{ pc/h}$$

$$c_W = c_{IW} \times f_{HV} \times f_p = 13{,}333 \times 1 \times 1 = 13{,}333 \text{ pc/h}$$

The controlling capacity is the smaller value, or 8,580 pc/h. At this point, the value is usually stated as vehicles per hour. In this case, because inputs were already adjusted and were stated in passenger cars per hour, conversions back to vehicles per hour are not possible.

As the capacity is larger than the demand flow rate of 5,000 pc/h, LOS F does not exist, and the analysis continues.

Step 6: Determine Lane-Changing Rates

Equation 12-10 through Equation 12-15 are used to estimate the lane-changing rates of weaving and nonweaving vehicles in the weaving segment. In turn, these will be used to estimate weaving and nonweaving vehicle speeds.

Weaving Vehicle Lane-Changing Rate

$$LC_W = LC_{MIN} + 0.39\left[(L_s - 300)^{0.5}(N^2)(1+ID)^{0.8}\right]$$

$$LC_W = 900 + 0.39\left[(1{,}000-300)^{0.5}4^2(1+1)^{0.8}\right] = 1{,}187 \text{ lc/h}$$

Nonweaving Vehicle Lane-Changing Rate

$$I_{NW} = \frac{L_S ID v_{NW}}{10{,}000} = \frac{1{,}000 \times 1 \times 4{,}100}{10{,}000} = 410 < 1{,}300$$

$$LC_{NW} = (0.206 v_{NW}) + (0.542 L_S) - (192.6N)$$

$$LC_{NW} = (0.206 \times 4{,}100) + (0.542 \times 1{,}000) - (192.6 \times 4) = 616 \text{ lc/h}$$

Total Lane-Changing Rate

$$LC_{ALL} = LC_W + LC_{NW} = 1{,}187 + 616 = 1{,}803 \text{ lc/h}$$

Step 7: Determine Average Speeds of Weaving and Nonweaving Vehicles

The average speeds of weaving and nonweaving vehicles are computed from Equation 12-18 through Equation 12-20:

$$W = 0.226\left(\frac{LC_{ALL}}{L_s}\right)^{0.789} = 0.226\left(\frac{1{,}803}{1{,}000}\right)^{0.789} = 0.360$$

Then

$$S_w = 15 + \left(\frac{FFS - 15}{1+W}\right) = 15 + \left(\frac{75-15}{1+0.360}\right) = 59.1 \text{ mi/h}$$

and

$$S_{NW} = FFS - (0.0072 LC_{MIN}) - \left(0.0048\frac{v}{N}\right)$$

$$S_{NW} = 75 - (0.0072 \times 900) - \left(0.0048 \times \frac{5{,}000}{4}\right) = 62.5 \text{ mi/h}$$

Equation 12-21 is now used to compute the average speed of all vehicles in the segment:

$$S = \frac{v_{NW} + v_W}{\left(\frac{v_{NW}}{S_{NW}}\right) + \left(\frac{v_W}{S_W}\right)} = \frac{4{,}100 + 900}{\left(\frac{4{,}100}{62.5}\right) + \left(\frac{900}{59.1}\right)} = 61.9 \text{ mi/h}$$

Step 8: Determine LOS

The average density in the weaving segment is estimated by using Equation 12-22.

$$D = \frac{\left(\frac{v}{N}\right)}{S} = \frac{\left(\frac{5{,}000}{4}\right)}{61.9} = 20.2 \text{ pc/mi/ln}$$

From Exhibit 12-10, this density is within the stated boundaries of LOS C (20 to 28 pc/mi/ln). It is, however, very close to the LOS B boundary condition.

Discussion

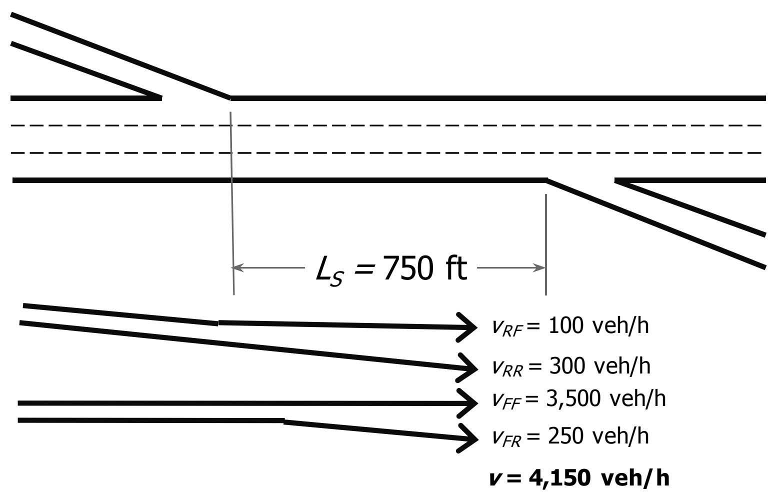
As noted, the segment is operating quite well (LOS C) and is very close to the LOS B boundary. Weaving and nonweaving speeds are relatively high, suggesting a stable flow. The demand flow rate of 5,000 pc/h is well below the capacity of the segment (8,580 pc/h). Weaving vehicles travel somewhat more slowly than nonweaving vehicles, which is typical of ramp-weave segments, where the vast majority of nonweaving vehicles are running from freeway to freeway.

EXAMPLE PROBLEM 3: LOS OF A TWO-SIDED WEAVING SEGMENT

The Weaving Segment

The weaving segment that is the subject of this example problem is shown in Exhibit 12-16.

Exhibit 12-16
Weaving Segment for Example Problem 3



What is the expected LOS and capacity for the weaving segment of Exhibit 12-16?

The Facts

In addition to the information contained in Exhibit 12-16, the following facts concerning the weaving segment are known:

PHF = 0.94 (all movements);

Heavy vehicles = 15% trucks, 0% RVs (all movements);

Driver population = regular commuters;

FFS = 60 mi/h;

c_{IFL} = 2,300 pc/h/ln (for FFS = 60 mi/h);

ID = 2 int/mi; and

Terrain = rolling.

Comments

Because this example illustrates the analysis of a two-sided weaving segment, several key parameters are redefined.

In a two-sided weaving segment, only the ramp-to-ramp flow is considered to be a weaving flow. While the freeway-to-freeway flow technically weaves with the ramp-to-ramp flow, the operation of freeway-to-freeway vehicles more closely resembles that of nonweaving vehicles. These vehicles generally make very few lane changes as they move through the segment in a freeway lane. This segment is in a busy urban corridor with a high interchange density and a relatively low FFS for the freeway.

Solution steps are the same as in the first two example problems. However, since the segment is a two-sided weaving segment, some of the key values will be computed differently as described in the methodology.

Component demand volumes will be converted to equivalent flow rates in passenger cars per hour under ideal conditions, and key demand parameters will be calculated. A maximum weaving length will be estimated to determine whether a weaving analysis is appropriate. The capacity of the weaving segment will be estimated to determine whether LOS F exists. If not, lane-changing parameters, speeds, density, and LOS will be estimated.

Step 1: Input Data

All information concerning this example problem is given in Exhibit 12-16 and the Facts section.

Step 2: Adjust Volume

To convert demand volumes to flow rates under equivalent ideal conditions, Chapter 11 must be consulted to obtain the following values:

E_T = 2.5 (for rolling terrain)

f_p = 1.0 (for regular commuters)

Then

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.15(2.5 - 1)} = 0.816$$

Component demand volumes may now be converted to flow rates under equivalent ideal conditions:

$$v_{FF} = \frac{3{,}500}{0.94 \times 0.816 \times 1} = 4{,}561 \text{ pc/h}$$

$$v_{FR} = \frac{250}{0.94 \times 0.816 \times 1} = 326 \text{ pc/h}$$

$$v_{RF} = \frac{100}{0.94 \times 0.816 \times 1} = 130 \text{ pc/h}$$

$$v_{RR} = \frac{300}{0.94 \times 0.816 \times 1} = 391 \text{ pc/h}$$

Because this is a two-sided weaving segment, the only weaving flow is the ramp-to-ramp flow. All other flows are treated as nonweaving. Then

v_W = 391 pc/h

v_{NW} = 4,561 + 326 + 130 = 5,017 pc/h

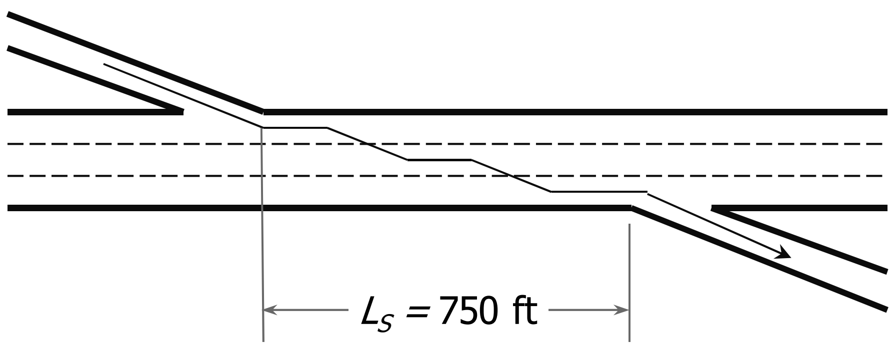
v = 5,017 + 391 = 5,408 pc/h

VR = 391/5,408 = 0.072

Step 3: Determine Configuration Characteristics

The determination of configuration characteristics is also affected by the existence of a two-sided weaving segment. Exhibit 12-17 illustrates the determination of LC_{RR}, the key variable for two-sided weaving segments. For such segments, $N_{WL} = 0$ by definition.

Exhibit 12-17
Configuration Characteristics for Example Problem 3



From Exhibit 12-17, ramp-to-ramp vehicles must make two lane changes to complete their desired weaving maneuver. Then

$$LC_{MIN} = LC_{RR} \times v_{RR} = 2 \times 391 = 782 \text{ lc/h}$$

Step 4: Determine Maximum Weaving Length

The maximum length of a weaving segment for this configuration and demand scenario is estimated by using Equation 12-4:

$$L_{MAX} = \left[5{,}728(1+VR)^{1.6}\right] - \left[1{,}566 N_{WL}\right]$$

$$L_{MAX} = \left[5{,}728(1+0.072)^{1.6}\right] - \left[1{,}566 * 0\right] = 6{,}405 \text{ ft} > 750 \text{ ft}$$

In this two-sided configuration, the impacts of weaving on operations could be felt at lengths as long as 6,405 ft. As this is significantly greater than the actual length of 750 ft, this segment clearly operates as a weaving segment and, therefore, the methodology of this chapter should be applied.

Step 5: Determine Weaving Segment Capacity

The capacity of a two-sided weaving segment can only be estimated when a density of 43 pc/h/ln is reached. This estimation is made by using Equation 12-5 and Equation 12-6:

$$c_{IWL} = c_{IFL} - \left[438.2(1+VR)^{1.6}\right] + \left[0.0765 L_s\right] + \left[119.8 N_{WL}\right]$$

$$c_{IWL} = 2{,}300 - \left[438.2(1+0.072)^{1.6}\right] + \left[0.0765 \times 750\right] + \left[119.8 \times 0\right]$$

$$c_{IWL} = 1{,}867 \text{ pc/h/ln}$$

$$c_W = c_{IWL} \times N \times f_{HV} \times f_p = 1{,}867 \times 3 \times 0.816 \times 1 = 4{,}573 \text{ veh/h} > 4{,}150 \text{ veh/h}$$

Because the capacity of the segment exceeds the demand volume (in vehicles per hour), LOS F is not expected, and the analysis may be continued.

Step 6: Determine Lane-Changing Rates

Equation 12-10 through Equation 12-15 are used to estimate the lane-changing rates of weaving and nonweaving vehicles in the weaving segment. In turn, these will be used to estimate weaving and nonweaving vehicle speeds.

Weaving Vehicle Lane-Changing Rate

$$LC_W = LC_{MIN} + 0.39\left[(L_s - 300)^{0.5}(N^2)(1+ID)^{0.8}\right]$$

$$LC_W = 782 + 0.39\left[(750-300)^{0.5} 3^2 (1+2)^{0.8}\right] = 961 \text{ lc/h}$$

Nonweaving Vehicle Lane-Changing Rate

$$I_{NW} = \frac{L_S ID v_{NW}}{10{,}000} = \frac{750 \times 2 \times 5{,}017}{10{,}000} = 753 < 1{,}300$$

$$LC_{NW} = (0.206 v_{NW}) + (0.542 L_s) - (192.6 N)$$

$$LC_{NW} = (0.206 \times 5{,}017) + (0.542 \times 750) - (192.6 \times 3) = 862 \text{ lc/h}$$

Total Lane-Changing Rate

$$LC_{ALL} = LC_W + LC_{NW} = 961 + 862 = 1{,}823 \text{ lc/h}$$

Step 7: Determine Average Speeds of Weaving and Nonweaving Vehicles

The average speeds of weaving and nonweaving vehicles are computed from Equation 12-18 through Equation 12-20:

$$W = 0.226\left(\frac{LC_{ALL}}{L_S}\right)^{0.789} = 0.226\left(\frac{1{,}823}{750}\right)^{0.789} = 0.456$$

Then

$$S_W = 15 + \left(\frac{FFS - 15}{1+W}\right) = 15 + \left(\frac{60-15}{1+0.456}\right) = 45.9 \text{ mi/h}$$

and

$$S_{NW} = FFS - (0.0072 LC_{MIN}) - \left(0.0048 \frac{v}{N}\right)$$

$$S_{NW} = 75 - (0.0072 \times 782) - \left(0.0048 \times \frac{5{,}408}{3}\right) = 45.7 \text{ mi/h}$$

Equation 12-21 is now used to compute the average speed of all vehicles in the segment:

$$S = \frac{v_{NW} + v_W}{\left(\frac{v_{NW}}{S_{NW}}\right) + \left(\frac{v_W}{S_W}\right)} = \frac{5{,}017 + 391}{\left(\frac{5{,}017}{45.7}\right) + \left(\frac{391}{45.9}\right)} = 45.7 \text{ mi/h}$$

Step 8: Determine LOS

The average density in this two-sided weaving segment is estimated by using Equation 12-22:

$$D = \frac{\left(\frac{v}{N}\right)}{S} = \frac{\left(\frac{5{,}408}{3}\right)}{45.7} = 39.4 \text{ pc/mi/ln}$$

From Exhibit 12-10, this density is clearly in LOS E. It is not far from the 43 pc/h/ln that would likely cause a breakdown.

Discussion

This two-sided weaving segment operates at LOS E, not far from the LOS E/F boundary. The v/c ratio is 4,150/4,573 = 0.91. The major problem is that 300 veh/h crossing the freeway from ramp to ramp creates a great deal of turbulence in the traffic stream and limits capacity. Two-sided weaving segments do not operate well with such large numbers of ramp-to-ramp vehicles. If this were a basic freeway segment, the per lane flow rate of 5,408/3 = 1,803 pc/h/ln would not be considered excessive and would be well within a basic freeway segment's capacity of 2,300 pc/h/ln.

EXAMPLE PROBLEM 4: DESIGN OF A MAJOR WEAVING SEGMENT FOR A DESIRED LOS

The Weaving Segment

A weaving segment is to be designed between two major junctions in which two urban freeways join and then separate as shown in Exhibit 12-18. Entry and exit legs have the numbers of lanes shown. The maximum length of the weaving segment is 1,000 ft, based on the location of the junctions. The FFS of all entry and exit legs is 75 mi/h. All demands are shown as flow rates under equivalent ideal conditions.

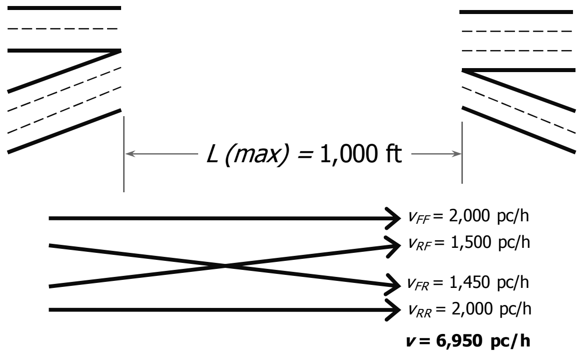


Exhibit 12-18
Weaving Segment for Example Problem 4

What design would be appropriate to deliver LOS C for the demand flow rates shown?

The Facts

In addition to the information contained in Exhibit 12-18, the following facts are known concerning this weaving segment:

PHF = 1.00 (all demands stated as flow rates);

Heavy vehicles = 0% trucks, 0% RVs (all demands in pc/h);

Driver population = regular commuters;

FFS = 75 mi/h;

c_{IFL} = 2,400 pc/h/ln (for FFS = 75 mi/h);

ID = 1 int/mi; and

Terrain = level.

Comments

As is the case in any weaving segment design, there are considerable constraints imposed. The problem states that the maximum length is 1,000 ft, no doubt limited by locational issues for the merge and diverge junctions. It is probably not worth investigating shorter lengths, and the maximum should be assumed for all trial designs. The simplest design merely connects entering lanes with exit lanes in a straightforward manner, producing a section of five lanes. A section with four lanes could be considered by merging two lanes into one at the entry gore and separating it into two again at the exit gore. In any event, the design is limited to a section of four or five lanes. No other widths would work without major additions to input and output legs. The configuration cannot be changed without adding a lane to at least one of the entry or exit legs. Thus, the initial trial will be at a length of 1,000 ft, with the five entry lanes connected directly to the five exit lanes, with no changes to the exit or entry leg designs. If this does not produce an acceptable operation, changes will be considered.

While the problem clearly states that all legs are freeways, no feasible configuration produces a two-sided weaving section. Thus, to fit within the one-sided analysis methodology, the right-side entry and exit legs will be classified as ramps in the computational analysis.

Step 1: Input Data – Trial 1

All input information is given in Exhibit 12-18 and in the accompanying Facts section for this example problem.

Step 2: Adjust Volume – Trial 1

All demands are already stated as flow rates in passenger cars per hour under equivalent ideal conditions. No further adjustments are needed. Critical demand values are as follows:

$$v_{FF} = 2{,}000 \text{ pc/h}$$

$$v_{FR} = 1{,}450 \text{ pc/h}$$

$$v_{RF} = 1{,}500 \text{ pc/h}$$

$$v_{RR} = 2{,}000 \text{ pc/h}$$

$$v_{W} = 1{,}500 + 1{,}450 = 2{,}950 \text{ pc/h}$$

$$v_{NW} = 2{,}000 + 2{,}000 = 4{,}000 \text{ pc/h}$$

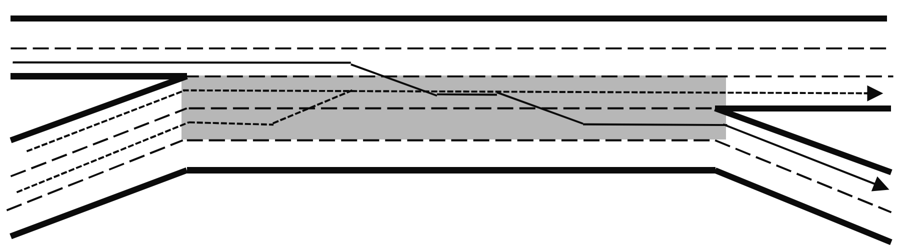
$$v = 2{,}950 + 4{,}000 = 6{,}950 \text{ pc/h}$$

$$VR = \frac{2{,}950}{6{,}950} = 0.424$$

Step 3: Determine Configuration Characteristics – Trial 1

Exhibit 12-19 illustrates the weaving segment formed under the assumed design discussed previously.

Exhibit 12-19
Trial Design 1
for Example Problem 4



The direct connection of entry and exit legs produces a weaving segment in which the ramp-to-freeway movement can be made without a lane change (LC_{RF} = 0). Freeway-to-ramp vehicles, however, must make two lane changes (LC_{FR} = 2). If the lane-changing pattern is considered, there are no lanes on the entering freeway leg from which a weaving maneuver can be made with one or no lane changes. Ramp drivers wishing to weave, however, can enter on either of the two left ramp lanes and weave with one or no lane changes. Thus, N_{WL} = 2.

By using Equation 12-2, LC_{MIN} is computed as

$$LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR})$$

$$LC_{MIN} = (0 \times 1{,}500) + (2 \times 1{,}450) = 2{,}900 \text{ lc/h}$$

Step 4: Determine Maximum Weaving Length – Trial 1

The maximum length of a weaving segment for this configuration and demand scenario is estimated by using Equation 12-4:

$$L_{MAX} = \left[5{,}728(1+VR)^{1.6}\right] - \left[1{,}566 N_{WL}\right]$$

$$L_{MAX} = \left[5{,}728(1+0.424)^{1.6}\right] - \left[1{,}566 \times 2\right] = 6{,}950 \text{ ft} > 1{,}000 \text{ ft}$$

As the maximum length is much greater than the actual length of 1,000 ft, it is appropriate to analyze the segment by using this chapter's methodology.

Step 5: Determine Weaving Segment Capacity – Trial 1

The capacity of the weaving segment is controlled by one of two limiting factors: density reaches 43 pc/mi/ln or weaving demand reaches 2,400 pc/h for the configuration of Exhibit 12-19.

Capacity Limited by Density

The capacity limited by reaching a density of 43 pc/mi/ln is estimated by using Equation 12-5 and Equation 12-6:

$$c_{IWL} = c_{IFL} - \left[438.2(1+VR)^{1.6}\right] + \left[0.0765 L_s\right] + \left[119.8 N_{WL}\right]$$

$$c_{IWL} = 2{,}400 - \left[438.2(1+0.424)^{1.6}\right] + \left[0.0765 \times 1{,}000\right] + \left[119.8 \times 2\right]$$

$$c_{IWL} = 1{,}944 \text{ pc/h/ln}$$

$$c_W = c_{IWL} \times N \times f_{HV} \times f_p = 1{,}944 \times 5 \times 1 \times 1 = 9{,}721 \text{ pc/h}$$

Capacity Limited by Weaving Demand Flow

The capacity limited by the weaving demand flow is estimated by using Equation 12-7 and Equation 12-8:

$$c_{IW} = \frac{2{,}400}{VR} = \frac{2{,}400}{0.424} = 5{,}654 \text{ pc/h}$$

$$c_W = c_{IW} \times f_{HV} \times f_p = 5{,}654 \times 1 \times 1 = 5{,}654 \text{ pc/h}$$

In this case, the capacity of the segment is limited by the maximum weaving flow rate of 5,654 pc/h, which is smaller than the total demand flow rate of 6,950 pc/h. Thus, this section is expected to operate at LOS F. No further analysis is possible with this methodology.

Discussion – Trial 1

This section would be expected to fail under the proposed design. The critical feature appears to be the configuration. Note that the capacity is limited by the maximum weaving flows that can be sustained, not by a density expected to produce queuing. This is primarily due to the freeway-to-ramp flow, which must make two lane changes. This number can be reduced to one by adding one lane to the "ramp" at the exit gore area. Not only does this reduce the number of lane changes made by 1,450 freeway-to-ramp vehicles, but it also increases the value of N_W from 2 to 3. In turn, this effectively increases the segment's capacity (as limited by weaving flow rate) to 3,500/VR = 3,500/0.424 = 8,255 pc/h, which is well in excess of the demand flow rate of 6,950 pc/h. Another analysis (Trial 2) will be conducted by using this approach.

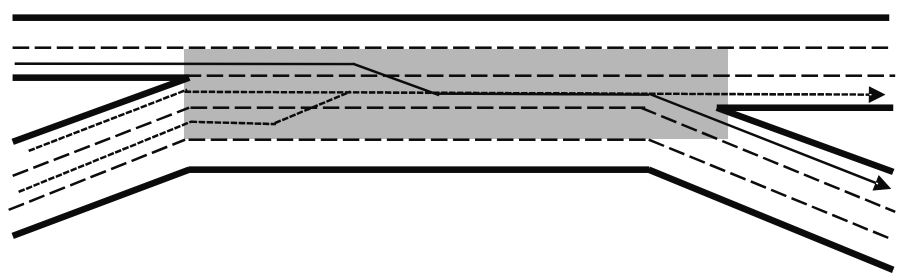
Steps 1 and 2: Input Data and Adjust Volume – Trial 2

Steps 1 and 2 are the same as for Trial 1. They are not repeated here. The new configuration affects the results beginning with Step 3.

Step 3: Determine Configuration Characteristics – Trial 2

Exhibit 12-20 illustrates the new configuration that will result from the changes discussed above. By adding a lane to the exit-ramp leg, the freeway-to-ramp movement can now be completed with only one lane change (LC_{FR} = 1). The value of LC_{RF} is not affected and remains 0. The right lane of the freeway-entry leg can also be used by freeway-to-ramp drivers to make a weaving maneuver with a single lane change, increasing N_{WL} to 3.

Exhibit 12-20
Trial Design 2
for Example Problem 4



Then

$$LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR})$$

$$LC_{MIN} = (0 \times 1{,}500) + (1 \times 1{,}450) = 1{,}450 \text{ lc/h}$$

Step 4: Determine Maximum Weaving Length – Trial 2

The maximum length of a weaving segment for this configuration and demand scenario is estimated by using Equation 12-4:

$$L_{MAX} = \left[5{,}728(1+VR)^{1.6}\right] - \left[1{,}566 N_{WL}\right]$$

$$L_{MAX} = \left[5{,}728(1+0.424)^{1.6}\right] - \left[1{,}566 \times 3\right] = 5{,}391 \text{ ft} > 1{,}000 \text{ ft}$$

As the maximum length is much greater than the actual length of 1,000 ft, analyzing the segment by using this chapter's methodology is appropriate.

Step 5: Determine Weaving Segment Capacity – Trial 2

The capacity of the weaving segment is controlled by one of two limiting factors: density reaches 43 pc/mi/ln or weaving demand reaches 3,500 pc/h for the configuration of Exhibit 12-20.

Capacity Limited by Density

The capacity limited by reaching a density of 43 pc/mi/ln is estimated by using Equation 12-5 and Equation 12-6:

$$c_{IWL} = c_{IFL} - [438.2(1+VR)^{1.6}] + [0.0765L_s] + [119.8N_{WL}]$$

$$c_{IWL} = 2{,}400 - [438.2(1+0.424)^{1.6}] + [0.0765 \times 1{,}000] + [119.8 \times 3]$$

$$c_{IWL} = 2{,}064 \text{ pc/h/ln}$$

$$c_W = c_{IWL} \times N \times f_{HV} \times f_p = 2{,}064 \times 5 \times 1 \times 1 = 10{,}320 \text{ pc/h}$$

Capacity Limited by Weaving Demand Flow

The capacity limited by the weaving demand flow is estimated by using Equation 12-7 and Equation 12-8:

$$c_{IW} = \frac{3{,}500}{VR} = \frac{3{,}500}{0.424} = 8{,}255 \text{ pc/h}$$

$$c_W = c_{IW} \times f_{HV} \times f_p = 8{,}255 \times 1 \times 1 = 8{,}255 \text{ pc/h}$$

Once again, the capacity of the segment is limited by the maximum weaving flow rate: the difference is that now the capacity is 8,255 pc/h. This is larger than the total demand flow rate of 6,950 pc/h. Thus, this section is expected to operate without breakdown, and the analysis may continue.

Step 6: Determine Lane-Changing Rates – Trial 2

Equation 12-10 through Equation 12-15 are used to estimate the lane-changing rates of weaving and nonweaving vehicles in the weaving segment. In turn, these will be used to estimate weaving and nonweaving vehicle speeds.

Weaving Vehicle Lane-Changing Rate

$$LC_W = LC_{MIN} + 0.39[(L_s - 300)^{0.5}(N^2)(1+ID)^{0.8}]$$

$$LC_W = 1{,}450 + 0.39[(1{,}000 - 300)^{0.5}5^2(1+1)^{0.8}] = 1{,}899 \text{ lc/h}$$

Nonweaving Vehicle Lane-Changing Rate

$$I_{NW} = \frac{L_S ID v_{NW}}{10{,}000} = \frac{1{,}000 \times 1 \times 4{,}000}{10{,}000} = 400 < 1{,}300$$

$$LC_{NW} = (0.206v_{NW}) + (0.542L_S) - (192.6N)$$

$$LC_{NW} = (0.206 \times 4{,}000) + (0.542 \times 1{,}000) - (192.6 \times 5) = 403 \text{ lc/h}$$

Total Lane-Changing Rate

$$LC_{ALL} = LC_W + LC_{NW} = 1{,}899 + 403 = 2{,}302 \text{ lc/h}$$

Step 7: Determine Average Speeds of Weaving and Nonweaving Vehicles – Trial 2

The average speeds of weaving and nonweaving vehicles are computed from Equation 12-18 through Equation 12-20.

$$W = 0.226\left(\frac{LC_{ALL}}{L_s}\right)^{0.789} = 0.226\left(\frac{2{,}302}{1{,}000}\right)^{0.789} = 0.436$$

Then

$$S_W = 15 + \left(\frac{FFS - 15}{1 + W}\right) = 15 + \left(\frac{75 - 15}{1 + 0.436}\right) = 56.8 \text{ mi/h}$$

and

$$S_{NW} = FFS - (0.0072 LC_{MIN}) - \left(0.0048\frac{v}{N}\right)$$

$$S_{NW} = 75 - (0.0072 \times 1{,}450) - \left(0.0048\frac{6{,}950}{5}\right) = 57.9 \text{ mi/h}$$

Equation 12-21 is now used to compute the average speed of all vehicles in the segment:

$$S = \frac{v_{NW} + v_W}{\left(\frac{v_{NW}}{S_{NW}}\right) + \left(\frac{v_W}{S_W}\right)} = \frac{4{,}000 + 2{,}950}{\left(\frac{4{,}000}{57.9}\right) + \left(\frac{2{,}950}{56.8}\right)} = 57.4 \text{ mi/h}$$

Step 8: Determine the Level of Service – Trial 2

The average density in the weaving segment is estimated by using Equation 12-22:

$$D = \frac{\left(\frac{v}{N}\right)}{S} = \frac{\left(\frac{6{,}950}{5}\right)}{57.4} = 24.2 \text{ pc/mi/ln}$$

From Exhibit 12-10, this density is within the stated boundaries of LOS C (20 to 28 pc/mi/ln). As the design target was LOS C, the second trial design is acceptable.

Discussion – Trial 2

The relatively small change in the configuration makes all the difference in this design. LOS C can be achieved by adding a lane to the right exit leg; without it, the section fails due to excessive weaving turbulence. If the extra lane is not needed on the departing freeway leg, it would be dropped somewhere downstream, perhaps as part of the next interchange. The extra lane would have to be carried for several thousand feet to be effective. An added lane generally will not be fully utilized by drivers if they are aware that it will be immediately dropped.

EXAMPLE PROBLEM 5: CONSTRUCTING A SERVICE VOLUME TABLE FOR A WEAVING SEGMENT

This example shows how a table of service flow rates or service volumes or both can be constructed for a weaving section with certain specified characteristics. The methodology of this chapter does not directly yield service flow rates or service volumes, but they can be developed by using spreadsheets or more sophisticated computer programs.

The key issue is the definition of the threshold values for the various levels of service. For weaving sections on freeways, levels of service are defined as limiting densities as follows:

LOS	Maximum Density (pc/mi/ln)
A	10
B	20
C	28
D	35

By definition, the service flow rate at LOS E is the capacity of the weaving section, which may or may not be keyed to a density.

Before the construction of such a table is illustrated, several key definitions should be reviewed:

- *Service flow rate (under ideal conditions):* The maximum rate of flow under equivalent ideal conditions that can be sustained while maintaining the designated LOS (*SFI*, passenger cars per hour).
- *Service flow rate (under prevailing conditions):* The maximum rate of flow under prevailing conditions that can be sustained while maintaining the designated LOS (*SF*, vehicles per hour).
- *Service volume:* The maximum hourly volume under prevailing conditions that can be sustained while maintaining the designated LOS in the worst 15 min of the hour (*SV*, vehicles per hour).
- *Daily service volume:* The maximum AADT under prevailing conditions that can be sustained while maintaining the designated LOS in the worst 15 min of the peak hour (*DSV*, vehicles per day).

Note that flow rates are for a 15-min period, often a peak 15 min within the analysis hour, or the peak hour. These values are related as follows:

$$SF_i = SFI_i \times f_{HV} \times f_p$$

$$SV_i = SF_i \times PHF$$

$$DSV_i = \frac{SV_i}{KD}$$

This chapter's methodology estimates both the capacity and the density expected in a weaving segment of given geometric and demand characteristics. Conceptually, the approach to generating values of *SFI* is straightforward: for any given situation, keep increasing the input flow rates until the boundary density for the LOS is reached; the input flow rate is the *SFI* for that situation and LOS. This obviously involves many iterations. A spreadsheet can be programmed to do this, either semiautomatically with manual input of demands, or fully automatically, with the spreadsheet automatically generating solutions until a density match is found. The latter method is not very efficient and involves a typical spreadsheet program running for several hours. A program could, of course, be written to automate the entire process.

An Example

While all of the computations cannot be shown, demonstration results for a specific case can be illustrated. A service volume table is desired for a weaving section with the following characteristics:

- One-sided major weaving section
- Demand splits as follows:
  - v_{FF} = 65% of v
  - v_{RF} = 15% of v
  - v_{FR} = 12% of v
  - v_{RR} = 8% of v
- Trucks = 10%, RVs = 0%
- Level terrain
- PHF = 0.93
- f_p = 1.00
- *ID* = 1 int/mi
- FFS = 65 mi/h

For these characteristics, a service volume table can be constructed for a range of lengths and widths and for configurations in which N_W is 2 and 3. For illustrative purposes, lengths of 500, 1,000, 1,500, 2,000, and 2,500 ft and widths of three, four, or five lanes will be used. In a major weaving section, one weaving flow does not have to make a lane change. For the purposes of this example, it is assumed that the ramp-to-freeway movement has this characteristic. The freeway-to-ramp movement would require one or two lane changes, on the basis of the value of N_{WL}.

First Computations

Initial computations will be aimed at establishing values of *SFI* for the situations described. A spreadsheet will be constructed in which the first column is the flow rate to be tested (in passenger cars per hour under ideal conditions), and the last column produces a density. Each line will be iterated (manually in this case) until each threshold density value is reached. Intermediate columns will be programmed to produce the intermediate results needed to get to this result. Because maximum length and capacity are decided at intermediate points, the applicable results will be manually entered before continuing. Such a procedure is less difficult than it seems once the basic computations are programmed. Manual iteration using the input flow rate is very efficient, as the operator will observe how fast the results are converging to the desired threshold and will change the inputs accordingly.

The results of a first computation are shown in Exhibit 12-21. They represent service flow rates under ideal conditions, *SFI*. Consistent with the HCM's results presentation guidelines (Chapter 7, Interpreting HCM and Alternative Tool Results), all hourly service flow rates and volumes in the following exhibits have been rounded down to the nearest 100 passenger cars or vehicles for presentation.

Exhibit 12-21
Service Flow Rates Under Ideal Conditions (*SFI*) for Example Problem 5 (pc/h)

	Length of Weaving Section (ft)									
LOS	**500**	**1,000**	**1,500**	**2,000**	**2,500**	**500**	**1,000**	**1,500**	**2,000**	**2,500**
	N = 3; N_{WL} = 2					**N = 3; N_{WL} = 3**				
A	1,700	1,700	1,700	1,700	1,700	1,800	1,800	1,800	1,800	1,800
B	3,200	3,200	3,200	3,200	3,200	3,300	3,300	3,400	3,400	3,400
C	4,200	4,200	4,300	4,300	4,300	4,400	4,500	4,500	4,500	4,500
D	5,000	5,100	5,100	5,100	5,100	5,300	5,400	5,400	5,500	5,500
E	5,900	6,000	6,100	6,300	6,400	6,300	6,400	6,500	6,600	6,700
	N = 4; N_{WL} = 2					**N = 4; N_{WL} = 3**				
A	2,200	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300
B	4,100	4,200	4,200	4,200	4,200	4,300	4,400	4,400	4,400	4,400
C	5,400	5,500	5,500	5,500	5,600	5,800	5,900	5,900	5,900	5,900
D	6,300	6,500	6,500	6,600	6,600	6,900	7,000	7,100	7,100	7,100
E	7,900	8,000	8,200	8,400	8,500	8,400	8,500	8,700	8,800	9,000
	N = 5; N_{WL} = 2					**N = 5; N_{WL} = 3**				
A	2,800	2,800	2,800	2,800	2,800	2,900	2,900	2,900	2,900	2,900
B	5,000	5,100	5,100	5,100	5,100	5,400	5,400	5,400	5,500	5,500
C	6,500	6,600	6,700	6,700	6,700	7,100	7,200	7,200	7,300	7,300
D	7,600	7,800	7,900	7,900	7,900	8,400	8,600	8,700	8,700	8,700
E	8,800	8,800	8,800	8,800	8,800	10,500	10,700	10,900	11,100	11,200

Exhibit 12-22 shows service flow rates under prevailing conditions, *SF*. Each value in Exhibit 12-21 (before rounding) is multiplied by

$$f_{HV} = \frac{1}{1 + 0.10(1.5 - 1)} = 0.952$$

$$f_p = 1.00$$

Exhibit 12-22
Service Flow Rates Under Prevailing Conditions (*SF*) for Example Problem 5 (veh/h)

	Length of Weaving Section (ft)									
LOS	**500**	**1,000**	**1,500**	**2,000**	**2,500**	**500**	**1,000**	**1,500**	**2,000**	**2,500**
	N = 3; N_{WL} = 2					**N = 3; N_{WL} = 3**				
A	1,600	1,600	1,600	1,600	1,600	1,700	1,700	1,700	1,700	1,700
B	3,000	3,000	3,100	3,100	3,100	3,100	3,200	3,200	3,200	3,200
C	4,000	4,000	4,100	4,100	4,100	4,200	4,300	4,300	4,300	4,300
D	4,700	4,800	4,900	4,900	4,900	5,100	5,100	5,200	5,200	5,200
E	5,600	5,700	5,800	5,900	6,100	6,000	6,100	6,200	6,200	6,400
	N = 4; N_{WL} = 2					**N = 4; N_{WL} = 3**				
A	2,100	2,100	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200
B	3,900	4,000	4,000	4,000	4,000	4,100	4,200	4,200	4,200	4,200
C	5,100	5,200	5,200	5,300	5,300	5,500	5,600	5,600	5,600	5,600
D	5,900	6,200	6,200	6,300	6,300	6,600	6,700	6,700	6,800	6,800
E	7,500	7,700	7,800	7,900	8,100	8,000	8,100	8,200	8,400	8,500
	N = 5; N_{WL} = 2					**N = 5; N_{WL} = 3**				
A	2,600	2,700	2,700	2,700	2,700	2,700	2,700	2,800	2,800	2,800
B	4,700	4,800	4,900	4,900	4,900	5,100	5,100	5,200	5,200	5,200
C	6,200	6,300	6,300	6,400	6,400	6,700	6,800	6,900	6,900	6,900
D	7,300	7,400	7,500	7,500	7,500	8,000	8,200	8,200	8,300	8,300
E	8,400	8,400	8,400	8,400	8,400	10,000	10,200	10,300	10,500	10,700

Exhibit 12-23 shows service volumes, *SV*. Each value in Exhibit 12-22 (before rounding) is multiplied by a PHF of 0.93.

Exhibit 12-23
Service Volumes Under Prevailing Conditions (*SV*) for Example Problem 5 (veh/h)

	Length of Weaving Section (ft)									
LOS	**500**	**1,000**	**1,500**	**2,000**	**2,500**	**500**	**1,000**	**1,500**	**2,000**	**2,500**
	$N = 3; N_{WL} = 2$					$N = 3; N_{WL} = 3$				
A	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
B	2,800	2,800	2,800	2,800	2,900	2,900	2,900	3,000	3,000	3,000
C	3,700	3,700	3,800	3,800	3,800	3,900	4,000	4,000	4,000	4,000
D	4,400	4,500	4,500	4,500	4,500	4,700	4,800	4,800	4,800	4,800
E	5,200	5,300	5,400	5,500	5,600	5,500	5,600	5,700	5,800	5,900
	$N = 4; N_{WL} = 2$					$N = 4; N_{WL} = 3$				
A	2,000	2,000	2,000	2,000	2,000	2,000	2,100	2,100	2,100	2,100
B	3,600	3,700	3,700	3,700	3,700	3,800	3,900	3,900	3,900	3,900
C	4,700	4,800	4,900	4,900	4,900	5,100	5,200	5,200	5,200	5,200
D	5,500	5,700	5,800	5,800	5,800	6,100	6,200	6,300	6,300	6,300
E	7,000	7,100	7,300	7,400	7,500	7,400	7,500	7,700	7,800	7,900
	$N = 5; N_{WL} = 2$					$N = 5; N_{WL} = 3$				
A	2,400	2,500	2,500	2,500	2,500	2,500	2,500	2,600	2,600	2,600
B	4,400	4,500	4,500	4,500	4,500	4,700	4,800	4,800	4,800	4,800
C	5,700	5,800	5,900	5,900	5,900	6,200	6,400	6,400	6,400	6,400
D	6,700	6,900	7,000	7,000	7,000	7,500	7,600	7,700	7,700	7,700
E	7,800	7,800	7,800	7,800	7,800	9,300	9,400	9,600	9,800	9,900

Exhibit 12-24 shows daily service volumes, *DSV*. An illustrative K-factor of 0.08 (typical of a large urban area) and an illustrative D-factor of 0.55 (typical of an urban route without strong peaking by direction) are used. Each (nonrounded) value used to generate Exhibit 12-23 was divided by both of these numbers.

Exhibit 12-24
Daily Service Volumes Under Prevailing Conditions (*DSV*) for Example Problem 5 (veh/day)

	Length of Weaving Section (ft)									
LOS	**500**	**1,000**	**1,500**	**2,000**	**2,500**	**500**	**1,000**	**1,500**	**2,000**	**2,500**
	$N = 3; N_{WL} = 2$					$N = 3; N_{WL} = 3$				
A	35,200	35,200	35,400	35,500	35,600	36,200	36,300	36,300	36,300	36,300
B	64,300	65,300	65,500	65,700	66,100	67,600	68,000	68,400	68,400	68,400
C	84,700	86,100	86,700	87,200	87,500	89,700	90,900	91,500	91,700	91,900
D	100,800	102,800	103,600	104,000	104,400	107,800	109,600	110,200	110,600	110,800
E	119,800	122,100	124,400	126,700	129,100	127,000	129,400	131,600	132,800	136,300
	$N = 4; N_{WL} = 2$					$N = 4; N_{WL} = 3$				
A	45,800	46,200	46,600	46,600	46,600	47,600	47,800	47,800	47,900	47,900
B	83,300	84,700	85,100	85,500	85,700	88,300	89,300	89,500	89,700	89,900
C	108,600	110,800	111,600	112,200	112,600	117,100	118,700	119,500	120,100	120,300
D	126,700	131,300	132,400	133,200	133,600	140,000	142,400	143,600	144,000	144,400
E	159,800	162,800	165,900	169,000	172,100	169,400	172,500	175,400	178,600	181,700
	$N = 5; N_{WL} = 2$					$N = 5; N_{WL} = 3$				
A	56,300	57,100	57,300	57,500	57,500	58,700	58,900	59,300	59,400	59,400
B	101,400	103,000	103,600	104,200	104,400	108,600	109,600	110,000	110,600	110,800
C	131,300	133,800	135,000	135,800	136,200	142,800	145,400	146,200	146,800	147,400
D	154,500	157,700	159,100	159,900	160,300	170,600	173,600	175,000	175,800	175,800
E	178,800	178,800	178,800	178,800	178,800	211,800	215,600	219,500	223,300	227,200

6. REFERENCES

Some of these references can be found in the Technical Reference Library in Volume 4.

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