The following revisions to Chapters 13, 14, 27, and 28 of the *Highway Capacity Manual* are supplemental to *NCHRP Research Report 1038 Update of Highway Capacity Manual: Merge, Diverge, and Weaving Methodologies* (NCHRP Project 07-27, "Update of Highway Capacity Manual: Merge, Diverge, and Weaving Methodologies"). The full report can be found by searching on the report title on the National Academies Press website (www.nap.edu).

The National Cooperative Highway Research Program (NCHRP) is sponsored by the individual state departments of transportation of the American Association of State Highway and Transportation Officials. NCHRP is administered by the Transportation Research Board (TRB), part of the National Academies of Sciences, Engineering, and Medicine, under a cooperative agreement with the Federal Highway Administration (FHWA). Any opinions and conclusions expressed or implied in resulting research products are those of the individuals and organizations who performed the research and are not necessarily those of TRB; the National Academies of Sciences, Engineering, and Medicine; the FHWA; or NCHRP sponsors.

CHAPTER 13
FREEWAY WEAVING SEGMENTS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

New text, figures or paragraphs denoted with black margin notes

Revised text, figures or paragraphs denoted with green margin notes and red text

OVERVIEW

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. This chapter provides a methodology for analyzing the operation of weaving segments on the basis of 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’s methodology estimates the average speed of all vehicles in the weaving segment using a model developed from field observations (*1*). This model reduces the speed in the weaving segment, relative to an equivalent basic segment, as a function of the ramp-to-freeway, freeway-to-ramp, and overall segment flows; the number of lanes; and the length marked for weaving maneuvers. Capacity is then determined in accordance with the fundamental equation of traffic flow, as a function of the segment speed at capacity (defined as occurring at a density of 35 pc/mi/ln). Finally, segment speed is converted to density and used to determine the segment’s level of service (LOS).

This chapter describes how the methodology can be applied to planning, operations, and design applications. The methodology can further be used to estimate the effects of weather and incidents on weaving segment computations, and it includes an extension to apply concepts to weaving segments on managed lanes. Example problems are included in Chapter 27, Freeway Weaving: Supplemental.

CHAPTER ORGANIZATION

Chapter 13 presents methodologies for analyzing weaving segment operations in uninterrupted-flow conditions. The chapter presents a methodology for evaluating isolated freeway weaving segments, as well as several extensions to the core method, including analysis of weaving maneuvers on managed lanes.

Section 2 of this chapter presents the following aspects of weaving segments: length and width of a weaving segment, configurations of weaving segments, definition of key terms used in the methodology, and discussion of special cases.

Section 3 presents the core method for evaluating automobile operations on weaving segments. This method generates the following performance measures:

- Weaving segment capacity;
- Average speed of all vehicles;
- Average density in the weaving segment; and
- LOS of the weaving segment.

Section 4 extends the core method presented in Section 3 to incorporate considerations for multiple weaving segments, collector–distributor (C-D) roads, and weaving on multilane highways. This section also discusses operational impacts of weaving maneuvers on managed lane facilities.

Section 5 presents guidance on using the results of a freeway weaving segment analysis, including example results from the methods, information on the sensitivity of results to various inputs, and a discussion of service volume tables for weaving segments.

RELATED HCM CONTENT

Other *Highway Capacity Manual* (HCM) content related to this chapter includes the following:

- Chapter 3, Modal Characteristics, discusses general characteristics of the motorized vehicle mode on freeway facilities.
- Chapter 4, Traffic Operations and Capacity Concepts, provides background speed–flow–density concepts of freeway segments that form the basis of weaving concepts presented in this chapter's Section 2.
- Chapter 10, Freeway Facility Core Methodology, provides a method for evaluating weaving segments within an extended freeway facility and their interaction with basic, merge, and diverge segments.
- Chapter 11, Freeway Reliability Analysis, provides a method for evaluating freeway facilities with weaving segments in a reliability context. The chapter also provides default speed and capacity adjustment factors that can be applied in this chapter's methodology.
- Chapter 12, Basic Freeway and Multilane Highway Segments, must be used to evaluate the weaving in segments that exceed the maximum weaving length. For such segments, Chapter 14, Freeway Merge and Diverge Segments, is also used to perform ramp capacity checks.
- Chapter 27, Freeway Weaving: Supplemental, presents example problems and additional methodological details for weaving segments.
- Chapter 38, Network Analysis, evaluates the effects of queue spillback between freeway and arterial facilities.
- Case Study 4, New York State Route 7, in the *HCM Applications Guide* in Volume 4, demonstrates how HCM weaving methods can be applied to the evaluation of an actual freeway facility.
- Section H, Freeway Analyses, in the *Planning and Preliminary Engineering Applications Guide to the HCM,* found in Volume 4, describes how to incorporate this chapter's methods and performance measures into a planning effort.

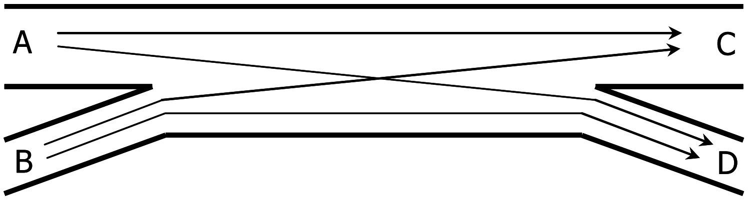
2. CONCEPTS

OVERVIEW

Exhibit 13-1 illustrates a freeway weaving segment with four principal entry and exit points: A, left entering flow; B, right entering flow; C, left exiting flow; and D, right exiting flow. In many cases, one entry and one exit roadway are ramps, which may be on the right or left side of the freeway mainline. Some weaving segments, however, involve major merge or diverge points at which neither roadway can clearly be labeled a ramp.

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. Therefore, Flows A–D and B–C are referred to as *weaving movements*. Flows A–C and B–D are not required to cross the path of any other flow and are referred to as *nonweaving movements*.

Exhibit 13-1
Formation of a Weaving Segment



Weaving segments require intense lane-changing maneuvers because 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. The added turbulence presents operational problems and design requirements that are addressed by this chapter’s methodology.

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

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

- Length,
- Width, and
- Configuration.

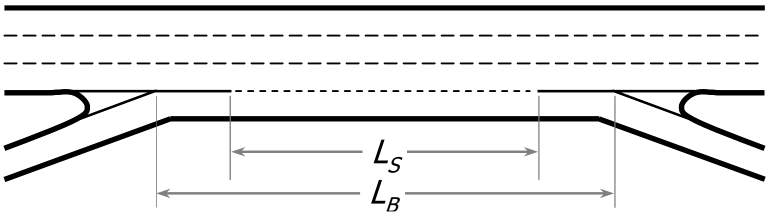
A weaving segment’s geometry affects its operating characteristics.

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 13-2.

Exhibit 13-2
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.

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.

This methodology involves 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 the short 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 the base length.

For weaving segments in which no solid white lines are used, the two lengths illustrated in Exhibit 13-2 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 0.80 × 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 point and downstream of the diverge point because of pre-segregation of movements in each case.

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

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 generally increases its capacity and improves its operation (assuming a constant demand). The one exception to this statement is if capacity is controlled by the weave configuration itself, causing the segment to break down at the ramp entry point.

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 (including auxiliary 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.

Additional lanes provide more space for both weaving and nonweaving vehicles, but they encourage optional lane-changing activity. Thus, while they reduce overall densities, additional lanes can increase lane-changing activity and intensity. However, in most cases, 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

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.

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

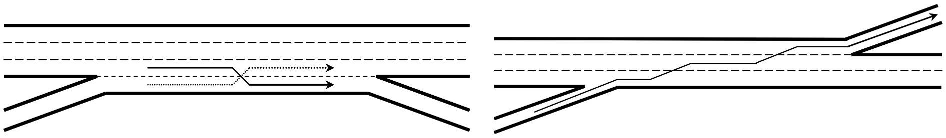
One- and two-sided weaving segments are defined as follows:

- A *one-sided weaving segment* is one in which no weaving maneuvers require more than two lane changes to be completed successfully and in which the on-ramp and off-ramp are located on the same side of the freeway.
- 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.

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.

Exhibit 13-3 compares one- and two-sided weaving segments.

Exhibit 13-3
One- and Two-Sided Weaving Segments Illustrated



(a) One-Sided Weave

(b) Two-Sided Weave

Exhibit 13-3(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.

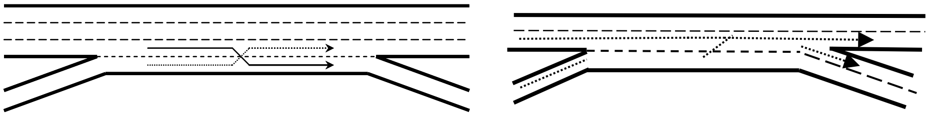
Exhibit 13-3(b) is the most common form of a two-sided weave. A one-lane, right-side on-ramp is closely followed by a one-lane, left-side off-ramp (or vice versa). Although the ramp-to-ramp weaving movement requires only two lane changes, this movement is still classified as a two-sided weave because the geometry of the segment features on-ramp and off-ramps on opposite sides of the freeway.

Simple and Complex Weaving Segments

Exhibit 13-4 illustrates the difference between a simple weaving segment and a complex weaving segment. Exhibit 13-4(a) shows a typical ramp-weaving segment, which is defined as follows:

- A *simple weave* is 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 simple 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.

Exhibit 13-4
Simple and Complex Weaving Segments Illustrated



(a) Simple Weaving Segment

(b) Complex Weaving Segment

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 14) and not as weaving segments.

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 and are analyzed with the methodology described in Chapter 14. The distance between the on-ramp and the off-ramp is not a factor in this determination.

Exhibit 13-4(b) shows a typical *complex weaving segment*, which is formed when three or more entry or exit legs have multiple lanes. A major weaving segment is distinguished from a major merge or diverge segment in the sense that the latter segments do not feature an auxiliary lane movement between an on-ramp and a downstream off-ramp. A major weave can arise because of a system interchange and connection with another freeway or because of an interchange with an arterial street with multiple lanes on the on-ramp, the off-ramp, or both.

Numerical Measures of Configuration

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

Four numerical measures of a one-sided weaving segment characterize its configuration:

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.

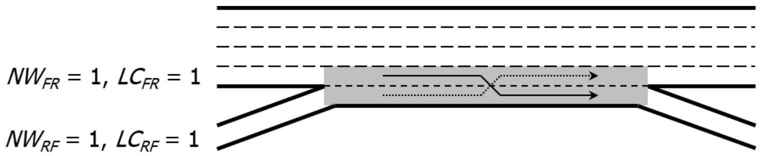
NW_{RF} = number of on-ramp lanes from which a weaving maneuver to the freeway may be completed with one lane change or no lane changes.

NW_{FR} = number of freeway lanes from which a weaving maneuver to the off-ramp may be completed with one lane change or no lane changes.

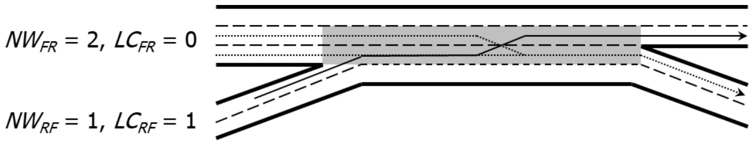
Two-sided weaving segments are described by LC_{RR}, the minimum number of lane changes that a ramp-to-ramp weaving vehicle must make to complete the ramp-to-ramp movement successfully. The parameter NW_{RR} is also used to describe two-sided weaving segments and is the number of freeway lanes from which a weaving maneuver to the off-ramp may be completed with one lane change or no lane changes.

Exhibit 13-5 illustrates how these parameters are determined for one-sided weaving segments. It is assumed 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. Shading indicates lanes from which a weaving maneuver can be made with zero or one lane changes.

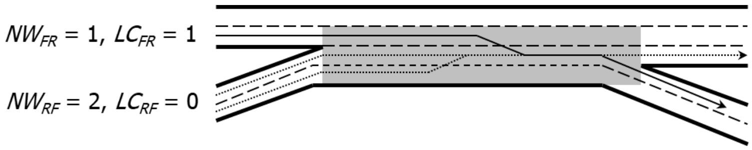
Exhibit 13-5
One-Sided Configuration Parameters Illustrated



(a) Simple Weaving Segment



(b) Complex 1–0 Weaving Segment



(c) Complex 0–1 Weaving Segment

Exhibit 13-5(a) is a five-lane simple weave. If a driver enters the segment on in the rightmost freeway lane and wishes to exit on the off-ramp, the driver must make a single lane change to enter the auxiliary lane and leave via the off-ramp. Thus, for this case, $LC_{FR} = 1$. Furthermore, the only lane from which this maneuver can be made with one or no lane changes is the rightmost freeway lane; thus, $NW_{FR} = 1$. A weaving driver entering the freeway via the on-ramp has no choice but to enter on the freeway auxiliary lane. To depart the segment on the freeway, that driver must make a single lane change from the auxiliary lane to the rightmost freeway lane. Thus, $LC_{RF} = 1$ and $NW_{RF} = 1$ as well. These parameter values are the same for all simple weaves.

Lane balance within a weaving segment provides operational flexibility.

Exhibit 13-5(b) and Exhibit 13-5(c) are both complex 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 13-5(b) is not typical. It is used here only to demonstrate the concept of lane balance in a complex weaving segment. Five lanes approach the entry to the segment and four lanes leave it, with the left-hand on-ramp lane and the rightmost freeway lane having an inside merge. Four lanes approach the exit from the segment and four lanes leave it, with the rightmost freeway lane forced to exit. Because of this configuration, vehicles approaching the exit gore must already be in an appropriate lane for their intended exit leg.

In Exhibit 13-5(b), the ramp-to-freeway movement requires at least one lane change ($LC_{RF} = 1$). A vehicle entering the segment on the leftmost on-ramp lane can merge into the rightmost freeway lane and make a single lane change to exit the segment on the freeway mainline; thus $NW_{RF} = 1$. The freeway-to-ramp weaving movement can be made without any lane changes ($LC_{FR} = 0$). A vehicle can enter on the rightmost freeway lane and leave on the leftmost off-ramp lane without executing a lane change. A vehicle can also enter on the center freeway lane and exit by making a single lane change; thus $NW_{FR} = 2$.

The exit junction in Exhibit 13-5(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 13-5(c), on-ramp vehicles may enter on either on-ramp lane and complete a weaving maneuver with either one or no lane changes ($LC_{RF} = 0$ and $NW_{RF} = 2$). Vehicles entering the segment on the freeway may enter on the rightmost freeway lane and weave with a single lane change ($LC_{FR} = 1$ and $NW_{FR} = 1$).

Paragraph describing N_{WL} deleted, as this variable is no longer used.

The values of LC_{RF} and LC_{FR} can be used to describe the type of complex weaving segment. In Exhibit 13-5(c), $LC_{RF} = 0$ and $LC_{FR} = 1$, and the segment is described as a "Complex 0–1" weaving segment. Other "0–1" configurations are possible; for example, a two-lane on-ramp with an inside merge and a one-lane off-ramp. However, the values of LC_{RF}, LC_{FR}, NW_{RF}, and NW_{FR} will be the same for all "0–1" configurations. As a result, the relative effects of entering and exiting traffic demand on the segment's speed and capacity will be the same across the various "0–1" configurations. The same holds true for other complex configurations; for example, all "0–2" configurations will share the same four parameter values and have the same relative effects of entering and exiting traffic.

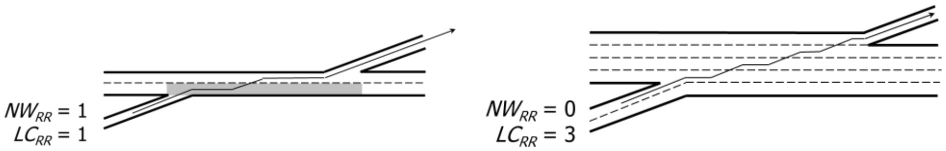
Configuration of Two-Sided Weaving Segments

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

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.

The same general principles used to determine weaving parameters for one-sided weaving segments also apply to two-side weaving segments. With one-lane on- and off-ramps, LC_{RR} equals the number of lanes in the segment minus one and both NW_{RR} and N_{WL} take either the value of 1 (for a 2-lane mainline) or 0 (for a mainline with 3 or more lanes). Exhibit 13-6 illustrates these parameters for two-sided weaving segments, with shading indicating a lane where a weaving maneuver can be made with zero or one lane changes.

Exhibit 13-6
Two-Sided Configuration Parameters Illustrated



(a) One Lane Change

(b) Three Lane Changes

In Exhibit 13-6(a), a vehicle entering from the on-ramp needs to make one lane change within the weaving segment to access the left-hand off-ramp. Thus, $LC_{RR} = 1$ and $NW_{RR} = 1$. In Exhibit 13-6(b), the minimum number of lane changes to complete the weaving maneuver is three, assuming the vehicle enters the freeway using the leftmost on-ramp lane. In this case, $LC_{RR} = 3$ and $NW_{RR} = 0$.

LOS CRITERIA

The LOS in a weaving segment, as in all freeway analysis, is related to the density in the segment. Exhibit 13-7 provides LOS criteria for weaving segments on freeways, C-D roads, and multilane highways. This methodology was developed from observations of freeway weaving segments, but may be applied to weaving segments on C-D roads, multilane highways, and uninterrupted segments of multilane surface facilities, although its use in such cases is approximate.

Exhibit 13-7
LOS for Weaving Segments

LOS	Density (pc/mi/ln)
A	0–11
B	>11–18
C	>18–25
D	>25–30
E	>30–35
F	>35, or demand exceeds capacity

Deleted mention of separate density thresholds for multilane highways and freeways.

The boundary between stable and unstable flow—the boundary between LOS E and F—occurs when the demand flow rate exceeds the capacity of the weaving segment, when density exceeds 35 pc/mi/ln. The thresholds for LOS A/B and B/C are set the same as for basic freeway segments, because weaving segment operations in this range are typically the same as, or slightly worse than, basic segment operations. Thresholds between other levels of service were set to provide a relatively even progression of densities.

3. CORE METHODOLOGY

The methodology presented in this chapter was developed in part by National Cooperative Highway Research Program (NCHRP) Project 07-26, Update of *Highway Capacity Manual*: Merge, Diverge, and Weaving Methodologies (*1*) and a concurrent study (*2*). Elements of this methodology have also been adapted from earlier studies and earlier editions of this manual (*3–11*).

SCOPE OF THE METHODOLOGY

Spatial and Temporal Limits

The methodology of this chapter is based on analysis of the peak 15-min interval within the analysis hour. The analysis hour is most often the peak hour, but the method can be applied to any hour of the day. As in most capacity analysis methodologies, demand flow rates are expressed as hourly equivalent flow rates in vehicles per hour, and not as 15-min volume counts.

The output of the analysis describes operations in all lanes within the defined weaving segment. The influence area of a weaving segment includes the base length of the segment L_B, plus 500 ft upstream and downstream. Research on the operations of weaving segments has found that the weave turbulence and associated speed reductions extend beyond the physical (gore-to-gore) boundaries of the weaving segments. This effect is accounted for in the expanded influence area, extending 500 ft on either side of the gore-to-gore distance.

Performance Measures

The procedures described in this chapter result in estimates of the average speed of all vehicles in the weaving segment S, the average density D within the weaving segment, and the segment's overall capacity. Average density is used as the service measure for the determination of LOS.

Strengths of the Methodology

The procedures in this chapter were developed from extensive research supported by a significant quantity of field data (*1, 2*). The methodology recognizes that freeway segment operations depend not only on weaving segment configuration but also the level of turbulence caused by weaving traffic.

Specific strengths of the HCM procedure include

- Providing capacity estimates that are consistent with traffic flow fundamentals related to volume, speed, and density;
- Recognizing the linkage between all freeway segment types explicitly in the procedure;
- Eliminating the use of multiple intermediate models, including lane change rates by movement; the method directly estimates overall weaving segment speed, thus improving the procedure's accuracy and utility;
- Producing a single deterministic estimate of LOS, which is important for some purposes, such as development impact reviews;

- Simplifying the method calibration and validation through the use of single speed and capacity estimates; and
- Evaluating the performance of managed lane (ML) access segments, as well as cross-weaving effects on general purpose lanes due to nearby managed lane access points.

Limitations of the Methodology

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

Bullet on speed enforcement deleted.

- Ramp metering on entrance ramps forming part of the weaving segment;
- Segment speed and other performance measure estimation during oversaturated conditions, downstream congestion, or upstream demand starvation; however, these are addressed in Chapter 10, Freeway Facility Core Methodology;
- Effects of intelligent transportation system technologies on weaving segment operations;
- Multiple weaving segments, which must be divided into appropriate merge, diverge, and simple weaving segments for analysis; and
- Weaving segments on urban streets and arterials, since urban street weaving is strongly affected by the proximity and timing of signals along the road. At the present time, there are no generally accepted methodologies for analyzing weaving movements on urban streets, including one-way frontage roads.

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

The methodology has been calibrated primarily for one-sided simple ramp weaves, although its application to major weave operations has yielded improved speed estimates compared to previous HCM methodologies. In addition, although the methodology can be applied with caution to two-sided weaves, this configuration is uncommon and was not fully calibrated with field observations.

Alternative Tool Consideration

Weaving segments can be analyzed by using a variety of stochastic and deterministic simulation tools that address freeways. These tools can be 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.

REQUIRED DATA AND SOURCES

To implement this analysis methodology, demand volumes for each weaving and nonweaving flow must be provided or estimated, or hourly flows must be combined with a peak hour factor (PHF), which allows their conversion to flow rates.

A complete geometric description of the weaving segment, including the number and alignment of lanes, lengths, and pavement markings, is also required.

Data can be collected specifically for this purpose. Where detectors exist on entry and exit legs, they may be used to gather volume or flow rate data, and possibly to estimate weaving and nonweaving demand volumes. Aerial photos can be used to assist in defining the segment geometry.

Exhibit 13-8 lists the information necessary to apply the freeway weaving methodology and suggests potential sources for obtaining these data. It also suggests default values for use when segment-specific information is not available. The user is cautioned that every use of a default value instead of a field-measured, segment-specific value may make the analysis results more approximate and less related to the specific conditions that describe the highway. HCM defaults should only be used when (*a*) field data cannot be collected and (*b*) locally derived defaults do not exist.

Exhibit 13-8
Required Input Data, Potential Data Sources, and Default Values for Freeway Weaving Analysis

Required Data and Units	Potential Data Source(s)	Suggested Default Value
	Geometric Data	
Number of lanes in the segment	Road inventory, aerial photo	Must be provided
One-sided versus two-sided weave	Road inventory, aerial photo	Must be provided
Short length of weaving segment	Road inventory, aerial photo	Must be provided
Minimum number of lane changes, ramp to freeway (one-sided weave)	Road inventory, aerial photo	Must be provided
Minimum number of lane changes, freeway to ramp (one-sided weave)	Road inventory, aerial photo	Must be provided
Minimum number of lane changes, ramp to ramp (two-sided weave)	Road inventory, aerial photo	Must be provided
Number of weaving lanes (on-ramp and freeway)	Road inventory, aerial photo	Must be provided
Terrain type (level, rolling, specific grade)	Design plans, analyst judgment	Must be provided
Free-flow speed (mi/h)	Direct speed measurements, estimate from design speed or speed limit	Speed limit + 5 mi/h
Equivalent capacity of basic freeway segment	Estimated from free-flow speed and Chapter 12	Must be provided
	Demand Data	
Hourly demand volume, freeway to freeway (veh/h)	Field data, modeling	Must be provided[a]
Hourly demand volume, freeway to ramp (veh/h)	Field data, modeling	Must be provided[a]
Hourly demand volume, ramp to freeway (veh/h)	Field data, modeling	Must be provided[a]
Hourly demand volume, ramp to ramp (veh/h)	Field data, modeling	Must be provided[a]
Analysis period length (min)	Set by analyst	15 min (0.25 h)
Peak hour factor[b] (decimal)	Field data	0.94 urban and rural
Speed and capacity adjustment factors for driver population[c]	Field data	1.0
Speed and capacity adjustment factors for weather, incidents[d]	Field data	1.0
Heavy vehicle percentage (%)	Field data	5% urban, 12% rural[e]

Notes: ***Bold italic*** indicates high sensitivity (>20% change) of service measure to the choice of default value.
Bold indicates moderate sensitivity (10%–20% change) of service measure to the choice of default value.
[a] Can be estimated using the simple weaving volume estimation method (Equation 13-2 to Equation 13-6).
[b] Moderate to high sensitivity of service measures for very low PHF values. See the discussion in the text. PHF is not required when peak 15-min demand volumes are provided.
[c] See Chapter 26 in Volume 4 for default adjustment factors for driver population.
[d] See Chapter 11 for default capacity and speed adjustment factors for weather and incidents.
[e] See Chapter 26 in Volume 4 for state-specific default heavy vehicle percentages.

The exhibit distinguishes between urban and rural conditions for certain defaults. The classification of a facility into urban and rural is made on the basis of the Federal Highway Administration smoothed or adjusted urbanized boundary definition (*12*), which in turn is derived from Census data.

Care should be taken in using default values. The service measure results are sensitive to some input data listed in Exhibit 13-7. For example, the numbers of lane changes from freeway to ramp, ramp to freeway, and ramp to ramp, as well as the number of weaving lanes, all change the service measure result by more than 20% when these inputs are varied over their normal range. In addition, the short length of the weaving segment results in a 10%–20% change in service measure when it is varied over its normal range. Low PHF values (<0.80) result in a greater than 20% change, compared with the results obtained for the default value for PHF; more typical PHFs vary the service measure results by less than 10%. The peak hour factor, heavy vehicle factor, and free-flow speed can each change the service measure by greater than 20%. Other inputs change the service measure result by less than 10% when they are varied over their normal range.

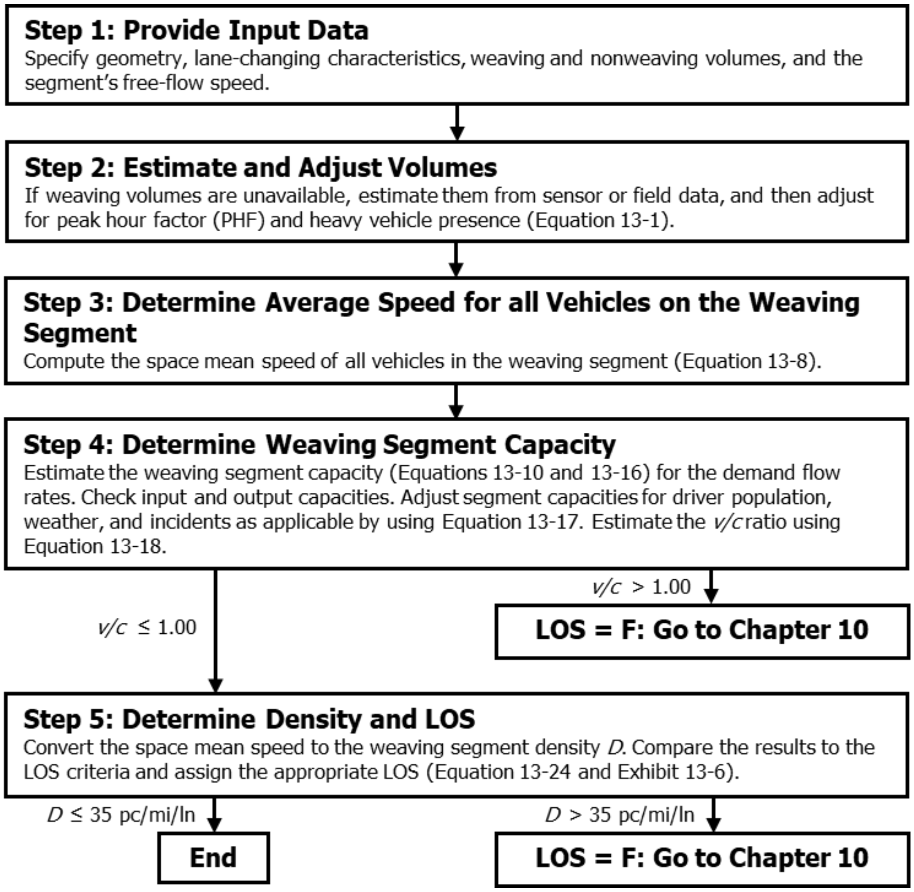
OVERVIEW OF THE METHODOLOGY

Models Used by the Methodology

Exhibit 13-9 is a flowchart illustrating the steps that define the methodology for analyzing freeway weaving segments.

Exhibit 13-9
Weaving Methodology Flowchart

LOS F exists in a weaving segment when demand exceeds capacity or density exceeds 35 pc/mi/ln.



Step 1: Provide Input Data
Specify geometry, lane-changing characteristics, weaving and nonweaving volumes, and the segment's free-flow speed.

Step 2: Estimate and Adjust Volumes
If weaving volumes are unavailable, estimate them from sensor or field data, and then adjust for peak hour factor (PHF) and heavy vehicle presence (Equation 13-1).

Step 3: Determine Average Speed for all Vehicles on the Weaving Segment
Compute the space mean speed of all vehicles in the weaving segment (Equation 13-8).

Step 4: Determine Weaving Segment Capacity
Estimate the weaving segment capacity (Equations 13-10 and 13-16) for the demand flow rates. Check input and output capacities. Adjust segment capacities for driver population, weather, and incidents as applicable by using Equation 13-17. Estimate the *v/c* ratio using Equation 13-18.

Step 5: Determine Density and LOS
Convert the space mean speed to the weaving segment density *D*. Compare the results to the LOS criteria and assign the appropriate LOS (Equation 13-24 and Exhibit 13-6).

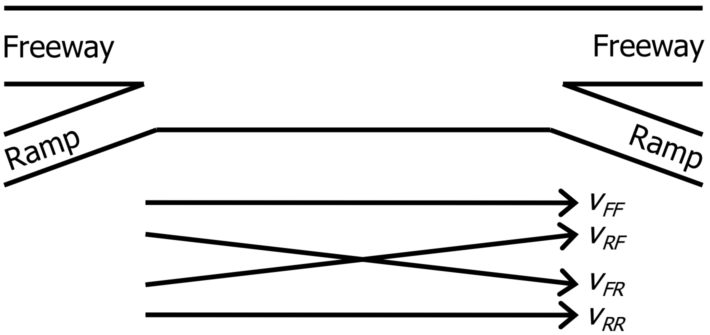
The methodology uses several types of predictive algorithms, all of which are based on a mix of theoretical and regression models, but in essence boil down to two models. These models are:

- A model to predict the average speed of vehicles in a weaving segment under stable operating conditions, that is, not operating at LOS F, including adjustments to account for the impacts of weather and incidents. Along with volume, speed is converted to density for LOS estimation.
- A model to predict the capacity of a weaving segment, including adjustments to account for the effects of weather and incidents.

Parameters Describing a Weaving Segment

Several parameters describing weaving segments have already been introduced and defined. Exhibit 13-10 illustrates additional variables that must be specified as inputs and defines those that will be used within or as outputs of the methodology. Some of them apply only to one-sided weaving segments. Exhibit 13-11 lists the variables that are different in applications to two-sided weaving segments.

Exhibit 13-10
Weaving Variables for One-Sided Weaving Segments



Variables no longer used by the methodology deleted.

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_F = entering freeway demand flow rate in the weaving segment = $v_{FF} + v_{FR}$;

v_N = on-ramp demand flow rate in the weaving segment = $v_{RF} + v_{RR}$;

v_X = off-ramp demand flow rate in the weaving segment = $v_{FR} + v_{RR}$;

v = total demand flow rate in the weaving segment (pc/h) = $v_F + v_N$;

VR = volume ratio (decimal) = $(v_{RF} + v_{FR}) / v$;

N = number of general-purpose lanes within the weaving segment (ln);

NW_{RF} = number of ramp lanes from which a weaving maneuver to the freeway may be completed with one lane change or no lane changes (ln);

NW_{FR} = number of freeway lanes from which a weaving maneuver to the ramp may be completed with one lane change or no lane changes (ln);

S_o = overall mean speed of all vehicles within the weaving segment (mi/h);

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

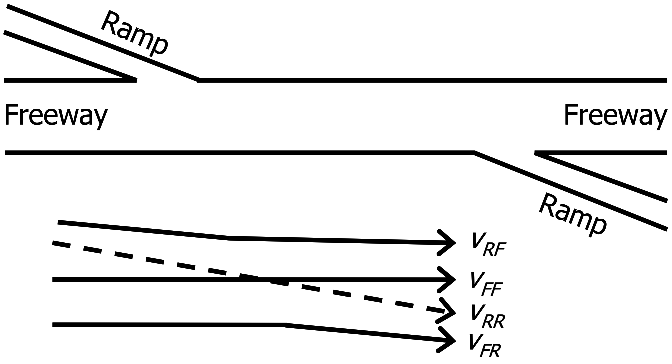
D = average density of all vehicles within the weaving segment in passenger cars per mile per lane (pc/mi/ln);

L_S = length of the weaving segment (ft), based on the short length definition of Exhibit 13-2;

LC_{RF} = minimum number of lane changes (lc) that must be made by a single weaving vehicle moving from the on-ramp to the freeway (see Exhibit 13-5); and

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).

Exhibit 13-11
Weaving Variables for Two-Sided Weaving Segments



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

All variables are defined as in Exhibit 13-10, except for the following variables relating to flow designations and lane-changing:

Variables no longer used by the method have been deleted.

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 (lc);

NW_{RR} = number of freeway lanes from which a weaving maneuver to the off-ramp may be completed with one lane change or no lane changes (ln); and

VR = volume ratio (decimal) = v_{RR} / v.

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 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.

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

COMPUTATIONAL STEPS

Each of the procedural steps noted in Exhibit 13-9 is discussed in detail in the sections that follow.

Step 1: Provide 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 expected LOS.

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.

Step 2: Estimate and Adjust Volumes

Converting Demand Volumes to Ideal Equivalents

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 13-1:

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

Equation 13-1

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 (decimal), and

f_{HV} = adjustment factor for heavy vehicle presence (decimal).

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.

The heavy vehicle adjustment factor f_{HV} is taken from Chapter 12, Basic Freeway and Multilane Highway Segments. If flow rates for a 15-min period have been provided as inputs, the PHF is taken to be 1.00 and the 15-min count is used directly after conversion to an hourly flow rate.

In the event all weaving and nonweaving movements are observed in the field, Equation 13-1 is applied to all four weaving and nonweaving movements before proceeding to Step 3. Otherwise, a simple weaving volume estimation method can be applied as explained next.

Simple Weaving Volume Estimation Method

The simple method assumes that the off-ramp attracts a similar proportion of traffic flows P from both the mainline and the on-ramp. It also assumes the availability of flow rates for both the on- and off-ramps, information which may be available from ramp sensors. The proportion P is calculated from Equation 13-2 as follows:

Equation 13-2

$$P = \frac{v_x}{v_F + v_N}$$

where all other variables are as defined in Exhibit 13-10. Once P is determined, the individual weaving movements can be estimated as follows:

Equation 13-3

$$v_{RF} = v_N(1 - P)$$

Equation 13-4

$$v_{RR} = v_N P$$

Equation 13-5

$$v_{FR} = v_x - v_{RR}$$

Equation 13-6

$$v_{FF} = v_F - v_{FR}$$

where all variables are as defined previously.

Weaving Diagram Construction

Old Step 3 (Determine Configuration Characteristics) and Step 4 (Determine Maximum Weaving Segment Length) deleted.

Once demand flow rates have been established, it may be convenient to construct a weaving diagram similar to those illustrated in Exhibit 13-10 (for one-sided weaving segments) and Exhibit 13-11 (for two-sided weaving segments).

Step 3: Determine Average Speed for all Vehicles on the Weaving Segment

Weaving segment capacity estimation is intimately tied to speed estimation to satisfy the fundamental equation of traffic flow. Conceptually, the overall speed in a weaving segment can be expressed in the following manner:

Equation 13-7

$$S_o = S_b - SIW$$

where

S_o = overall mean speed for all vehicles in the weaving segment (mi/h);

S_b = mean speed for all vehicles in an equivalent basic segment with the same number of lanes N, same demand volume v, and same free-flow speed FFS (mi/h); and

SIW = speed impedance term due to weaving and segment configuration (mi/h).

One-sided Weaving Segments

Equation 13-8 gives the general form of the speed model for S_o for one-sided weaving segments (*1*).

Equation 13-8

$$S_o = \min\left[S_b, S_b - \alpha\left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1}v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1}v_{FR}}{N^{\varepsilon}}\right)^{\gamma}\left(\frac{1}{L_S}\right)^{\delta}\left(\frac{v}{N} - 500\right)\right]$$

where α, γ, δ, and ε are regression coefficients from Exhibit 13-12 and all other variables are as previously defined.

Exhibit 13-12
Speed Model Coefficients

Segment Type	α	γ	δ	ε
Simple	0.025	0.156	0.311	3
Two-sided	0.025	0.156	0.311	3
Complex	0.056	0.300	0.400	3

The speed impedance term (SIW) of Equation 13-8 (everything to the right of S_b) behaves properly. It includes a weighted function of the weaving flows v_{RF} and v_{FR}, increases as the overall volume v increases, decreases with an increase in the number of lanes N, and increases as the short length of weave L_S decreases. In addition, when the segment flow rate drops below 500 pc/h/ln, the segment speed approaches that of a corresponding basic segment. At flow rates below 500 pc/h/ln, the speed impedance term is negative; in these cases, the mean speed for the weaving segment is constrained to be no greater than the mean speed of an equivalent basic segment.

For convenience, because it is also used in Step 4 to determine capacity, a weaving intensity factor W can be defined from the first two portions of the speed impedance term, as shown in Equation 13-9.

Equation 13-9

$$W = \alpha\left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1}v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1}v_{FR}}{N^{\varepsilon}}\right)^{\gamma}\left(\frac{1}{L_S}\right)^{\delta}$$

Substituting W into Equation 13-8 produces Equation 13-10:

Equation 13-10

$$S_o = \min\left[S_b, S_b - W\left(\frac{v}{N} - 500\right)\right]$$

It can be seen from Equation 13-9 that the relative weights of the ramp-to-freeway and freeway-to-ramp weaving flows in determining segment speed are dependent on the weaving segment configuration. This characteristic allows Equation 13-9 to be simplified for use with common weaving configurations.

For example, as described in Section 2, a simple weaving segment always has the value of 1 for LC_{RF}, LC_{FR}, NW_{RF}, and NW_{FR}. Substituting these values into Equation 13-9, along with the coefficients for a simple weave from Exhibit 13-12, reduces the equation into the following form for a simple weave:

Equation 13-11

$$W = 0.025\left(\frac{v_{RF} + v_{FR}}{N^3}\right)^{0.156}\left(\frac{1}{L_s}\right)^{0.311}$$

Thus, in a simple weave, the ramp-to-freeway and freeway-to-ramp flow equally influence weaving segment speed (and, as will be shown in Step 4, capacity).

As another example, consider a "Complex 1–0" weave (e.g., a single lane on-ramp and a two-lane off-ramp). Here, $LC_{RF} = 1$, $LC_{FR} = 0$, $NW_{RF} = 1$, and $NW_{FR} = 2$. Substituting these values into Equation 13-9, along with the coefficients for a complex weave from Exhibit 13-12, reduces the equation into the following form:

Equation 13-12

$$W = 0.056\left(\frac{v_{RF} + \frac{1}{3}v_{FR}}{N^3}\right)^{0.3}\left(\frac{1}{L_s}\right)^{0.4}$$

Thus, in a "Complex 1–0" weave, the freeway-to-ramp flow has one-third the influence on the weaving segment speed as does the ramp-to-freeway flow. This is logical, given that freeway-to-ramp traffic does not have to change lanes and thus creates less turbulence than does the ramp-to-freeway traffic, which must change lanes.

Two-sided Weaving Segments

The general form of the speed model for two-sided weaves is given by Equation 13-13.

Equation 13-13

$$S_o = \min\left[S_b, S_b - \alpha\left(\frac{\frac{LC_{RR} + 1}{NW_{RR} + 1}v_{RR}}{N^{\varepsilon}}\right)^{\gamma}\left(\frac{1}{L_s}\right)^{\delta}\left(\frac{v}{N} - 500\right)\right]$$

Similar to one-sided weaves, a simplified form of the weaving intensity factor W can be developed for two-sided weaves and then used with Equation 13-10. For example, consider a two-sided weave with one-lane on- and off-ramps and a three-lane cross-section. Here, $LC_{RR} = 2$ and $NW_{RR} = 0$ and the weaving intensity factor reduces to:

Equation 13-14

$$W = 0.025\left(\frac{3v_{RR}}{N^3}\right)^{0.156}\left(\frac{1}{L_s}\right)^{0.311}$$

Compared to a simple weave, the weaving volume in a two-sided weave has three times the influence on the weaving segment speed. This makes sense, given that the weaving volume creates turbulence across all the freeway lanes.

Check for Undersaturated Conditions

The speed estimated in Step 3 assumes that the segment operates at or below capacity; this check is performed next in Step 4.

Step 4: Determine Weaving Segment Capacity

A weaving segment's capacity is controlled by the average vehicle density exceeding 35 pc/mi/ln.

Breakdown of a weaving segment is expected to occur when the average density of all vehicles in the segment exceeds 35 pc/mi/ln. This value represents an average condition based on observed breakdown densities (*1*), with some sites showing breakdown at higher or lower density values. This condition is partially a function of the segment short length, with longer short lengths resulting in an increase in segment capacity. Note that the criteria listed in Chapter 12, Basic Freeway and Multilane Highway Segments, state that basic segment breakdowns occur at a density of 45 pc/mi/ln, which is unchanged in this methodology. Given the additional turbulence in a weaving segment, breakdown is expected to occur at lower densities than for a basic segment.

The capacity check based on weaving demand flows has been removed from the methodology.

Base Weaving Segment Capacity

Given that weaving capacity is based on reaching a density of 35 pc/mi/ln, Equation 13-7 can be rewritten as Equation 13-15, which evaluates the overall speed at the weaving segment capacity:

$$\frac{C_W}{35} = S_b(C_W) - SIW$$

Equation 13-15

where

C_W = weaving segment capacity (pc/h/ln);

$S_b(C_W)$ = basic segment speed evaluated at the weaving segment capacity (mi/h); and

SIW = speed impedance term due to weaving and segment configuration (mi/h).

Equation 13-15 is a quadratic equation in C_W since the basic segment speed uses the squared value of the flow rate in its calculation. Thus it can be solved analytically to estimate capacity. Substituting the speed impedance term of Equation 13-8 into Equation 13-15 and solving for C_W yields Equation 13-16 to estimate weaving segment capacity:

$$C_W = \frac{-b + \sqrt{b^2 - 4\,ac}}{2a}$$

Equation 13-16

with

$$a = 1$$

Equation 13-17

$$b = \frac{W}{B} + \frac{1}{35B} - 2BP$$

Equation 13-18

Equation 13-19

$$c = BP^2 - \frac{FFS}{B} - \frac{500W}{B}$$

Equation 13-20

$$B = \frac{FFS - S_c}{(C_b - BP)^2}$$

where

C_W = weaving segment capacity (pc/h/ln);

a, b, c = intermediate calculation parameters;

W = weaving segment intensity, from Equation 13-14;

B = basic segment term;

BP = basic segment breakpoint, from Exhibit 12-6 (pc/h/ln);

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

S_c = speed at capacity of an equivalent basic segment = C_b / 45 (mi/h); and

C_b = equivalent per-lane basic segment capacity, from Exhibit 12-6 (pc/h/ln).

Adjustment to Capacity for Adverse Weather, Incidents, or Driver Population

The capacity of the weaving segment may be adjusted to account for the impacts of adverse weather, driver population, occurrence of traffic incidents, or a combination of these factors. The methodology for making such adjustments is the same as that for other types of freeway segments. Default adjustment factors are found in Section 5 of Chapter 11, Freeway Reliability Analysis. The adjustments for weather and incidents are most commonly applied in the context of a reliability analysis. For convenience, a brief summary is provided here.

The segment's per-lane capacity is adjusted as shown in Equation 13-21:

Equation 13-21

$$C_{Wa} = C_W \times CAF$$

where

C_{Wa} = adjusted weaving segment capacity (pc/h/ln),

C_W = weaving segment capacity (pc/h/ln), and

CAF = capacity adjustment factor from Chapter 11 (unitless).

The CAF can have several components, including weather, incident, work zone, driver population, and calibration adjustments. CAF defaults for weather and incident effects are found in Chapter 11, along with additional discussion on how to apply them. If desired, capacity can be further adjusted to account for unfamiliar drivers in the traffic stream. While the default CAF for this effect is set to 1.0, Chapter 26 provides guidance for estimating the CAF on the basis of the composition of the driver population.

Chapter 12 provides additional guidance on capacity definitions, and Chapter 26 provides guidance on estimating freeway segment capacity, including weaving segment capacity, from field data.

Volume-to-Capacity Ratio

With the final capacity determined, the volume-to-capacity ratio (v/c ratio) for the weaving segment may be computed from Equation 13-22. The total volume v in this case represents the sum of weaving and nonweaving flows.

Equation 13-22

$$v/c = \frac{v/N}{C_{Wa}}$$

where all variables are as previously defined.

Level of Service F

LOS F occurs when demand exceeds capacity. The methodologies in Chapter 10 can be used to evaluate oversaturated weaving segments.

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, queues are expected to form within the segment, possibly extending upstream beyond the weaving segment itself. Queuing on the on-ramp that is part of the weaving segment would also be expected. The methodologies of Chapters 10 and 11, on freeway facilities, can be used to analyze the impacts of the existence of LOS F on upstream and downstream freeway segments during the analysis period and over time. Chapter 38, Network Analysis, can be used to evaluate the effects of on-ramp queue spillback into the ramp terminal.

Checking Input and Output Capacities

Last sentence in the paragraph deleted.

In most cases, the controlling capacity factor in a weaving segment is the weaving activity itself. The computational procedure for capacity of the weaving segment *guarantees* that the result will be less than the capacity of a basic freeway segment with the same number of lanes.

In rare cases, there may be insufficient capacity to accommodate the demand flows on one or more of the entry and exit roadways. Input and output roadways must be classified as either basic freeway lanes or ramps. The capacity of basic freeway lanes is checked by using the procedures of Chapter 12, Basic Freeway and Multilane Highway Segments. Ramp capacities should be checked by using the methodology of Chapter 14, Freeway Merge and Diverge Segments.

If either an entry roadway or an exit roadway has insufficient capacity, the weaving segment will not function properly, and queuing resulting from the capacity deficiency will result. LOS F is assigned, and further analysis must use the methodology of Chapter 38.

Step 5: Determine Density and LOS

Old Step 6 (Determine Lane-Changing Rates) and Step 7 (Determine Average Speeds of Weaving and Nonweaving Vehicles in Weaving Segment) deleted.

The average speed of all vehicles, computed in Step 3, must be converted to density by using Equation 13-23.

Equation 13-23

$$D = \frac{(v/N)}{S_o}$$

where D is density in passenger cars per mile per lane and all other variables are as previously defined. The density value obtained can then be used with Exhibit 13-7 to assign a LOS letter to the weaving segment. LOS can be determined for weaving segments on freeways, multilane highways, and C-D roads.

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

4. EXTENSIONS TO THE METHODOLOGY

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 segregated into separate merge, diverge, and simple weaving segments, with each segment appropriately analyzed by using this chapter's methodology or that of Chapter 14, Freeway Merge and Diverge Segments. Chapter 12, Basic Freeway and Multilane Highway Segments, contains information relative to the process of identifying appropriate segments for analysis.

C-D ROADS

The methodology applies approximately to C-D roads, 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 roads 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 road. It would have to be measured on an existing or similar C-D road, since the predictive methodology of FFS given in Chapter 12 does not apply to such roads. Whether the LOS criteria of Exhibit 13-7 are appropriate is less clear. Many C-D roads operate at lower speeds and higher densities than do basic segments, and the criteria of Exhibit 13-7 may produce an inappropriately negative view of operations on a C-D road.

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

MULTILANE HIGHWAYS

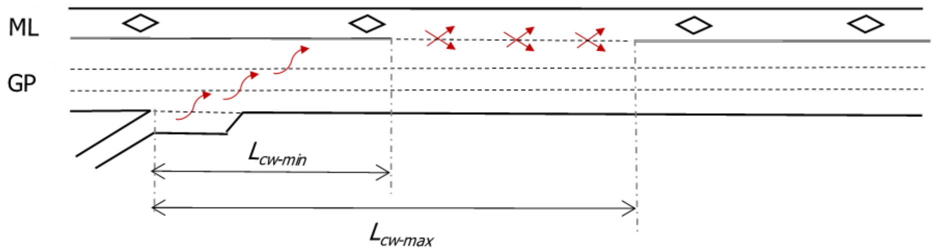
Multilane highway weaving segments may be analyzed with this methodology, except in the vicinity of signalized intersections.

Weaving segments may occur on 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.

ML ACCESS SEGMENTS

Where managed lanes have defined intermittent access segments, two types of weaving movements may be created. Exhibit 13-13 illustrates the two types of situations.

Exhibit 13-13
Weaving Movements Associated with Managed Lane Access and Egress



Note: ML = managed lane and GP = general purpose.

Exhibit 13-13 illustrates a managed lane with three general purpose freeway lanes. Where an on-ramp is near the ML access segment, on-ramp vehicles destined for the managed lane must cross all of the general purpose freeway lanes in the distance $L_{cw\text{-}min}$. The cross-weave demand can cause a reduction in the capacity of the general purpose lanes, which must be considered. While not shown, the same effect exists when an off-ramp is near the ML access segment, with the distance $L_{cw\text{-}min}$ measured from the end of the access segment to the off-ramp junction point.

The second type of weaving occurs within the ML access segment, as vehicles entering and exiting from the managed lane cross each other within the distance $L_{cw\text{-}max} - L_{cw\text{-}min}$. $L_{cw\text{-}min}$ is defined as the distance between the on-ramp gore area and the beginning of the ML access segment, while $L_{cw\text{-}max}$ is the distance from the gore to the end of the ML access segment.

Cross-Weaving Between Ramps and the ML Access Segment

The impact of cross-weaving movements on general purpose lane capacity is handled by using a CAF, as shown in Equation 13-24. The approach was developed as part of NCHRP Project 03-96 (*13*).

Equation 13-24

$$CAF = 1 - CRF$$
$$CRF = -0.0897 + 0.0252\ln(CW) - 0.00001453L_{cw\text{-}min} + 0.002967N_{GP}$$

where

CRF = capacity reduction factor (decimal),
CAF = capacity adjustment factor (decimal),
CW = cross-weave demand flow rate (pc/h),
$L_{cw\text{-}min}$ = cross-weave length (ft), and
N_{GP} = number of general purpose lanes (ln).

The capacity of the general purpose lanes is then computed as

Equation 13-25

$$c_{GPA} = c_{GP} \times CAF$$

where

c_{GPA} = adjusted capacity of the general purpose lanes (veh/h) and
c_{GP} = unadjusted capacity of the general purpose lanes, estimated by using basic freeway procedures in Chapter 12 (veh/h).

Weaving Within the ML Access Segment

Weaving within the ML access segment is treated by using the procedures of this chapter. The access segment is treated as a left-side ramp-weave segment with a length of $L_{cw\text{-}max} - L_{cw\text{-}min}$.

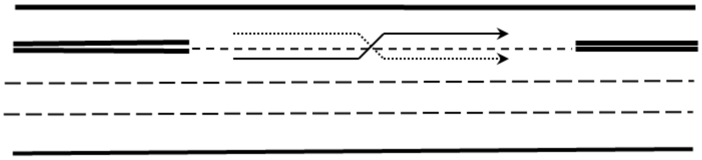
The interaction and weave turbulence effect is assumed to apply to the entire ML access segment, including all general purpose lanes. Consequently, the methodology is identical to the evaluation of a weaving segment on the left side of a freeway. When an ML access segment is evaluated as part of an extended freeway facility with managed lanes with the procedures in Chapter 10, the ML access segment represents the one exception where the general purpose and managed lanes are not treated as two separate lane groups. Instead, the calculated performance measures are applied across all lanes. In applying the weaving method, the basic segment capacity from Chapter 12, Basic Freeway and Multilane Highway Segments, should be used across all lanes when the weave capacity computations are performed (Equation 13-7).

Care should be taken when an overall managed lane facility is evaluated and the separation between the managed and general purpose lanes requires considering the adjacent friction effect, as described in Chapter 12. In those cases, the freeway facility methodology in Chapter 10 offers additional adjustments to the ML access segment for consistency with upstream or downstream ML basic segments.

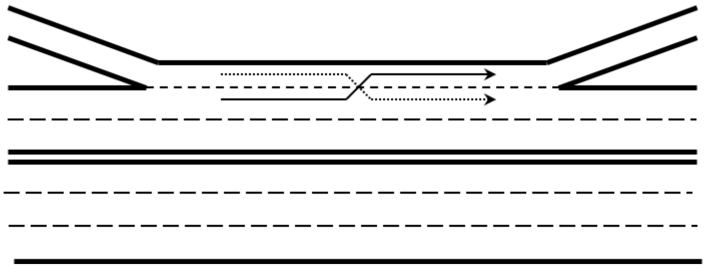
ML WEAVE SEGMENTS

The procedure described in this chapter may also be used to analyze an ML weave segment. An ML weave segment is limited to managed lane facilities with nontraversable separation from the general purpose lanes. The ML weave segment type is created when an on-ramp onto the managed lane is followed by an off-ramp from the managed lane and the two are connected by an auxiliary lane. The distinction between a ML weave and a ML access segment is illustrated in Exhibit 13-14.

Exhibit 13-14
Distinguishing ML Access and Weave Segments



(a) ML Access Segment



(b) ML Weave Segment

Note: ML = managed lane and GP = general purpose.

The procedure for analyzing an ML weave segment generally follows the methodology for a standard weaving segment. The only modification is the use of the managed lane's basic segment capacity from Chapter 12 in the weave capacity computations (Equation 13-7).

Care should be taken when an overall managed lane facility is evaluated, and the separation between the managed and general purpose lanes requires considering the adjacent friction effect, as described in Chapter 12. In those cases, the freeway facility methodology in Chapter 10 offers additional adjustments to the ML weave segment for consistency with upstream or downstream ML basic segments.

5. APPLICATIONS

This chapter's methodology 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. However, other types of analysis are possible.

EXAMPLE PROBLEMS

Chapter 27, Freeway Weaving: Supplemental, contains seven detailed sample problems addressing the following scenarios:

1. LOS of a major weaving segment,
2. LOS of a ramp-weaving segment,
3. LOS of a two-sided weaving segment,
4. Design of a major weaving segment,
5. Construction of a service volume table for a weaving segment,
6. LOS of an ML access segment with cross weaving, and
7. ML access segment with a downstream off-ramp.

RELATED CONTENT IN THE HCMAG

The *Highway Capacity Manual Applications Guide* (HCMAG), accessible through the online HCM Volume 4, provides guidance on applying the HCM on freeway weaving segments. Case Study 4 goes through the process of identifying the goals, objectives, and analysis tools for investigating LOS on New York State Route 7, a 3-mi route north of Albany. The case study applies the analysis tools to assess the performance of the route, to identify areas that are deficient, and to investigate alternatives for correcting the deficiencies.

This case study includes the following problems related to freeway weaving segments:

1. Problem 2: Analysis of a complex interchange on the western end of the route
   a. Subproblem 2b: Weaving section LOS in the I-87/Alternate Route 7
2. Problem 3: Weaving and ramp analysis
   a. Subproblem 3a: Analysis of a freeway weaving section
   b. Subproblem 3c: Nonstandard ramp and weave analysis in the southwestern quadrant
   c. Subproblem 3d: Analysis of a C-D road

Other problems in the case study evaluate the operations of a freeway weaving segment as part of a greater freeway facility as discussed in the methodology in Chapter 10, Freeway Facilities Core Methodology.

Although the HCMAG was based on the HCM2000's procedures and chapter organization, the general process for applying the weaving procedure described in its case studies continues to be applicable to the methods in this chapter.

EXAMPLE RESULTS

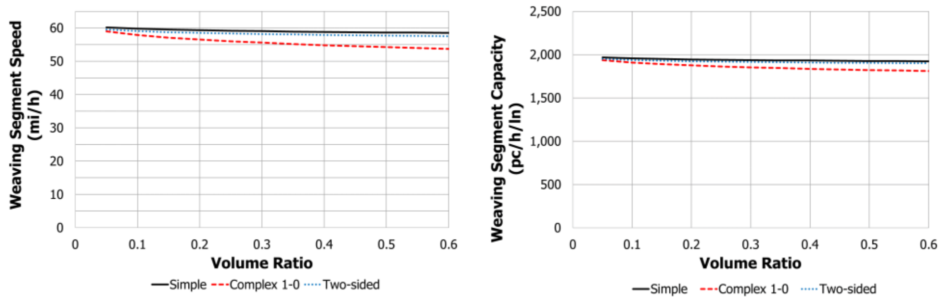
This section presents the results of applying this chapter's method in typical situations. Analysts can use the illustrative results presented in this section to observe the sensitivity of output performance measures to various inputs, as well as to help evaluate whether their analysis results are reasonable. The exhibits in this section are not intended to substitute for an actual analysis and are deliberately provided in a format large enough to depict general trends in the results but not large enough to pull out specific results.

Sensitivity of Results to Volume Ratio

Exhibit 13-15 presents illustrative results of the effect of volume ratio on the overall speed in the weaving segment, as well as on the weave segment capacity. Results are given for a three-lane weaving segment for a simple weave, a two-sided weave with one-lane on- and off-ramps, and a complex weave with a one-lane on-ramp and a two-lane off-ramp. The analysis was performed by using a fixed total volume in the weaving segment and varying the proportion of weaving versus nonweaving traffic.

It can be seen that weaving speed and capacity are relatively insensitive to the volume ratio, showing slight downward trends with increasing volume ratio. Complex weaves are somewhat more sensitive to the volume ratio than are simple or two-sided weaves.

Exhibit 13-15
Illustrative Effect of Volume Ratio on Weaving Speed and Capacity



(a) Weaving Segment Speed (b) Weaving Segment Capacity

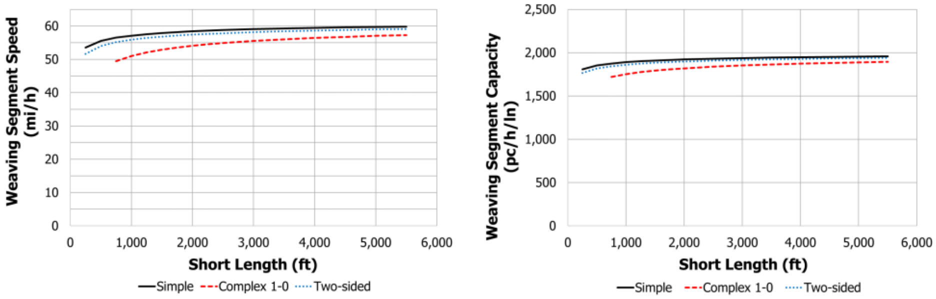
Note: Calculated by using this chapter's method, assuming short length L_S = 3,000 ft, N = 3 ln, FFS = 65 mi/h, PHF = 0.94, f_{HV} = 1, and $V_{FF} + V_{RF} + V_{FR} + V_{RR}$ = 5,400 veh/h.

Sensitivity of Results to Segment Short Length

Exhibit 13-16 presents illustrative results of the effect of the short length of the weaving segment on the segment's speed and capacity. Results are given for a three-lane weaving segment for a simple weave, a two-sided weave with one-lane on- and off-ramps, and a complex weave with a one-lane on-ramp and a two-lane off-ramp. The analysis used a fixed total volume and volume ratio.

The results for both speed and capacity show the greatest reductions at shorter short lengths, followed by a gradual linear increase in weaving segment speed and capacity as the segment short length increases. For otherwise identical conditions, a two-sided weaving segment's speed and capacity are slightly lower than that of a simple weaving segment, while a complex weaving segment's speed and capacity are noticeably lower.

Exhibit 13-16
Illustrative Effect of Short Length on Weaving Speed and Capacity



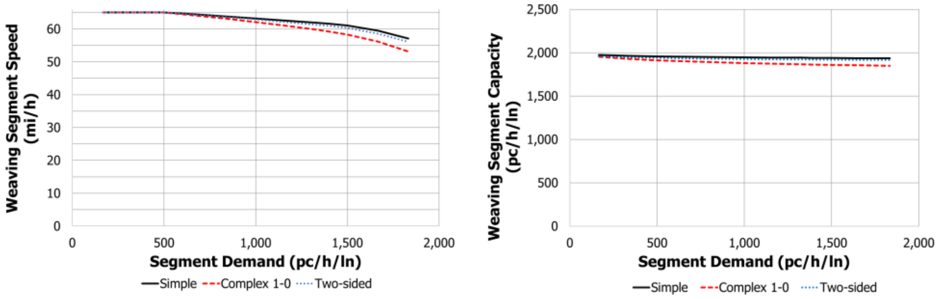
(a) Weaving Segment Speed (b) Weaving Segment Capacity

Note: Calculated by using this chapter's method, assuming N = 3 ln, FFS = 65 mi/h, PHF = 0.94, f_{HV} = 1, V = 5,400 veh/h, and VR = 0.308.

Sensitivity of Results to Weaving Segment Demand

Exhibit 13-17 presents illustrative results of the effect of weaving segment demand on the segment's speed and capacity. Results are given for a three-lane weaving segment for a simple weave, a two-sided weave with one-lane on- and off-ramps, and a complex weave with a one-lane on-ramp and a two-lane off-ramp. Results are generated for a fixed proportion of weaving to nonweaving traffic.

Exhibit 13-17
Illustrative Effect of Segment Demand on Weaving Speed



(a) Weaving Segment Speed (b) Weaving Segment Capacity

Note: Calculated by using this chapter's method, assuming short length (L_S) = 3,000 ft, N = 3 ln, FFS = 65 mi/h, PHF = 1.00, VR = 0.3, and f_{HV} = 1.

The results show three different responses in weaving segment speed to increasing demand. At low demands, the weaving segment operates similar to a basic freeway segment and the average speed equals the FFS. At somewhat higher demands, the average speed decreases slowly with increasing demand due to weaving area turbulence. Once the demand exceeds the breakpoint of an equivalent basic freeway segment, speed begins to decrease more sharply, being affected by both increased segment density (which affects S_b) and increased weaving area turbulence (which affects *SIW*). As before, the complex weave's speed is lower than that of the simple or two-sided weave, all else being equal.

The capacity estimate shows a slight downward trend at lower traffic demand flows as the demand (and thus the assumed weaving volumes v_{FR} and v_{RF}) increases. For the simple weave illustrated in Exhibit 13-17, the difference is approximately 40 pc/h between (*a*) the capacity estimate at the lowest demand flow and (*b*) the capacity determined by iteratively increasing demand until the density reaches 35 pc/mi/ln. For the complex weave, the difference is approximately 100 pc/h. This result suggests that if capacity is a desired analysis output and the calculated *v*/*c* ratio is less than 0.5, the analyst should repeat the calculation using the first capacity estimate as the assumed segment demand, increasing all demand flows proportionately.

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 and the overall density in the segment.

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 there is 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 can 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 addition, system performance monitoring applications may require planning-level applications of methodologies with simplified inputs. Further details and discussion on planning applications can be found in the *Planning and Preliminary Engineering Applications Guide to the HCM.*

In the planning and preliminary design phase, demand flows are sometimes stated as average annual daily traffic, in which case statistics must be converted to directional design hour volumes before this methodology is applied. Other planning applications use peak hour flow rates, which can be used directly in the methods in this chapter. A number of variables may be unknown (e.g., PHF and percentage of heavy vehicles), which may be replaced by default values.

Service Volumes and Service Flow Rates

The method can be applied to determine service volumes for LOS A–E for a specified set of conditions.

Service volume is the maximum hourly volume that can be accommodated without exceeding the limits of the various levels of service during the worst 15 min of the analysis hour. Service volumes can be found for LOS A–E. LOS F, which represents unstable flow, does not have a service volume.

Service flow rates are the maximum rates of flow (within a 15-min period) that can be accommodated without exceeding the limits of the various levels of service. As is the case for service volumes, service flow rates can be found for LOS A–E, but none is defined for LOS F. The relationship between a service volume and a service flow rate is as follows:

Equation 13-26

$$SV_i = SF_i \times PHF$$

where

SV_i = service volume for LOS i (pc/h),

SF_i = service flow rate for LOS i (pc/h), and

PHF = peak hour factor.

The methodology uses demand volumes in vehicles per hour converted to demand flow rates in passenger cars per hour. Therefore, service flow rates and service volumes would originally be estimated in terms of flow rates in passenger cars per hour. They would then be converted back to demand volumes in vehicles per hour.

Service volumes and service flow rates for weaving segments are stated in terms of the maximum volume (or flow) levels that can be accommodated without violating the definition of the LOS. The volume ratio, the proportion of total traffic that weaves, is held constant. Any change in the volume ratio would cause a change in all service volumes or service flow rates.

A large number of characteristics will influence service volumes and service flow rates, including the PHF, percent heavy vehicles, and any of the weaving segment's geometric attributes. Therefore, definition of a representative "typical" case with broadly applicable results is virtually impossible. Each case must be individually considered. An example is included in Chapter 27, Freeway Weaving: Supplemental, which is located in Volume 4.

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.

The limitations stated earlier in this chapter may be addressed by using available simulation tools. In some cases, the limitations are addressed by the Chapter 10 and 11 methodologies. The following conditions, which are beyond the scope of this chapter, are treated explicitly by simulation tools:

- *Ramp metering on entrance ramps forming part of the weaving segment.* These features are 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.
- *Multiple weaving segments.* Multiple weaving segments were removed from the 6th edition of the manual. They may be addressed to some extent by the procedures given in Chapters 10 and 11 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

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

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.

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 alternative tools are used, the analyst must be careful to note the definitions of simulation outputs. The principal measures involved in the 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

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

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.

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.

Paragraph comparing weaving and nonweaving speeds deleted.

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 in that 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?

6. REFERENCES

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

1. Placeholder for the NCHRP Project 07-26 final report.
2. Rouphail, N., B. Aghdashi, L. Elefteriadou, E. Amini and D. Xu. *Assessing and Addressing Deficiencies in the HCM Weaving Segment Analysis*. STRIDE Project K2 Final Report. Southeastern Transportation Research, Innovation, Development, and Education Center, Gainesville, Fla., 2021.
3. Polytechnic University and Kittelson & Associates, Inc. *Analysis of Freeway Weaving Sections*. NCHRP Project 03-75 Final Report. Brooklyn, N.Y., 2008.
4. Reilly, W., J. H. Kell, and P. J. Johnson. *Weaving Analysis Procedures for the New* Highway Capacity Manual. JHK & Associates, Tucson, Ariz., 1984.
5. Pignataro, L. J., W. R. McShane, R. P. Roess, B. Lee, and K. W. Crowley. *NCHRP Report 159: Weaving Areas: Design and Analysis.* Transportation Research Board, National Research Council, Washington, D.C., 1975.
6. Roess, R., W. McShane, E. Linzer, and L. Pignataro. *Freeway Capacity Analysis Procedures.* Project DOT-FH-11-9336. Final Report. Polytechnic Institute of New York, Brooklyn, 1979.
7. Roess, R., E. Prassas, and W. McShane. *Traffic Engineering*, 3rd ed. Pearson/Prentice Hall, Upper Saddle River, N.J., 2004.
8. Leisch, J. *Completion of Procedures for Analysis and Design of Weaving Sections.* Final Report. Jack E. Leisch and Associates, Chicago, Ill., 1983.
9. Roess, R. P. Development of Weaving Area Analysis Procedures for the 1985 *Highway Capacity Manual*. In *Transportation Research Record 1112*, Transportation Research Board, National Research Council, Washington, D.C., 1987, pp. 17–22.
10. Fazio, J. *Development and Testing of a Weaving Operational and Design Procedure.* MS thesis. University of Illinois at Chicago, 1985.
11. Fazio, J. *Modeling Safety and Traffic Operations in Freeway Weaving Sections.* PhD dissertation. University of Illinois at Chicago, 1990.
12. *Highway Functional Classification Concepts, Criteria and Procedures, 2013 Edition*. Federal Highway Administration, Washington, D.C., 2013.
13. Wang, Y., X. Liu, N. Rouphail, B. Schroeder, Y. Yin, and L. Bloomberg. *NCHRP Web-Only Document 191: Analysis of Managed Lanes on Freeway Facilities.* Transportation Research Board of the National Academies, Washington, D.C., Aug. 2012. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w191.pdf.

CHAPTER 14
FREEWAY MERGE AND DIVERGE SEGMENTS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

VOLUME 2: UNINTERRUPTED FLOW

OVERVIEW

Freeway merge and diverge segments occur primarily at on-ramp and off-ramp junctions with the freeway mainline. They can also occur at major merge or diverge points where mainline roadways join or separate.

Freeway merge and diverge segments include ramp junctions and points where mainline roadways join or separate.

A ramp is a dedicated roadway providing a connection between two highway facilities. On freeways, all movements onto and off of the freeway are made at ramp junctions, which are designed to permit relatively high-speed merging and diverging maneuvers while limiting the disruption to the main traffic stream. Some ramps on freeways connect to collector–distributor (C-D) roadways, which in turn provide a junction with the freeway mainline. Ramps may appear on multilane highways, two-lane highways, arterials, and urban streets, but such facilities may also use signalized and unsignalized intersections at such junctions.

This chapter provides guidance for using the procedures on multilane highways and C-D roadways.

The procedures in this chapter focus on ramp–freeway junctions, but guidance is also provided to allow approximate use of such procedures on multilane highways and on C-D roadways.

CHAPTER ORGANIZATION

■ New text, figures or paragraphs denoted with black margin notes

🟩 Revised text, figures or paragraphs denoted with green margin notes and red text

Chapter 14 presents methodologies for analyzing merge and diverge segment operations in uninterrupted-flow conditions. The chapter presents a methodology for evaluating isolated freeway merge and diverge segments, as well as several extensions to the core method, including analysis of two-lane ramps, left-hand ramps, and major merge and diverge segments.

Section 2 of this chapter presents the following concepts related to merge and diverge segments: overview and ramp components, classification of ramps, ramp and ramp junction analysis boundaries, ramp–freeway junction operations, base conditions, and level of service (LOS) criteria for merge and diverge segments.

Section 3 presents a method for evaluating automobile operations on merge and diverge segments. The method generates the following performance measures:

- Average speed of vehicles in the ramp influence area,
- Average density in the ramp influence area and in the aggregate across the entire segment, and
- LOS of the merge or diverge segment.

Section 4 extends the core method presented in Section 3 to incorporate considerations for single-lane ramp additions and lane drops, two-lane on-ramps and off-ramps, left-hand on-ramps and off-ramps, and ramp–freeway junctions on 10-lane freeways. The section also discusses extension of the method to major merge and diverge segments.

Section 5 presents guidance on using the results of a freeway merge or diverge segment analysis, including example results from the methods, information on the sensitivity of results to various inputs, and a discussion of service volume tables for merge and diverge segments.

RELATED HCM CONTENT

Other *Highway Capacity Manual* (HCM) content related to this chapter includes the following:

- Chapter 3, Modal Characteristics, where general characteristics of the motorized vehicle mode on freeway facilities are discussed;
- Chapter 4, Traffic Operations and Capacity Concepts, which provides background speed–flow–density concepts of freeway segments that form the basis of merge and diverge concepts presented in this chapter's Section 2;
- Chapter 10, Freeway Facilities Core Methodology, which provides a method for evaluating merge and diverge segments within an extended freeway facility and their interaction with basic segments and weaving segments;
- Chapter 11, Freeway Reliability Analysis, which provides a method for evaluating freeway facilities with weaving segments in a reliability context; the chapter also provides default speed and capacity adjustment factors that can be applied in this chapter's methodology;
- Chapter 12, Basic Freeway and Multilane Highway Segments, which must be used to evaluate a merge or diverge segment with a continuous lane add or drop, respectively;
- Chapter 28, Freeway Merges and Diverges: Supplemental, where additional methodological details and example problems for merge and diverge segments are presented;
- Case Study 4, New York State Route 7, in the *HCM Applications Guide* in Volume 4, which demonstrates how this chapter's methods can be applied to the evaluation of an actual freeway facility; and
- Section H, Freeway Analyses, in the *Planning and Preliminary Engineering Applications Guide to the HCM,* found in Volume 4, which describes how to incorporate this chapter's methods and performance measures into a planning effort.

2. CONCEPTS

OVERVIEW AND RAMP COMPONENTS

A ramp consists of three elements: the ramp roadway and two junctions. Junctions vary greatly in design and control features but generally fit into one of these categories:

- Ramp–freeway junctions (or a junction with a C-D roadway or multilane highway segment), or
- Ramp–street junctions.

Ramps to multilane highways and C-D roadways that are designed for high-speed merging or diverging may be classified as ramp–freeway junctions for analysis purposes.

When a ramp connects one freeway to another, the ramp consists of two ramp–freeway junctions and the ramp roadway. When a ramp connects a freeway to a surface facility, it generally consists of a ramp–freeway junction, the ramp roadway, and a ramp–street junction. A ramp connection to a surface facility (such as a multilane highway) or a C-D roadway that is designed for high-speed merging or diverging without control may be classified as a ramp–freeway junction for the purpose of analysis.

See Chapter 23 for a discussion of ramp–street junctions.

Ramp queuing from a junction of an off-ramp and street can influence the operations of the ramp–freeway junction and the upstream freeway.

Ramp–street junctions may be uncontrolled, STOP-controlled, YIELD-controlled, or signalized. Analysis of ramp–street junctions is not detailed in this chapter; it is discussed in Chapter 23, Ramp Terminals and Alternative Intersections. Note, however, that an off-ramp–street junction, particularly if signalized, can result in queuing on the ramp roadway that can influence operations at the ramp–freeway junction and even mainline freeway conditions. Chapter 23 includes a methodology for estimating the queue storage ratio for the off-ramp approach; the queue is expected to spill back onto the freeway when this ratio exceeds 1.0. Chapter 38, Network Analysis, provides a methodology for evaluating freeway operations when queue spillback occurs from a ramp. Mainline operations can also be affected by platoon entries created by ramp–street intersection control.

The geometric characteristics of ramp–freeway junctions vary. The length and type (parallel, taper) of acceleration or deceleration lane(s), the free-flow speed (FFS) of both the ramp and the freeway in the vicinity of the ramp, the proximity of other ramps, and other elements all affect merging and diverging operations.

CLASSIFICATION OF RAMP SEGMENTS

Ramps and ramp–freeway junctions may occur in a wide variety of configurations. Some of the key characteristics of ramps and ramp junctions are summarized below:

- Ramp–freeway junctions that accommodate merging maneuvers are classified as *on-ramps*. Those that accommodate diverging maneuvers are classified as *off-ramps*. Where the junctions accommodate the merging of two major facilities, they are classified as *major merge* junctions. Where they accommodate the divergence of two major roadways, they are classified as *major diverge* junctions.

Left-hand ramps are considered as special cases in Section 4 of this chapter.

- The majority of ramps are right-hand ramps. However, some join with the left lane(s) of the freeway and are classified as left-hand ramps. This chapter's methodology is based on right-hand ramps, but the methodology can be applied with caution to consider left-hand ramps.
- Ramp roadways may have one or two lanes. At on-ramp freeway junctions, most two-lane ramp roadways merge into a single lane before merging with the freeway. In other cases, the ramp lanes merge after the gore point. Both configurations can be evaluated by the methodology.
- For two-lane off-ramps, a single lane may exist at the ramp–freeway diverge, with the roadway widening to two lanes after the diverge. However, two-lane off-ramp roadways often have two lanes at the diverge point as well. Both configurations can be evaluated by the methodology.
- At some interchanges, two closely spaced off-ramps or on-ramps may be present. These configurations can also be evaluated by the methodology.

Section 4, Extensions to the Methodology, provides guidance for the following types of ramp configurations:

- On-ramps that add lanes to the freeway mainline.
- Major merge and major diverge junctions.

RAMP AND RAMP JUNCTION ANALYSIS BOUNDARIES

With undersaturated conditions, the operational impacts of ramp–freeway junctions occur within a 1,500-ft-long influence area.

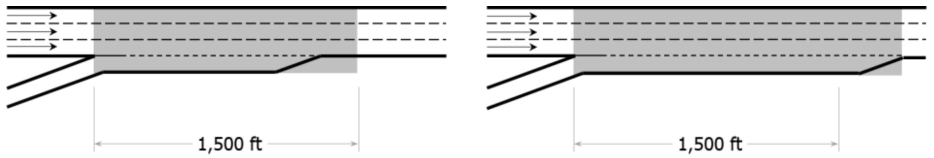
Ramps and ramp junctions do not operate independently of the roadways they connect. Thus, operating conditions on the main roadways can affect operations on the ramp and ramp junctions, and vice versa. In particular, a breakdown (LOS F) at a ramp–freeway junction may have serious effects on the freeway upstream or downstream of the junction. Freeway operations can be affected for miles in the worst cases.

The influence area includes the acceleration/deceleration lane and the right two lanes of the freeway (left two lanes for left-hand ramps).

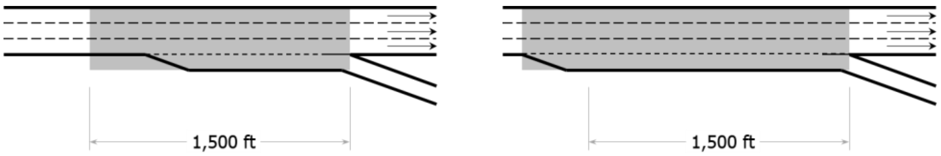
However, for most stable operations, studies (*1*) have shown that the operational impacts of ramp–freeway junctions are more localized. Thus, the methodology presented in this chapter predicts the operating characteristics within a defined ramp influence area. For right-hand on-ramps, the ramp influence area includes the acceleration lane(s) and *all* of the freeway mainline extending for a distance of 1,500 ft downstream of the merge point or the length of the acceleration lane, whichever is greater. For right-hand off-ramps, the ramp influence area includes *all* of the freeway mainline extending for a distance of 1,500 ft upstream of the diverge point *or* the length of the deceleration lane, whichever is greater. The same applies for left-hand ramps.

Exhibit 14-1 depicts single-lane ramp influence areas, with the figures on the left showing influence areas with acceleration/deceleration lanes less than 1,500 ft long, and the figures on the right showing influence areas with acceleration/deceleration lanes greater than 1,500 ft long. For two-lane right-hand ramps, the characteristics are basically the same, except that two acceleration or deceleration lanes may be present; the ramp influence area is defined by the longer of the two lanes. For left-hand ramps, merging and diverging obviously take place on the left side of the freeway.

Exhibit 14-1
Ramp Influence Areas Illustrated



(a) Merge Influence Area



(b) Diverge Influence Area

Where ramp or weaving influence areas overlap, the worst LOS of the overlapping areas is applied.

In many cases, the influence areas of adjacent ramps may overlap one another. In such cases, each influence area is analyzed separately with the methodology of this chapter. For the overlap area, the analysis resulting in the worse operating characteristics or LOS is applied. This general approach also applies to merge or diverge influence areas that overlap weaving segments.

RAMP–FREEWAY JUNCTION OPERATIONAL CONDITIONS

Ramp–freeway junctions create turbulence in the merging or diverging traffic stream. In general, the turbulence is the result of high lane-changing rates.

Ramp influence areas experience higher rates of lane-changing than normally occur in basic freeway segments.

The action of individual merging vehicles entering the traffic stream creates turbulence in the vicinity of the ramp. Approaching freeway vehicles move toward the left to avoid the turbulence. Thus, the ramp influence area experiences a higher rate of lane-changing than is normally present on ramp-free portions of freeway.

At off-ramps, the basic maneuver is a diverge, which is a single traffic stream separating into two streams. Exiting vehicles must occupy the lane(s) adjacent to the off-ramp. Thus, as the off-ramp is approached, vehicles leaving the freeway must move to the right. This causes other freeway vehicles to redistribute as they move left to avoid the turbulence of the immediate diverge area. Again, the ramp influence area has a higher rate of lane-changing than is normally present on ramp-free portions of freeway.

Vehicle interactions are dynamic in ramp influence areas. Approaching freeway through vehicles will move left as long as there is capacity to do so. Whereas the intensity of ramp flow influences the behavior of through freeway vehicles, general freeway congestion can also limit ramp flow and cause diversion to other interchanges or routes.

BASE CONDITIONS

Base conditions for merge and diverge segments are the same as for other types of freeway segments.

The base conditions for the methodology presented in this chapter are the same as for other types of freeway segments:

- No heavy vehicles,
- 12-ft lanes,
- Adequate lateral clearances (≥6 ft), and
- Motorists who are familiar with the facility.

CAPACITY OF MERGE AND DIVERGE SEGMENTS

Some research (e.g., 2, 3) has identified that the capacity of merge areas (and to a lesser extent, diverge areas) can be reduced as a result of the merge turbulence generated when a segment has both heavy mainline and heavy on-ramp flow. A merge segment with low on-ramp traffic (and thus little resulting merge turbulence) is expected to have a capacity similar to that of a basic segment. However, some merge segments that function as active bottlenecks may have capacities below that of a basic segment.

Paragraph relating to the old method deleted.

Exhibit 14-2 presents the results of a study (2) that found that merge capacities can be less than those of a basic segment. The values in the exhibit are from a study of metered on-ramps, and capacities of unmetered sites may be different. Note that capacity is related to the "maximum prebreakdown flow" shown in Exhibit 14-2. The values are given in vehicles per hour per lane and would be higher if converted to passenger cars per hour per lane on the basis of truck presence. Chapter 12, Basic Freeway and Multilane Highway Segments, offers additional discussion of prebreakdown capacity and the queue discharge flow rate.

Exhibit 14-2
Capacity Estimates at Merge Bottleneck Locations (veh/h/ln)

		Average (Standard Deviation)		
Location	No. of Lanes	Breakdown Flow	Maximum Prebreakdown Flow	Queue Discharge Flow
Minneapolis, Minn.	2	1,876 (218)	2,181 (163)	1,644 (96)
Portland, Ore.	2	2,010 (246)	2,238 (161)	1,741 (146)
Toronto, Canada	3	2,090 (247)	2,330 (162)	1,865 (124)
Sacramento, Calif.	3	1,943 (199)	2,174 (107)	1,563 (142)
Sacramento, Calif.	4	1,750 (256)	2,018 (108)	1,567(115)
San Diego, Calif.	4	1,868 (160)	2,075 (113)	1,665 (85)
San Diego, Calif.	5	1,774 (160)	1,928 (70)	1,635 (66)

Source: Elefteriadou (*2*).

This chapter's methodology develops a capacity estimate for a merge or diverge segment as a function of ramp demand, mainline demand, lane configuration, and acceleration/deceleration lane length. This base capacity can then be adjusted by the analyst through the use of a capacity adjustment factor (CAF), as described in Section 3 of the chapter. A correct calibration of the merge and diverge segment capacity is especially important in the context of a freeway facilities analysis in Chapter 10, Freeway Facilities Core Methodology.

LOS CRITERIA FOR MERGE AND DIVERGE SEGMENTS

Merge/diverge segment LOS is defined in terms of density for all cases of stable operation (LOS A–E). The boundary between stable and unstable flow—the boundary between LOS E and F—occurs when the demand flow rate exceeds the capacity of the weaving segment, when density exceeds 35 pc/mi/ln. LOS F also exists when the freeway demand exceeds the capacity of the upstream (diverges) or downstream (merges) freeway segment or when the on- or off-ramp demand exceeds the on- or off-ramp capacity.

The thresholds for LOS A/B and B/C are set the same as for basic freeway segments, because merge and diverge segment operations in this range are typically the same as, or only slightly worse than, basic segment operations. Thresholds between other levels of service were set to provide a relatively even progression of densities. At LOS C, speed within the ramp influence area begins to decline as turbulence levels become much more noticeable. Both ramp and freeway vehicles begin to adjust their speeds to accomplish smooth transitions. At LOS D, turbulence levels in the influence area become intrusive, and virtually all vehicles slow to accommodate merging or diverging maneuvers. Some ramp queues may form at heavily used on-ramps, but freeway operation remains stable. LOS E represents operating conditions approaching or at capacity. Small changes in demand or disruptions within the traffic stream can cause both ramp and freeway queues to form.

LOS F defines operating conditions within queues that form on both the ramp and the freeway mainline when capacity is exceeded by demand. When on-ramp demand exceeds on-ramp capacity, the ramp demand reaching the merge area is limited to the capacity of the on-ramp. Queues will develop at the entry to the ramp, but the merge area may experience stable operations. However, when off-ramp demand exceeds the capacity of the off-ramp roadway or ramp terminal, queues will develop and may spill back into the freeway mainline. Chapter 38, Network Analysis, can be used to analyze freeway operations when spillback occurs.

Exhibit 14-3 summarizes the LOS criteria for freeway merge and diverge segments. These criteria apply to all ramp–freeway junctions and may also be applied to major merges and diverges; high-speed, uncontrolled merge or diverge ramps on multilane highway sections; and merges and diverges on freeway C-D roadways. LOS is not defined for ramp roadways, while the LOS of a ramp–street junction is defined in Chapter 23, Ramp Terminals and Alternative Intersections.

Exhibit 14-3
LOS Criteria for Freeway Merge and Diverge Segments

LOS	Density (pc/mi/ln)
A	0–11
B	>11–18
C	>18–25
D	>25–30
E	>30–35
F	>35, or demand exceeds capacity

3. CORE METHODOLOGY

SCOPE OF THE METHODOLOGY

This chapter focuses on the operation of ramp–freeway junctions. The procedures may be applied in an approximate manner to completely uncontrolled ramp terminals on other types of facilities, such as multilane highways, two-lane highways, and freeway C-D roadways that are part of interchanges.

This chapter's procedures can be used to identify likely congestion at ramp–freeway junctions and to analyze undersaturated operations at ramp–freeway junctions. Chapter 10, Freeway Facilities Core Methodology, provides procedures for a more detailed analysis of oversaturated flow and congested conditions along a freeway section, including weaving, merge and diverge, and basic freeway segments.

Sentences referencing special cases and geometric design deleted.

The procedures in this chapter result primarily from studies conducted under National Cooperative Highway Research Program Project 07-26 (4) using the same modeling concepts (5) applied in Chapter 13, Freeway Weaving Segments.

Spatial and Temporal Limits

As discussed, this chapter's methodology focuses on the defined ramp influence area for each merge and diverge segment (Exhibit 14-1). The influence area includes all freeway lanes, including the acceleration and deceleration lanes, for a distance of 1,500 ft downstream of the merge point or upstream of the diverge point, or the length of the acceleration or deceleration lane, whichever is greater. Where LOS F is experienced, queues can extend this influence for much greater distances. Such cases must be analyzed by using the procedures of Chapters 10 and 11 on freeway facilities.

Performance Measures

Second sentence deleted, as the ramp influence area now covers all freeway lanes.

The methodology of this chapter results in predictions of the aggregate capacity, average speed, and vehicle density within the ramp influence area as defined in Exhibit 14-1.

Strengths of the Methodology

Simulation-related text deleted in this section.

This chapter's procedures were developed on the basis of extensive research supported by a significant quantity of field data. They have evolved over a number of years and represent an expert consensus. The HCM procedure's strengths are as follows:

- The methodology provides capacity estimates consistent with the fundamental traffic flow measures, where the relationship between speed, density, and flows is preserved.
- The methodology ties ramp junction operations to other freeway segment types, consistent with the approach used for weaving segments in Chapter 13.

- It uses just two models for capacity and speed estimation, thus making the methodology much more accessible to practitioners.
- The methodology's speed and capacity estimates can be adjusted to account for weather, incident, and driver population effects.
- It produces a single deterministic estimate of density and LOS, which is important for some purposes, such as development impact review.

Limitations of the Methodology

The methodology in this chapter does not take into account, nor is it applicable to (without modification by the analyst), cases involving

- Special lanes, such as high-occupancy vehicle (HOV) lanes, as ramp entry lanes;
- Significant interaction between the merge or diverge segment and other nearby on- or off-ramps.
- Ramp metering; or
- Intelligent transportation system features.

The methodology does not explicitly take into account posted speed limits or level of police enforcement. In some cases, low speed limits and strict enforcement could result in lower speeds and higher densities than those anticipated by this methodology.

Alternative Tool Considerations

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

REQUIRED DATA AND SOURCES

The analysis of a ramp–freeway junction requires details concerning the junction under analysis and adjacent upstream and downstream ramps, in addition to the data required for a typical freeway analysis.

Exhibit 14-4 lists the information necessary for applying the freeway merge and diverge segment methodology and suggests potential sources for obtaining these data. It suggests default values for use when segment-specific information is not available. The user is cautioned that every use of a default value instead of a field-measured, segment-specific value may make the analysis results more approximate and less related to the conditions that describe the highway. HCM defaults should only be used when (*a*) field data cannot be collected and (*b*) locally derived defaults do not exist.

Exhibit 14-4
Required Input Data, Potential Data Sources, and Default Values for Freeway Merge and Diverge Segment Analysis

Required Data and Units	Potential Data Source(s)	Suggested Default Value
Geometric Data		
Number of mainline freeway lanes	Road inventory, aerial photo	Must be provided
Ramp type	Road inventory, aerial photo	Must be provided
Number of lanes on ramp	Road inventory, aerial photo	1
Ramp location (right, left)	Road inventory, aerial photo	Right side
Length of acceleration lane	Road inventory, aerial photo	800 ft
Length of deceleration lane	Road inventory, aerial photo	400 ft
Terrain type (level, rolling, specific grade)	Design plans, analyst judgment	Must be provided
Free-flow speed (mi/h)	Direct speed measurements, estimate from design speed or speed limit	Speed limit + 5 mi/h
Ramp free-flow speed (mi/h)	Direct speed measurements, estimate from design speed or speed limit	35 mi/h
Demand Data		
Hourly demand volume on freeway (veh/h)	Field data, modeling	Must be provided
Hourly demand volume on ramp (veh/h)	Field data, modeling	Must be provided
Analysis period length (min)	Set by analyst	15 min (0.25 h)
Peak hour factor (decimal)	Field data	0.94 urban and rural
Speed and capacity adjustment factors for driver population[a]	Field data	1.0
Speed and capacity adjustment factors for weather and incidents[b]	Field data	1.0
Heavy vehicle percentage (%)	Field data	5% urban, 12% rural[c]

Notes: ***Bold italic*** indicates high sensitivity (>20% change) of service measure to the choice of default value.
Bold indicates moderate sensitivity (10%–20% change) of service measure to the choice of default value.
[a] See Chapter 26 in Volume 4 for default adjustment factors for driver population.
[b] See Chapter 11 for default capacity and speed adjustment factors for weather and incidents.
[c] See Chapter 26 in Volume 4 for state-specific default heavy vehicle percentages.

Inputs no longer used by the method deleted from the exhibit.

The exhibit distinguishes between urban and rural conditions for certain defaults. The classification of a facility as urban or rural is made on the basis of the Federal Highway Administration smoothed or adjusted urbanized boundary definition (*6*), which in turn is derived from Census data.

Care should be taken in using default values. The service measures are sensitive to some of the input data listed in Exhibit 14-4. For example, the FFS, the length of the acceleration lane, the peak hour factor (PHF), and the heavy vehicle percentage can bring about a greater than 20% change in the service measure when they are varied over their normal range. Assumed traffic demand volumes on mainline (for merge segments) and ramp (for merge and diverge segments) can also change the output by more than 20%. Changes in the length of the deceleration lane can result in a 10%–20% change in the service measure when varied over its normal range. Other inputs change the service measure result by less than 10% when they are varied over their normal range.

Data Describing the Freeway

The following information concerning the freeway mainline is needed to conduct an analysis:

1. FFS: 55–75 mi/h;
2. Number of mainline freeway lanes: 2–6;
3. Terrain: level or rolling, or percent grade and length;
4. Heavy vehicle presence: percent trucks and buses;
5. Demand flow rate immediately upstream of the ramp–freeway junction;
6. PHF: up to 1.00; and
7. Driver population speed and capacity adjustment factors: defaults to 1.00 (see Chapter 26, Freeway and Highway Segments: Supplemental for additional guidance)

FFS is best measured in the field but can be estimated by using the methodology for basic freeway segments or multilane highways, as applicable.

The freeway FFS is best measured in the field. If a field measurement is not available, FFS may be estimated by using the methodology for basic freeway segments presented in Chapter 12, Basic Freeway and Multilane Highway Segments. To use this methodology, information on lane widths, lateral clearances, number of lanes, and total ramp density is required. If the ramp junction is located on a multilane highway or C-D roadway, the FFS range is somewhat lower (45–60 mi/h) and can be estimated by using the methodology in Chapter 12 if no field measurements are available. The methodology can be applied to facilities with any FFS. Its use with multilane highways or C-D roadways must be considered approximate, however, since it was not calibrated with data from these types of facilities.

Where the ramp–freeway junction is on a specific grade, the length of the grade is measured from its beginning to the point of the ramp junction.

The driver population speed and capacity adjustment factors are generally set to 1.00 unless the traffic stream consists primarily of drivers who are not regular users of the facility. In such cases, an appropriate value should be based on field observations at the location under study or at similar nearby locations. Additional guidance on these factors is provided in Chapter 26.

Data Describing the Ramp–Freeway Junction

The following information concerning the ramp–freeway junction is needed to conduct an analysis:

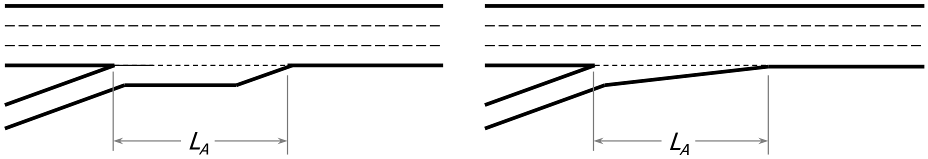
1. Type of ramp–freeway junction: merge, diverge;
2. Side of junction: right-hand, left-hand;
3. Number of lanes on freeway mainline;
4. Number of lanes on ramp roadway: 1 lane, 2 lanes;
5. Length of acceleration/deceleration lane(s);
6. FFS of the ramp roadway: 20–50 mi/h;
7. Ramp terrain: level, rolling, or mountainous; or percent grade, length;
8. Demand flow rate on ramp;

9. Heavy vehicle presence: percent trucks and buses;
10. PHF: up to 1.0; and
11. Driver population speed and capacity adjustment factors: up to 1.0.

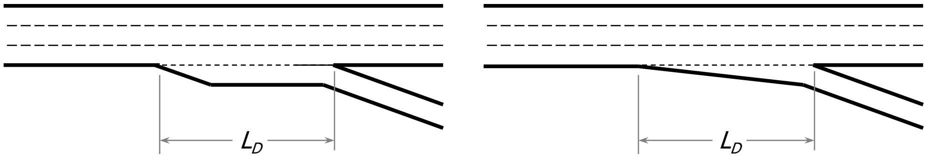
The length of the acceleration or deceleration lane includes the tapered portion of the ramp.

The length of the acceleration or deceleration lane includes the tapered portion of the ramp. Exhibit 14-5 illustrates lengths for both parallel and tapered ramp designs.

Exhibit 14-5
Measuring the Length of Acceleration and Deceleration Lanes



(a) Parallel Acceleration Lane (b) Tapered Acceleration Lane



(c) Parallel Deceleration Lane (d) Tapered Deceleration Lane

Source: Roess et al. (7).

Length of Analysis Period

The analysis period for any freeway analysis, including ramp junctions, is generally the peak 15-min period within the peak hour. Any 15-min period can be analyzed, however.

OVERVIEW OF THE METHODOLOGY

Exhibit 14-6 illustrates the computational methodology applied to the analysis of ramp–freeway junctions. The analysis is generally entered with known geometric and demand factors. The primary outputs of the analysis are LOS and capacity. The methodology estimates the capacity, density, and speed for the entire segment across all lanes.

The computational process illustrated in Exhibit 14-6 may be categorized into four primary steps:

1. Specifying input variables and converting demand volumes to demand flow rates in passenger cars per hour under equivalent base conditions;
2. Estimating the speed within the ramp influence area for stable operations (i.e., if demand turns out to be less than or equal to capacity); and
3. Estimating the capacity of the merge or diverge area and comparing the capacity with the converted demand flow rates, and checking capacity at the segment entry and exit points and on the ramp; if demand exceeds capacity, Chapter 10 procedures need to be followed;
4. Based on the estimated speed and demand flow rate within the ramp junction, computing the segment density and determining LOS.

Exhibit 14-6
Flowchart for Analysis of Ramp–Freeway Junctions

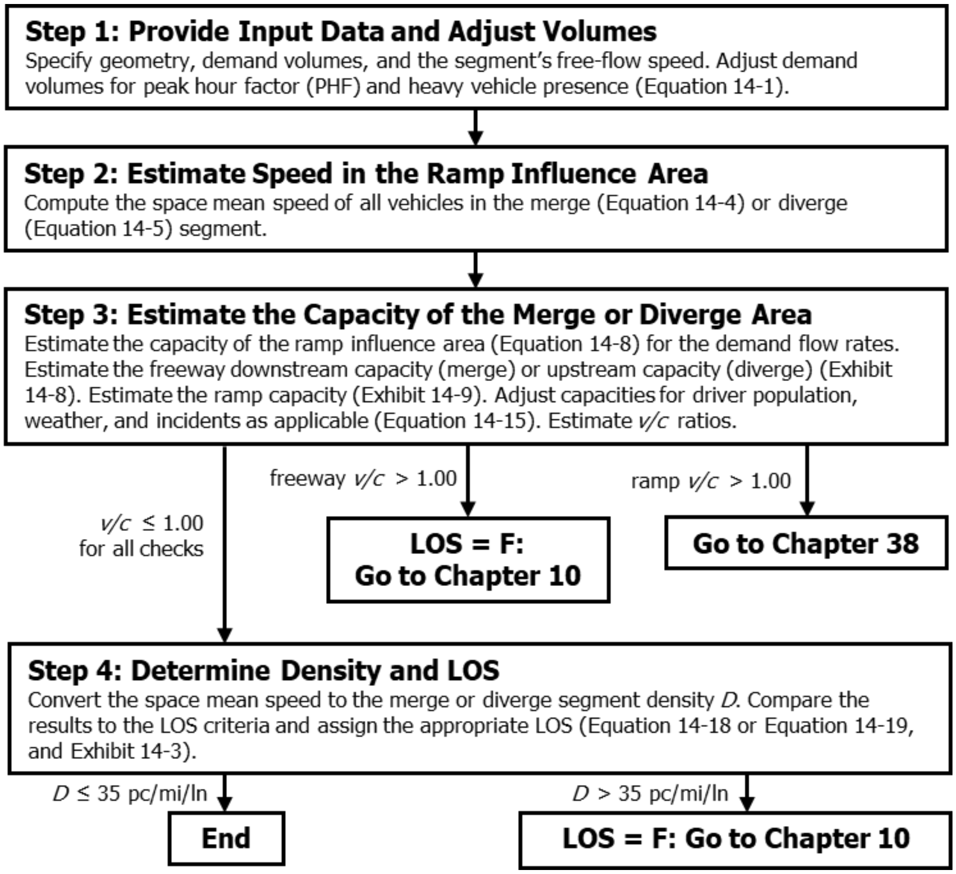
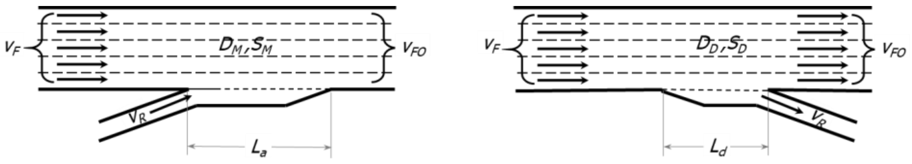


Exhibit 14-7 illustrates key variables involved in the methodology.

Exhibit 14-7
Key Ramp Junction Variables



(a) Merge Segment (b) Diverge Segment

The variables illustrated in Exhibit 14-7 are defined as follows:

Variables no longer used by the methodology deleted.

v_F = flow rate on freeway immediately upstream of the ramp influence area under study (pc/h),

v_{FO} = flow rate on the freeway immediately downstream of the merge or diverge area (pc/h),

v_R = flow rate on the on-ramp or off-ramp (pc/h),

D_M, D_D = density in the merge or diverge ramp influence area (pc/mi/ln),

S_M, S_D = average speed in the merge or diverge ramp influence area (mi/h), and

L_a, L_d = length of the acceleration or deceleration lane (ft).

COMPUTATIONAL STEPS

The methodology was calibrated for one-lane, right-side ramp–freeway junctions.

The methodology described in this section was calibrated for one-lane, right-side ramp–freeway junctions. Other cases—two-lane ramp junctions, left-side ramps, and major merge and diverge configurations—may be analyzed with this procedure as well.

Step 1: Provide Input Data and Adjust Volumes

All geometric and traffic variables for the ramp–freeway junction should be specified as inputs to the methodology, as discussed previously. Flow rates on the approaching freeway, on the ramp, and on any existing upstream or downstream adjacent ramps must be converted from hourly volumes (in vehicles per hour) to peak 15-min flow rates (in passenger cars per hour) under equivalent ideal conditions (Equation 14-1):

Equation 14-1

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

where

v_i = demand flow rate for freeway or ramp movement i (pc/h),

V_i = demand volume for movement i (veh/h),

PHF = peak hour factor (decimal), and

f_{HV} = adjustment factor for heavy vehicle presence (decimal).

If demand data or forecasts are already stated as 15-min flow rates, *PHF* is set at 1.00. Adjustment factors are the same as those used in Chapter 12, Basic Freeway and Multilane Highway Segments. These factors can also be used when the primary facility is a multilane highway or a C-D roadway in a freeway interchange.

Old Step 2 (Estimate the Approaching Flow Rate in Lanes 1 and 2 of the Freeway Immediately Upstream of the Ramp Influence Area) deleted.

Step 2: Estimate Speed in the Ramp Influence Area

Similar to the method used in Chapter 13, merge and diverge segment capacity estimation is intimately tied to speed estimation to satisfy the fundamental equation of traffic flow. Conceptually, the average speed in a merge or diverge segment can be expressed in the following manner:

Equation 14-2

$$S_M = S_b - SIM$$

Equation 14-3

$$S_D = S_b - SID$$

where

S_M = average speed for all vehicles in the merge segment (mi/h);

S_b = mean speed for all vehicles in an equivalent basic segment with the same number of freeway mainline lanes N, same demand volume v, and same free-flow speed FFS (mi/h);

SIM = speed impedance term due to merging (mi/h);

S_D = average speed for all vehicles in the diverge segment (mi/h); and

SID = speed impedance term due to diverging (mi/h).

Equation 14-4 and Equation 14-5 give the field-calibrated speed model for S_M and S_D respectively (*4*).

Equation 14-4

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_R}{N} - 500\right)\left(\frac{v_R}{L_a}\right)\right]$$

Equation 14-5

$$S_D = \min\left[S_b, S_b - 0.00014\left(\frac{v_F}{N} - 500\right)\left(\frac{v_R}{{L_d}^{0.536}}\right)\right]$$

where all variables are as previously defined.

The speed impedance term in Equation 14-4 and Equation 14-5 (everything to the right of S_b) behaves properly. Speed decreases with an increase in the overall segment demand per lane in the junction, increases as the ramp flow v_R increases, decrease as the number of lanes N decreases, and increases as the length of the acceleration L_a or deceleration lane L_d decreases. In addition, when the segment flow rate drops below 500 pc/h/ln, the segment speed approaches that of a corresponding basic segment. At flow rates below 500 pc/h/ln, the speed impedance term is negative; in these cases, the mean speed for the merge or diverge segment is constrained to be no greater than the mean speed of an equivalent basic segment.

Step 3: Estimate the Capacity of the Merge or Diverge Area and Compare with Demand

There are three checkpoints for the capacity of a ramp–freeway junction:

Locations for checking the capacity of a ramp–freeway junction.

1. The capacity of the ramp influence area itself,
2. The capacity of the freeway immediately downstream of an on-ramp or immediately upstream of an off-ramp, and
3. The capacity of the on- or off-ramp roadway.

Ramp influence area capacity is usually the controlling factor.

In most cases, the capacity of the ramp influence area is the controlling factor. While some studies (*1*) have shown that the turbulence in the vicinity of a ramp–freeway junction does not necessarily diminish the capacity of the freeway, other studies (*2–5*) have pointed to some merge and diverge segments having significantly lower capacities, with those segments acting as major bottlenecks along freeway facilities. With increasing turbulence in the merge area (and to a lesser extent, the diverge area), the segment capacity can be reduced, resulting in a breakdown of the segment and the overall freeway facility.

This chapter estimates the capacity of a merge or diverge segment as a function of on-ramp demand, mainline demand, lane configuration, and acceleration/deceleration lane length. The base capacity can then be adjusted by using a capacity adjustment factor as described below.

Capacity of the Ramp Influence Area

Research (*4*) indicates that the operation of merge and diverge segments reaches capacity when the aggregate density in the ramp influence area approaches a value of 35 pc/mi/ln. As a result, Equation 14-2 and Equation 14-3 can be rewritten as Equation 14-6 and Equation 14-7, respectively, to evaluate the segment's speed at its per-lane capacity.

Equation 14-6

$$\frac{C_M}{35} = S_b(C_M) - SIM$$

Equation 14-7

$$\frac{C_D}{35} = S_b(C_D) - SID$$

where

C_M = merge segment capacity (pc/h/ln),

$S_b(C_M)$ = basic segment speed evaluated at the merge segment capacity (mi/h),

C_D = diverge segment capacity (pc/h/ln),

$S_b(C_D)$ = basic segment speed evaluated at the diverge segment capacity (mi/h), and

other variables are as defined previously.

Equation 14-6 and Equation 14-7 can be shown to be quadratic equations in C_M and C_D, respectively, since the basic segment speed uses the squared value of the flow rate in its calculation. However, if the overall flow rate per lane on the segment is lower than the basic segment breakpoint BP, S_b will be equal to the FFS and the capacity equation becomes linear, as will be shown later. The methodology defaults to the case where $S_b < FFS$.

Substituting the *SIM* and *SID* terms in Equation 14-2 and Equation 14-3, respectively, with their values in Equation 14-6 and Equation 14-7, and solving the quadratic equation for C_M and C_D yields the following generalized capacity model in Equation 14-8:

Equation 14-8

$$C_M \text{ or } C_D = \frac{-B + \sqrt{B^2 - 4\,AC}}{2A}$$

with, for a merge ramp influence area

Equation 14-9

$$A = 35\ \times \frac{FFS - \frac{C_B}{45}}{(C_B - BP)^2}$$

Equation 14-10

$$B = 1 + 0.143\left(\frac{v_R}{L_a}\right) - (2A \times BP)$$

Equation 14-11

$$C = (A \times BP^2) - (35 \times FFS) - 71.4\left(\frac{v_R}{L_a}\right)$$

and with, for a diverge ramp influence area

Equation 14-12

$$A = 35\ \times \frac{FFS - \frac{C_B}{45}}{(C_B - BP)^2}$$

$$B = 1 + 0.0049\left(\frac{v_R}{L_d^{\,0.536}}\right) - (2A \times BP)$$

Equation 14-13

$$C = (A \times BP^2) - (35 \times FFS) - 2.45\left(\frac{v_R}{L_d^{\,0.536}}\right)$$

Equation 14-14

where

A, B, C = intermediate calculation parameters;

C_B = equivalent per-lane basic segment capacity, from Exhibit 12-6 (pc/h);

BP = basic segment breakpoint, from Exhibit 12-6 (pc/h); and

all other variables are as defined previously.

Note the parallels between the merge and diverge capacity models. In general, the merge model will in most cases yield a lower capacity than the diverge model, all other parameters being equal. This subsection has produced the first capacity check to ensure that the total demand flow per lane v/N is below the capacity calculated by Equation 14-8. If the per-lane demand flow in the merge or diverge segment exceeds the calculated capacity, the segment will operate at LOS F. The analyst can use the methods of Chapter 10 to estimate the oversaturated freeway operations.

Importantly, the two capacity models are sensitive to ramp volume. The models' capacity estimates are intended as checks that the method's speed and density estimates are valid. If the segment's true capacity is a desired output, the analyst will need to adjust demand iteratively until the input demand matches the calculated capacity; the resulting demand would then represent the true capacity for the assumed proportion of mainline and ramp demand.

Capacity of Upstream and Downstream Freeway Segments

The second capacity check is the freeway capacity immediately downstream of a merge or immediately upstream of a diverge. This capacity is the same as that of a basic freeway segment given in Chapter 12, as shown in Exhibit 14-8. If the demand in the upstream/downstream segment exceeds its capacity, the merge or diverge segment will operate at LOS F. In this situation, the analyst can use the methods of Chapter 10 to evaluate the oversaturated freeway operations.

Portions of the following two exhibits deleted that presented maximum desirable flow rates in the right two lanes.

Exhibit 14-8
Capacity Check for Neighboring Freeway Segments

FFS (mi/h)	Capacity (pc/h) of Upstream or Downstream Freeway Segment			
	2 lanes	3 lanes	4 lanes	>4 lanes
≥70	4,800	7,200	9,600	2,400/ln
65	4,700	7,050	9,400	2,350/ln
60	4,600	6,900	9,200	2,300/ln
55	4,500	6,750	9,000	2,250/ln

Notes: Number of lanes in one direction. Demand in excess of these capacities results in LOS F.

Exhibit 14-9 shows similar capacity values for high-speed ramps on multilane highways and C-D roadways within freeway interchanges. If the upstream/ downstream segment demand exceeds its capacity, the merge or diverge segment will operate at LOS F and the analysis ends at this point. The HCM does not provide a method to evaluate oversaturated multilane highways or C-D roadways.

Exhibit 14-9
Capacity Check for Neighboring Multilane Highway Segments and C-D Roadways

FFS (mi/h)	Capacity (pc/h) of Upstream or Downstream Highway or C-D Segment		
	2 lanes	3 lanes	>3 lanes
≥60	4,400	6,600	2,200/ln
55	4,200	6,300	2,100/ln
50	4,000	6,000	2,000/ln
45	3,800	5,700	1,900/ln

Notes: Number of lanes in one direction. Demand in excess of these capacities results in LOS F.

Capacity of the Ramp Roadway

The final capacity check is the capacity of the ramp roadway. The capacity of the ramp roadway is rarely a factor at on-ramps, but it can play a major role at off-ramp (diverge) junctions. Failure of diverge junctions is most often caused by a capacity deficiency on the off-ramp roadway or at its ramp–street terminal. Exhibit 14-10 provides the capacity of ramp roadways; the values for two-lane ramps are based on limited data and thus may require local calibration.

Exhibit 14-10
Capacity of Ramp Roadways (pc/h)

Ramp FFS, S_{FR} (mi/h)	Single-Lane Ramps	Two-Lane Ramps
>50	2,200	4,400
>40–50	2,100	4,200
>30–40	2,000	4,000
≥20–30	1,900	3,800
<20	1,800	3,600

Notes: Capacity of a ramp roadway does not ensure an equal capacity at its freeway or other high-speed junction. Junction capacity must be checked against criteria in Exhibit 14-8 and Exhibit 14-9.

If the on-ramp demand exceeds the on-ramp capacity, the volume able to merge onto the freeway will be constrained, while the excess demand may spill back into the ramp terminal. If the off-ramp demand exceeds the off-ramp capacity, the excess demand may spill back onto the freeway. In these situations, the analyst can use the methods in Chapter 38 to evaluate the operation of the freeway, ramp, ramp terminal, and connecting facility (urban street or freeway).

This methodology only checks the off-ramp roadway capacity. The analyst may also perform an off-ramp queue storage ratio check by using the procedures in Chapter 23, Ramp Terminals and Alternative Intersections. If the queue storage ratio exceeds 1.0, the queue may spill back onto the freeway, and the methods in Chapter 38 can be used to evaluate the operation of the ramp and freeway.

Adjustments to Capacity for Bottlenecks, Inclement Weather, or Incidents

The capacity of freeway lanes, ramp roadways, or both may be adjusted further to account for high turbulence in the merge or diverge segment, as well as for the impacts of adverse weather, driver population, and traffic incidents. This adjustment is the same as that for other freeway segment types; default values are provided in Chapter 11, Freeway Reliability Analysis. The weather and incident adjustments are most commonly applied in the context of a reliability analysis as described in that chapter. For convenience, a brief summary is provided here.

The per-lane capacity of a merge or diverge segment is adjusted as follows:

Equation 14-15

$$(C_{Ma} \text{ or } C_{Da}) = (C_M \text{ or } C_D) \times CAF$$

where

C_{Ma}, C_{Da} = adjusted capacity of merge/diverge area (pc/h/ln);

C_M, C_D = unadjusted capacity of merge/diverge area (pc/h/ln); and

CAF = capacity adjustment factor, from Chapter 11 (unitless).

The CAF can have several components, including adjustments for merge or diverge turbulence, weather, incidents, work zones, driver population, and calibration. CAF adjustments for turbulence at bottlenecks are best calibrated from local data or, alternatively, are based on regional or state defaults. CAF defaults for weather and incident effects are found in Chapter 11, along with additional discussion on how to apply them.

If desired, capacity can be further adjusted to account for unfamiliar drivers in the traffic stream. While the default CAF for driver population is set to 1.0, guidance is provided in Chapter 26 that gives estimates of CAF based on the composition of the driver population.

Chapter 12 provides additional guidance on capacity definitions, while Chapter 26 provides guidance on estimating freeway segment capacity, including weaving segment capacity, from field data.

Step 4: Estimate Density and LOS

Sections describing regression equations for estimating density deleted.

LOS in ramp influence areas is directly related to the estimated density within the area, as given by Equation 14-16 for merge segments or Equation 14-17 for diverge segments. Exhibit 14-3 contains the criteria for this determination. Note again that density definitions of LOS apply only to stable flow (i.e., LOS A–E). LOS F exists only when the capacity of the ramp junction is insufficient to accommodate the existing or projected demand flow rate.

Equation 14-16

$$D_M = \frac{(v_F + v_R)}{N \times S_M}$$

Equation 14-17

$$D_D = \frac{v_F}{N \times S_D}$$

Old Step 5 (Estimate Speeds in the Vicinity of Ramp–Freeway Junctions) and Aggregating Densities section deleted.

If a merge or diverge segment is determined (or expected) to operate at LOS F, the analyst should go to Chapters 10 and 11 to conduct a facility analysis that will estimate the spatial and time impacts of queuing resulting from the breakdown.

4. EXTENSIONS TO THE METHODOLOGY

Extensions now covered by the methodology deleted from this section.

SPECIAL CASES

The computational procedure for ramp–freeway junctions was developed from a dataset containing a variety of right-side ramp configurations, including:

- Single-lane on- and off-ramps,
- Two consecutive merges or diverges,
- Lane-drop diverges,
- Two-lane on-ramps with one added lane,
- Two-lane off-ramps with and without a lane drop, and
- Metered on-ramps.

This section provides guidance for extending the methodology addressing the following configurations:

- Lane additions and drops, and
- Major merges and diverges.

Lane Additions and Lane Drops

On-ramps and off-ramps do not always include merge and diverge elements. In some cases, there are lane additions at on-ramps or lane drops at off-ramps. Lane additions are defined as merge segments where all the ramp lanes at the gore continue past the next downstream on- or off-ramp. Lane drops are defined as diverge segments where one or more mainline lanes that existed at the previous upstream on- or off-ramp are forced to exit.

Analysis of lane additions and lane drops is relatively straightforward. The freeway segment downstream of the on-ramp or upstream of the off-ramp is simply considered to be a basic freeway segment with an additional lane or lanes. The procedures in Chapter 12, Basic Freeway and Multilane Highway Segments, should be applied in this case.

The case of an on-ramp lane addition followed by an off-ramp lane drop is treated as a weaving segment and should be evaluated with the procedures of Chapter 13, Freeway Weaving Segments.

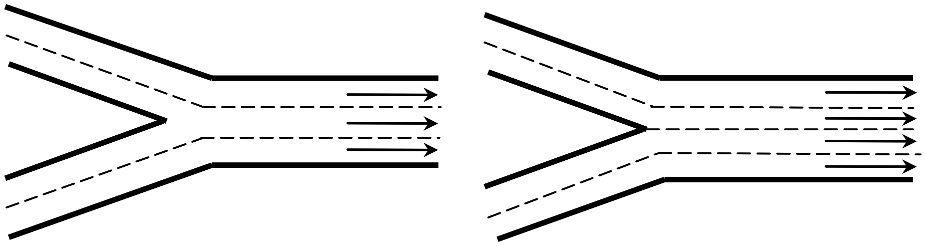
Ramps with two or more lanes frequently have lane additions or drops for some, but not all of the ramp lanes. These configurations incorporate an element of merging or diverging turbulence for the other ramp lanes and are evaluated using this chapter’s core methodology.

Major Merge Areas

A major merge area is one in which two primary roadways, each having multiple lanes, merge to form a single freeway segment. Such junctions occur when two freeways join to form a single freeway or when a major multilane high-speed ramp joins with a freeway. Major merges are different from one- and two-lane on-ramps in that each of the merging roadways is generally at or near freeway design standards and no clear ramp or acceleration lane is involved in the merge.

Such merge areas come in a variety of geometries, all of which fall into one of two categories. In one geometry, the number of lanes leaving the merge area is one less than the total number of lanes entering it. In the other, the number of lanes leaving the merge area is the same as that entering it. These geometries are illustrated in Exhibit 14-11.

Exhibit 14-11
Major Merge Areas Illustrated



(a) Major Merge with One Lane Dropped (b) Major Merge with No Lane Dropped

There are no effective models of performance for a major merge area. Therefore, analysis is limited to checking capacities on the approaching legs and the downstream freeway segment. A merge failure would be indicated by a v/c ratio in excess of 1.00.

LOS cannot be determined for major merge areas.

LOS cannot be determined specifically for major merge areas. Problems in major merge areas usually result from insufficient capacity of the downstream freeway basic, merge/diverge, or weaving segment. A rough estimate of LOS in a major merge area could be obtained by applying the basic freeway segment criteria to the segment immediately downstream of the merge. However, this would not account for the effect of turbulence in the segment, and operating conditions would likely be worse than predicted.

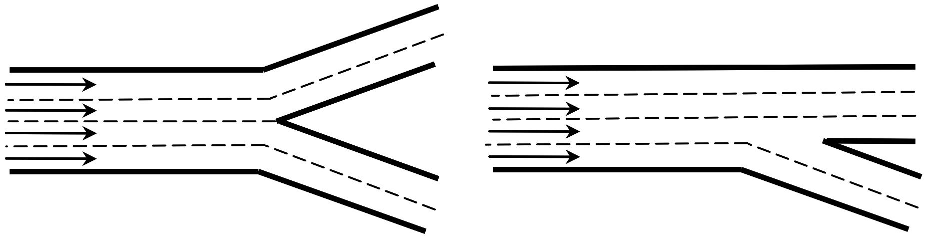
Major Diverge Areas

A major diverge area is one in which two primary roadways, each having multiple lanes, diverge from a single freeway segment. Such junctions occur when a freeway splits to become two separate freeways or when a major multilane high-speed ramp diverges from the freeway. Major diverges are different from one- and two-lane off-ramps in that each of the diverging roadways is generally at or near freeway design standards and no clear ramp or deceleration lane is involved in the merge.

The two common geometries for major diverge areas are illustrated in Exhibit 14-12. In the first case, the number of lanes leaving the diverge area is the same as the number entering it. In the second, the number of lanes leaving the diverge area is one more than the number entering it.

The principal analysis of a major diverge area involves checking the capacity of entering and departing roadways, all of which are generally built to mainline standards. A failure results when any of the demand flow rates exceeds the capacity of the segment.

Exhibit 14-12
Major Diverge Areas Illustrated


(a) Major Diverge Area with No Lane Addition (b) Major Diverge Area with Lane Addition

For major diverge areas, a model exists for computing the average density across all approaching freeway lanes within 1,500 ft of the diverge, as given in Equation 14-18:

Equation 14-18

$$D_{MD} = 0.0175\left(\frac{v_F}{N}\right)$$

where

D_{MD} = density in the major diverge influence area (which includes all approaching freeway lanes) (pc/mi/ln),

v_F = demand flow rate immediately upstream of the major diverge influence area (pc/h), and

N = number of lanes approaching the major diverge (ln).

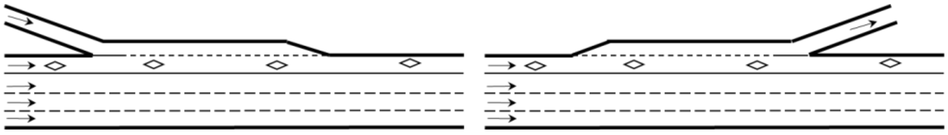
The result can be compared with the criteria of Exhibit 14-3 to determine a LOS for the major diverge influence area. Note that the density and LOS estimates are only valid for stable cases (i.e., not in cases in which LOS F exists because of a capacity deficiency on the approaching or departing legs of the diverge).

MANAGED LANE ACCESS POINTS

Managed lanes on freeways may be accessed in many ways. One possible design is the provision of direct entries and exits to a managed lane or lanes by ramps. This is illustrated in Exhibit 14-13.

These merge or diverge segments onto a one-lane managed lane facility may be treated as isolated merge and diverge areas onto a one-lane mainline and evaluated by using an adaptation of the methods in this chapter. This accounts for the fact that there is no interaction between general purpose lanes and the managed lane in the vicinity of the ramp. Since the procedures of this chapter have been calibrated to segments with two or more lanes on a mainline segment, a modification to the inputs is needed.

Exhibit 14-13
Direct Ramp Access to Managed Lanes


(a) Merge (b) Diverge

Managed lane segment types were defined in Chapter 10.

The operations of a managed lane (ML) merge or ML diverge segment with a single mainline lane can be approximated by doubling the managed lane mainline volume before analysis and evaluating the segment as if there were two through lanes on the managed lanes. The resulting computational results for segment speed and density will then be true to the assumptions used in development of the methods in this chapter. The results should then be applied only to the single managed lane.

Care should be taken to consider only the single managed lane in performing a capacity check on the segment. For the on-ramp case, the capacity of the ramp roadway and the downstream managed lane should be compared with demand flows. For the off-ramp case, the capacities of the ramp roadway and the upstream managed lane are used. Where either capacity is exceeded by demand, a failure (LOS F) is anticipated. The capacity of the ML merge or ML diverge segment should further be capped to not exceed the capacity of a basic managed lane segment, especially where there is an adjacent friction effect on managed lane operations.

For managed lane segments with more than one through lane, the procedures in this chapter can be applied without further adjustments to estimate the capacity, segment speed, and other performance measures for the ML merge or ML diverge segment. However, care should be taken when an overall managed lane facility is being evaluated and the separation between the managed lane and general purpose lanes requires consideration of the adjacent friction effect, as described in Chapter 12, Basic Freeway and Multilane Highway Segments. In these cases, the core freeway facilities methodology in Chapter 10 offers additional adjustments.

EFFECT OF RAMP CONTROL AT RAMPS

For the purposes of this methodology, procedures are not modified in any way to account for the local effect of ramp control—except for the limitation that the ramp meter may have on the ramp demand flow rate. Research (*8*) has found that the breakdown of a merge area may be a probabilistic event based on the platoon characteristics of the arriving ramp vehicles. Ramp meters facilitate uniform gaps between entering ramp vehicles and may reduce the probability of a breakdown on the associated freeway mainline.

Section 4 of Chapter 37, ATDM: Supplemental, provides guidance on estimating the effects of ramp metering strategies in the context of a freeway facilities analysis.

5. APPLICATIONS

The methodology of this chapter is most often used to estimate the capacity and LOS of ramp–freeway junctions. The steps are most easily applied in the operational analysis mode (i.e., all traffic and roadway conditions are specified), and the capacity (and *v/c* ratio) and expected LOS are found. Other types of analysis are also possible.

EXAMPLE PROBLEMS

The following example problems illustrating the application of the methodology of this chapter are found in Chapter 28, Freeway Merge and Diverge Segments: Supplemental:

- Isolated, single-lane, right-hand on-ramp to a four-lane freeway;
- Two adjacent single-lane, right-hand off-ramps on a six-lane freeway;
- Single-lane on-ramp followed by a one-lane off-ramp on an eight-lane freeway;
- Single-lane left-hand on-ramp on a six-lane freeway; and
- Service flow rates and service volumes for an isolated on-ramp on a six-lane freeway.

RELATED CONTENT IN THE HCMAG

The *Highway Capacity Manual Applications Guide* (HCMAG), accessible through the online HCM Volume 4, provides guidance on applying the HCM on freeway merge and diverge segments. Case Study 4 goes through the process of identifying the goals, objectives, and analysis tools for investigating LOS on New York State Route 7, a 3-mi route north of Albany. The case study applies the analysis tools to assess the performance of the route, to identify areas that are deficient, and to investigate alternatives for correcting the deficiencies.

This case study includes the following problems related to freeway merge and diverge segments:

1. Problem 2: Analysis of a complex interchange on the western end of the route.
    a. Subproblem 2c: Ramp and ramp junction LOS for the on-ramp from Alternate Route 7 to I-87 northbound
    b. Subproblem 2d: Mitigation techniques for the on-ramp from Alternate Route 7 to I-87 northbound
2. Problem 3: Weaving and ramp analysis
    a. Subproblem 3b: Freeway ramp analysis
    b. Subproblem 3c: Nonstandard ramp and weave analysis in the southwestern quadrant

Other problems in the case study evaluate the operations of freeway merge and diverge segments as part of a greater freeway facility as discussed in the methodology in Chapter 10, Freeway Facilities Core Methodology.

Although the HCMAG was based on the HCM2000's procedures and chapter organization, the general thought process described in its case studies is also applicable to this edition of the HCM.

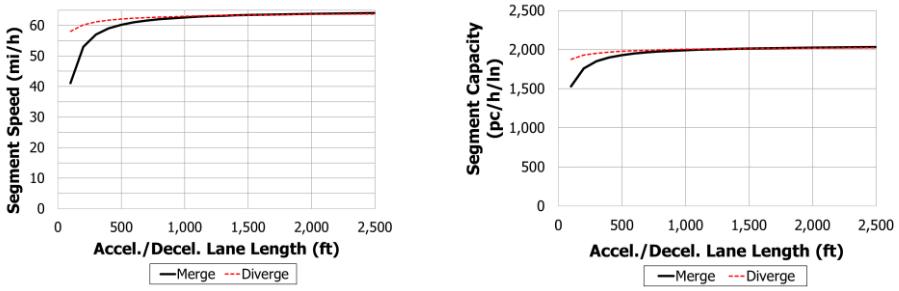
EXAMPLE RESULTS

This section presents the results of applying this chapter's method in typical situations. Analysts can use the illustrative results presented in this section to observe the sensitivity of output performance measures to various inputs, as well as to help evaluate whether their analysis results are reasonable. The exhibits in this section are not intended to substitute for an actual analysis and are deliberately provided in a format large enough to depict general trends in the results, but not large enough to pull out specific results.

Sensitivity of Results to Acceleration Lane Length

Exhibit 14-14 presents illustrative results of the effect of acceleration lane length on the overall speed and capacity of merge and diverge segments, when demand is close to the merge capacity at short acceleration lane lengths.

Exhibit 14-14
Illustrative Effect of Acceleration Lane Length on Merge and Diverge Segment Speed and Capacity



(a) Speed (b) Capacity

Notes: Accel. = acceleration, decel. = deceleration. Calculated by using this chapter's method, assuming 3 mainline lines, 1 ramp lane, freeway FFS = 65 mi/h, ramp FFS = 40 mi/h, mainline through demand = 3,200 veh/h, ramp demand = 640 veh/h, PHF = 0.94, and f_{HV} = 1.

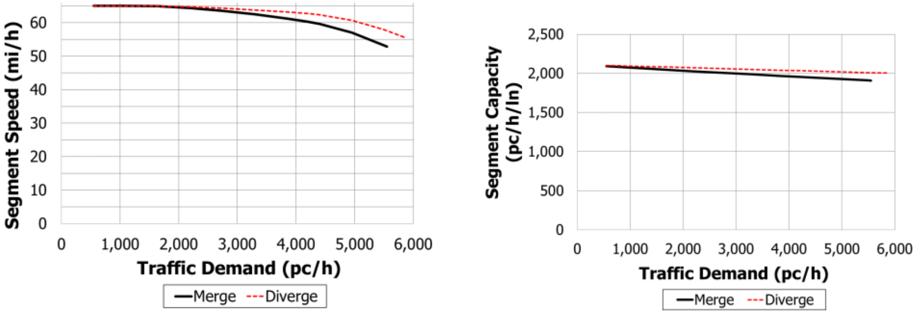
The results illustrate that an increase in the acceleration lane length increases a merge segment's speed and capacity substantially when the acceleration lane is less than 500 ft long. Speed and capacity increase more gradually at lengths between 500 and 1,500 ft, while additional length over 1,500 ft provides minimal additional improvement. This result is explained practically, because greater acceleration lane length gives vehicles more space for completing the merge maneuver. In the methodology, the added acceleration lane length also translates to a reduced density.

The results also illustrate a diverge segment's speed and capacity is greater than that of an equivalent merge segment at short deceleration lane lengths, but that merge and diverge segments operate similarly when acceleration and deceleration lane lengths exceed 1,000 ft. Increasing the deceleration lane length above 500 ft provides minimal additional improvement in diverge segment performance. The capacity of merge and diverge segments is less than that of an equivalent basic segment (in this example, 2,350 pc/h/ln).

Sensitivity of Results to Overall Traffic Demand Level

Exhibit 14-15 presents illustrative results of the effect of increasing traffic demand on the overall speed and capacity of merge and diverge segments. The on-ramp demand was assumed at a fixed ratio of 10% of mainline flow, and the acceleration and deceleration lane lengths were set at 300 ft.

Exhibit 14-15
Illustrative Effect of Traffic Demand Level on Merge and Diverge Segment Speed and Capacity



(a) Speed (b) Capacity

Note: Calculated by using this chapter's method, assuming 3 mainline lines, 1 ramp lane, freeway FFS = 65 mi/h, ramp FFS = 40 mi/h, acceleration/deceleration lane length = 300 ft, and ramp demand = 10% of mainline through demand.

The results illustrate that an increase in traffic demand level decreases the overall segment speed, with diverge segment speeds being greater than or equal to that of an equivalent merge segment. Higher traffic demand results in a greater density of vehicles and decreased headways between vehicles. At greater densities, drivers respond by reducing their travel speed. The speed curves have three distinct sections. When the traffic demand is less or equal to than 500 pc/h/ln, the merge or diverge segment speed equals that of an equivalent basic segment. Between 500 pc/h/ln and the basic segment breakpoint of 1,400 pc/h/ln, increasing turbulence in the merge and diverge segment causes a gradual reduction in speed. Above the breakpoint value, merge and diverge segment speeds decrease more rapidly, being influenced both by decreasing equivalent basic segment speeds (i.e., increasing density) and by merge/diverge turbulence.

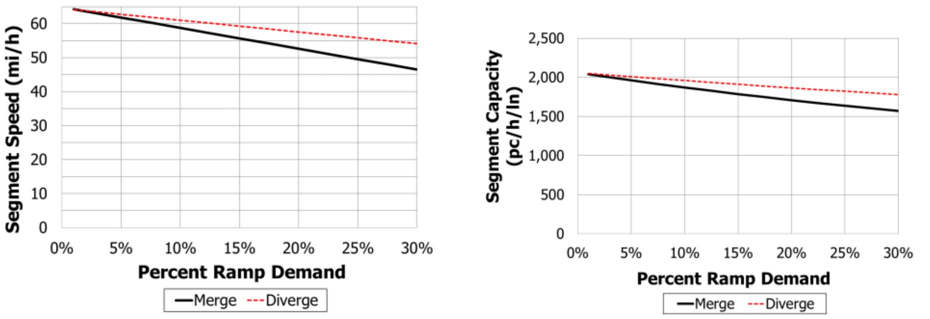
The capacity estimate shows a downward trend as traffic demand (and thus the assumed ramp volume) increases. This result indicates that if (1) the segment's true capacity is a desired analysis output and (2) ramp demand is assumed to be a fixed proportion of total segment demand, the analyst would need to adjust the freeway mainline and ramp demands proportionately and iteratively until the demand equaled the calculated capacity. The resulting demand value would then represent the segment's true capacity.

Because the assumed acceleration and deceleration lane lengths are short, the diverge segment has a higher capacity than that of its equivalent merge segment. However, as shown in the previous example, the two segments would have essentially the same capacity if somewhat longer (e.g., 1,000 ft or greater) lengths were assumed.

Sensitivity of Results to Proportion of Ramp Demand

Exhibit 14-16 presents illustrative results of the effect of the proportion of ramp demand on the overall speed and capacity of merge and diverge segments. Overall demand in the segment is assumed to be fixed at 4,500 veh/h, and acceleration and deceleration lanes are assumed to be 300 ft long.

Exhibit 14-16
Illustrative Effect of Proportion of Ramp Demand on Merge and Diverge Segment Speed and Capacity



(a) Speed

(b) Capacity

Note: Calculated by using this chapter's method, assuming 3 mainline lines, 1 ramp lane, freeway FFS = 65 mi/h, ramp FFS = 40 mi/h, acceleration/deceleration lane length = 300 ft, segment demand = 4,500 veh/h, PHF = 0.94, and f_{HV} = 1.

The results illustrate that speed decreases linearly in proportion to the percentage of segment demand coming from an on-ramp or going to an off-ramp. Diverge segment speeds are higher for a given percentage of ramp demand, relative to an equivalent merge segment. The capacity results indicate similar, although not quite linear, trends.

TYPES OF ANALYSIS

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

Establish Analysis Boundaries

No ramp–freeway junction is completely isolated. However, for the purposes of this methodology, many may operate as if they were. In the analysis of ramp–freeway junctions, establishing the segment of freeway over which ramp junctions are to be analyzed is important. Once this is done, each ramp may be analyzed in conjunction with the possible impacts of upstream and downstream adjacent ramps according to the methodology.

Analysis boundaries may also include different demand scenarios related to the time of the day or to different development scenarios that produce different demand flow rates.

Any application of the methodology presented in this chapter can be made easier by carefully defining the spatial and time boundaries of the analysis.

Operational Analysis

Operational analysis determines density, LOS, and speed within the ramp influence area for a specified set of conditions.

The methodology is most easily applied in the operational analysis mode. In operational analysis, all traffic and geometric characteristics of the analysis segment must be specified, including

- Analysis hour demand volumes for the subject ramp, adjacent ramps, and freeway (veh/h);
- Heavy vehicle percentages for all component demand volumes (ramps, adjacent ramps, freeway);
- PHF for all component demand volumes (ramp, adjacent ramps, freeway);
- Freeway terrain (level, rolling, mountainous, specific grade);
- FFS of the freeway and ramp (mi/h); and
- Ramp geometrics: number of lanes, length of acceleration lane(s) or deceleration lane(s).

Terrain deleted as a ramp input. Distance to upstream and downstream adjacent ramps deleted.

The outputs of an operational analysis will be estimates of density, LOS, and speed for the ramp influence area. The capacity of the ramp–freeway junction will also be established.

The steps of the methodology, described in the Methodology section, are to be followed directly without modification.

Design Analysis

Design analysis seeks to determine the geometric characteristics of the ramp that are needed to deliver a target LOS.

In design analysis, a target LOS is set and all relevant demand volumes are specified. The analysis seeks to determine the geometric characteristics of the ramp that are needed to deliver the target LOS. These characteristics include

- FFS of the ramp (mi/h),
- Length of acceleration L_a or deceleration lane L_d (ft), and
- Number of lanes on the ramp.

In some cases, variables such as the type of junction (e.g., major merge, two-lane) may also be under consideration.

There is no convenient way to compute directly the optimal value of any one variable without specifying all of the others. Even then, the computational methodology does not easily create the desired result.

Therefore, most design analysis becomes a trial-and-error application of the operational analysis procedure. Individual characteristics can be incrementally changed, as can groups of characteristics, to find scenarios that produce the desired LOS.

In many cases, some of the variables may be fixed by site-specific conditions. These can be set at their limiting values before an attempt is made to optimize the others.

A spreadsheet can be programmed to complete such an analysis. Scenario results are provided by simply changing some of the input variables under consideration. HCM-implementing software can also be used to simplify the computational process.

Planning and Preliminary Engineering Analysis

Planning and preliminary engineering analysis also seeks to determine the geometric characteristics of the ramp that are needed to deliver a target LOS, but it relies on more general input data.

The desired outputs of planning and preliminary engineering analysis are virtually the same as those for design analysis. The primary difference is that planning and preliminary engineering analysis occurs very early in the process of project consideration.

The first criterion that categorizes such applications is the need to use more general estimates of input data. Many of the default values specified in Chapter 12, Basic Freeway and Multilane Highway Segments; Chapter 13, Freeway Weaving Segments; and this chapter would be applied; alternatively, local default values can be substituted. Demand volumes might be specified only as expected values of annual average daily traffic (AADT) for a target year. Directional design-hour volumes are based on AADTs; default (local or global) values are used for the K-factor (the proportion of AADT occurring in the peak hour) and the D-factor (the proportion of peak hour traffic traveling in the peak direction). Guidance on these values is given in Chapter 3, Modal Characteristics.

On the basis of these default and estimated values, the analysis is conducted in the same manner as a design analysis.

Service Volumes and Service Flow Rates

The method can be applied to determine service volumes for LOS A–E for a specified set of conditions.

Service volume is the maximum hourly volume that can be accommodated without exceeding the limits of the various levels of service during the worst 15 min of the analysis hour. Service volumes can be found for LOS A–E. LOS F, which represents unstable flow, does not have a service volume.

Service flow rates are the maximum rates of flow (within a 15-min period) that can be accommodated without exceeding the limits of the various levels of service. As is the case for service volumes, service flow rates can be found for LOS A–E, but none is defined for LOS F. The relationship between a service volume and a service flow rate is as follows:

$$SV_i = SF_i \times PHF$$

Equation 14-29

where

SV_i = service volume for LOS i (pc/h),

SF_i = service flow rate for LOS i (pc/h), and

PHF = peak hour factor.

For ramp–freeway junctions, service flow rate or service volume could be defined in several ways. It might be argued that since ramp–freeway junction capacities are usually limited by the upstream or downstream freeway segment, service flow rates and service volumes should be based on basic freeway criteria applied to the upstream or downstream freeway segments. This, however, would ignore the levels of service defined for the ramp influence area, which are the only unique service descriptors for ramps.

Levels of service for ramp–freeway junctions are defined in Exhibit 14-3 and relate to the density within the ramp influence area. The methodology estimates this density by using a series of algorithms affected by demand flows on the freeway, ramp, and adjacent ramps; ramp geometrics; and distances to adjacent ramps. The methodology uses demand volumes in vehicles per hour converted to demand flow rates in passenger cars per hour. Therefore, service flow rates and service volumes would originally be estimated in terms of flow rates in passenger cars per hour. They would then be converted back to demand volumes in vehicles per hour.

Because the balance of ramp and freeway demands has a significant impact on densities, there are several ways to consider service flow rates and volumes:

- The limiting total upstream demand volume that produces a given LOS within the ramp influence area. The split between arriving freeway volume and ramp volume would have to be specified.
- The limiting volume entering the ramp influence area that produces a given LOS within the ramp influence area. Since this relies on the approaching freeway volume, the split between freeway and ramp demand would still have to be specified.
- The limiting ramp volume that produces a given LOS within the ramp influence area, based on a fixed upstream freeway demand.

All of these concepts are viable for establishing a ramp service flow rate or service volume.

In addition to different ways of interpreting a service volume or service flow rate, a large number of characteristics will influence the result, including the PHF, percentage of heavy vehicles, length of acceleration or deceleration lane(s), ramp FFS, and any relevant data for adjacent ramps. Therefore, defining a representative “typical” case with broadly applicable results is virtually impossible. Each case must be individually considered. Chapter 28, Freeway Merges and Diverges: Supplemental, includes an example of how ramp junction service flow rates and volumes can be computed.

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 applying alternative tools to the analysis of ramps and ramp junctions. Additional information on this topic may be found in the Volume 4 Technical Reference Library.

The HCM methodology for analyzing merge and diverge segments estimates the density of the ramp influence area (which includes the two rightmost lanes of the freeway and the acceleration or deceleration lane) and provides the respective LOS. As an intermediate step, the methodology estimates the capacity at various points through the section, and if the capacity is exceeded, the LOS is determined to be F without further calculation of density. The methodology is primarily based on the estimation of the demand into the influence area v_{12}.

Since the HCM methodology for analysis of merge and diverge segments has been calibrated on the basis of extensive field data, the method serves as a good comparison and calibration aid for alternative tools, to ensure that merge and diverge segment operations are modeled consistently with this chapter’s expectations.

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

A listing of the HCM's limitations for freeway merge and diverge is provided in Exhibit 14-17.

Exhibit 14-17
Limitations of the HCM Ramps and Ramp Junctions Procedure

Limitation	Potential for Improved Treatment by Alternative Tools
Managed lanes, such as HOV lanes, as ramp entrance lanes	Modeled explicitly by simulation
Ramp metering	Modeled explicitly by simulation
Oversaturated conditions (*Refer to Chapters 10 and 11 for further discussion*)	Modeled explicitly by simulation
Posted speed limit and extent of police enforcement	Can be approximated by using assumptions related to the desired speed along a given segment
Presence of intelligent transportation system features	Several features modeled explicitly by simulation; others may be approximated by using assumptions (for example, by modifying origin–destination demands by time interval)
Capacity-enhancing effects of ramp metering	Can be approximated by using assumptions related to car-following, lane-changing, and gap-acceptance behavior

Deleted row relating to the 1,500-ft ramp influence area in the exhibit.

Ramp junctions can also be analyzed with a variety of stochastic and deterministic simulation packages that address freeways. These packages can be useful in analyzing the extent of congestion when there are failures either within or downstream of the simulated facility range.

Additional Features and Performance Measures Available from Alternative Tools

This chapter provides a methodology for estimating the capacity, speed, and density in the area of influence of on- and off-ramps, given traffic demands and segment characteristics. Alternative tools offer additional performance measures including delay, stops, queue lengths, fuel consumption, pollution, and operating costs. In addition, alternative tools can readily be used to estimate travel time for ramp junctions, which is not a performance measure available through this chapter (but which can be obtained from Chapter 10).

As with most other HCM procedural chapters, 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 downstream conditions on lane utilization and backup beyond the segment boundary is a good example of a situation that can benefit from the increased insight offered by a microscopic model.

Development of HCM-Compatible Performance Measures Using Alternative Tools

The subject of performance measure comparisons was discussed in more detail in Chapter 7, Interpreting HCM and Alternative Tool Results. This section deals with topics that apply specifically to ramps and ramp junctions.

Deleted text in this section related to two rightmost freeway lanes (used by the old methodology).

When alternative tools are used, the analyst must be careful to note the definitions of simulation outputs. For example, in a simulator, there are lane changes along the entire segment. Therefore, how a simulator should address the partial presence of vehicles in the link to ensure compatibility with the HCM is not clear. Also, as is generally the case for basic freeway segments, increased speed variability in driver behavior (which simulators usually include) results in lower average space mean speed and higher density.

In obtaining density from alternative models, the following should be considered:

- The vehicles included in the density estimation and how partial presence of vehicles on the link is considered;
- The manner in which the acceleration and deceleration lanes are considered in the density estimation;
- The units used by the simulator to measure density [most use vehicles rather than passenger cars; converting vehicles to passenger cars by using the HCM's passenger car equivalence (PCE) values is typically not appropriate, given that simulator assumptions with regard to heavy vehicle performance vary widely];
- The units used in the reporting of density (i.e., whether density is reported per lane mile);
- The homogeneity of the analysis segment in the simulator, since the HCM assumes conditions to be homogeneous (unless it is a specific upgrade or downgrade segment, in which case the segment length is used to estimate the PCE values); and
- The treatment of driver variability by the simulator, since increased driver variability in the simulator will generally increase the average density.

The HCM provides capacity estimates in units of passenger cars per hour per lane for the locations approaching and departing the merge junction. In comparing the HCM estimates with capacity estimates from a simulator, the following should be considered:

- The manner in which a simulator provides the number of vehicles exiting a segment may require the provision of virtual detectors at specific points on the simulated segment in some cases so that the maximum throughput can be obtained.
- The simulator provides the maximum throughput at a particular location in units of vehicles rather than passenger cars. Converting these units to passenger cars by using the HCM's PCE values is typically not appropriate, given that simulator assumptions with regard to heavy vehicle performance vary widely.
- A simulator will likely include inputs such as the "minimum separation of vehicles," which greatly affects the maximum throughput.

Adjustment of Simulation Parameters to the HCM Results

Deleted the "Conceptual Differences Between the HCM and Simulation Model" section because the new method addresses the issues discussed.

The most important element to be adjusted in analyzing a ramp junction is the capacity of the junction at the critical locations indicated in the HCM (i.e., downstream of the junction and approaching the influence area).

Step-by-Step Recommendations for Applying Alternative Tools

The following steps are recommended when an alternative tool is applied to the analysis of ramps and ramp junctions:

Steps adjusted to reflect the new methodology.

1. Determine the FFS of the study site either from field data or by estimating it according to the Chapter 12 method for basic freeway segments.
2. Enter all available input characteristics (both geometric and traffic characteristics) into the simulator. The length of the segment or link to be simulated should be the longer of 1,500 ft or the acceleration/deceleration lane length, to correspond to the HCM-defined area of influence. Install virtual detectors within the area of influence and at the downstream end of the study segment to obtain density, speeds, and flows.
3. Load the study network above capacity to obtain the maximum throughput, and compare the result with the HCM estimate. Calibrate the simulator by modifying parameters related to the minimum time headway so that the simulated capacity matches the HCM estimate. Estimate the number of simulation runs that will need to be conducted to produce a statistically valid comparison.

Example Problems Illustrating Alternative Tool Applications

Chapter 28, Freeway Merges and Diverges: Supplemental, includes two example problems that examine situations beyond the scope of this chapter's methodology by using a typical microsimulation-based tool. Both problems are based on that chapter's Example Problem 3, which analyzes an eight-lane freeway segment with an entrance and an exit ramp. The first problem evaluates the effects of the addition of ramp metering, and the second evaluates the impacts of converting the leftmost lane of the mainline into an HOV lane.

6. REFERENCES

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

1. Roess, R. P., and J. M. Ulerio. *Capacity of Ramp–Freeway Junctions.* Final Report, NCHRP Project 3-37. Polytechnic University, Brooklyn, N.Y., Nov. 1993.
2. Elefteriadou, L. *Proactive Ramp Management Under the Threat of Freeway-Flow Breakdown*. Final Report, NCHRP Project 03-87. Transportation Research Board of the National Academies, Washington, D.C., 2015.
3. Kondyli, A., P. Gubbala, and L. Elefteriadou. 2016. "The Contribution of Ramp Demand in the Capacity of Merge Bottleneck Locations." *Proceedings,* International Symposium on Enhancing Highway Performance (ISEHP), Berlin, Germany, pp. 346–355.
4. Placeholder for the NCHRP Project 07-26 final report.
5. Rouphail, N., B. Aghdashi, L. Elefteriadou, E. Amini and D. Xu. *Assessing and Addressing Deficiencies in the HCM Weaving Segment Analysis*. STRIDE Project K2 Final Report. Southeastern Transportation Research, Innovation, Development, and Education Center, Gainesville, Fla., 2021.
6. *Highway Functional Classification Concepts, Criteria and Procedures, 2013 Edition*. Federal Highway Administration, Washington, D.C., 2013.
7. Roess, R. P., E. S. Prassas, and W. R. McShane. *Traffic Engineering*, 3rd ed. Pearson/Prentice Hall, Upper Saddle River, N.J., 2004.
8. Elefteriadou, L. *A Probabilistic Model of Breakdown at Freeway–Merge Junctions.* PhD dissertation. Polytechnic University, Brooklyn, N.Y., June 1994.

CHAPTER 27
FREEWAY WEAVING: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Chapter 27 is the supplemental chapter for Chapter 13, Freeway Weaving Segments, which is found in Volume 2 of the *Highway Capacity Manual* (HCM). Section 2 provides seven example problems demonstrating the application of the Chapter 13 core methodology and its extension to freeway managed lanes. Section 3 presents examples of applying alternative tools to the analysis of freeway weaving sections to address limitations of the Chapter 13 methodology.

VOLUME 4: APPLICATIONS GUIDE

⬛ New text, figures or paragraphs denoted with black margin notes

🟩 Revised text, figures or paragraphs denoted with green margin notes and red text

2. EXAMPLE PROBLEMS

The example problems in this section illustrate various applications of the freeway weaving segment methodology detailed in Chapter 13. Exhibit 27-1 lists the example problems included. Example problem results from intermediate and final calculations were derived from a spreadsheet computational engine implementing the methodology. For displaying equation results in text, the results were appropriately rounded. Users may obtain slightly different results if rounded parameters are used in intermediate and final calculations.

Exhibit 27-1
List of Example Problems for Weaving Segment Analysis

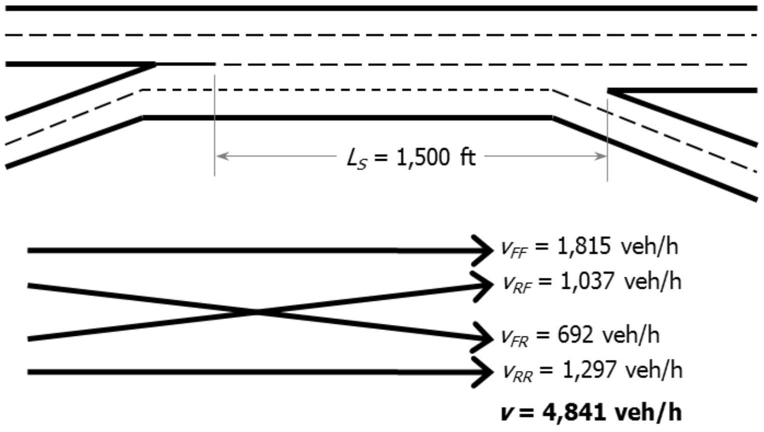
Example Problem	Description	Application
1	LOS of a complex weave	Operational analysis
2	LOS of a simple weave	Operational analysis
3	LOS of a two-sided weave	Operational analysis
4	Design of a complex weave for a desired LOS	Design analysis
5	Service volume table construction	Planning analysis
6	LOS of an ML access segment with cross-weaving	Operational analysis
7	ML access segment with downstream off-ramp	Operational analysis

EXAMPLE PROBLEM 1: LOS OF A COMPLEX WEAVE

The Weaving Segment

The subject of this operational analysis is a major weaving segment on an urban freeway under nonsevere weather conditions and without incidents, as shown in Exhibit 27-2. The short length of the weaving segment L_S is 1,500 ft.

Exhibit 27-2
Example Problem 1: Complex Weaving Segment Data



What is the level of service (LOS) and capacity of the weaving segment shown in Exhibit 27-2?

The Facts

In addition to the information contained in Exhibit 27-2, the following characteristics of the weaving segment are known:

PHF = 0.91 (for all movements);

Heavy vehicles = 5% trucks;

Driver population = regular commuters;

Free-flow speed (FFS) = 65 mi/h; ramp FFS = 50 mi/h; and

Terrain = level.

Paragraph about basic segment capacity deleted, as this value will be calculated later.

Comments

Chapter 12, Basic Freeway and Multilane Highway Segments, must be consulted to find appropriate values for the heavy-vehicle adjustment factor f_{HV}. Chapter 26, Section 2, should be consulted if the driver population includes a significant proportion of noncommuters.

Referring to Exhibit 27-2, vehicles in either on-ramp lane can complete a weaving maneuver with zero or one lane changes; therefore, the minimum number of lane changes $LC_{RF} = 0$ and the number of ramp-to-freeway weaving lanes $NW_{RF} = 2$. Vehicles in the right-hand mainline lane can complete a weaving maneuver with one lane change; therefore, $LC_{FR} = 1$ and the number of freeway-to-ramp weaving lanes $NW_{FR} = 1$. With $LC_{RF} = 0$ and $LC_{FR} = 1$, this is a "Complex 0–1" weave.

Text related to the old version of the methodology deleted.

All other 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 with the weaving methodology. The capacity of the weaving segment is estimated and compared with the total demand flow to determine whether LOS F exists. The problem statement specifies nonsevere weather, no incidents, and regular commuters, so no capacity adjustment will be performed. Average overall speed and density are computed and compared with the criteria of Exhibit 13-6 to determine LOS.

Step 1: Provide Input Data

All inputs have been specified in Exhibit 27-2 and the Facts and Comments sections of the problem statement.

Step 2: Estimate and Adjust Volumes

Equation 13-1 is used to convert the four component demand volumes to flow rates under equivalent ideal conditions. Chapter 12 is consulted to obtain a value of E_T (2.0 for level terrain). From Chapter 12, the heavy-vehicle adjustment factor is computed as

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.05(2 - 1)} = 0.952$$

Equation 13-1 is now used to convert all demand volumes:

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

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

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

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

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

Then

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

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

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

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

On a per-lane basis, the total volume in the weaving segment is:

$$\frac{v}{N} = \frac{5{,}586}{4} = 1{,}397 \text{ pc/h/ln}$$

Step 3: Determine Average Speed for All Vehicles on the Weaving Segment

This is a "Complex 1–0" weaving segment. A simplified form of the equation to determine the weaving intensity factor *W* was not given in Chapter 13; therefore, the average speed for all vehicles will be calculated based on the general form of the speed equation, Equation 13-8:

$$S_o = \min\left[S_b, S_b - \alpha\left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1}v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1}v_{FR}}{N^{\varepsilon}}\right)^{\gamma}\left(\frac{1}{L_s}\right)^{\delta}\left(\frac{v}{N} - 500\right)\right]$$

First, the average speed in an equivalent basic segment S_b is calculated using Equation 12-1:

$$S = FFS_{adj} \qquad v_p \le BP$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(c_{adj} - BP\right)^a} \qquad BP < v_p \le c$$

Exhibit 12-6 provides information for determining the inputs required for Equation 12-1. For base conditions, no speed adjustment factor *SAF* is applied; therefore, FFS_{adj} is equal to the FFS of 65 mi/h. Similarly, for base conditions, and with a driver population of regular commuters, the capacity adjustment factor *CAF* equals 1.00. The density at capacity D_c is 45 pc/mi/ln and the parameter *a* is 2. The breakpoint *BP* and basic segment capacity *c* are then calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 65)] \times (1.0)^2 = 1{,}400 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50)$$

$$c = 2{,}200 + 10 \times (65 - 50) = 2{,}350 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,397 pc/h/ln is less than the breakpoint of 1,400 pc/h/ln, the basic segment speed S_b equals the FFS of 65 mi/h.

The weaving intensity factor *W* is calculated from Equation 13-9, substituting the regression coefficients for complex weaves given in Exhibit 13-12.

$$W = \alpha \left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1} v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1} v_{FR}}{N^{\varepsilon}} \right)^{\gamma} \left(\frac{1}{L_S} \right)^{\delta}$$

$$W = 0.056 \left(\frac{\frac{0+1}{2+1}(1{,}197) + \frac{1+1}{1+1}(798)}{4^3} \right)^{0.3} \left(\frac{1}{1{,}500} \right)^{0.4} = 0.007233$$

It can be seen from this calculation that the weighting of the freeway-to-ramp and ramp-to-freeway volumes in this "Complex 1–0" weave is the opposite of the weighting for the "Complex 0–1" weave given in Equation 13-11. In a "Complex 1–0" weave, the ramp-to-freeway flow has one-third the influence on the weaving segment speed compared to the freeway-to-ramp flow.

Finally, Equation 13-10 is used to estimate the average speed of vehicles in the weaving segment:

$$S_o = \min\left[65, 65 - W\left(\frac{v}{N} - 500\right)\right]$$

$$S_o = \min[65, 65 - 0.007233(1{,}397 - 500)]$$

$$S_o = \min[65, 65 - 6.49] = 58.51 \text{ mi/h}$$

The weaving turbulence in the segment reduces the segment's speed by about 6.5 mi/h, relative to the speed of an equivalent basic segment.

Step 4: Determine Weaving Segment Capacity

Equation 13-15 is used to determine capacity C_W, with Equation 13-16 through Equation 13-19 used to determine the inputs to Equation 13-15.

Working backwards, Equation 13-19 is used to determine the value of *B,* the basic segment term. The free-flow speed *FFS* was given in the Facts section, while the equivalent basic segment capacity C_b and breakpoint *BP* were determined previously in Step 3. From the fundamental speed–flow relationship, the equivalent basic segment speed at capacity S_c is the basic segment capacity (2,350 pc/h/ln) divided by the basic segment density at capacity (45 pc/mi/ln), or 52.22 mi/h. Then:

$$B = \frac{FFS - S_c}{(C_b - BP)^2} = \frac{65 - 52.22}{(2{,}350 - 1{,}400)^2} = 1.416 \times 10^{-5}$$

Equation 13-18 is then used to determine the value of the parameter *c*, where *W* is the weaving intensity factor determined in Step 3:

$$c = BP^2 - \frac{FFS}{B} - \frac{500W}{B}$$

$$c = (1{,}400)^2 - \frac{65}{1.416 \times 10^{-5}} - \frac{500 \times 0.007233}{1.416 \times 10^{-5}}$$

$$c = -2{,}885{,}798$$

Next, Equation 13-17 is used to determine the value of the parameter *b*:

$$b = \frac{W}{B} + \frac{1}{35B} - 2BP$$

$$b = \frac{0.007233}{1.416 \times 10^{-5}} + \frac{1}{35(1.416 \times 10^{-5})} - 2 \times 1{,}400$$

$$b = -271.4$$

The value of parameter *a* is given as 1 by Equation 13-16. With all the parameter values now determined, Equation 13-15 can be used to estimate capacity.

$$C_W = \frac{-b + \sqrt{b^2 - 4\,ac}}{2a}$$

$$C_W = \frac{271.4 + \sqrt{(271.4)^2 - [4\ \times (-2{,}885{,}798) \times 1]}}{2 \times 1}$$

$$C_W = 1{,}840 \text{ pc/h/ln}$$

There are no severe weather or incidents being modeled, so the adjusted capacity C_{Wa} is the same as C_W. The volume-to-capacity ratio is determined using Equation 13-21:

$$v/c = \frac{v/N}{C_{Wa}} = \frac{1{,}397}{1{,}840} = 0.76$$

Capacity of Input and Output Roadways

The capacity of the entry and exit roadways should also be checked, although this is rarely a factor in weaving segment operation. Basic capacities for the freeway entry and exit legs (with FFS = 65 mi/h) are taken from Chapter 12, while the capacity for the two-lane entry and exit ramps (with ramp FFS = 50 mi/h) is taken from Chapter 14. The comparisons are shown in Exhibit 27-3.

Exhibit 27-3
Example Problem 1: Capacity of Entry and Exit Roadways

Leg	Demand Flow (pc/h)	Capacity (pc/h)
Freeway entry	2,094 + 798 = 2,892	2 × 2,350 = 4,700
Freeway exit	1,197 + 2,094 = 3,291	3 × 2,350 = 7,050
Ramp entry	1,197 + 1,497 = 2,694	4,200
Ramp exit	798 + 1,497 = 2,295	4,200

As can be seen, capacity is sufficient on each of the entry and exit roadways and will therefore not affect operations within the weaving segment.

Step 5: Determine Density and LOS

Density is determined using Equation 13-22:

$$D = \frac{(v/N)}{S_o} = \frac{1{,}397}{58.51} = 23.9 \text{ pc/mi/ln}$$

From Exhibit 13-6, this density is LOS C.

HCM6 results:
c = 2,110 pc/h/ln
v/c = 0.66
S = 53.1 mi/h
D = 26.3 pc/mi/ln
LOS C

Discussion

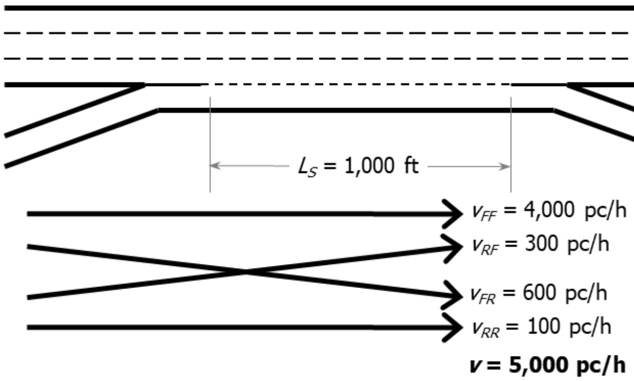
As indicated by the results, this weaving segment operates at LOS C, with an average speed of 58.5 mi/h for all vehicles. The demand flow rate is considerably less than the segment's capacity. In other words, demand can grow significantly before reaching the segment's capacity.

EXAMPLE PROBLEM 2: LOS OF A SIMPLE WEAVE

The Weaving Segment

The weaving segment that is the subject of this operational analysis, under nonsevere weather conditions and without incidents, is shown in Exhibit 27-4. It is a typical simple weaving segment.

Exhibit 27-4
Example Problem 2: Simple Weaving Segment Data



What is the capacity of the weaving segment of Exhibit 27-4, 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 27-4, the following facts are known about the subject weaving segment:

PHF = 1.00 (demands stated as flow rates);
Heavy vehicles = 0%; demand given in passenger car equivalents;
Driver population = regular commuters;
FFS = 75 mi/h; ramp FFS = 40 mi/h;
c_{IFL} = 2,400 pc/h/ln (for FFS = 75 mi/h); and
Terrain = level.

Comments

Because the demands have been specified as flow rates in passenger cars per hour under equivalent ideal conditions, adjustment factors from Chapter 12 will not be needed. The segment's speed and capacity will be estimated and the capacity will be compared with the demand to determine whether LOS F exists. If it does not, density will be estimated and compared with the criteria of Exhibit 13-6 to determine the expected LOS. As with all simple weaves, $LC_{RF} = 1$, $LC_{FR} = 1$, $NW_{RF} = 1$, and $NW_{FR} = 1$.

Step 1: Provide Input Data

All input data are stated in Exhibit 27-4 and the Facts and Comments sections of the problem statement.

Step 2: Estimate and Adjust Volumes

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:

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

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

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

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

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

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

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

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

On a per-lane basis, the total volume in the weaving segment is:

$$\frac{v}{N} = \frac{5{,}000}{4} = 1{,}250 \text{ pc/h/ln}$$

Step 3: Determine Average Speed for All Vehicles on the Weaving Segment

The average speed of all vehicles in this simple weaving segment is calculated using Equation 13-10:

$$S_o = \min\left[S_b, S_b - W\left(\frac{v}{N} - 500\right)\right]$$

First, the average speed in an equivalent basic segment S_b is calculated using Equation 12-1:

$$S = FFS_{adj} \qquad v_p \le BP$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(c_{adj} - BP\right)^a} \qquad BP < v_p \le c$$

Exhibit 12-6 provides information for determining the inputs required for Equation 12-1. For base conditions, no speed adjustment factor SAF is applied; therefore, FFS_{adj} is equal to the FFS of 75 mi/h. Similarly, for base conditions, and with a driver population of regular commuters, the capacity adjustment factor CAF equals 1.00. The density at capacity D_c is 45 pc/mi/ln and the parameter a is 2. The breakpoint BP and basic segment capacity c are then calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 75)] \times (1.0)^2 = 1{,}000 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50), \text{ with } c \leq 2{,}400$$

$$c = 2{,}200 + 10 \times (75 - 50) = 2{,}450 \ \rightarrow 2{,}400 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,250 pc/h/ln is greater than the breakpoint, but less than the basic segment capacity, S_b is calculated as:

$$S_b = FFS_{adj} - \frac{(FFS_{adj} - \frac{c}{D_c})(v_p - BP)^2}{(c - BP)^2}$$

$$S_b = 75 - \frac{(75 - \frac{2{,}400}{45})(1{,}250 - 1{,}000)^2}{(2{,}400 - 1{,}000)^2}$$

$$S_b = 74.31 \text{ mi/h}$$

Because this is a simple weaving segment, Equation 13-11 can be used to quickly determine the weaving intensity factor W rather than substituting the minimum number of lane changes, number of weaving lanes, and regression coefficients into Equation 13-9.

$$W = 0.025\left(\frac{v_{RF} + v_{FR}}{N^3}\right)^{0.156}\left(\frac{1}{L_s}\right)^{0.311}$$

$$W = 0.025\left(\frac{300 + 600}{4^3}\right)^{0.156}\left(\frac{1}{1{,}000}\right)^{0.311}$$

$$W = 0.004406$$

Finally, Equation 13-10 is used to estimate the average speed of vehicles in the weaving segment:

$$S_o = \min\left[S_b, S_b - W\left(\frac{v}{N} - 500\right)\right]$$

$$S_o = \min[74.31, 74.31 - 0.004406(1{,}250 - 500)]$$

$$S_o = \min[74.31, 74.31 - 3.30] = 71.01 \text{ mi/h}$$

Step 4: Determine Weaving Segment Capacity

Equation 13-15 is used to determine capacity C_W, with Equation 13-16 through Equation 13-19 used to determine the inputs to Equation 13-15.

Working backwards, Equation 13-19 is used to determine the value of B, the basic segment term. The free-flow speed FFS was given in the Facts section, while the equivalent basic segment capacity C_b and breakpoint BP were determined previously in Step 3. From the fundamental speed–flow relationship, the equivalent basic segment speed at capacity S_c is the basic segment capacity (2,400 pc/h/ln) divided by the basic segment density at capacity (45 pc/mi/ln), or 53.33 mi/h. Then:

$$B = \frac{FFS - S_c}{(C_b - BP)^2} = \frac{75 - 53.33}{(2{,}400 - 1{,}000)^2} = 1.106 \times 10^{-5}$$

Equation 13-18 is then used to determine the value of the parameter c, where W is the weaving intensity factor determined in Step 3:

$$c = BP^2 - \frac{FFS}{B} - \frac{500W}{B}$$

$$c = (1{,}000)^2 - \frac{75}{1.106 \times 10^{-5}} - \frac{500 \times 0.004406}{1.106 \times 10^{-5}}$$

$$c = -5{,}980{,}380$$

Next, Equation 13-17 is used to determine the value of the parameter *b*:

$$b = \frac{W}{B} + \frac{1}{35B} - 2BP$$

$$b = \frac{0.004406}{1.106 \times 10^{-5}} + \frac{1}{35(1.106 \times 10^{-5})} - 2 \times 1{,}000$$

$$b = 981.7$$

The value of parameter *a* is given as 1 by Equation 13-16. With all the parameter values now determined, Equation 13-15 can be used to estimate capacity.

$$C_W = \frac{-b + \sqrt{b^2 - 4\,ac}}{2a}$$

$$C_W = \frac{-981.7 + \sqrt{(-981.7)^2 - [4 \times (-5{,}980{,}380) \times 1]}}{2 \times 1}$$

$$C_W = 2{,}003 \text{ pc/h/ln}$$

There are no severe weather or incidents being modeled, so the adjusted capacity C_{Wa} is the same as C_W. The volume-to-capacity ratio is determined using Equation 13-21:

$$v/c = \frac{v/N}{C_{Wa}} = \frac{1{,}250}{2{,}003} = 0.62$$

Capacity of Input and Output Roadways

Although it is rarely a factor in weaving operations, the capacity of input and output roadways should be checked to ensure that no deficiencies exist. There are three input and output freeway lanes (with FFS = 75 mi/h) and one lane on the entrance and exit ramps (with ramp FFS = 40 mi/h). The criteria of Chapter 12 and Chapter 14, respectively, are used to determine the capacity of freeway legs and ramps. Demand flows and capacities are compared in Exhibit 27-5.

Exhibit 27-5
Example Problem 2: Capacity of Entry and Exit Legs

Leg	Demand Flow (pc/h)	Capacity (pc/h)
Freeway entry	4,000 + 300 = 4,300	3 × 2,400 = 7,200
Freeway exit	4,000 + 600 = 4,600	3 × 2,400 = 7,200
Ramp entry	600 + 100 = 700	2,000
Ramp exit	300 + 100 = 400	2,000

The capacity of all input and output roadways is sufficient to accommodate the demand flow rates.

Step 5: Determine Density and LOS

Density is determined using Equation 13-22:

$$D = \frac{(v/N)}{S_o} = \frac{1{,}250}{71.01} = 17.6 \text{ pc/mi/ln}$$

From Exhibit 13-6, this density is LOS B, close to the threshold of LOS C.

HCM6 results:
c = 2,145 pc/h/ln
v/c = 0.58
S = 61.9 mi/h
D = 20.2 pc/mi/ln
LOS C

Discussion

The segment is operating well (LOS B), with an average segment speed about 4 mi/h lower than the FFS.

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 27-6. The analysis assumes no adverse weather effects or incidents in the segment.

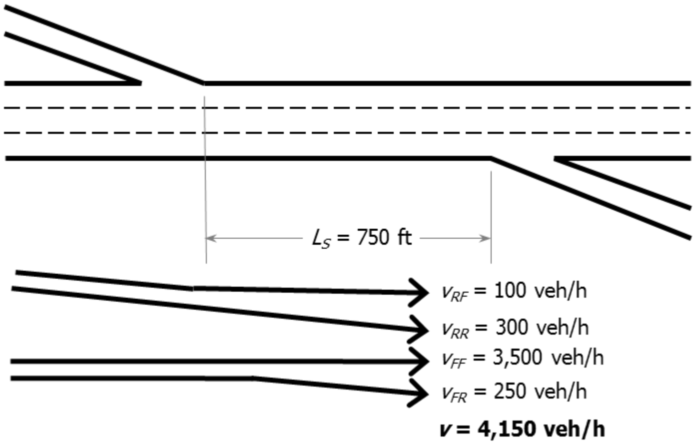


Exhibit 27-6
Example Problem 3: Two-Sided Weaving Segment Data

What is the expected LOS and capacity for the weaving segment of Exhibit 27-6?

The Facts

In addition to the information contained in Exhibit 27-6, the following facts concerning the weaving segment are known:

PHF = 0.94 (all movements);
Heavy vehicles = 11% trucks;
Driver population = regular commuters;
FFS = 60 mi/h; ramp FFS = 30 mi/h; and
Terrain = rolling.

Comments

Because this example illustrates the analysis of a two-sided weaving segment, several key parameters are different from those for a more typical one-side weaving segment.

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 few lane changes as they move through the segment in a freeway lane. This segment is in a busy urban corridor with 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. Because this two-sided weaving segment has a three-lane cross-section and both ramps are single-lane, the minimum number of lane changes LC_{RR} is 2 and the number of weaving lanes for ramp-to-ramp traffic NW_{RR} is 0.

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. The speed and capacity of the weaving segment will be estimated, along with a determination of whether LOS F exists. If it does not, density and LOS will be estimated.

Step 1: Provide Input Data

All information concerning this example problem is given in Exhibit 27-6 and the Facts and Comments sections of the problem statement.

Step 2: Estimate and Adjust Volumes

To convert demand volumes to flow rates under equivalent ideal conditions, Chapter 12 must be consulted to obtain the following values:

E_T = 3.0 (for rolling terrain)

Then

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.11(3 - 1)} = 0.82$$

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

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

$$v_{FF} = \frac{3{,}500}{0.94 \times 0.82} = 4{,}541 \text{ pc/h}$$

$$v_{FR} = \frac{250}{0.94 \times 0.82} = 324 \text{ pc/h}$$

$$v_{RF} = \frac{100}{0.94 \times 0.82} = 130 \text{ pc/h}$$

$$v_{RR} = \frac{300}{0.94 \times 0.82} = 389 \text{ pc/h}$$

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

$$v_W = 389 \text{ pc/h}$$

$$v_{NW} = 4{,}541 + 324 + 130 = 4{,}995 \text{ pc/h}$$

$$v = 4{,}995 + 389 = 5{,}384 \text{ pc/h}$$

$$VR = 389/5{,}384 = 0.072$$

On a per-lane basis, the total volume in the weaving segment is:

$$\frac{v}{N} = \frac{5{,}384}{3} = 1{,}795 \text{ pc/h/ln}$$

Step 3: Determine Average Speed for All Vehicles on the Weaving Segment

The average speed of all vehicles in the weaving segment can be calculated using the general form of the speed model for two-sided weaving segments (Equation 13-13). However, this weaving segment's configuration matches that used to develop the simplified form of the weaving intensity factor *W* in Equation 13-14, the results of which can then be used with Equation 13-10. The solution will follow the latter approach.

First, the average speed in an equivalent basic segment S_b is calculated using Equation 12-1:

$$S = FFS_{adj} \qquad v_p \le BP$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(c_{adj} - BP\right)^a} \qquad BP < v_p \le c$$

Exhibit 12-6 provides information for determining the inputs required for Equation 12-1. For base conditions, no speed adjustment factor *SAF* is applied; therefore, FFS_{adj} is equal to the FFS of 60 mi/h. Similarly, for base conditions, and with a driver population of regular commuters, the capacity adjustment factor *CAF* equals 1.00. The density at capacity D_c is 45 pc/mi/ln and the parameter *a* is 2. The breakpoint *BP* and basic segment capacity *c* are then calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 60)] \times (1.0)^2 = 1{,}600 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50)$$

$$c = 2{,}200 + 10 \times (60 - 50) = 2{,}300 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,795 pc/h/ln is greater than the breakpoint, but less than the basic segment capacity, S_b is then calculated as:

$$S_b = FFS_{adj} - \frac{(FFS_{adj} - \frac{c}{D_c})(v_p - BP)^2}{(c - BP)^2}$$

$$S_b = 60 - \frac{(60 - \frac{2{,}300}{45})(1{,}795 - 1{,}600)^2}{(2{,}300 - 1{,}600)^2}$$

$$S_b = 59.31 \text{ mi/h}$$

Next, using Equation 13-14:

$$W = 0.025\left(\frac{3v_{RR}}{N^3}\right)^{0.156}\left(\frac{1}{L_s}\right)^{0.311} = 0.025\left(\frac{3 \times 389}{3^3}\right)^{0.156}\left(\frac{1}{750}\right)^{0.311} = 0.005741$$

Finally, Equation 13-10 is used to estimate the average speed of vehicles in the weaving segment:

$$S_o = \min\left[S_b, S_b - W\left(\frac{v}{N} - 500\right)\right]$$

$$S_o = \min[59.31, 59.31 - 0.005741(1{,}795 - 500)]$$

$$S_o = \min[59.31, 59.31 - 7.43] = 51.88 \text{ mi/h}$$

Step 4: Determine Weaving Segment Capacity

Equation 13-15 is used to determine capacity C_W, with Equation 13-16 through Equation 13-19 used to determine the inputs to Equation 13-15.

Working backwards, Equation 13-19 is used to determine the value of B, the basic segment term. The free-flow speed FFS was given in the Facts section, while the equivalent basic segment capacity C_b and breakpoint BP were determined previously in Step 3. From the fundamental speed–flow relationship, the equivalent basic segment speed at capacity S_c is the basic segment capacity (2,300 pc/h/ln) divided by the basic segment density at capacity (45 pc/mi/ln), or 51.11 mi/h. Then:

$$B = \frac{FFS - S_c}{(C_b - BP)^2} = \frac{60 - 51.11}{(2{,}300 - 1{,}600)^2} = 1.814 \times 10^{-5}$$

Equation 13-18 is then used to determine the value of the parameter c, where W is the weaving intensity factor determined in Step 3:

$$c = BP^2 - \frac{FFS}{B} - \frac{500W}{B}$$

$$c = (1{,}600)^2 - \frac{60}{1.814 \times 10^{-5}} - \frac{500 \times 0.005741}{1.814 \times 10^{-5}}$$

$$c = -905{,}849$$

Next, Equation 13-17 is used to determine the value of the parameter b:

$$b = \frac{W}{B} + \frac{1}{35B} - 2BP$$

$$b = \frac{0.005741}{1.814 \times 10^{-5}} + \frac{1}{35(1.814 \times 10^{-5})} - 2 \times 1{,}600$$

$$b = -1{,}308.5$$

The value of parameter a is given as 1 by Equation 13-16. With all the parameter values now determined, Equation 13-15 can be used to estimate capacity.

$$C_W = \frac{-b + \sqrt{b^2 - 4\,ac}}{2a}$$

$$C_W = \frac{1{,}308.5 + \sqrt{(-1{,}308.5)^2 - [4\ \times (-905{,}849) \times 1]}}{2 \times 1}$$

$$C_W = 1{,}809 \text{ pc/h/ln}$$

There are no severe weather or incidents being modeled, so the adjusted capacity C_{Wa} is the same as C_W. The volume-to-capacity ratio is determined using Equation 13-21:

$$v/c = \frac{v/N}{C_{Wa}} = \frac{1{,}795}{1{,}809} = 0.99$$

Capacity of Input and Output Roadways

The capacity of input and output roadways must also be checked. The freeway input and output roadways have three lanes and a capacity of 2,300 × 3 = 6,900 pc/h (Chapter 12). The one-lane ramps (with ramp FFS = 30 mi/h) have a capacity of 1,900 pc/h (Chapter 14). Exhibit 27-7 compares these capacities with the demand flow rates (in pc/h).

Exhibit 27-7
Example Problem 3: Capacity of Entry and Exit Legs

Leg	Demand Flow (pc/h)	Capacity (pc/h)
Freeway entry	4,541 + 324 = 4,865	6,900
Freeway exit	4,541 + 130 = 4,671	6,900
Ramp entry	130 + 389 = 519	1,900
Ramp exit	324 + 389 = 713	1,900

All demands are below their respective capacities.

Step 5: Determine Density and LOS

Density is determined using Equation 13-22:

$$D = \frac{(v/N)}{S_o} = \frac{1{,}795}{51.88} = 34.6 \text{ pc/mi/ln}$$

From Exhibit 13-6, this density is LOS E.

HCM6 results:
c = 1,867 pc/h/ln
v/c = 0.90
S = 45.8 mi/h
D = 39.2 pc/mi/ln
LOS E

Discussion

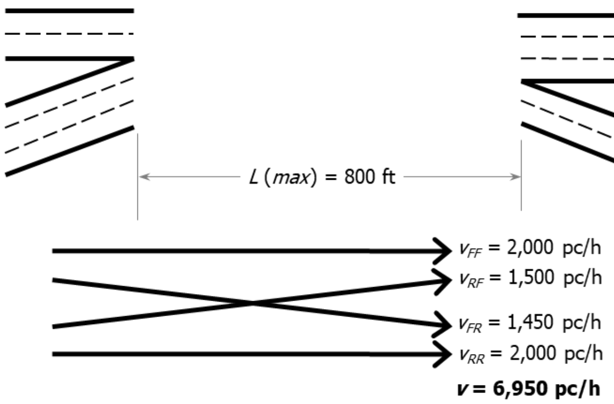
This two-sided weaving segment operates at LOS E, not far from the LOS E/F boundary. The v/c ratio is 0.99. The major problem is that 300 veh/h crossing the freeway from ramp to ramp creates a great deal of turbulence in the traffic stream and limits capacity. Two-sided weaving segments do not operate well with such large numbers of ramp-to-ramp vehicles. If this were a basic freeway segment, the per-lane flow rate of 1,795 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 COMPLEX WEAVE 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 27-8. The analysis assumes no adverse weather effects or incidents in the segment. Entry and exit legs have the numbers of lanes shown. The maximum length of the weaving segment is 800 ft, based on the location of the junctions. The FFS of all entry and exit legs is 65 mi/h. All demands are shown as flow rates under equivalent ideal conditions.

Exhibit 27-8
Example Problem 4: Complex Weaving Segment Data



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 27-8, the following facts are known concerning this weaving segment:

PHF = 1.00 (all demands stated as flow rates),
Heavy vehicles = 0% trucks (all demands in pc/h),
Driver population = regular commuters,
FFS = 65 mi/h (all legs and weaving segment), and
Terrain = level.

Comments

As is the case in any weaving segment design, considerable constraints are imposed. The problem states that the maximum length is 800 ft, no doubt limited by locational issues for the merge and diverge junctions. Shorter lengths are probably not worth investigating, 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 800 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. Note that by inspection, the capacity of all entry and exit legs is more than sufficient to handle the demand flow rates indicated.

Step 1: Provide Input Data—Trial 1

Exhibit 27-9 illustrates the weaving segment formed under the assumed design discussed previously.

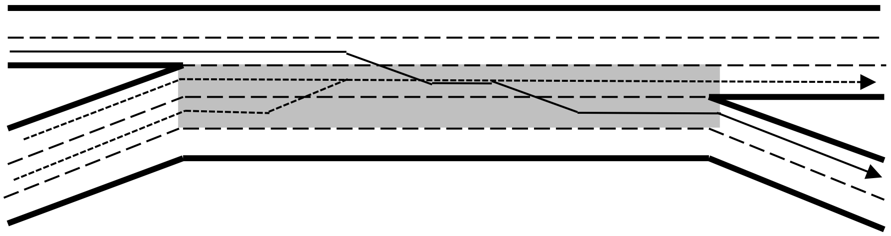


Exhibit 27-9
Example Problem 4: Trial Design 1

The direct connection of entry and exit legs produces a weaving segment in which the minimum number of lane changes from freeway to ramp is two. Therefore, $LC_{FR} = 2$ and $NW_{FR} = 0$. Ramp drivers wishing to weave can enter on either of the two left ramp lanes and weave with one or no lane changes. Thus, $LC_{RF} = 0$ and $NW_{RF} = 2$. This is a “Complex 0–2” weaving configuration.

All other input information is given in Exhibit 27-8 and in the accompanying Facts section for this example problem.

Step 2: Estimate and Adjust Volumes—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:

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

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

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

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

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

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

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

$$VR = 2{,}950/6{,}950 = 0.424$$

On a per-lane basis, the total volume in the weaving segment is:

$$\frac{v}{N} = \frac{6{,}950}{5} = 1{,}390 \text{ pc/h/ln}$$

Step 3: Determine Average Speed for All Vehicles on the Weaving Segment—Trial 1

This is a "Complex 0–2" weaving segment. A simplified form of the equation to determine the weaving intensity factor *W* was not given in Chapter 13; therefore, the average speed for all vehicles will be calculated based on the general form of the equation, Equation 13-8:

$$S_o = \min\left[S_b, S_b - \alpha\left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1}v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1}v_{FR}}{N^{\varepsilon}}\right)^{\gamma}\left(\frac{1}{L_s}\right)^{\delta}\left(\frac{v}{N} - 500\right)\right]$$

First, the average speed in an equivalent basic segment S_b is calculated using Equation 12-1:

$$S = FFS_{adj} \qquad v_p \le BP$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(c_{adj} - BP\right)^a} \qquad BP < v_p \le c$$

Exhibit 12-6 provides information for determining the inputs required for Equation 12-1. For base conditions, no speed adjustment factor *SAF* is applied; therefore, FFS_{adj} is equal to the FFS of 65 mi/h. Similarly, for base conditions, and with a driver population of regular commuters, the capacity adjustment factor *CAF* equals 1.00. The density at capacity D_c is 45 pc/mi/ln and the parameter *a* is 2. The breakpoint *BP* and basic segment capacity *c* are then calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 65)] \times (1.0)^2 = 1{,}400 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50), \text{ with } c \le 2{,}400$$

$$c = 2{,}200 + 10 \times (65 - 50) = 2{,}350 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,390 pc/h/ln is less than the breakpoint of 1,400 pc/h/ln, the basic segment speed S_b equals the FFS of 65 mi/h.

Equation 13-9 is the general form of the equation for the weaving intensity factor. The regression parameter values for complex weaves used by the equation are obtained from Exhibit 13-12.

$$W = \alpha\left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1}v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1}v_{FR}}{N^{\varepsilon}}\right)^{\gamma}\left(\frac{1}{L_s}\right)^{\delta}$$

$$W = 0.056\left(\frac{\frac{0+1}{2+1}(1{,}500) + \frac{2+1}{0+1}(1{,}450)}{5^3}\right)^{0.3}\left(\frac{1}{800}\right)^{0.4}$$

$$W = 0.01158$$

Finally, Equation 13-10 is used to estimate the average speed of vehicles in the weaving segment:

$$S_o = \min\left[65, 65 - W\left(\frac{v}{N} - 500\right)\right]$$

$$S_o = \min[65, 65 - 0.01158(1{,}390 - 500)]$$

$$S_o = \min[65, 65 - 10.31] = 54.69 \text{ mi/h}$$

Step 4: Determine Weaving Segment Capacity—Trial 1

It is not necessary to calculate the weaving segment capacity to determine density and LOS; therefore, this step is skipped.

Step 5: Determine Density and LOS—Trial 1

Density is determined using Equation 13-22:

$$D = \frac{(v/N)}{S_o} = \frac{1{,}390}{54.69} = 25.4 \text{ pc/mi/ln}$$

From Exhibit 13-6, this density is LOS D.

Discussion: Trial 1

Discussion of the weaving demand flow check (not part of the new methodology) has been removed.

Although this weaving segment configuration would operate considerably below the capacity threshold of 35 pc/mi/ln, the LOS would be worse than the desired LOS C. The critical feature appears to be the configuration, where the freeway-to-ramp flow must make two lane changes. The number of lane changes can be reduced to one by adding one lane to the “ramp” at the exit gore area. Another analysis (Trial 2) will be conducted by using this approach.

Step 1: Provide Input Data—Trial 2

Exhibit 27-10 illustrates the new configuration that will result from the changes discussed above. The addition of a lane to the exit-ramp leg allows the freeway-to-ramp movement to be completed with only one lane change. As a result, $LC_{FR} = 1$. The right lane of the freeway-entry leg can be used by freeway-to-ramp drivers to make a weaving maneuver with a single lane change, increasing NW_{FR} to 1. The new configuration is a “Complex 0–1” weave. All other input data are the same as in Trial 1.

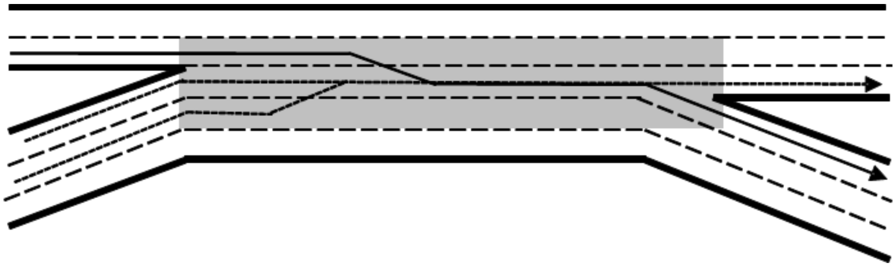


Exhibit 27-10
Example Problem 4:
Trial Design 2

Step 2: Estimate and Adjust Volumes—Trial 2

Step 2 is the same as for Trial 1 and is not repeated here.

Step 3: Determine Average Speed for All Vehicles on the Weaving Segment—Trial 2

The FFS, equivalent basic segment capacity, speed at capacity, and breakpoint are the same as in Trial 1. Only the weaving intensity factor W changes. The calculation process is the same as in Trial 1, but applying the new values of LC_{FR} and NW_{FR}.

$$W = \alpha \left(\frac{\frac{LC_{RF}+1}{NW_{RF}+1} v_{RF} + \frac{LC_{FR}+1}{NW_{FR}+1} v_{FR}}{N^{\varepsilon}} \right)^{\gamma} \left(\frac{1}{L_S} \right)^{\delta}$$

$$W = 0.056 \left(\frac{\frac{0+1}{2+1}(1{,}500) + \frac{1+1}{1+1}(1{,}450)}{5^3} \right)^{0.3} \left(\frac{1}{800} \right)^{0.4}$$

$$W = 0.008808$$

Equation 13-10 is used to estimate the average speed of vehicles in the weaving segment:

$$S_o = \min \left[65, 65 - W \left(\frac{v}{N} - 500 \right) \right]$$

$$S_o = \min[65, 65 - 0.008808(1{,}390 - 500)]$$

$$S_o = \min[65, 65 - 7.84] = 57.16 \text{ mi/h}$$

Step 4: Determine Weaving Segment Capacity—Trial 2

As before, it is not necessary to calculate the weaving segment capacity to determine density and LOS; therefore, this step is skipped.

Step 5: Determine Density and LOS—Trial 1

Density is determined using Equation 13-22:

$$D = \frac{(v/N)}{S_o} = \frac{1{,}390}{57.16} = 24.3 \text{ pc/mi/ln}$$

From Exhibit 13-6, this density is LOS C.

HCM6 results:
c = 1,651 pc/h/ln
v/c = 0.84
S = 57.4 mi/h
D = 24.2 pc/mi/ln
LOS C

The results are not directly comparable because Trial 1 in the HCM6 problem failed due to the weaving demand flow check, which is not present in the new methodology. The short length and FFS were reduced from the HCM6 values to provide a similar design problem.

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 excessive weaving turbulence creates densities that exceed the desired level. If the extra lane is not needed on the departing freeway leg, it will 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 shown in Exhibit 27-11:

Exhibit 27-11
Example Problem 5: Maximum Density Thresholds for LOS A–E

LOS	Maximum Density (pc/mi/ln)
A	10
B	18
C	25
D	30
E	35

Sentence removed about capacity not necessarily being tied to a specific 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*, pc/h).
- *Service flow rate (under prevailing conditions):* The maximum rate of flow under prevailing conditions that can be sustained while maintaining the designated LOS (*SF*, veh/h).
- *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*, veh/h).
- *Daily service volume:* The maximum annual average daily traffic under prevailing conditions that can be sustained while maintaining the designated LOS in the worst 15 min of the peak hour (*DSV*, veh/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:

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

$$SV_i = SF_i \times PHF$$

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

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

Sentence about the length of time required to perform calculations deleted.

until a density match is found. 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 complex weaving section with the following characteristics:

- One-sided complex weaving section, with one weaving movement requiring no lane changes and the other weaving movement requiring at least one lane change
- 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 = 5%
- Level terrain
- PHF = 0.93
- Regular commuters in the traffic stream
- FFS = 65 mi/h

For these characteristics, a service volume table can be constructed for a range of lengths, widths, and configurations. 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 this example, the ramp-to-freeway movement is assumed not to require a lane change. The freeway-to-ramp movement would require a minimum of one or two lane changes. Thus, this service volume table will apply to “Complex 0–1” and “Complex 0–2” weaving sections with characteristics similar to those assumed.

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 efficient; 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 27-12. 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 these exhibits have been rounded down to the nearest 100 passenger cars or vehicles for presentation.

Exhibit 27-12
Example Problem 5: Service Flow Rates (pc/h) Under Ideal Conditions (*SFI*)

	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	2,000	2,000	2,100	2,100	2,100	2,000	2,000	2,000	2,000	2,000
B	3,100	3,200	3,200	3,200	3,300	3,000	3,100	3,200	3,200	3,200
C	4,000	4,200	4,300	4,300	4,300	3,900	4,000	4,100	4,200	4,200
D	4,600	4,800	4,900	4,900	5,000	4,400	4,600	4,700	4,800	4,800
E	5,000	5,200	5,400	5,400	5,500	4,800	5,000	5,200	5,200	5,300
	$N = 4; N_{WL} = 2$					$N = 4; N_{WL} = 3$				
A	2,700	2,800	2,800	2,800	2,800	2,700	2,700	2,700	2,800	2,800
B	4,200	4,300	4,400	4,400	4,400	4,100	4,200	4,300	4,300	4,300
C	5,500	5,700	5,800	5,800	5,900	5,300	5,500	5,600	5,700	5,800
D	6,300	6,500	6,600	6,700	6,800	6,000	6,300	6,400	6,500	6,600
E	6,900	7,200	7,300	7,400	7,400	6,600	6,900	7,100	7,200	7,300
	$N = 5; N_{WL} = 2$					$N = 5; N_{WL} = 3$				
A	3,400	3,500	3,500	3,500	3,500	3,400	3,400	3,500	3,500	3,500
B	5,400	5,500	5,500	5,500	5,500	5,200	5,400	5,400	5,500	5,500
C	7,000	7,200	7,300	7,400	7,400	6,800	7,000	7,200	7,200	7,300
D	8,000	8,300	8,400	8,500	8,500	7,700	8,000	8,200	8,300	8,400
E	8,800	9,100	9,300	9,400	9,400	8,400	8,800	9,000	9,100	9,200

Exhibit 27-13 shows service flow rates under prevailing conditions, *SF*. Each value in Exhibit 27-12 (before rounding) is multiplied by

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.05(2 - 1)} = 0.952$$

Exhibit 27-13
Example Problem 5: Service Flow Rates (veh/h) Under Prevailing Conditions (*SF*)

	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	1,900	1,900	2,000	2,000	2,000	1,900	1,900	1,900	1,900	1,900
B	3,000	3,000	3,100	3,100	3,100	2,900	3,000	3,000	3,000	3,100
C	3,800	4,000	4,000	4,100	4,100	3,700	3,800	3,900	4,000	4,000
D	4,400	4,500	4,600	4,700	4,700	4,100	4,400	4,500	4,500	4,600
E	4,800	5,000	5,100	5,200	5,200	4,500	4,800	4,900	5,000	5,100
	$N = 4; N_{WL} = 2$					$N = 4; N_{WL} = 3$				
A	2,600	2,600	2,600	2,600	2,600	2,600	2,600	2,600	2,600	2,600
B	4,000	4,100	4,100	4,200	4,200	3,900	4,000	4,100	4,100	4,100
C	5,200	5,400	5,500	5,600	5,600	5,100	5,300	5,400	5,400	5,500
D	6,000	6,200	6,300	6,400	6,400	5,700	6,000	6,100	6,200	6,300
E	6,600	6,800	6,900	7,000	7,100	6,300	6,600	6,700	6,800	6,900
	$N = 5; N_{WL} = 2$					$N = 5; N_{WL} = 3$				
A	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
B	5,100	5,200	5,200	5,300	5,300	5,000	5,100	5,200	5,200	5,200
C	6,700	6,900	7,000	7,000	7,100	6,500	6,700	6,800	6,900	6,900
D	7,600	7,900	8,000	8,100	8,100	7,300	7,600	7,800	7,900	8,000
E	8,400	8,700	8,800	8,900	9,000	8,000	8,400	8,600	8,700	8,800

Exhibit 27-14 shows service volumes, *SV*. Each value in Exhibit 27-13 (before rounding) is multiplied by a PHF of 0.93.

Exhibit 27-14
Example Problem 5: Service Volumes (veh/h) Under Prevailing Conditions (*SV*)

	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	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800
B	2,800	2,800	2,800	2,900	2,900	2,700	2,800	2,800	2,800	2,800
C	3,600	3,700	3,800	3,800	3,800	3,400	3,600	3,600	3,700	3,700
D	4,000	4,200	4,300	4,400	4,400	3,900	4,100	4,200	4,200	4,300
E	4,400	4,600	4,700	4,800	4,800	4,200	4,400	4,600	4,600	4,700
	$N = 4; N_{WL} = 2$					$N = 4; N_{WL} = 3$				
A	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400
B	3,700	3,800	3,900	3,900	3,900	3,700	3,700	3,800	3,800	3,800
C	4,900	5,000	5,100	5,200	5,200	4,700	4,900	5,000	5,000	5,100
D	5,600	5,800	5,900	5,900	6,000	5,300	5,600	5,700	5,800	5,800
E	6,100	6,300	6,500	6,500	6,600	5,800	6,100	6,300	6,300	6,400
	$N = 5; N_{WL} = 2$					$N = 5; N_{WL} = 3$				
A	3,000	3,100	3,100	3,100	3,100	3,000	3,000	3,100	3,100	3,100
B	4,700	4,800	4,900	4,900	4,900	4,600	4,700	4,800	4,800	4,800
C	6,200	6,400	6,500	6,500	6,600	6,000	6,200	6,300	6,400	6,500
D	7,100	7,300	7,400	7,500	7,600	6,800	7,100	7,200	7,300	7,400
E	7,800	8,100	8,200	8,300	8,300	7,500	7,800	8,000	8,100	8,100

Exhibit 27-15 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 27-14 was divided by both of these numbers.

Exhibit 27-15
Example Problem 5: Daily Service Volumes (veh/day) Under Prevailing Conditions (*DSV*)

	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	41,800	42,000	42,200	42,200	42,200	41,300	41,800	42,000	42,000	42,000
B	63,600	65,000	65,600	66,100	66,500	62,000	63,600	64,500	65,000	65,400
C	82,000	85,000	86,500	87,500	88,100	78,600	82,000	83,800	85,200	85,900
D	92,900	96,800	98,800	100,000	100,900	88,600	93,100	95,400	97,000	98,100
E	101,800	106,300	108,600	110,000	111,100	96,500	102,000	104,700	106,500	107,700
	$N = 4; N_{WL} = 2$					$N = 4; N_{WL} = 3$				
A	55,900	56,300	56,300	56,500	56,500	55,400	55,900	56,100	56,300	56,300
B	86,100	87,700	88,600	89,000	89,500	84,000	86,100	87,200	87,700	88,100
C	111,800	115,400	117,200	118,600	119,300	107,900	112,000	114,300	115,600	116,800
D	127,200	131,800	134,300	135,600	136,800	122,000	127,500	130,200	132,000	133,400
E	139,500	145,000	147,700	149,500	150,600	133,400	139,700	143,100	145,200	146,800
	$N = 5; N_{WL} = 2$					$N = 5; N_{WL} = 3$				
A	70,200	70,400	70,600	70,900	70,900	69,700	70,200	70,400	70,600	70,600
B	108,600	110,600	111,500	112,000	112,500	106,300	108,800	110,000	110,600	111,100
C	142,200	146,300	148,400	149,700	150,600	137,500	142,500	145,000	146,500	147,700
D	162,000	167,200	170,000	171,500	172,900	155,900	162,200	165,400	167,500	169,000
E	177,900	184,000	187,200	189,300	190,600	170,900	178,100	182,000	184,500	186,100

This example problem illustrates how service volume tables may be created for a given set of weaving parameters. So many variables affect the operation of a weaving segment that “typical” service volume tables are not recommended. They may be significantly misleading when they are applied to segments with different parameters.

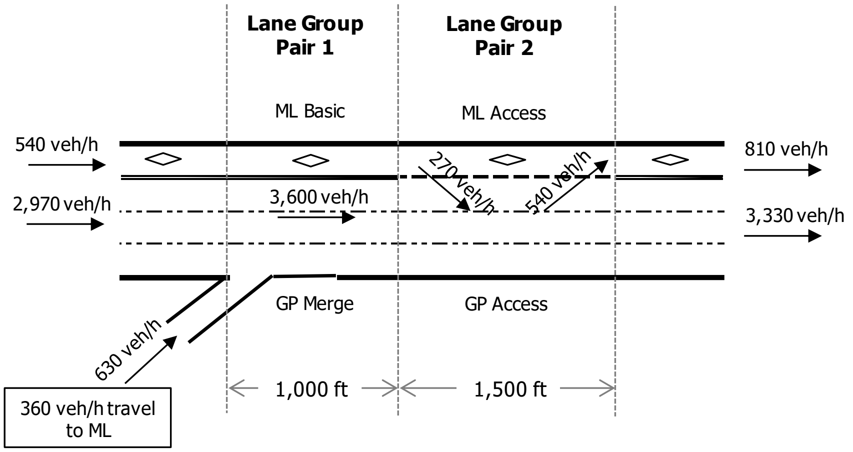
EXAMPLE PROBLEM 6: LOS OF AN ML ACCESS SEGMENT WITH CROSS-WEAVING

Example problem not updated.

The ML Access Segment

Exhibit 27-16 shows a freeway facility that includes both general purpose and managed lanes. The analysis assumes no adverse weather effects or incidents in the segment. A freeway with an adjacent managed lane facility is evaluated as two parallel lane groups, as discussed in more detail in Chapter 10, Freeway Facilities Core Methodology. The example below shows two segments, each with two adjacent lane groups. Lane Group Pair 1 in the first segment includes a general purpose (GP) merge segment and a managed lane (ML) basic segment. Lane Group Pair 2 consists of GP and ML access segments.

Exhibit 27-16
Example Problem 6:
ML Access Segment with Cross-Weaving



Note: GP = general purpose, ML = managed lane.

What is the capacity reduction in the GP merge segment due to cross-weaving, and what is the expected LOS for the ML access segment with the demand flow rates shown?

The Facts

In addition to the information given in Exhibit 27-16, the following facts are known about the subject weaving segment:

PHF = 0.90;
Heavy vehicles = 0% single-unit trucks, 0% tractor-trailer;
Driver population = regular commuters;
FFS = 65 mi/h (for both managed and general purpose lanes);
c_{IFL} = 2,350 pc/h/ln (for FFS = 65 mi/h);
ID = 1.0 interchange/mi; and
Terrain = level.

Comments

Lane-changing characteristics will be estimated for Lane Group Pair 2. The maximum length for weaving operations in the access segments will be estimated and compared with the segment's actual length. The access segment's capacity will be estimated and compared with demand to determine whether LOS F exists. If it does not, component flow speeds will be estimated and averaged. Finally, the access segment density will be estimated and Exhibit 13-6 used to determine the expected LOS.

Capacity Reduction in GP Merge Segment (Lane Group Pair 1)

The capacity reduction due to the cross-weave effect is evaluated for Lane Group Pair 1. On the basis of the facility configuration provided in Exhibit 27-16, the $L_{cw\text{-}min}$ and $L_{cw\text{-}max}$ values are 1,000 ft and 2,500 ft, respectively. The cross-weave demand volume is 360/0.9 = 400 veh/h. The number of general purpose lanes N_{GP} is 3. Thus the capacity reduction factor CRF will be

$$CRF = -0.0897 + 0.0252 \ln(CW) - 0.00001453 L_{cw\text{-}min} + 0.002967 N_{GP}$$

$$CRF = 0.056$$

Performance of ML Access Segment (Lane Group Pair 2)

The following steps illustrate the computations in the ML access segment, which is described above as Lane Group Pair 2.

Step 1: Input Data

All input data are stated in Exhibit 27-16 and the Facts section.

Step 2: Adjust Volume

The flow rates are computed on the basis of the hourly demand flow rates by using the specified PHF.

$$v_{FF} = \frac{3{,}060}{0.9} = 3{,}400 \text{ pc/h}$$

$$v_{FR} = \frac{540}{0.9} = 600 \text{ pc/h}$$

$$v_{RF} = \frac{270}{0.9} = 300 \text{ pc/h}$$

$$v_{RR} = \frac{270}{0.9} = 300 \text{ pc/h}$$

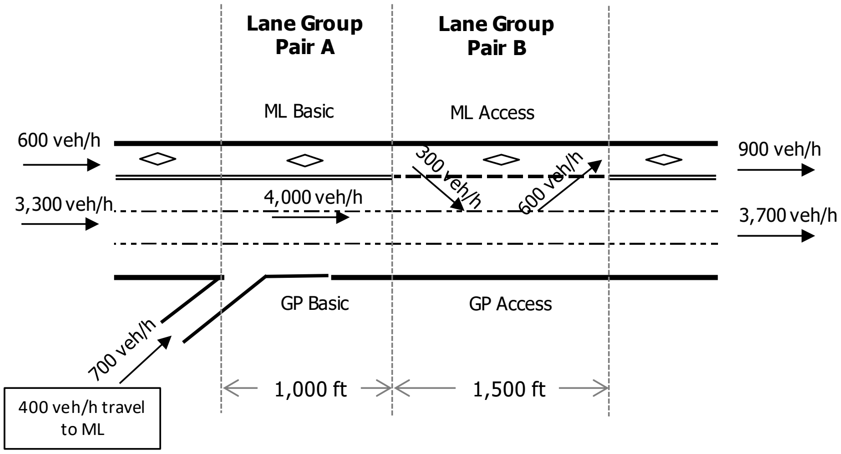
$$v_W = 600 + 300 = 900 \text{ pc/h}$$

$$v_{NW} = 3{,}400 + 300 = 3{,}700 \text{ pc/h}$$

$$v = 3{,}700 + 900 = 4{,}600 \text{ pc/h}$$

$$VR = \frac{900}{4{,}600} = 0.196$$

Exhibit 27-17 summarizes the hourly flow rates computed on the basis of hourly demand flow rates.

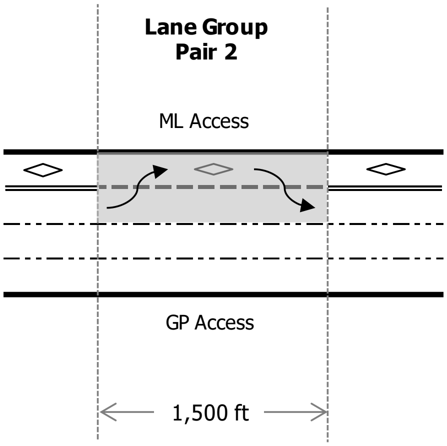


Note: GP = general purpose, ML = managed lane.

Exhibit 27-17
Example Problem 6: Hourly Flow Rates After PHF Is Applied

Step 3: Determine Configuration Characteristics

The configuration of the ML access segment is examined to determine the values of LC_{RF}, LC_{FR}, and N_{WL}. The lane geometry is illustrated in Exhibit 27-18. From these values, the minimum number of lane changes by weaving vehicles LC_{MIN} is computed.



Note: GP = general purpose, ML = managed lane.

Exhibit 27-18
Example Problem 6: Configuration Characteristics

From Exhibit 27-18, it is clear that all ramp-to-freeway vehicles must make at least one lane change ($LC_{RF} = 1$). Similarly, all freeway-to-ramp vehicles must make at least one lane change ($LC_{FR} = 1$). In addition, a weaving maneuver can only be completed with a single lane change from the leftmost lane of the freeway or the auxiliary lane ($N_{WL} = 2$). Then, by using Equation 13-2, LC_{MIN} is computed as

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

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

Step 4: Determine Maximum Weaving Length

The maximum length over which weaving operations may exist for the segment described is found by using Equation 13-4:

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

$$L_{MAX} = [5{,}728(1 + 0.196)^{1.6}] - (1{,}566 \times 2) = 4{,}495 \text{ ft} > 1{,}500 \text{ ft}$$

Because the maximum length for weaving operations significantly exceeds the actual length, the segment qualifies as 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 reaching 43 pc/mi/ln or weaving demand reaching 2,350 pc/h for the configuration of Exhibit 27-16 (a ramp-weave with $N_{WL} = 2$).

Capacity Limited by Density

The capacity limited by reaching a density of 43 pc/mi/ln is estimated by using Equation 13-5 and Equation 13-6:

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

$$c_{IWL} = 2{,}350 - [438.2(1 + 0.196)^{1.6}] + (0.0765 \times 1{,}500) + (119.8 \times 2)$$

$$c_{IWL} = 2{,}121 \text{ pc/h/ln}$$

$$c_W = c_{IWL} \times N \times f_{HV}$$

$$c_W = 2{,}121 \times 4 \times 1 = 8{,}483 \text{ pc/h}$$

Capacity Limited by Weaving Demand Flow

The capacity limited by the weaving demand flow is estimated by using Equation 13-7 and Equation 13-8:

$$c_{IW} = \frac{2{,}400}{VR} = \frac{2{,}400}{0.196} = 12{,}245 \text{ pc/h}$$

$$c_W = c_{IW} \times f_{HV}$$

$$c_W = 12{,}245 \times 1 = 12{,}245 \text{ pc/h}$$

The controlling capacity is the smaller of the two values, or 8,483 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.

Since the capacity of the weaving segment is larger than the demand flow rate of 4,600 pc/h, LOS F does not exist, and the analysis may continue.

Capacity of Input and Output Roadways

Although it is rarely a factor in weaving operations, the capacity of input and output roadways should be checked to ensure that no deficiencies exist. There are three input and output freeway lanes (with FFS = 65 mi/h). The capacities of the entry and exit ramps are determined for a basic managed lane segment with a free-flow speed of 65 mi/h, separated by markings. The criteria of Chapter 12 are used to determine the capacity of the freeway legs and the managed lane entry and exit lanes. Demand flows and capacities are compared in Exhibit 27-19.

Exhibit 27-19
Example Problem 6: Capacity of Entry and Exit Legs

Leg	Demand Flow (pc/h)	Capacity (pc/h)
Freeway entry	4,000	3 × 2,350 = 7,050
Freeway exit	4,000 + 300 – 600 = 3,700	3 × 2,350 = 7,050
Ramp entry	600	1,700
Ramp exit	600 – 300 + 600 = 900	1,700

The capacities of all input and output roadways are sufficient to accommodate the demand flow rates.

Step 6: Determine Lane-Changing Rates

Equation 13-11 through Equation 13-17 are used to estimate the lane-changing rates of weaving and nonweaving vehicles in the access segment. These rates will be used in Step 7 to estimate the weaving and nonweaving vehicle speeds.

Weaving Vehicle Lane-Changing Rate

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

$$LC_W = 900 + 0.39[(1{,}500 - 300)^{0.5}(4^2)(1 + 1)^{0.8}] = 1{,}276 \text{ lc/h}$$

Nonweaving Vehicle Lane-Changing Rate

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

$$I_{NW} = \frac{1{,}500 \times 1 \times 3{,}700}{10{,}000} = 555 < 1{,}300$$

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

$$LC_{NW} = (0.206 \times 3{,}700) + (0.542 \times 1{,}500) - (192.6 \times 4) = 805 \text{ lc/h}$$

Total Lane-Changing Rate

$$LC_{ALL} = LC_W + LC_{NW} = 1{,}276 + 805 = 2{,}081 \text{ lc/h}$$

Step 7: Determine Average Speeds of Weaving and Nonweaving Vehicles

The average speeds of weaving and nonweaving vehicles are computed from Equation 13-18 through Equation 13-21:

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

$$W = 0.226\left(\frac{2{,}081}{1{,}500}\right)^{0.789} = 0.293$$

Then

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

$$S_W = 15 + \left(\frac{65 \times 1 - 15}{1 + 0.293}\right) = 53.7 \text{ mi/h}$$

and

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

$$S_{NW} = 65 \times 1 - (0.0072 \times 900) - \left(0.0048\frac{4{,}600}{4}\right) = 53.0 \text{ mi/h}$$

Equation 13-22 is now used to compute the average speed of all vehicles in the segment:

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

$$S = \frac{900 + 3{,}700}{\left(\frac{900}{53.7}\right) + \left(\frac{3{,}700}{53.0}\right)} = 53.1 \text{ mi/h}$$

Step 8: Determine LOS

The average density in the weaving segment is estimated by using Equation 13-23.

$$D = \frac{(v/N)}{S} = \frac{(4{,}600/4)}{53.1} = 21.7 \text{ pc/mi/ln}$$

From Exhibit 13-6, this density is within the stated boundaries of LOS C (20 to 28 pc/mi/ln).

Discussion

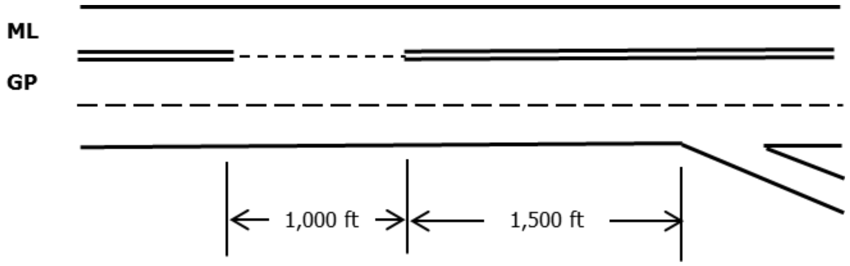
As noted, the access segment is operating at LOS C. Weaving and nonweaving speeds are relatively high, suggesting a nearly stable flow. The demand flow rate of 4,600 pc/h is well below the access segment's capacity of 8,483 pc/h.

EXAMPLE PROBLEM 7: ML ACCESS SEGMENT WITH DOWNSTREAM OFF-RAMP

Example problem not updated.

An ML access segment is illustrated in Exhibit 27-20. The movements in and out of the managed lane may be considered to be analogous to a ramp-weave segment and analyzed accordingly. The impact of cross-weaving traffic between the managed lane and the nearby off-ramp must also be analyzed to determine its impact on capacity of the general purpose lanes.

Exhibit 27-20
Example Problem 7:
ML Access Segment Data



Note: GP = general purpose, ML = managed lane.

The FFS of the segment is 70 mi/h and the interchange density, *ID*, is 1 interchange per mile. Demand flow rates for this segment are shown in Exhibit 27-21. Note that all demand flows are stated in passenger car equivalents and represent the flow rate in the worst 15-min period of the hour.

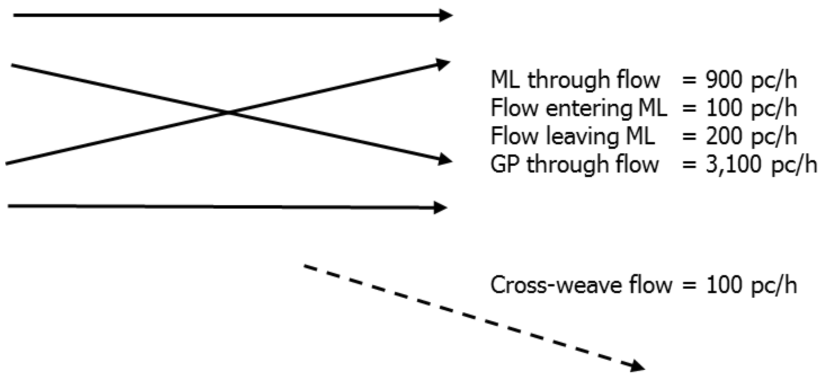


Exhibit 27-21
Example Problem 7: Weaving Flows for Managed Lane Segment

Note: GP = general purpose, ML = managed lane.

Part 1: Analysis of the Weaving Between Managed Lanes and General Purpose Lanes

The first major issue to consider is the weaving segment created by movements into and out of the managed lane in the 1,000-ft access segment. This segment is treated as a ramp-weave configuration with a total of three lanes (including the managed lane). This is a bit of an approximation, given that the geometry of the managed lane is better than that of typical ramps in a ramp-weave segment. Speeds of weaving vehicles are likely to be underestimated, since approach speeds on the managed lane are considerably higher than what would be expected on a typical ramp.

Weaving Movements and Parameters

The primary weaving activity is between vehicles entering and leaving the managed lane in the 1,000-ft access segment. This may be treated as a three-lane ramp-weave segment and is analyzed with the basic methodology of this chapter.

Because of the simplicity of this case, certain parameters may be established by inspection:

N_{WL} = 2 lanes,

LC_{MIN} = 100 + 200 = 300 lc/h, and

VR = 300 / 4,300 = 0.07.

All ramp weaves have two weaving lanes, and each weaving vehicle in a ramp weave must execute one lane change.

Maximum Weaving Length

The maximum weaving length is determined with Equation 13-4.

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

$$L_{MAX} = [5{,}728(1 + 0.07)^{1.6}] - (1{,}566 \times 2) = 3{,}251 \text{ ft} > 1{,}000 \text{ ft}$$

The result is significantly longer than the actual weaving length of 1,000 ft. Thus, the access segment may be treated by using the weaving procedure.

Weaving Segment Capacity

The capacity of the ML access segment (a weaving segment) may be based on density limits (43 pc/mi/ln) or on the maximum weaving flow that can be accommodated by the ramp-weave configuration (2,400 pc/h).

The former is estimated by using Equations 13-5 and 13-6.

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

$$c_{IWL} = 2{,}400 - [438.2(1 + 0.07)^{1.6}] + (0.0765 \times 1{,}000) + (119.8 \times 2)$$

$$c_{IWL} = 2{,}228 \text{ pc/h/ln}$$

$$c_W = c_{IWL} \times N \times f_{HV}$$

$$c_W = 2{,}228 \times 3 \times 1 = 6{,}684 \text{ pc/h}$$

The capacity limited by maximum weaving flow is computed by using Equations 13-7 and 13-8.

$$c_{IW} = \frac{2{,}400}{VR} = \frac{2{,}400}{0.07} = 34{,}286 \text{ pc/h}$$

$$c_W = c_{IW} \times f_{HV} = 34{,}286 \times 1 = 34{,}286 \text{ pc/h}$$

Obviously, the capacity is controlled by maximum density and is established as 6,684 pc/h. Since the total flow in the segment is 900 + 100 + 200 + 3,100 = 4,300 pc/h, failure (LOS F) is not expected, and the analysis of the weaving area continues. By inspection and comparison with Chapter 12 criteria, demand does not exceed capacity on any of the entry or exit roadways.

Estimate Lane-Changing Rates

To estimate total lane-changing rates, the total number of lane changes made by weaving and nonweaving vehicles (within the 1,000-ft access segment) must be estimated.

The total lane-changing rate for weaving vehicles is determined by using Equation 13-11.

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

$$LC_W = 300 + 0.39[(1{,}000 - 300)^{0.5}(3^2)(1 + 1)^{0.8}] = 462 \text{ lc/h}$$

The total lane-changing rate for nonweaving vehicles is found by using Equation 13-13 or 13-14, depending on the value of the nonweaving vehicle index computed with Equation 13-12.

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

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

Since this value is less than 1,300, Equation 13-13 is applied.

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

$$LC_{NW} = (0.206 \times 4{,}000) + (0.542 \times 1{,}000) - (192.6 \times 3) = 788 \text{ lc/h}$$

The total lane-changing rate for the ML access segment is

$$LC_{ALL} = LC_W + LC_{NW} = 462 + 788 = 1{,}250 \text{ lc/h}$$

Estimate Speed of Weaving and Nonweaving Vehicles

The speed of weaving vehicles in the ML access segment is estimated by using Equations 13-19 and 13-20.

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

$$W = 0.226\left(\frac{1{,}250}{1{,}000}\right)^{0.789} = 0.2695$$

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

$$S_W = 15 + \left(\frac{70 \times 1 - 15}{1 + 0.2695}\right) = 58.3 \text{ mi/h}$$

The speed of nonweaving vehicles is estimated by using Equation 13-21.

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

$$S_{NW} = 70 \times 1 - (0.0072 \times 300) - \left(0.0048\frac{4{,}300}{3}\right) = 61.0 \text{ mi/h}$$

The average speed of all vehicles is found by using Equation 13-22.

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

$$S = \frac{300 + 4{,}000}{\left(\frac{300}{58.3}\right) + \left(\frac{4{,}000}{61.0}\right)} = 60.8 \text{ mi/h}$$

Estimate the Density in the ML Access Segment and Determine the LOS

The density in the segment is found by using Equation 13-23.

$$D = \frac{(v/N)}{S} = \frac{(4{,}300/3)}{60.8} = 23.6 \text{ pc/mi/ln}$$

From Exhibit 13-12, this is LOS B but close to the LOS B/C boundary of 24 pc/mi/ln.

Part 2: Estimate the Impact of Cross-Weaving Vehicles on the Capacity of the General Purpose Lanes

The capacity of the two general purpose lanes (with FFS = 70 mi/h) is expected to be 2,400 × 2 = 4,800 pc/h. However, there are 100 pc/h executing cross-weaving movements to access the off-ramp that is 1,500 ft downstream of the ML access segment.

Equation 13-24 describes the impact that these cross-weaving vehicles are expected to have on general purpose lane capacity.

$$CRF = -0.0897 + 0.0252\ln(CW) - 0.00001453 L_{cw\text{-}min} + 0.002967 N_{GP}$$

$$CRF = -0.0897 + 0.0252\ln(100) - 0.00001453(1{,}500) + 0.002967(2)$$

$$CRF = 0.0105$$

$$CAF = 1 - CRF = 1 - 0.0105 = 0.9895$$

Therefore, the remaining capacity of the general purpose lanes is

$$c_{GPA} = c_{GP} \times CAF = 4{,}800 \times 0.9895 = 4{,}750 \text{ pc/h}$$

Discussion

In this case, the ML access segment is expected to work well. The actual weaving involving vehicles entering and leaving the segment results in an overall LOS B designation. The impact of cross-weaving vehicles using the off-ramp is negligible.

3. ALTERNATIVE TOOL EXAMPLES FOR WEAVING SEGMENTS

Chapter 13, Freeway Weaving Segments, described a methodology for analyzing freeway weaving segments to estimate their capacity, speed, and density as a function of traffic demand and geometric configuration. Supplemental problems involving the use of alternative tools for freeway weaving sections to address limitations of the Chapter 13 methodology are presented here. All of these examples are based on Example Problem 1 in this chapter, shown in Exhibit 27-2.

Three questions are addressed by using a typical microscopic traffic simulation tool that is based on the link–node structure:

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

The first step is to identify the link–node structure, as shown in Exhibit 27-22.

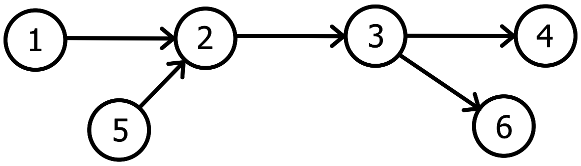


Exhibit 27-22
Link–Node Structure for the Simulated Weaving Segment

The next step is to develop input data for various demand levels. Several demand levels ranging from 80% to 180% of the original volumes were analyzed by simulation. The demand data, adjusted for a peak hour factor of 0.91, are given in Exhibit 27-23.

Exhibit 27-23
Input Data for Various Demand Levels (veh/h)

	Percent of Specified Demand					
Type of Demand	**80**	**100**	**120**	**140**	**160**	**180**
Freeway-to-freeway demand, V_{FF}	1,596	1,995	2,393	2,792	3,191	3,590
Ramp-to-freeway demand, V_{RF}	912	1,140	1,367	1,595	1,823	2,051
Freeway-to-ramp demand, V_{FR}	608	760	913	1,065	1,217	1,369
Ramp-to-ramp demand, V_{RR}	1,140	1,425	1,710	1,995	2,280	2,565
Total demand	4,256	5,320	6,384	7,448	8,512	9,576
Total freeway entry	2,204	2,755	3,306	3,857	4,408	4,959
Total freeway exit	2,507	3,134	3,761	4,388	5,015	5,641
Total ramp entry	2,052	2,565	3,078	3,591	4,104	4,617
Total ramp exit	1,749	2,186	2,623	3,060	3,497	3,934

Thirty simulation runs were made for each demand level. The results are discussed in the following sections. The need to determine performance measures from an analysis of vehicle trajectories was emphasized in Chapter 7, Interpreting HCM and Alternative Tool Results. Specific procedures for defining measures in terms of vehicle trajectories were proposed to guide the future development of alternative tools. Pending further development, the examples presented in this chapter have applied existing versions of alternative tools and therefore do not reflect the trajectory-based measures described in Chapter 7.

DETERMINING THE WEAVING SEGMENT CAPACITY

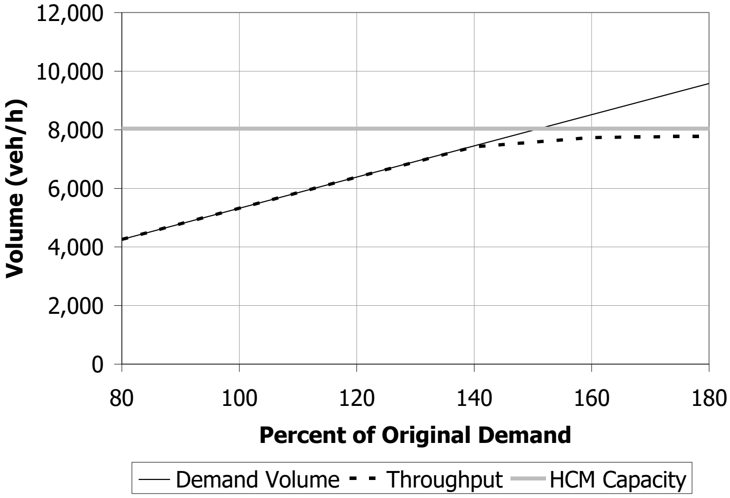
Section not updated to reflect the new method.

Simulation tools do not produce capacity estimates directly. The traditional way to estimate the capacity of a given system element is to overload it and determine the maximum throughput under the overloaded conditions. Care must be taken in this process because a severe overload can reduce the throughput by introducing self-aggravating phenomena upstream of the output point.

Exhibit 27-24 shows the relationship between demand volume and throughput, represented by the output of the weaving segment. As expected, throughput tracks demand precisely up to the point where no more vehicles can be accommodated. After that point it levels off and reaches a constant value that indicates the capacity of the segment. In this case, capacity was reached at approximately the same value as the HCM estimate. However, this degree of agreement between the two estimation techniques should not be expected as a general rule because of differences in the treatment of vehicle and geometric characteristics.

On the basis of observation, it is reasonable to conclude that the capacity of this weaving segment can be determined by overloading the facility and that the results are in general agreement with those of the HCM. In comparing capacity estimates, the analyst should remember that the HCM expresses results in passenger car equivalent vehicles, while simulation tools express results in actual vehicles. The results will diverge as the proportion of trucks increases.

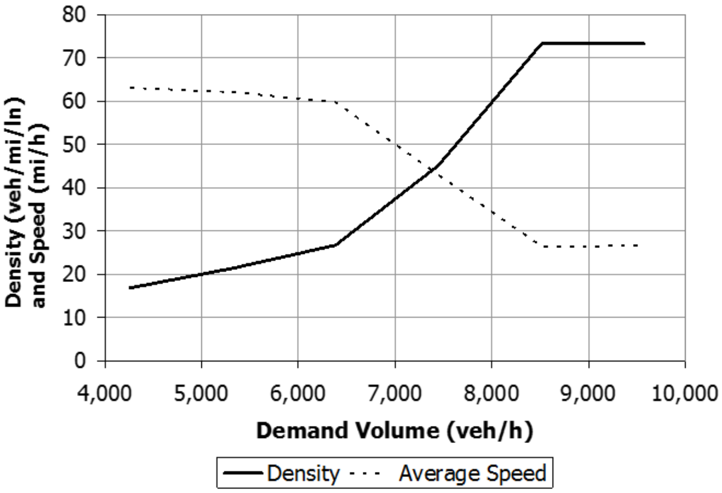
Exhibit 27-24
Determining the Capacity of a Weaving Segment by Simulation



EFFECT OF DEMAND ON PERFORMANCE

Exhibit 27-25 shows the effect of demand on density and speed. Density increases with demand volume up to the segment capacity and then levels off at a constant value of approximately 75 veh/mi/ln, which represents very dense conditions. The speed remains close to the free-flow speed at lower demand volumes. It then drops in a more or less linear fashion and eventually levels off when capacity is reached. The minimum speed is approximately 26 mi/h.

Exhibit 27-25
Simulated Effect of Demand Volume on Weaving Segment Capacity and Speed



At the originally specified demand volume level of 5,320 veh/h (peak hour adjusted), the estimated speed was 62.0 mi/h and the density was 21.4 veh/mi/ln. The corresponding values from simulation were 53.1 mi/h and 26.3 pc/ln/mi. Because of differences in definition, these results are not easy to compare. These differences illustrate the pitfalls of applying LOS thresholds to directly simulated density to determine the segment LOS.

The densities produced when demand exceeded capacity were greater than 70 veh/ln/mi. This level of density is usually associated with queues that back up from downstream bottlenecks; however, in this case, no such bottlenecks were present. Inspection of the animated graphics suggests that the increase in density within the weaving segment is caused by vehicles that are not able to get into the required lane for their chosen exit. Some vehicles were forced to stop and wait for a lane-changing opportunity, and the reduction in average speed produced a corresponding increase in the average density.

For purposes of illustration, this example focuses on a single link containing the weaving segment. The overloading of demand prevented all of the vehicles from entering the link and would have increased the delay substantially if the vehicles denied entry were considered. For this reason, the delay measures from the simulation were not included in this discussion.

EFFECT OF QUEUE BACKUP FROM A DOWNSTREAM SIGNAL ON THE EXIT RAMP

The operation of a weaving segment may be expected to deteriorate when congestion on the exit ramp causes a queue to back up into the weaving segment. This condition was one of the stated limitations of the methodology in Chapter 13, Freeway Weaving Segments.

Signal Operation

To create this condition, a pretimed signal with a slightly oversaturated operation is added 700 ft from the exit point. The operating parameters for the signal are given in Exhibit 27-26. Note that the right-turn capacity estimated by the Chapter 19, Signalized Intersections, procedure is slightly lower than the left-turn capacity because of the adjustment factors applied to turns by that procedure.

Exhibit 27-26
Exit Ramp Signal Operating Parameters

Cycle length	150 s
Green interval	95 s
Yellow interval	4 s
All-red clearance	1 s
Saturation flow rate	1,800 veh/hg/ln
g/C ratio	0.633
Left-turn movement	
• Lanes	1
• Capacity (by HCM Chapter 19)	1,083 veh/h
Right-turn movement	
• Lanes	1
• Capacity (by HCM Chapter 19)	969 veh/h
Link capacity (by HCM Chapter 19)	2,052 veh/h

Capacity Calibration

To ensure that the simulation model is properly calibrated to the HCM, the simulation tool's operating parameters for the link were modified by trial and error to match the HCM estimate of the link capacity by overloading the link to determine its throughput. With a start-up lost time of 2.0 s and a steady-state headway of 1.8 s/veh, the simulated capacity for the link was 2,040 veh/h, which compares well with the HCM's estimate of 2,052 veh/h.

Results with the Specified Demand

An initial run with the demand levels specified in the original example problem indicated severe problems on the freeway caused by the backup of vehicles from the signal. Two adverse conditions are observed in the graphics capture shown in Exhibit 27-27:

1. Some vehicles in the freeway mainline through lanes were unable to access the auxiliary lane for the exit ramp because of blockage in the lane.
2. The resulting use of the exit ramp lanes prevented the signal operation from reaching its full capacity. This caused a self-aggravating condition in which the queue backed up farther onto the freeway.

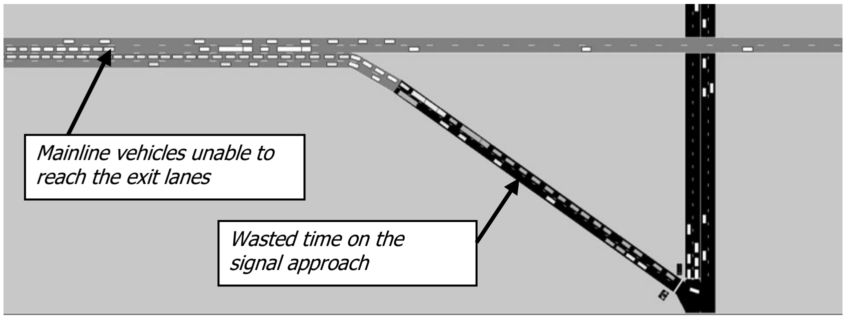


Exhibit 27-27
Deterioration of Weaving Segment Operation due to Queue Backup from a Traffic Signal

A reasonable conclusion is that the weaving segment would not operate properly at the specified demand levels. The logical solution to the problem would be to improve signal capacity. To support a recommendation for such an improvement, varying the demand levels to gain further insight into the operation might be desirable. Since it has already been discovered that the specified demand is too high, the original levels of 80% to 180% of the specified demand are clearly inappropriate. The new demand range will therefore be reduced to a level of 80% to 105%.

Effect of Reducing Demand on Throughput

Exhibit 27-28 illustrates the self-aggravating effect of too much demand. Throughput is generally expected to increase with demand up to the capacity of the facility and to level off at that point. Notice that the anticipated relationship was observed without the signal, as was shown in Exhibit 27-24.

When the signal was added, the situation changed significantly. The throughput peaked at about 95% of the specified demand and declined noticeably as more vehicles were allowed to enter the freeway. Another useful observation is that the peak throughput of approximately 4,560 veh/h is considerably below the estimated capacity of nearly 8,000 veh/h.

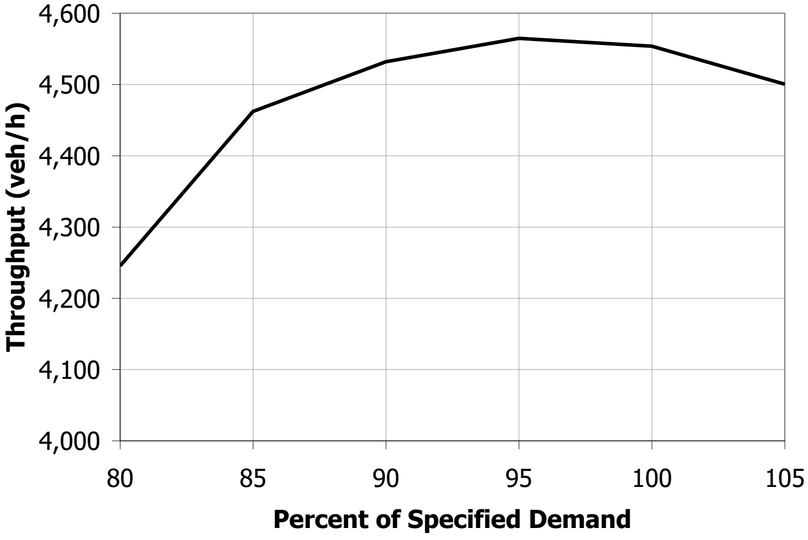
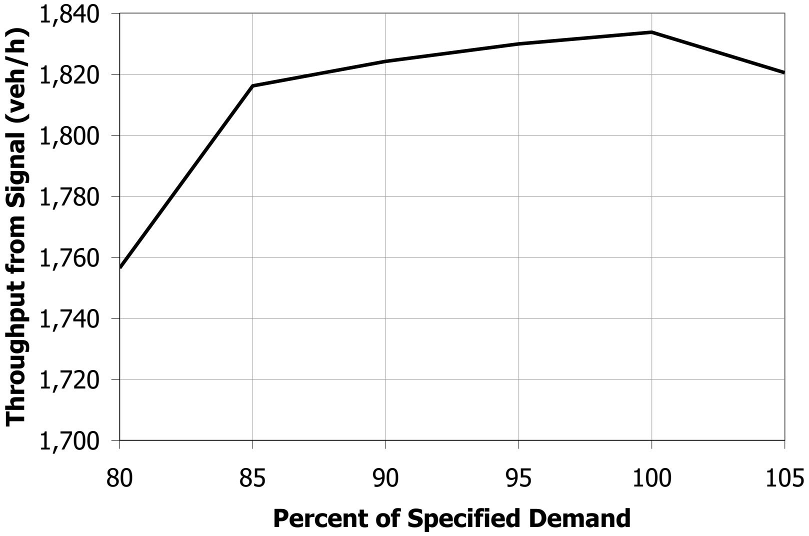


Exhibit 27-28
Effect of Demand on Weaving Segment Throughput with Exit Ramp Backup

The same phenomenon is observed on the exit ramp approach to the signal, as shown in Exhibit 27-29. The throughput declined with added demand after reaching its peak value of about 1,835 veh/h. Note that the peak throughput is also well below the capacity of 2,040 to 2,050 veh/h estimated by both the HCM and the simulation tool in the absence of upstream congestion.

Exhibit 27-29
Effect of Demand on Exit Ramp Throughput with Signal Queuing



This example illustrates the potential benefits of using simulation tools to address conditions that are beyond the scope of the HCM methodology. It also points out the need to consider conditions outside of the facility under study in making a performance assessment. Finally, it demonstrates that care must be taken in estimating the capacity of a facility through an arbitrary amount of demand overload.

CHAPTER 28
FREEWAY MERGES AND DIVERGES: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Chapter 28 is the supplemental chapter for Chapter 14, Freeway Merge and Diverge Segments, which is found in Volume 2 of the *Highway Capacity Manual* (HCM). Section 2 provides five example problems demonstrating the application of the Chapter 14 methodology. Section 3 presents examples of applying alternative tools to the analysis of freeway merge and diverge segments to address limitations of the Chapter 14 methodology.

█ New text, figures or paragraphs denoted with black margin notes

🟩 Revised text, figures or paragraphs denoted with green margin notes and red text

2. EXAMPLE PROBLEMS

Exhibit 28-1 lists the example problems presented in this section.

Exhibit 28-1
List of Example Problems

Example Problem	Title	Type of Analysis
1	Isolated One-Lane, Right-Hand On-Ramp to a Four-Lane Freeway	Operational analysis
2	Two Adjacent Single-Lane, Right-Hand Off-Ramps on a Six-Lane Freeway	Operational analysis
3	One-Lane On-Ramp Followed by a One-Lane Off-Ramp on an Eight-Lane Freeway	Operational analysis
4	Single-Lane, Left-Hand On-Ramp on a Six-Lane Freeway	Special case
5	Service Flow Rates and Service Volumes for an Isolated On-Ramp on a Six-Lane Freeway	Service flow rates and service volumes

EXAMPLE PROBLEM 1: ISOLATED ONE-LANE, RIGHT-HAND ON-RAMP TO A FOUR-LANE FREEWAY

The Facts

The following data are available to describe the traffic and geometric characteristics of this location. The example assumes no impacts of inclement weather or incidents.

1. Isolated location (no adjacent ramps to consider);
2. One-lane ramp roadway and junction;
3. Four-lane freeway (two lanes in each direction);
4. Upstream freeway demand volume = 2,500 veh/h;
5. Ramp demand volume = 535 veh/h;
6. 5% trucks throughout;
7. Acceleration lane = 740 ft;
8. FFS, freeway = 60 mi/h;
9. FFS, ramp = 45 mi/h;
10. Level terrain for freeway and ramp;
11. Peak hour factor (PHF) = 0.90; and
12. Drivers are regular commuters.

Comments

All input parameters are known, so no default values are needed or used. Adjustment factors for heavy vehicles and driver population are found in Chapter 12, Basic Freeway and Multilane Highway Segments.

Step 1: Provide Input Data and Adjust Volumes

Input parameters were specified in the Facts section above. Equation 14-1 is used to convert demand volumes to flow rates under equivalent ideal conditions:

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

Demand volumes are given for the freeway and the ramp. The PHF is specified. The driver population adjustment factor for commuters is 1.00 (Chapter 12), while the heavy vehicle adjustment factor is computed as follows:

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

Truck presence is given. The value of E_T for level terrain is 2.0 (Chapter 12). On the basis of these values, the freeway and ramp demand volumes are converted as follows:

For the freeway,

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.05(2.0 - 1)} = 0.952$$

$$v_F = \frac{2{,}500}{0.90 \times 0.952} = 2{,}918 \text{ pc/h}$$

For the ramp, the calculations are identical:

$$f_{HV} = \frac{1}{1 + 0.05(2.0 - 1)} = 0.952$$

$$v_R = \frac{535}{0.90 \times 0.952} = 624 \text{ pc/h}$$

The overall flow rate in the ramp influence area is then

$$v = v_F + v_R = 2{,}918 + 624 = 3{,}542 \text{ pc/h}$$

which, on a per lane basis, is equal to

$$\frac{v}{N} = \frac{3{,}542}{2} = 1{,}771 \text{ pc/h/ln}$$

Step 2: Estimate Speed in the Ramp Influence Area

The average speed in the ramp influence area is estimated using Equation 14-4 for a merge area:

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_R}{N} - 500\right)\left(\frac{v_R}{L_a}\right)\right]$$

First, the average speed in an equivalent basic segment S_b is calculated using Equation 12-1:

$$S = FFS_{adj} \qquad v_p \le BP$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(c_{adj} - BP\right)^a} \qquad BP < v_p \le c$$

Exhibit 12-6 provides information for determining the inputs required for Equation 12-1. For base conditions, no speed adjustment factor *SAF* is applied; therefore, FFS_{adj} is equal to the FFS of 60 mi/h. Similarly, for base conditions, and with a driver population of regular commuters, the capacity adjustment factor *CAF* equals 1.00. The density at capacity D_c is 45 pc/mi/ln and the parameter a is 2. The breakpoint *BP* and basic segment capacity *c* are then calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 60)] \times (1.0)^2 = 1{,}600 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50)$$

$$c = 2{,}200 + 10 \times (60 - 50) = 2{,}300 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,771 pc/h/ln is greater than the breakpoint, but less than the basic segment capacity, S_b is then calculated as:

$$S_b = FFS_{adj} - \frac{(FFS_{adj} - \frac{c}{D_c})(v_p - BP)^2}{(c - BP)^2}$$

$$S_b = 60 - \frac{(60 - \frac{2{,}300}{45})(1{,}771 - 1{,}600)^2}{(2{,}300 - 1{,}600)^2}$$

$$S_b = 59.47 \text{ mi/h}$$

Then, using Equation 14-4:

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_R}{N} - 500\right)\left(\frac{v_R}{L_a}\right)\right]$$

$$S_M = \min\left[59.47, 59.47 - 0.00408\left(\frac{2{,}918 + 624}{2} - 500\right)\left(\frac{624}{740}\right)\right]$$

$$S_M = \min[59.47, 59.47 - 4.37] = 55.10 \text{ mi/h}$$

The average speed in the merge segment is estimated to be 4.37 mi/h less than the average speed in an equivalent basic freeway segment due to the merging turbulence. The demand volume in the merge segment is greater than the breakpoint value, with the result that the average basic segment speed is more than 5 mi/h lower than the FFS.

Step 3: Estimate the Capacity of the Merge Area and Compare with Demand

In this step, the demand is compared to the three checkpoints for a ramp–freeway junction: (*a*) the capacity of the ramp influence area itself, (*b*) the capacity of the freeway immediately downstream of the on-ramp, and (*c*) the capacity of the on-ramp.

Capacity of the Ramp Influence Area

Equation 14-8 is used to estimate the capacity of the ramp influence area C_M. This equation requires three parameters *A, B,* and *C,* which are determined from Equation 14-9 through Equation 14-11.

$$A = 35 \times \frac{FFS - \frac{C_B}{45}}{(C_B - BP)^2}$$

$$A = 35 \times \frac{60 - \frac{2{,}300}{45}}{(2{,}300 - 1{,}600)^2}$$

$$A = 6.35 \times 10^{-4}$$

$$B = 1 + 0.143\left(\frac{v_R}{L_a}\right) - (2A \times BP)$$

$$B = 1 + 0.143\left(\frac{625}{740}\right) - (2 \times 6.35 \times 10^{-4} \times 1{,}600)$$

$$B = -0.911$$

$$C = (A \times BP^2) - (35 \times FFS) - 71.4\left(\frac{v_R}{L_a}\right)$$

$$C = (6.35 \times 10^{-4} \times [1{,}600]^2) - (35 \times 60) - 71.4\left(\frac{624}{740}\right)$$

$$C = -534.6$$

With the parameters now determined, C_M is calculated as follows:

$$C_M = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$C_M = \frac{-(-0.911) + \sqrt{(-0.911)^2 - 4(6.35 \times 10^{-4})(-534.6)}}{2(6.35 \times 10^{-4})}$$

$$C_M = 1{,}882 \text{ pc/h/ln}$$

It was determined in Step 2 that no capacity adjustment is needed; therefore, the adjusted per-lane capacity of the merge area C_{Ma} is the same as C_M. The segment demand of 1,771 pc/h/ln is less than the merge area capacity of 1,882 pc/h/ln; therefore, the first capacity check is satisfied.

Capacity of the Downstream Freeway Segment

From Exhibit 14-9, the capacity of a basic freeway segment with 2 directional lanes and a FFS of 60 mi/h is 4,600 pc/h. This capacity is greater than the overall flow rate in the ramp influence area of 3,542 pc/h, which was determined in Step 1. Therefore, the second capacity check is satisfied.

Capacity of the Ramp Roadway

From Exhibit 14-10, the capacity of a single-lane ramp with a FFS of 45 mi/h is 2,100 pc/h. Because this capacity is greater than the on-ramp demand of 624 pc/h, the third capacity check is satisfied. With all capacity checks now satisfied, the analysis can proceed to Step 4.

Step 4: Estimate Density and LOS

The estimated average merge area speed is converted to density by using Equation 14-16:

$$D_M = \frac{(v_F + v_R)}{N \times S_M} = \frac{(2{,}918 + 624)}{2 \times 55.10} = 32.1 \text{ pc/mi/ln}$$

HCM6 results:
c = 2,300 pc/h/ln
S = 53.0 mi/h
D = 28.2 pc/mi/ln
LOS D

From Exhibit 14-3, this density is LOS E.

Discussion

The results indicate that the merge area operates in a stable fashion, with some deterioration in density and speed due to merging operations.

EXAMPLE PROBLEM 2: TWO ADJACENT SINGLE-LANE, RIGHT-HAND OFF-RAMPS ON A SIX-LANE FREEWAY

The Facts

The following information concerning demand volumes and geometries is available for this problem. The example assumes no impacts of inclement weather or incidents.

1. Two consecutive one-lane, right-hand off-ramps;
2. Six-lane freeway with FFS = 60 mi/h;
3. Level terrain for freeway and both ramps;
4. 7.5% trucks on freeway and both ramps;
5. First-ramp FFS = 40 mi/h;
6. Second-ramp FFS = 25 mi/h;
7. Drivers are regular commuters;
8. Freeway demand volume = 4,500 veh/h (immediately upstream of the first off-ramp);
9. First-ramp demand volume = 300 veh/h;
10. Second-ramp demand volume = 500 veh/h;
11. Distance between ramps = 750 ft;
12. First-ramp deceleration lane length = 500 ft;
13. Second-ramp deceleration lane length = 300 ft; and
14. Peak hour factor = 0.95.

Comments

The solution will use adjustment factors for heavy vehicle presence and driver population selected from Chapter 12, Basic Freeway and Multilane Highway Segments. All input parameters are specified, so no default values are needed or used.

Step 1: Provide Input Data and Adjust Volumes

Input parameters were specified in the Facts section above. Equation 14-1 is used to convert demand volumes to flow rates under equivalent ideal conditions:

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

In this case, three demand volumes must be converted: the freeway volume immediately upstream of the first ramp and the two ramp demand volumes. Since all demands include 7.5% trucks, only a single heavy vehicle adjustment factor will be needed. From Chapter 12, the appropriate value of E_T for level terrain is 2.0.

Then

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.075(2 - 1)} = 0.930$$

and

$$v_F = \frac{4{,}500}{0.95 \times 0.930} = 5{,}093 \text{ pc/h}$$

$$v_{R1} = \frac{300}{0.95 \times 0.930} = 340 \text{ pc/h}$$

$$v_{R2} = \frac{500}{0.95 \times 0.930} = 566 \text{ pc/h}$$

The overall flow rate in the first ramp influence area is then

$$v = v_F = 5{,}093 \text{ pc/h}$$

which, on a per lane basis, is equal to

$$\frac{v}{N} = \frac{5{,}093}{3} = 1{,}698 \text{ pc/h/ln}$$

The overall flow rate in the second ramp influence area is then

$$v = v_F - v_{R1} = 5{,}093 - 340 = 4{,}753 \text{ pc/h}$$

which, on a per lane basis, is equal to

$$\frac{v}{N} = \frac{4{,}753}{3} = 1{,}584 \text{ pc/h/ln}$$

Step 2: Estimate Speed in the Ramp Influence Area

First Off-Ramp

The average speed in the ramp influence area is estimated using Equation 14-5 for a diverge area:

$$S_D = \min\left[S_b, S_b - 0.00014\left(\frac{v_F}{N} - 500\right)\left(\frac{v_R}{{L_d}^{0.536}}\right)\right]$$

The freeway FFS is the same as in Example Problem 1. Given that no speed or capacity adjustments are required, the breakpoint and basic segment capacity values are therefore the same as calculated in Example Problem 1: BP = 1,600 pc/h/ln and C_B = 2,300 pc/h/ln.

Given that the per-lane demand volume of 1,698 pc/h/ln is greater than the breakpoint, but less than the basic segment capacity, S_b is calculated as:

$$S_b = FFS_{adj} - \frac{(FFS_{adj} - \frac{c}{D_c})(v_p - BP)^2}{(c - BP)^2}$$

$$S_b = 60 - \frac{(60 - \frac{2{,}300}{45})(1{,}698 - 1{,}600)^2}{(2{,}300 - 1{,}600)^2}$$

$$S_b = 59.83 \text{ mi/h}$$

Then, using Equation 14-5:

$$S_D = \min\left[S_b, S_b - 0.00014\left(\frac{v_F}{N} - 500\right)\left(\frac{v_R}{{L_d}^{0.536}}\right)\right]$$

$$S_D = \min\left[59.83, 59.83 - 0.00014\left(\frac{5{,}093}{3} - 500\right)\left(\frac{340}{[500]^{0.536}}\right)\right]$$

$$S_D = \min[59.83, 59.83 - 2.04] = 57.79 \text{ mi/h}$$

Second Off-Ramp

The demand volume in the second ramp influence area, 1,584 pc/h/ln, is less than the breakpoint value of 1,600 pc/h/ln. Therefore, S_b is equal to the FFS of 60 mi/h. Then, using Equation 14-5:

$$S_D = \min\left[S_b, S_b - 0.00014\left(\frac{v_F}{N} - 500\right)\left(\frac{v_R}{{L_d}^{0.536}}\right)\right]$$

$$S_D = \min\left[60, 60 - 0.00014\left(\frac{4{,}753}{3} - 500\right)\left(\frac{566}{[300]^{0.536}}\right)\right]$$

$$S_D = \min[60, 60 - 4.04] = 55.96 \text{ mi/h}$$

Although the demand volume is lower in the second ramp influence area than in the first, the combination of the shorter deceleration lane length and the greater ramp demand results in greater turbulence and a lower overall speed.

Step 3: Estimate the Capacities of the Diverge Areas and Compare with Demand

In this step, the demand is compared to the three checkpoints for a ramp–freeway junction: (*a*) the capacity of the ramp influence area itself, (*b*) the capacity of the freeway immediately upstream of the off-ramp, and (*c*) the capacity of the off-ramp. These checks are performed for both off-ramps.

Capacity of the Ramp Influence Area

First Off-Ramp

Equation 14-8 is used to estimate the capacity of the ramp influence area C_D. This equation requires three parameters *A, B,* and *C,* which are determined from Equation 14-12 through Equation 14-14 for diverge areas.

$$A = 35\ \times \frac{FFS - \frac{C_B}{45}}{(C_B - BP)^2}$$

$$A = 35\ \times \frac{60 - \frac{2{,}300}{45}}{(2{,}300 - 1{,}600)^2}$$

$$A = 6.35 \times 10^{-4}$$

$$B = 1 + 0.0049\left(\frac{v_R}{{L_d}^{0.536}}\right) - (2A \times BP)$$

$$B = 1 + 0.0049\left(\frac{340}{[500]^{0.536}}\right) - (2 \times 6.35 \times 10^{-4} \times 1{,}600)$$

$$B = -0.972$$

$$C = (A \times BP^2) - (35 \times FFS) - 2.45\left(\frac{v_R}{{L_d}^{0.536}}\right)$$

$$C = (6.35 \times 10^{-4} \times [1{,}600]^2) - (35 \times 60) - 2.45\left(\frac{340}{[500]^{0.536}}\right)$$

$$C = -504.2$$

With the parameters now determined, C_D is calculated as follows:

$$C_D = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$C_D = \frac{-(-0.972) + \sqrt{(-0.972)^2 - 4(6.35 \times 10^{-4})(-504.2)}}{2(6.35 \times 10^{-4})}$$

$$C_D = 1{,}940 \text{ pc/h/ln}$$

It was determined in Step 2 that no capacity adjustment is needed; therefore, the adjusted per-lane capacity of the merge area C_{Da} is the same as C_D. The segment demand of 1,698 pc/h/ln is less than the diverge area capacity of 1,940 pc/h/ln; therefore, the first capacity check is satisfied for the first off-ramp.

Second Off-Ramp

Equation 14-8 also is used to estimate the capacity C_D of the second ramp influence area. The inputs used to calculate parameter A are the same as for the first off-ramp; therefore A is the same as for the first off-ramp, 6.35×10^{-4}. Parameters B and C are calculated as follows:

$$B = 1 + 0.0049\left(\frac{v_R}{{L_d}^{0.536}}\right) - (2A \times BP)$$

$$B = 1 + 0.0049\left(\frac{500}{[300]^{0.536}}\right) - (2 \times 6.35 \times 10^{-4} \times 1{,}600)$$

$$B = -0.917$$

$$C = (A \times BP^2) - (35 \times FFS) - 2.45\left(\frac{v_R}{{L_d}^{0.536}}\right)$$

$$C = (6.35 \times 10^{-4} \times [1{,}600]^2) - (35 \times 60) - 2.45\left(\frac{500}{[300]^{0.536}}\right)$$

$$C = -532.0$$

With the parameters now determined, C_D is calculated as follows:

$$C_D = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$C_D = \frac{-(-0.917) + \sqrt{(-0.917)^2 - 4(6.35 \times 10^{-4})(-532.0)}}{2(6.35 \times 10^{-4})}$$

$$C_D = 1{,}888 \text{ pc/h/ln}$$

It was determined in Step 2 that no capacity adjustment is needed; therefore, the adjusted per-lane capacity of the merge area C_{Da} is the same as C_D. The segment demand of 1,584 pc/h/ln is less than the diverge area capacity of 1,888 pc/h/ln; therefore, the first capacity check is satisfied for the second off-ramp.

Capacity of the Upstream Freeway Segment

From Exhibit 14-9, the capacity of a basic freeway segment with 3 directional lanes and a FFS of 60 mi/h is 6,900 pc/h. This capacity is greater than the overall flow rates in both ramp influence areas (5,093 and 4,753 pc/h, respectively), which were determined in Step 1. Therefore, the second capacity check is satisfied for both diverge segments.

Capacity of the Ramp Roadway

From Exhibit 14-10, the capacity of a single-lane ramp with a FFS of 40 mi/h is 2,100 pc/h, while the capacity of a single-lane ramp with a FFS of 25 mi/h is 1,900 pc/h. Because these capacities are greater than the respective off-ramp demands of 340 and 566 pc/h, the third capacity check is satisfied is satisfied for both diverge segments. With all capacity checks now satisfied, the analysis can proceed to Step 4.

Step 4: Estimate Density and LOS

First Off-Ramp

The estimated average diverge area speed is converted to density by using Equation 14-17:

$$D_D = \frac{v_F}{N \times S_M} = \frac{5{,}093}{3 \times 57.79} = 29.4 \text{ pc/mi/ln}$$

From Exhibit 14-3, this density is LOS D, close to the boundary of LOS E.

HCM6 results:
c = 2,300 pc/h/ln
S = 56.0 mi/h
D = 27.9 pc/mi/ln
LOS C

Second Off-Ramp

$$D_D = \frac{v_F}{N \times S_M} = \frac{4{,}753}{3 \times 55.96} = 28.3 \text{ pc/mi/ln}$$

From Exhibit 14-3, this density is LOS D.

HCM6 results:
c = 2,300 pc/h/ln
S = 53.1 mi/h
D = 28.6 pc/mi/ln
LOS D

Discussion

Note that the two ramp influence areas overlap. The influence area of the first off-ramp extends 1,500 ft upstream. The influence area of the second off-ramp also extends 1,500 ft upstream. Since the ramps are only 750 ft apart, the second ramp influence area overlaps the first for 750 ft (immediately upstream of the first diverge point). The worse of the two levels of service is applied to this overlap area. In this case, both influence areas have the same LOS and the overlapping influence area is assigned LOS D.

Since the operation is stable, there is no special concern here, short of a significant increase in demand flows. LOS is technically D but falls just below the LOS E boundary. In this case the step-function LOS assigned may imply operation better than actually exists. It emphasizes the importance of knowing not only the LOS but also the value of the service measure that produces it.

EXAMPLE PROBLEM 3: ONE-LANE ON-RAMP FOLLOWED BY A ONE-LANE OFF-RAMP ON AN EIGHT-LANE FREEWAY

The Facts

The following information is available concerning this pair of ramps to be analyzed. The example assumes no impacts of inclement weather or incidents.

1. Eight-lane freeway with an FFS of 65 mi/h;
2. One-lane, right-hand on-ramp with an FFS of 30 mi/h;
3. One-lane, right-hand off-ramp with an FFS of 25 mi/h;
4. Distance between ramps = 1,300 ft;
5. Acceleration lane on Ramp 1 = 260 ft;
6. Deceleration lane on Ramp 2 = 260 ft;
7. Level terrain on freeway and both ramps;
8. 10% trucks on freeway and off-ramp;
9. 5% trucks on on-ramp;
10. Freeway flow rate (upstream of first ramp) = 5,490 veh/h;
11. On-ramp flow rate = 410 veh/h;
12. Off-ramp flow rate = 600 veh/h;
13. PHF = 0.94; and
14. Drivers are regular commuters.

Comments

As with the previous example problems, the conversion of demand volumes to flow rates requires adjustment factors selected from Chapter 12, Basic Freeway and Multilane Highway Segments. All pertinent information is given, and no default values will be applied.

Step 1: Provide Input Data and Adjust Volumes

Input parameters were specified in the Facts section above. Equation 14-1 is used to convert demand volumes to flow rates under equivalent ideal conditions:

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

Three demand volumes must be converted to flow rates under equivalent ideal conditions: the freeway volume immediately upstream of the first ramp junction, the first ramp volume, and the second ramp volume. Because the freeway segment under study has level terrain, the value of E_T will be 2.0 for all volumes.

Then, for the freeway demand volume,

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.10(2 - 1)} = 0.909$$

$$v_F = \frac{5{,}490}{0.94 \times 0.909} = 6{,}425 \text{ pc/h}$$

For the on-ramp demand volume,

$$f_{HV} = \frac{1}{1 + 0.05(2 - 1)} = 0.952$$

$$v_{R1} = \frac{410}{0.94 \times 0.952} = 458 \text{ pc/h}$$

For the off-ramp demand volume,

$$f_{HV} = \frac{1}{1 + 0.10(2 - 1)} = 0.909$$

$$v_{R2} = \frac{600}{0.94 \times 0.909} = 702 \text{ pc/h}$$

In the remaining computations, these converted demand flow rates are used as input values.

The overall flow rate in the first (merge) ramp influence area is

$$v_1 = v_F + v_{R1} = 6{,}425 + 458 = 6{,}883 \text{ pc/h}$$

which, on a per lane basis, is equal to

$$\frac{v}{N} = \frac{6{,}883}{4} = 1{,}721 \text{ pc/h/ln}$$

The overall flow rate in the second (diverge) ramp influence area is the same as the flow rate departing the first ramp influence area, 6,883 pc/h, which equates to 1,721 pc/h/ln.

Step 2: Estimate Speed in the Ramp Influence Area

First Ramp (On-Ramp)

The average speed in the ramp influence area is estimated using Equation 14-4 for a merge area:

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_R}{N} - 500\right)\left(\frac{v_R}{L_a}\right)\right]$$

As with the previous example problems, the equivalent basic segment breakpoint BP and capacity c are used to determine the average speed of an equivalent basic segment. These values are calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 65)] \times (1.0)^2 = 1{,}400 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50)$$

$$c = 2{,}200 + 10 \times (65 - 50) = 2{,}350 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,721 pc/h/ln is greater than the breakpoint, but less than the basic segment capacity, S_b is then calculated as:

$$S_b = FFS_{adj} - \frac{(FFS_{adj} - \frac{c}{D_c})(v_p - BP)^2}{(c - BP)^2}$$

$$S_b = 65 - \frac{(65 - \frac{2{,}350}{45})(1{,}721 - 1{,}400)^2}{(2{,}350 - 1{,}400)^2}$$

$$S_b = 63.54 \text{ mi/h}$$

Then, using Equation 14-4:

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_{R1}}{N} - 500\right)\left(\frac{v_{R1}}{L_a}\right)\right]$$

$$S_M = \min\left[63.54, 63.54 - 0.00408\left(\frac{6{,}425 + 458}{4} - 500\right)\left(\frac{458}{260}\right)\right]$$

$$S_M = \min[63.54, 63.54 - 8.77] = 54.77 \text{ mi/h}$$

Second Ramp (Off-Ramp)

All of the inputs used to calculate the speed of an equivalent basic segment—FFS_{adj}, BP_{adj}, c, and v_p—are the same in the second ramp influence area. Therefore, the value of S_b is the same as in the first ramp influence area, 63.54 mi/h.

Because this ramp influence area is a diverge area, Equation 14-5 is used to calculate the average speed in the second ramp influence area. However, v_F in the equation is replaced in this instance by the freeway demand flow departing the first ramp influence area v_1:

$$S_D = \min\left[S_b, S_b - 0.00014\left(\frac{v_1}{N} - 500\right)\left(\frac{v_{R2}}{L_d^{\,0.536}}\right)\right]$$

$$S_D = \min\left[63.54, 63.54 - 0.00014\left(\frac{6{,}883}{4} - 500\right)\left(\frac{702}{[260]^{0.536}}\right)\right]$$

$$S_D = \min[63.54, 63.54 - 6.09] = 57.45 \text{ mi/h}$$

Step 3: Estimate the Capacities of the Merge and Diverge Areas and Compare with Demand

In this step, the demand is compared to the three checkpoints for a ramp–freeway junction: (*a*) the capacity of the ramp influence area itself, (*b*) the capacity of the freeway immediately upstream of the on-ramp or immediately downstream of the off-ramp, and (*c*) the capacity of the ramp. These checks are performed for both off-ramps.

Capacity of the Ramp Influence Area

First Ramp (On-Ramp)

Equation 14-8 is used to estimate the capacity of the ramp influence area C_M. This equation requires three parameters *A, B,* and *C,* which are determined from Equation 14-9 through Equation 14-11.

$$A = 35 \times \frac{FFS - \frac{C_B}{45}}{(C_B - BP)^2}$$

$$A = 35 \times \frac{65 - \frac{2{,}350}{45}}{(2{,}350 - 1{,}400)^2}$$

$$A = 4.96 \times 10^{-4}$$

$$B = 1 + 0.143\left(\frac{v_{R1}}{L_a}\right) - (2A \times BP)$$

$$B = 1 + 0.143\left(\frac{458}{260}\right) - (2 \times 4.96 \times 10^{-4} \times 1{,}400)$$

$$B = -0.137$$

$$C = (A \times BP^2) - (35 \times FFS) - 71.4\left(\frac{v_{R1}}{L_a}\right)$$

$$C = (4.96 \times 10^{-4} \times [1{,}400]^2) - (35 \times 65) - 71.4\left(\frac{458}{260}\right)$$

$$C = -1{,}428.6$$

With the parameters now determined, C_M is calculated as follows:

$$C_M = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$C_M = \frac{-(-0.137) + \sqrt{(-0.137)^2 - 4(4.96 \times 10^{-4})(-1{,}428.6)}}{2(4.96 \times 10^{-4})}$$

$$C_M = 1{,}841 \text{ pc/h/ln}$$

It was determined in Step 2 that no capacity adjustment is needed; therefore, the adjusted per-lane capacity of the merge area C_{Ma} is the same as C_M. The segment demand of 1,721 pc/h/ln is less than the merge area capacity of 1,841 pc/h/ln; therefore, the first capacity check is satisfied for the on-ramp.

Second Ramp (On-Ramp)

Equation 14-8 also is used to estimate the capacity of the ramp influence area C_D. The inputs used to calculate parameter A are the same as for the first off-ramp; therefore A is the same as for the first off-ramp, 4.96×10^{-4}. Parameters B and C are calculated as follows:

$$B = 1 + 0.0049\left(\frac{v_{R2}}{L_d^{\,0.536}}\right) - (2A \times BP)$$

$$B = 1 + 0.0049\left(\frac{702}{[260]^{0.536}}\right) - (2 \times 4.96 \times 10^{-4} \times 1{,}400)$$

$$B = -0.214$$

$$C = (A \times BP^2) - (35 \times FFS) - 2.45\left(\frac{v_{R2}}{L_d^{\,0.536}}\right)$$

$$C = (4.96 \times 10^{-4} \times [1{,}400]^2) - (35 \times 65) - 2.45\left(\frac{702}{[260]^{0.536}}\right)$$

$$C = -1{,}390.1$$

With the parameters now determined, C_D is calculated as follows:

$$C_D = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$C_D = \frac{-(-0.214) + \sqrt{(-0.214)^2 - 4(4.96 \times 10^{-4})(-1{,}390.1)}}{2(4.96 \times 10^{-4})}$$

$$C_D = 1{,}904 \text{ pc/h/ln}$$

It was determined in Step 2 that no capacity adjustment is needed; therefore, the adjusted per-lane capacity of the merge area C_{Da} is the same as C_D. The segment demand of 1,721 pc/h/ln is less than the diverge area capacity of 1,904 pc/h/ln; therefore, the first capacity check is satisfied for the off-ramp.

Capacity of the Downstream/Upstream Freeway Segments

From Exhibit 14-9, the capacity of a basic freeway segment with 4 directional lanes and a FFS of 65 mi/h is 9,400 pc/h. This capacity is compared to the flow rate immediately downstream of the merge and immediately upstream of the diverge which, in this case, is the same section of freeway. The capacity of 9,400 pc/h is greater than the flow rate of 6,883 pc/h; therefore, the second capacity check is satisfied for both ramps.

Capacity of the Ramp Roadway

From Exhibit 14-10, the capacity of a single-lane ramp with a FFS of 30 mi/h is 1,900 pc/h and the capacity of a single-lane ramp with a FFS of 25 mi/h is also 1,900 pc/h. Because these capacities are greater than the respective off-ramp demands of 458 and 702 pc/h, the third capacity check is satisfied is satisfied for both ramps. With all capacity checks now satisfied, the analysis can proceed to Step 4.

Step 4: Estimate Density and LOS

First Ramp (On-Ramp)

The estimated average merge area speed is converted to density by using Equation 14-16:

$$D_M = \frac{(v_F + v_{R1})}{N \times S_M} = \frac{(6{,}425 + 458)}{4 \times 54.77} = 31.4 \text{ pc/mi/ln}$$

From Exhibit 14-3, this density is LOS E.

HCM6 results:
$c = 2{,}350$ pc/h/ln
$S = 58.8$ mi/h
$D = 27.2$ pc/mi/ln
LOS C

Second Ramp (Off-Ramp)

The estimated average diverge area speed is converted to density by using Equation 14-17:

$$D_D = \frac{v_1}{N \times S_M} = \frac{6{,}883}{4 \times 57.45} = 29.95 \text{ pc/mi/ln}$$

From Exhibit 14-3, this density is LOS D, and nearly LOS E.

HCM6 results:
$c = 2{,}350$ pc/h/ln
$S = 58.3$ mi/h
$D = 31.1$ pc/mi/ln
LOS D

Discussion

Because the two ramps are separated by 1,300 feet, but the on-ramp's influence area extends 1,500 feet downstream and the off-ramp's influence area extends 1,500 feet upstream, the two influence areas fully overlap. Since a higher density is predicted for the on-ramp influence area, and LOS E results, this density should be applied to the entire area between the two ramps. Similarly, the slower speeds within the on-ramp influence area will also control the overlap area.

EXAMPLE PROBLEM 4: SINGLE-LANE, LEFT-HAND ON-RAMP ON A SIX-LANE FREEWAY

The Facts

The following information is available concerning this example problem. The example assumes no impacts of inclement weather or incidents.

1. One-lane, left-side on-ramp on a six-lane freeway (three lanes in each direction);
2. Freeway demand volume upstream of ramp = 4,000 veh/h;
3. On-ramp demand volume = 490 veh/h;
4. 7.5% trucks on freeway, 3% trucks on the on-ramp;
5. Freeway FFS = 65 mi/h;
6. Ramp FFS = 30 mi/h;
7. Acceleration lane = 820 ft;
8. Level terrain on freeway and ramp;
9. Drivers are regular commuters; and
10. PHF = 0.90.

Comments

This is a special application of the ramp analysis methodology developed for right-hand ramps presented in Chapter 14.

Text related to volume in the left/rightmost two lanes deleted.

Step 1: Provide Input Data and Adjust Volumes

Input parameters were specified in the Facts section above. Equation 14-1 is used to convert demand volumes to flow rates under equivalent ideal conditions:

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

From Chapter 12, Basic Freeway and Multilane Highway Segments, the passenger car equivalent E_T for trucks in level terrain is 2.0.

For the freeway demand volume,

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.075(2 - 1)} = 0.93$$

$$v_F = \frac{4{,}000}{0.90 \times 0.93} = 4{,}779 \text{ pc/h}$$

For the ramp demand volume,

$$f_{HV} = \frac{1}{1 + 0.03(2 - 1)} = 0.971$$

$$v_R = \frac{490}{0.90 \times 0.971} = 561 \text{ pc/h}$$

The overall flow rate in the ramp influence area is

$$v = v_F + v_{R1} = 4{,}779 + 561 = 5{,}340 \text{ pc/h}$$

which, on a per lane basis, is equal to

$$\frac{v}{N} = \frac{5{,}340}{3} = 1{,}780 \text{ pc/h/ln}$$

Step 2: Estimate Speed in the Ramp Influence Area

The average speed in the ramp influence area is estimated using Equation 14-4 for a merge area:

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_R}{N} - 500\right)\left(\frac{v_R}{L_a}\right)\right]$$

As with the previous example problems, the equivalent basic segment breakpoint *BP* and capacity *c* are used to determine the average speed of an equivalent basic segment. These values are calculated as follows:

$$BP = \left[1{,}000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2$$

$$BP = [1{,}000 + 40 \times (75 - 65)] \times (1.0)^2 = 1{,}400 \text{ pc/h/ln}$$

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50)$$

$$c = 2{,}200 + 10 \times (65 - 50) = 2{,}350 \text{ pc/h/ln}$$

Given that the per-lane demand volume of 1,780 pc/h/ln is greater than the breakpoint, but less than the basic segment capacity, S_b is then calculated as:

$$S_b = FFS_{adj} - \frac{(FFS_{adj} - \frac{c}{D_c})(v_p - BP)^2}{(c - BP)^2}$$

$$S_b = 65 - \frac{(65 - \frac{2{,}350}{45})(1{,}780 - 1{,}400)^2}{(2{,}350 - 1{,}400)^2}$$

$$S_b = 62.96 \text{ mi/h}$$

Then, using Equation 14-4:

$$S_M = \min\left[S_b, S_b - 0.00408\left(\frac{v_F + v_R}{N} - 500\right)\left(\frac{v_R}{L_a}\right)\right]$$

$$S_M = \min\left[62.96, 62.96 - 0.00408\left(\frac{4{,}779 + 561}{3} - 500\right)\left(\frac{561}{820}\right)\right]$$

$$S_M = \min[62.96, 62.96 - 3.57] = 59.39 \text{ mi/h}$$

Step 3: Estimate the Capacity of the Merge Area and Compare with Demand

In this step, the demand is compared to the three checkpoints for a ramp–freeway junction: (*a*) the capacity of the ramp influence area itself, (*b*) the capacity of the freeway immediately downstream of the on-ramp, and (*c*) the capacity of the on-ramp.

Capacity of the Ramp Influence Area

Equation 14-8 is used to estimate the capacity of the ramp influence area C_M. This equation requires three parameters *A, B,* and *C,* which are determined from

Equation 14-9 through Equation 14-11.

$$A = 35 \times \frac{FFS - \frac{C_B}{45}}{(C_B - BP)^2}$$

$$A = 35 \times \frac{65 - \frac{2{,}350}{45}}{(2{,}350 - 1{,}400)^2}$$

$$A = 4.96 \times 10^{-4}$$

$$B = 1 + 0.143\left(\frac{v_R}{L_a}\right) - (2A \times BP)$$

$$B = 1 + 0.143\left(\frac{561}{820}\right) - (2 \times 4.96 \times 10^{-4} \times 1{,}400)$$

$$B = -0.291$$

$$C = (A \times BP^2) - (35 \times FFS) - 71.4\left(\frac{v_R}{L_a}\right)$$

$$C = (4.96 \times 10^{-4} \times [1{,}400]^2) - (35 \times 65) - 71.4\left(\frac{561}{820}\right)$$

$$C = -1{,}351.7$$

With the parameters now determined, C_M is calculated as follows:

$$C_M = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$C_M = \frac{-(-0.291) + \sqrt{(-0.291)^2 - 4(4.96 \times 10^{-4})(-1{,}351.7)}}{2(4.96 \times 10^{-4})}$$

$$C_M = 1{,}970 \text{ pc/h/ln}$$

It was determined in Step 2 that no capacity adjustment is needed; therefore, the adjusted per-lane capacity of the merge area C_{Ma} is the same as C_M. The segment demand of 1,780 pc/h/ln is less than the merge area capacity of 1,970 pc/h/ln; therefore, the first capacity check is satisfied for the on-ramp.

Capacity of the Downstream/Upstream Freeway Segments

From Exhibit 14-9, the capacity of a basic freeway segment with 3 directional lanes and a FFS of 65 mi/h is 7,050 pc/h. This capacity is compared to the flow rate immediately downstream of the merge. The capacity of 7,050 pc/h is greater than the flow rate of 5,340 pc/h; therefore, the second capacity check is satisfied.

Capacity of the Ramp Roadway

From Exhibit 14-10, the capacity of a single-lane ramp with a FFS of 30 mi/h is 1,900 pc/h. This capacity is greater than the on-ramp demands of 561 pc/h; therefore, the third capacity check is satisfied. With all capacity checks now satisfied, the analysis can proceed to Step 4.

Step 4: Estimate Density and LOS

The estimated average merge area speed is converted to density by using Equation 14-16:

$$D_M = \frac{(v_F + v_R)}{N \times S_M} = \frac{(4{,}779 + 561)}{3 \times 59.39} = 29.97 \text{ pc/mi/ln}$$

From Exhibit 14-3, this density is LOS D, and nearly LOS E.

HCM6 results:
c = 2,350 pc/h/ln
S = 56.5 mi/h
D = 29.5 pc/mi/ln
LOS D

Discussion

This example problem is typical of the way the situations in the Special Cases section of Chapter 14 are treated. Modifications as specified are applied to the standard algorithms used for single-lane, right-hand ramp junctions. In this case, operations are acceptable, but just below the LOS D/E threshold. Because the left-hand lanes are expected to carry freeway traffic flowing faster than right-hand lanes, right-hand ramps are normally preferable to left-hand ramps when they can be provided without great difficulty.

EXAMPLE PROBLEM 5: SERVICE FLOW RATES AND SERVICE VOLUMES FOR AN ISOLATED ON-RAMP ON A SIX-LANE FREEWAY

The Facts

The following information is available concerning this example problem. The example assumes no impacts of inclement weather or incidents.

1. Single-lane, right-hand on-ramp with an FFS of 40 mi/h;
2. Six-lane freeway (three lanes in each direction) with an FFS of 70 mi/h;
3. Level terrain for freeway and ramp;
4. 6.5% trucks on both freeway and ramp segments;
5. Peak hour factor = 0.87;
6. Drivers are regular users of the facility; and
7. Acceleration lane = 1,000 ft.

Comments

This example illustrates the computation of service flow rates and service volumes for a ramp–freeway junction. The case selected is relatively straightforward to avoid extraneous complications that have been addressed in other example problems.

Two approaches will be demonstrated:

1. The ramp demand flow rate will be stated as a fixed percentage of the arriving freeway flow rate. The service flow rates and service volumes are expressed as arriving freeway flow rates that result in the threshold densities within the ramp influence area that define the limits of the various levels of service. For this computation, the ramp flow is set at 10% of the approaching freeway flow rate.
2. A fixed freeway demand flow rate will be stated, with service flow rates and service volumes expressed as ramp demand flow rates that result in the threshold densities within the ramp influence area that define the

limits of the various levels of service. For this computation, the approaching freeway flow rate is set at 4,000 veh/h.

Paragraph about LOS E not being defined by density deleted.

Since all algorithms in this methodology are calibrated for passenger cars per hour under equivalent ideal conditions, initial computations are made in those terms. Results are then converted to service flow rates by using the appropriate heavy vehicle and driver population adjustment factors. Service flow rates are then converted to service volumes by multiplying by the peak hour factor.

From Exhibit 14-3, the following densities define the limits of LOS A–E:

LOS A: 11 pc/mi/ln

LOS B: 18 pc/mi/ln

LOS C: 25 pc/mi/ln

LOS D: 30 pc/mi/ln

LOS E: 35 pc/mi/ln

From Exhibit 14-10 and Exhibit 14-12, capacity (or the threshold for LOS E) can also occur when the downstream freeway flow rate reaches 7,200 pc/h (FFS = 70 mi/h) or when the ramp flow rate reaches 2,000 pc/h (ramp FFS = 40 mi/h).

Case 1: Ramp Demand Flow Rate = 0.10 × Freeway Demand Flow Rate

Equation 14-16 defines the density in an on-ramp influence area as follows:

$$D_M = \frac{(v_F + v_R)}{N \times S_M}$$

In this case, $v_R = 0.10\ v_F$ and $N = 3$, so by substitution

$$D_M = \frac{1.1 v_F}{3 S_M}$$

$$v_F = 2.73 D_M S_M$$

When the freeway flow rate is less than the basic segment breakpoint, the merge area speed equals the freeway FFS. The service flow rate for a given LOS is then found by simply substituting the maximum density value associated with a given LOS. For example, for LOS A, the maximum density value is 11 pc/mi/ln. Given the freeway's FFS of 70 mi/h, the service flow rate for LOS A is then:

$$v_F(\text{LOS A}) = 2.73 \times 11 \times 70 = 2{,}100 \text{ pc}$$

According to Exhibit 12-37, the basic segment service flow rate for LOS B for a FFS of 70 mi/h is 1,260 pc/h/ln, which is greater than the breakpoint value of 1,200 pc/h/ln for this FFS. Thus, for LOS B–E, the service flow rate will be a function of S_M, which in turn is a function of v_F, the acceleration lane length, and the equivalent basic segment speed S_b, which is also a function of v_F. Instead of trying to solve for v_F, it is easier to program Equation 12-1 (for S_b) and Equation 14-4 (for S_M) into a spreadsheet and iteratively increase v_F until the density threshold for a given LOS is reached. Doing so for the merge area being studied in this example problem gives the following service flow rates under equivalent ideal conditions:

$$v_F(\text{LOS B}) = 3{,}385 \text{ pc/h}$$

$$v_F(\text{LOS C}) = 4{,}477 \text{ pc/h}$$

$$v_F(\text{LOS D}) = 5{,}080 \text{ pc/h}$$

$$v_F(\text{LOS E}) = 5{,}566 \text{ pc/h}$$

The result for LOS E must be checked to ensure that the ramp flow rate (0.10 × 5,566 = 557 pc/h) does not exceed the ramp capacity of 2,000 pc/h and that the total merge area demand does not exceed the basic segment capacity of 7,200 pc/h. Since they do not, the computation stands.

Paragraph deleted about service volumes for LOS D not existing.

The computed values are in terms of passenger cars per hour under equivalent ideal conditions. To convert them to service flow rates in vehicles per hour under prevailing conditions, they must be multiplied by the heavy vehicle adjustment factor and the driver population factor. The approaching freeway flow includes 6.5% trucks on both the ramp and the mainline. For level terrain (Chapter 12, Basic Freeway and Multilane Highway Segments), $E_T = 2.0$. Then

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

$$f_{HV} = \frac{1}{1 + 0.065(2 - 1)} = 0.939$$

Service volumes are obtained by multiplying service flow rates by the specified PHF, 0.87. These computations are illustrated in Exhibit 28-2.

Exhibit 28-2
Example Problem 5: Illustrative Service Flow Rates and Service Volumes Based on Approaching Freeway Demand

LOS	Service Flow Rate, Ideal Conditions (pc/h)	Service Flow Rate, Prevailing Conditions (SF) (veh/h)	Service Volume (SV) (veh/h)
A	2,100	2,100 × 0.939 × 1 = 1,972	1,972 × 0.87 = 1,716
B	3,385	3,385 × 0.939 × 1 = 3,179	3,179 × 0.87 = 2,765
C	4,477	4,477 × 0.939 × 1 = 4,204	4,204 × 0.87 = 3,657
D	5,080	5,080 × 0.939 × 1 = 4,770	4,770 × 0.87 = 4,150
E	5,566	5,566 × 0.939 × 1 = 5,226	5,226 × 0.87 = 4,547

The service flow rates and service volumes shown in Exhibit 28-2 are stated in terms of the approaching hourly freeway demand.

Case 2: Approaching Freeway Demand Volume = 4,000 veh/h

In this case, the approaching freeway demand will be held constant at 4,000 veh/h, and service flow rates and service volumes will be stated in terms of the ramp demand that can be accommodated at each LOS.

Since the freeway demand is stated in terms of an hourly volume in mixed vehicles per hour, it will be converted to passenger cars per hour under equivalent ideal conditions for use in the algorithms of this methodology:

$$v_F = \frac{V_F}{PHF \times f_{HV}} = \frac{4{,}000}{0.87 \times 0.939} = 4{,}896 \text{ pc/h}$$

The calculated flow rate of 4,896 pc/h is equivalent to 1,632 pc/h/ln. By comparison with the basic segment service flow rates given in Exhibit 12-37 for a freeway FFS of 70 mi/h, it can be seen that this flow rate is greater than the service flow rates for both LOS A and LOS B and therefore neither LOS A nor LOS B can be achieved. Consequently, service flow rates will be calculated starting with LOS C.

The flow rate of 1,632 pc/h/ln is greater than the breakpoint for a freeway with a FFS of 70 mi/h (1,200 pc/h/ln). Therefore, as in Case 1, a spreadsheet will be programmed to perform the calculations iteratively. The ramp volume will be increased incrementally until the density threshold for a given LOS is reached, with the following results:

$$v_R(\text{LOS C}) = 119 \text{ pc/h}$$

$$v_R(\text{LOS D}) = 647 \text{ pc/h}$$

$$v_R(\text{LOS E}) = 1{,}047 \text{ pc/h}$$

The ramp volume at LOS E is less than the ramp capacity of 2,000 pc/h and the segment volume at LOS E of (4,896 + 1,047 = 5,943 pc/h) is less than the basic segment capacity of 7,200 pc/h; therefore, the LOS E results stand.

As in Case 1, these values are all stated in terms of passenger cars per hour under equivalent ideal conditions. They are converted to service flow rates by multiplying by the appropriate heavy vehicle factor (0.939 from Case 1). Service flow rates are converted to service volumes by multiplying by the PHF. These computations for ramp service volumes are illustrated in Exhibit 28-3.

Exhibit 28-3
Example Problem 5: Illustrative Service Flow Rates and Service Volumes Based on a Fixed Freeway Demand

LOS	Service Flow Rate, Ideal Conditions (pc/h)	Service Flow Rate, Prevailing Conditions (veh/h)	Ramp Service Volume (veh/h)
A	NA	NA	NA
B	NA	NA	NA
C	119	119 × 0.939 × 1 = 112	112 × 0.87 = 97
D	647	647 × 0.939 × 1 = 608	608 × 0.87 = 529
E	1,047	1,047 × 0.939 × 1 = 983	983 × 0.87 = 855

These service flow rates and service volumes are based on a constant upstream arriving freeway demand and are stated in terms of limiting on-ramp demands for that condition.

Discussion

As this illustration shows, many considerations are involved in estimating service flow rates and service volumes for ramp–freeway junctions, not the least of which is specifying how such values should be defined. The concept of service flow rates and service volumes at specific ramp–freeway junctions is of limited utility. Since many of the details that affect the estimates will not be determined until final designs are prepared, operational analysis of the proposed design may be more appropriate.

Case 2 could have applications in considering how to time ramp meters. Appropriate limiting ramp flows can be estimated by using the same approach as for service volumes and service flow rates.

3. ALTERNATIVE TOOL EXAMPLES FOR FREEWAY RAMPS

Chapter 14, Freeway Merge and Diverge Segments, described a methodology for analyzing ramps and ramp junctions to estimate capacity, speed, and density as a function of traffic demand and geometric configuration. This chapter includes two supplemental problems that examine situations that are beyond the scope of the Chapter 14 methodology. A typical microsimulation-based tool is used for this purpose, and the simulation results are compared, where appropriate, with those of the HCM.

Both problems are based on this chapter's Example Problem 3, which analyzes an eight-lane freeway segment with an entrance and an exit ramp. The first problem evaluates the effects of the addition of ramp metering, while the second evaluates the impacts of converting the leftmost lane of the mainline into a high-occupancy vehicle (HOV) lane.

The need to determine performance measures based on the analysis of vehicle trajectories was emphasized in Chapter 7, Interpreting HCM and Alternative Tool Results. Specific procedures for defining measures in terms of vehicle trajectories were proposed to guide the future development of alternative tools. Pending further development, the examples presented in this chapter have applied existing versions of alternative tools and therefore do not reflect the trajectory-based measures described in Chapter 7.

For purposes of illustration, the default calibration parameters of the simulation tool (e.g., lane-changing behavioral characteristics) were applied to these examples. However, most simulation tools offer the ability to adjust these parameters. The parameter values can have a significant effect on the results, especially when the operation is close to full saturation.

PROBLEM 1: RAMP-METERING EFFECTS

This problem analyzes the impacts of ramp metering along the segment. The HCM procedure for ramp-merge junctions cannot estimate the impacts of ramp metering. These impacts can be approximated to some extent by not allowing the ramp demand to exceed the ramp-metering rate. To address ramp metering at a more detailed level, a typical microsimulation tool was used to evaluate the impacts of ramp metering on the density and capacity of the merge.

The subject segment consists of an on-ramp followed by an off-ramp, separated by 1,300 ft. The upstream segment is 1 mi long. Each simulation run was for 1 full hour. It was assumed that the mainline demand was 6,111 veh/h and that the ramp demand was 444 veh/h. The ramp metering is clock-time based (i.e., the metering rate does not change as a function of the mainline demand).

Experiments were conducted to obtain the density and capacity of the subject segment as a function of the ramp-metering rate. The queue length upstream of the ramp meter was also obtained as a function of the ramp-metering rate. Exhibit 28-4 provides a graphics capture of the simulated site.

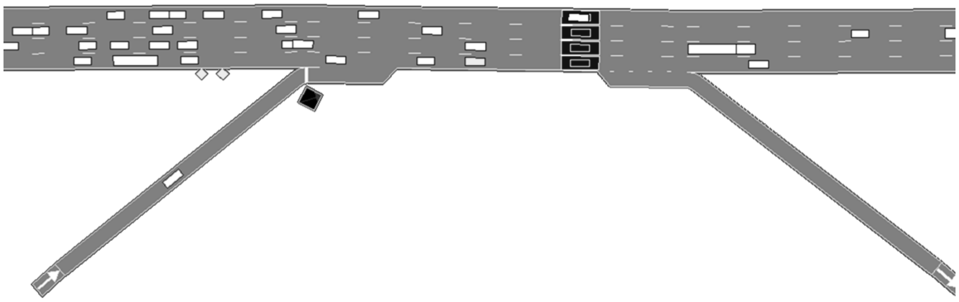


Exhibit 28-4
Graphics Capture of the Ramp Merge with Ramp Metering

Exhibit 28-5 provides the density of the segment between the on-ramp and the off-ramp as a function of the ramp-metering rate (or discharge headway from the on-ramp). As shown, the density is not much affected by the ramp-metering rate. As expected, the density of Lane 1 (the rightmost lane) is the highest, while the density in Lane 4 is the lowest.

Exhibit 28-5
Density as a Function of Ramp-Metering Headways

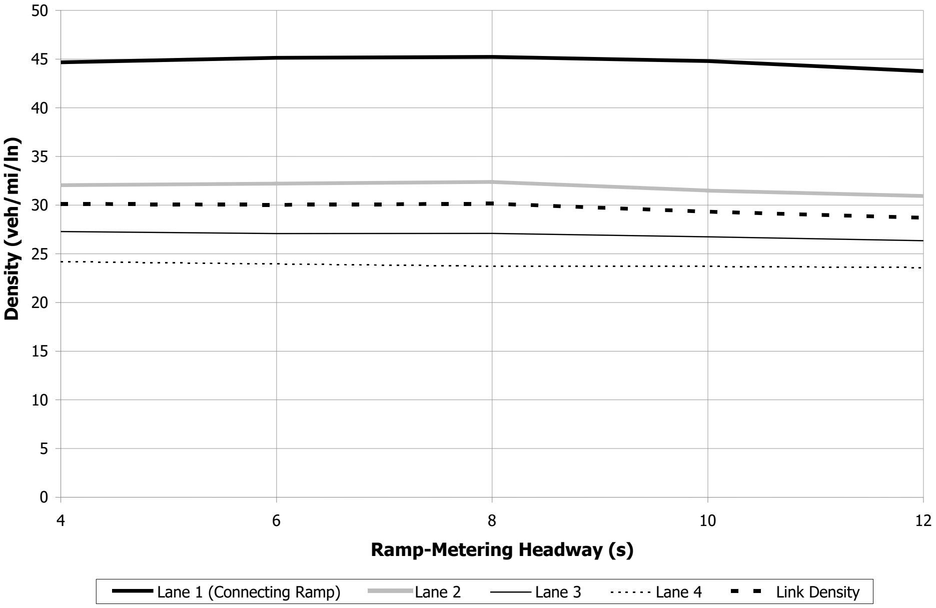


Exhibit 28-6 provides capacity as a function of the ramp-metering headway and when no ramp metering is implemented. As shown, the simulation model predicts that capacity is higher when ramp metering is implemented. Capacity in simulation is typically measured in the form of maximum throughput downstream of a queued segment and is therefore one of the outputs of the simulation, as opposed to an input as in the HCM.

Exhibit 28-6
Capacity at a Ramp Junction as a Function of Ramp-Metering Headways

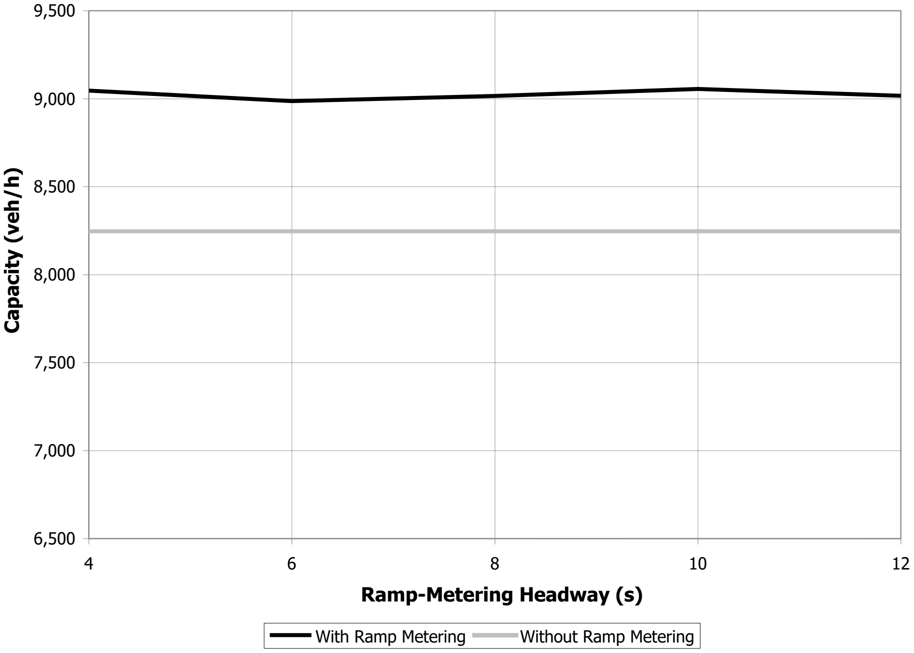
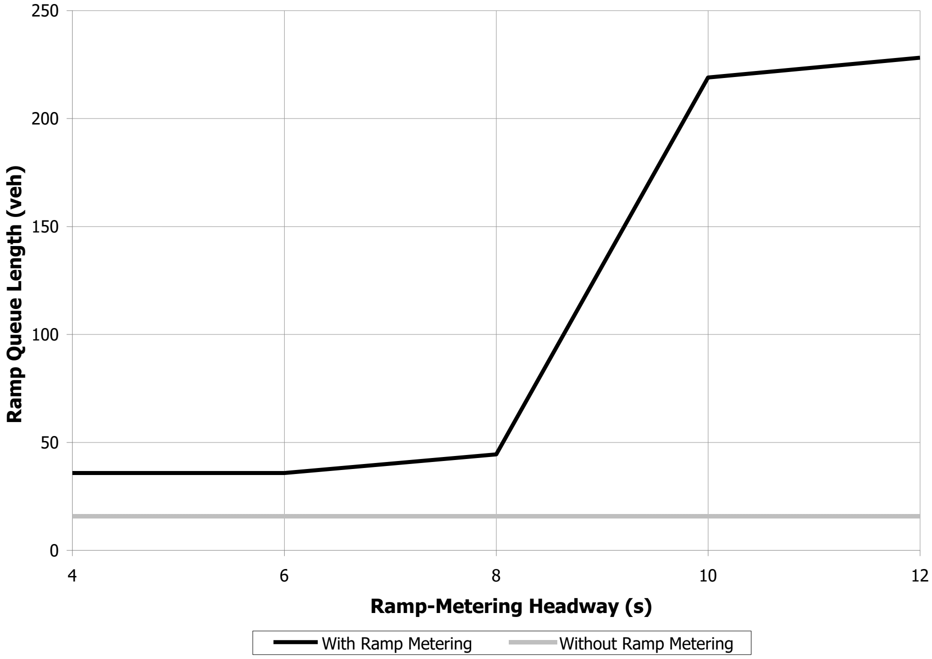


Exhibit 28-7 provides the queue length expected on the ramp as a function of the ramp-metering headway and when no ramp metering is implemented. As expected, the queue length is higher when ramp metering is implemented, and it increases dramatically when the ramp-metering rate exceeds 8 s/veh. The reason for this increase is that the demand on the ramp is approximately 8 s/veh (444 veh/h corresponds to an average headway of 8.1 s/veh).

Exhibit 28-7
Queue Length on the Ramp as a Function of Ramp-Metering Headways



As indicated above, the effects of ramp metering cannot be evaluated with the HCM. The freeway facilities methodology (HCM Chapter 10) can handle changes in segment capacity; however, other tools are required to estimate what the maximum throughput would be under various types of ramp-metering algorithms and rates. Also, the HCM cannot estimate the queue length on the on-ramp as a function of ramp metering. An analytical method could be developed to estimate queue length as a function of demand and service rate at the meter.

PROBLEM 2: CONVERSION OF LEFTMOST LANE TO AN HOV LANE

This problem is also based on this chapter's Example Problem 3. It evaluates operating conditions when the leftmost lane of the mainline is converted into an HOV lane. Exhibit 28-8 provides a graphics capture of the segment.

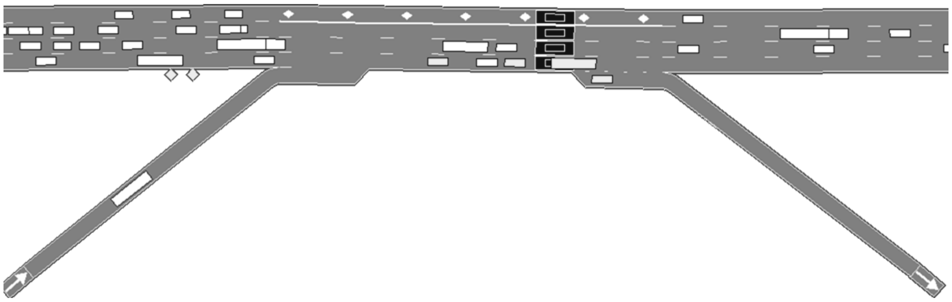


Exhibit 28-8
Graphics Capture of the Segment with an HOV Lane

Exhibit 28-9 and Exhibit 28-10 show the density and capacity of the ramp junction as a function of the percentage of carpools. As shown, when the percentage of carpools increases, the density of the HOV lane and the overall link capacity increase. This occurs because for the range of values tested here, the utilization of the HOV lane increases, which improves the overall link performance.

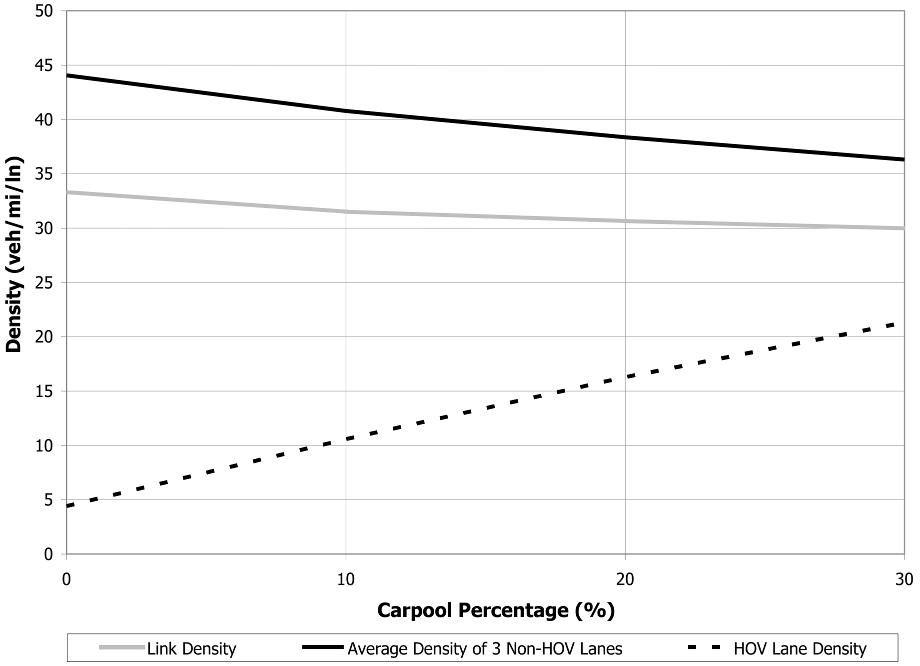


Exhibit 28-9
Density of a Ramp Junction as a Function of the Carpool Percentage

Exhibit 28-10
Capacity of a Ramp Junction as a Function of the Carpool Percentage

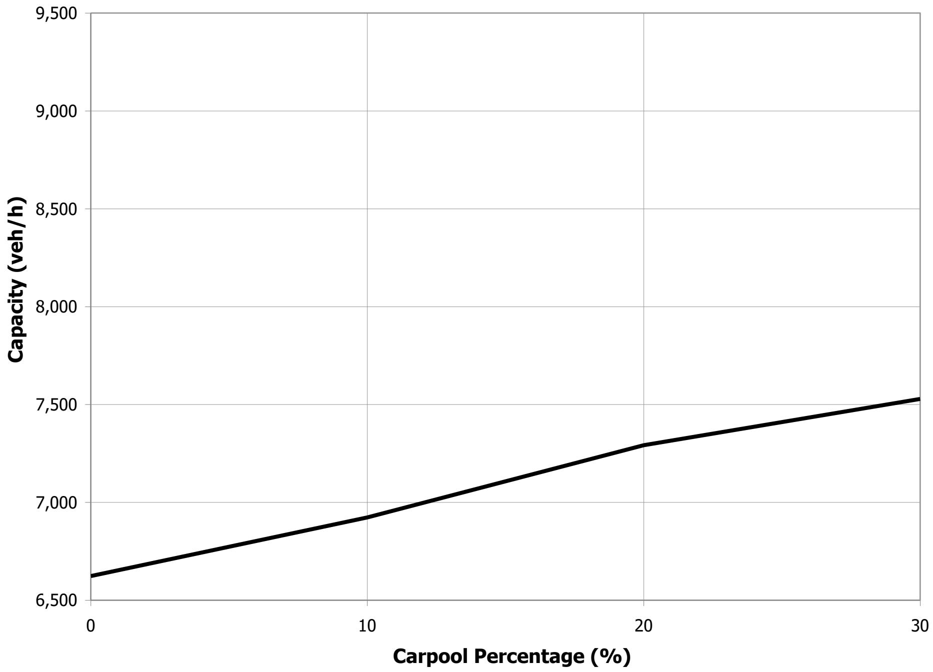
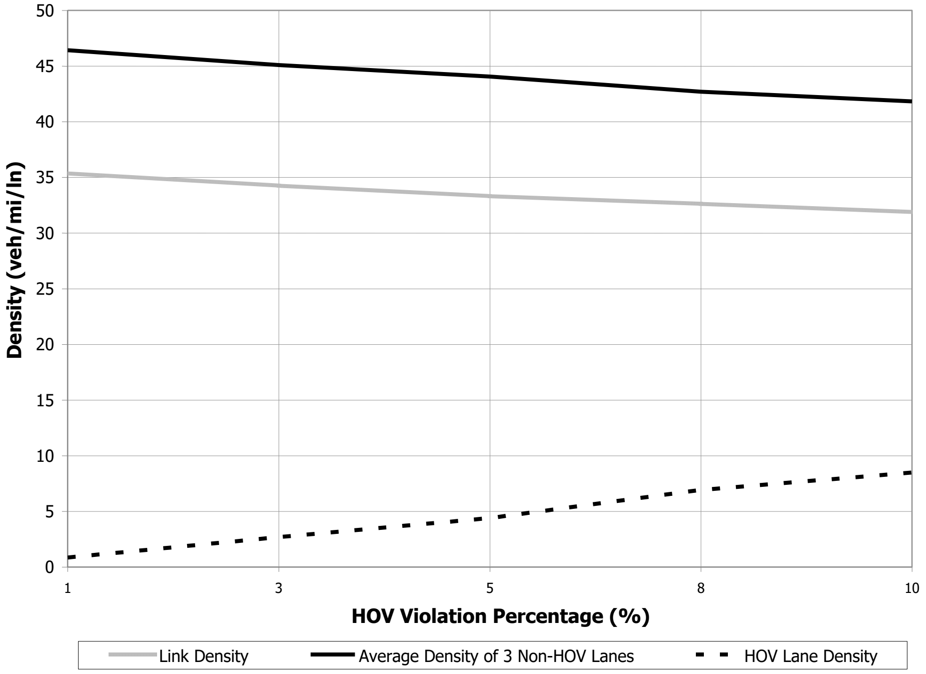


Exhibit 28-11 presents the density as a function of HOV violators, while Exhibit 28-12 presents the corresponding capacity. These two graphs assume that there are 10% carpools in the traffic stream. As shown, density generally decreases while capacity increases as the percentage of HOV violators increases. The reason is that under this scenario, the facility is more efficiently utilized as violations increase with general traffic using the HOV lane.

Exhibit 28-11
Density of a Ramp Junction as a Function of the HOV Violation Percentage



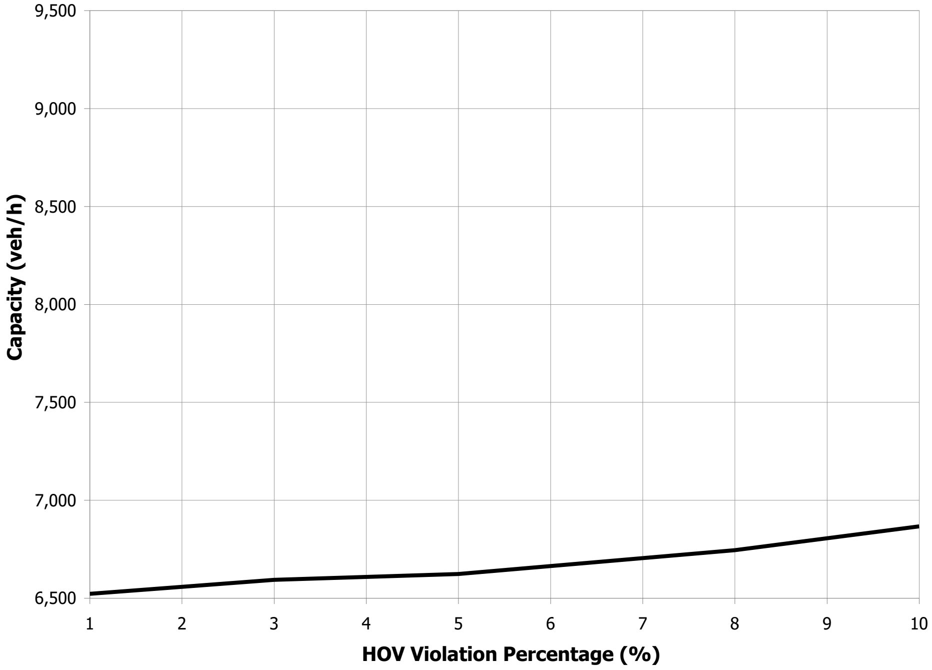


Exhibit 28-12
Capacity of a Ramp Junction as a Function of the HOV Violation Percentage

Exhibit 28-13 and Exhibit 28-14 present the density and capacity of the ramp junction as a function of the distance at which drivers begin to react to the presence of the HOV lane (i.e., the distance to the regulatory sign). As shown, the longer that distance, the lower the density of the HOV lane and the higher the density in the other lanes. The reason is that under this scenario the percentage of carpools is relatively low (10%). When the HOV lane begins, non-HOVs congregate in the remaining lanes. Capacity is reduced as the distance at which drivers begin to react increases, because the HOV lane is not utilized as much when drivers are given early warning to switch lanes.

Exhibit 28-13
Density of a Ramp Junction as a Function of the Distance at Which Drivers Begin to React

Exhibit 28-14
Capacity of a Ramp Junction as a Function of the Distance at Which Drivers Begin to React

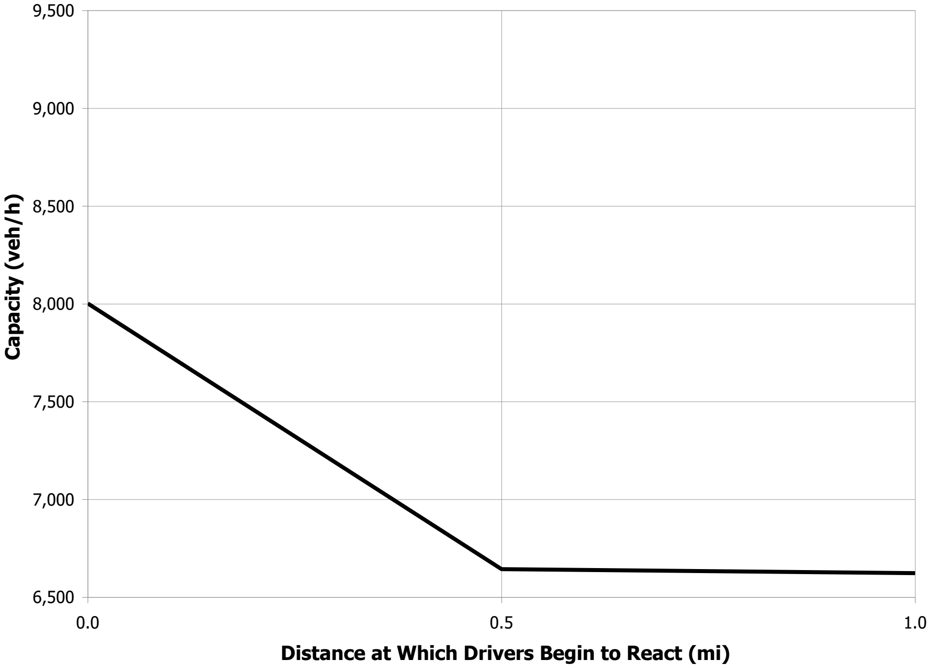
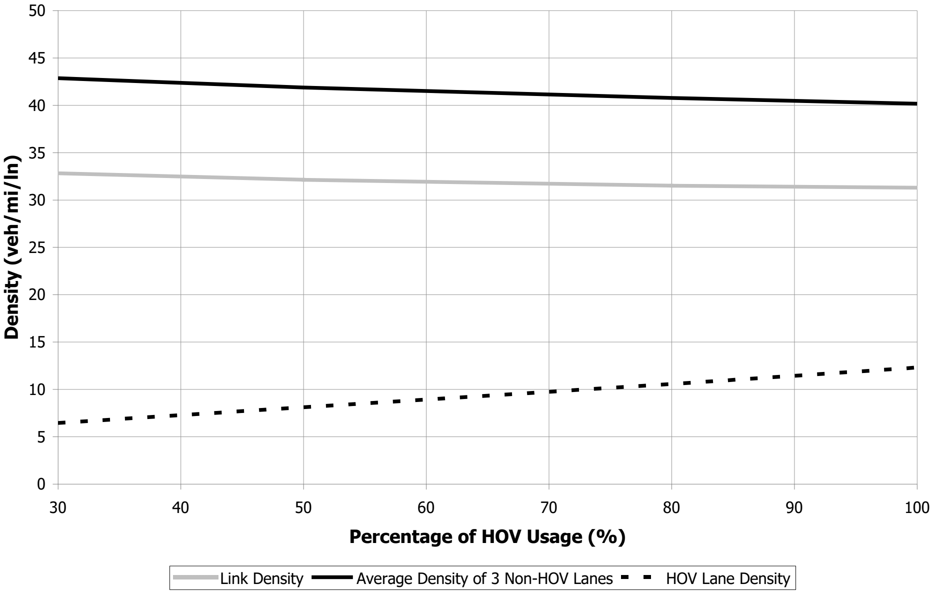


Exhibit 28-15 and Exhibit 28-16 present the density and capacity of the ramp junction as a function of the percentage of HOV usage. As expected, when usage of the HOV lane increases, the density of the HOV lane and the overall link capacity increase.

Exhibit 28-15
Density of a Ramp Junction as a Function of the Percentage of HOV Usage



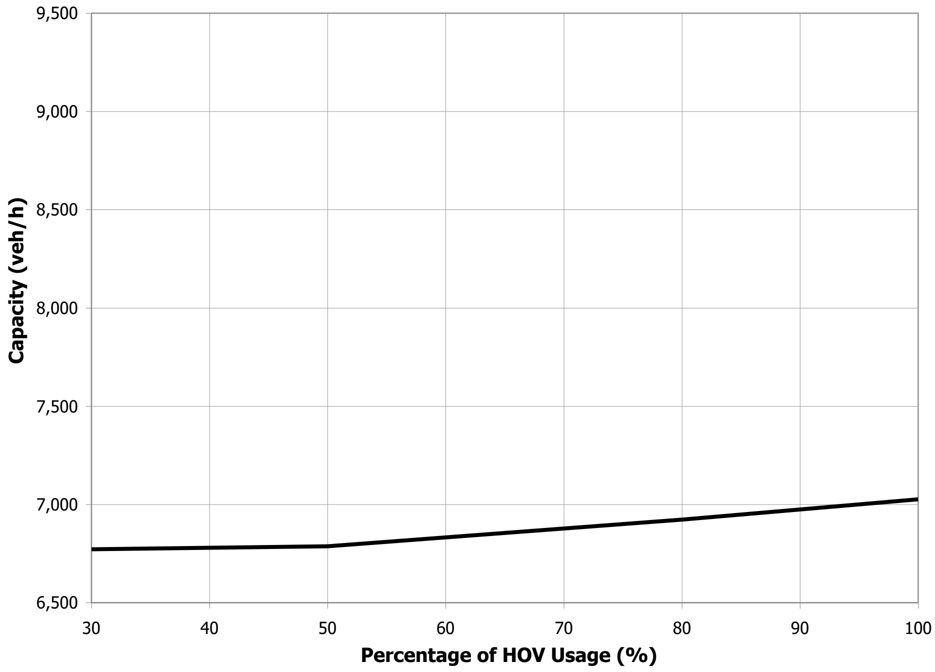


Exhibit 28-16
Capacity of a Ramp Junction as a Function of the Percentage of HOV Usage

The type of analysis presented in this example cannot be conducted with the HCM, since the method does not estimate the HOV lane density separately. Variables such as the impact of the distance of the HOV regulatory sign cannot be evaluated, since they pertain to driver behavior attributes and their impact on density and capacity. The impact of the percentage of carpools and the percentage of violators could perhaps be estimated with appropriate modifications of the existing HCM method.