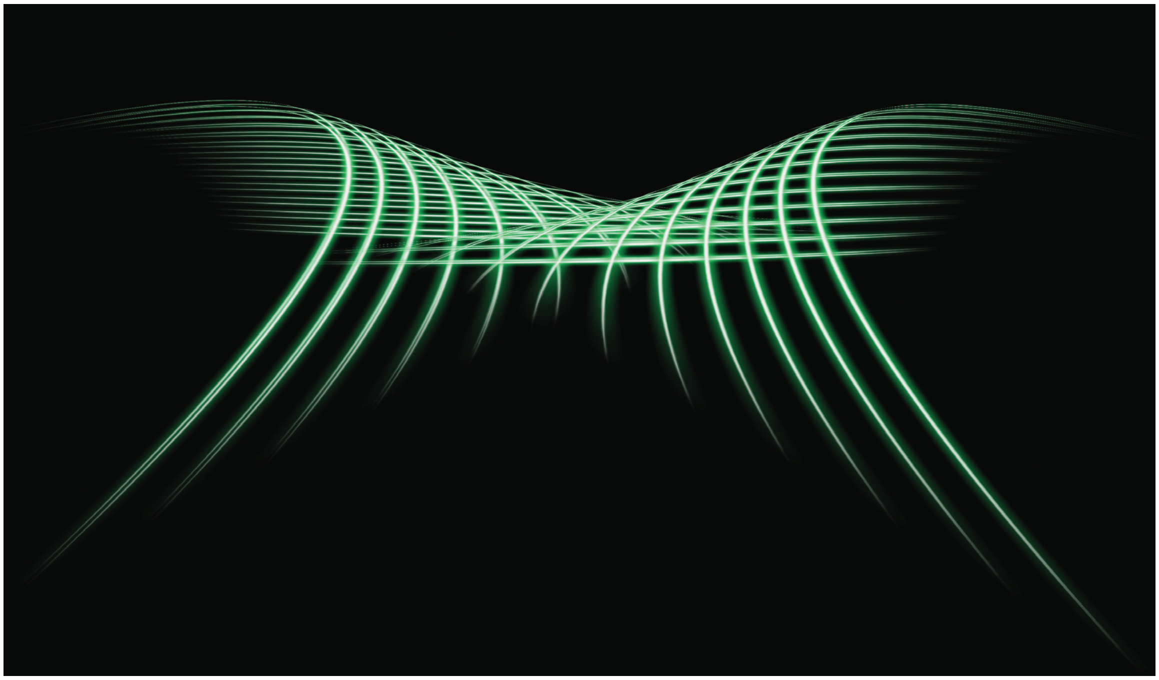
HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 10

FREEWAY FACILITIES

TRB TRANSPORTATION RESEARCH BOARD
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HCM2010

HIGHWAY CAPACITY MANUAL

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CHAPTER 10
FREEWAY FACILITIES

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LIST OF EXHIBITS

1. INTRODUCTION

A freeway is a separated highway with full control of access and two or more lanes in each direction dedicated to the exclusive use of traffic. Freeways are composed of various uniform segments that may be analyzed to determine capacity and level of service (LOS). Three types of segments are found on freeways:

- *Freeway merge and diverge segments:* Segments in which two or more traffic streams combine to form a single traffic stream (merge) or a single traffic stream divides to form two or more separate traffic streams (diverge).
- *Freeway weaving segments:* Segments in which two or more traffic streams traveling in the same general direction cross paths along a significant length of freeway without the aid of traffic control devices (except for guide signs). Weaving segments are formed when a diverge segment closely follows a merge segment or when a one-lane off-ramp closely follows a one-lane on-ramp and the two are connected by a continuous auxiliary lane.
- *Basic freeway segments:* All segments that are not merge, diverge, or weaving segments.

Analysis methodologies are detailed for basic freeway segments in Chapter 11, for weaving segments in Chapter 12, and for merge and diverge segments in Chapter 13.

Chapter 10, Freeway Facilities, provides a methodology for analyzing extended lengths of freeway composed of continuously connected basic freeway, weaving, merge, and diverge segments. Such extended lengths are referred to as a *freeway facility.* In this terminology, the term *facility* does not refer to an entire freeway from beginning to end; instead, it refers to a specific set of connected segments that have been identified for analysis. In addition, the term does not refer to a freeway system consisting of several interconnected freeways.

The methodologies of Chapters 11, 12, and 13 focus on a single time period of interest, generally the peak 15 min within a peak hour. This chapter's methodology allows for the analysis of multiple and continuous 15-min time periods and is capable of identifying breakdowns and the impact of such breakdowns over space and time.

The methodology is integral with the FREEVAL-2010 model, which implements the complex computations involved. This chapter discusses the basic principles of the methodology and its application. Chapter 25, Freeway Facilities: Supplemental, provides a complete and detailed description of all the algorithms that define the methodology. The Technical Reference Library in Volume 4 contains a user's guide to FREEVAL-2010 and an executable spreadsheet that implements the methodology.

SEGMENTS AND INFLUENCE AREAS

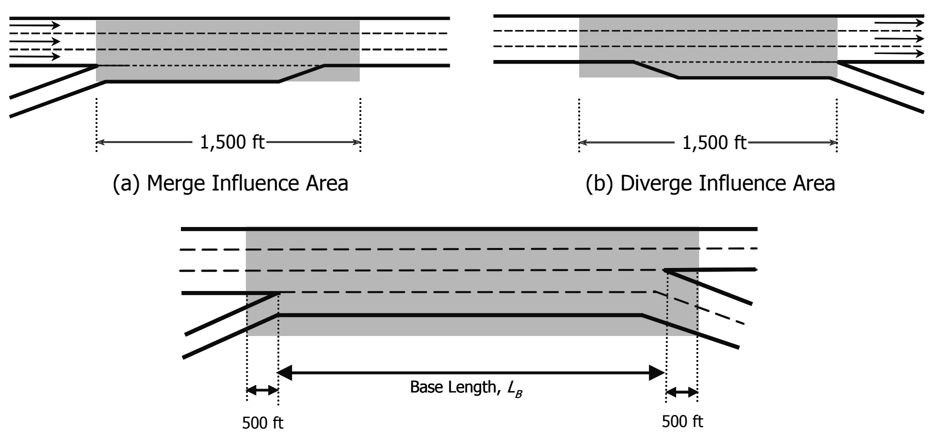
It is important that the definition of freeway segments and their influence areas be clearly understood. The influence areas of merge, diverge, and weaving segments are as follows:

- *Weaving segment:* The base length of the weaving segment plus 500 ft upstream of the entry point to the weaving segment and 500 ft downstream of the exit point from the weaving segment; entry and exit points are defined as the points where the appropriate edges of the merging and diverging lanes meet.
- *Merge segment:* From the point where the edges of the travel lanes of the merging roadways meet to a point 1,500 ft downstream of that point.
- *Diverge segment:* From the point where the edges of the travel lanes of the merging roadways meet to a point 1,500 ft upstream of that point.

Points where the "edges of travel lanes" meet are most often defined by pavement markings.

The influence areas of merge, diverge, and weaving segments are illustrated in Exhibit 10-1.

Exhibit 10-1
Influence Areas of Merge, Diverge, and Weaving Segments



(a) Merge Influence Area

(b) Diverge Influence Area

(c) Weaving Influence Area

Basic freeway segments are any other segments along the freeway that are not within these defined influence areas, which is not to say that basic freeway segments are not affected by the presence of adjacent and nearby merge, diverge, and weaving segments. Particularly when a segment breaks down, its effects will propagate to both upstream and downstream segments, regardless of type. Furthermore, the general impact of the frequency of merge, diverge, and weaving segments on the general operation of all segments is taken into account by the free-flow speed of the facility.

Basic freeway segments, therefore, do exist even on urban freeways where merge and diverge points (most often ramps) are closely spaced. Exhibit 10-2 illustrates this point. It shows a 9,100-ft (1.7-mi) length of freeway with four ramp terminals, two of which form a weaving segment. Even with an average ramp spacing less than 0.5 mi, this length of freeway contains three basic freeway segments. The lengths of these segments are relatively short, but, in terms of analysis methodologies, they must be treated as basic freeway segments. Thus, while it is true that many urban freeways will be dominated by frequent merge, diverge, and weaving segments, there will still be segments classified and analyzed as basic freeway segments.

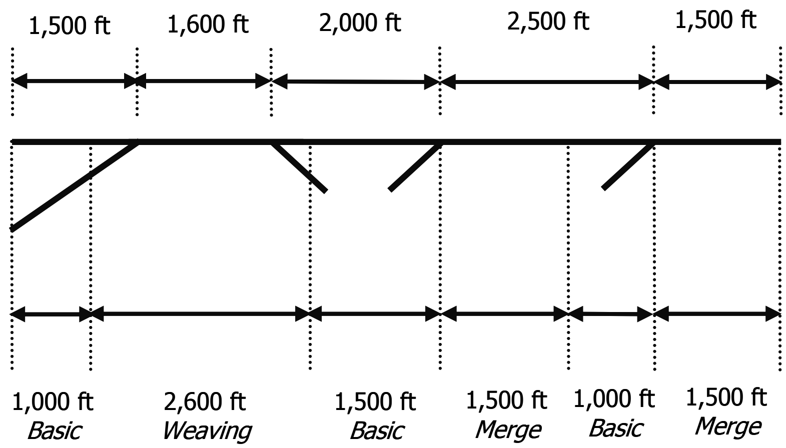


Exhibit 10-2
Basic Freeway Segments on an Urban Freeway

FREE-FLOW SPEED

Free-flow speed is strictly defined as the theoretical speed when the density and flow rate on the study segment are both zero. Chapter 11, Basic Freeway Segments, presents speed–flow curves that indicate that the free-flow speed on freeways is expected to prevail at flow rates between 0 and 1,000 passenger cars per hour per lane (pc/h/ln). In this broad range of flows, speed is insensitive to flow rates. This characteristic simplifies and allows for measurement of free-flow speeds in the field.

Chapter 11 also presents a methodology for estimating the free-flow speed of a basic freeway segment if it cannot be directly measured. The free-flow speed of a basic freeway segment is sensitive to three variables:

- Lane widths,
- Lateral clearances, and
- Total ramp density.

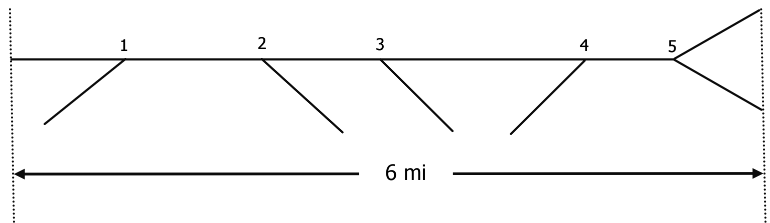
The most critical of these variables is total ramp density. *Total ramp density* is defined as the average number of on-ramp, off-ramp, major merge, and major diverge junctions per mile. It applies to a 6-mi segment of freeway facility, 3 mi upstream and 3 mi downstream of the midpoint of the study segment.

While the methodology for determining free-flow speed is provided in Chapter 11, Basic Freeway Segments, it is also applied in Chapter 12, Freeway Weaving Segments, and Chapter 13, Freeway Merge and Diverge Segments. Thus, free-flow speed affects the operation of all basic, weaving, merge, and diverge segments on a freeway facility.

The free-flow speed is an important characteristic, as the capacity *c*, service flow rates *SF*, service volumes *SV*, and daily service volumes *DSV* all depend on it.

Exhibit 10-3 illustrates the determination of total ramp density on a 6-mi length of freeway facility.

Exhibit 10-3
Ramp Density Determination



As illustrated in Exhibit 10-3, there are four ramp terminals and one major diverge point in the 6-mi segment illustrated. The total ramp density is, therefore, 5/6 = 0.83 ramp/mi.

CAPACITY OF FREEWAY FACILITIES

Capacity traditionally has been defined for segments of uniform roadway, traffic, and control conditions. When facilities consisting of a series of connected segments are considered, the concept of capacity is more complicated.

The methodologies of Chapters 11, 12, and 13 allow the capacity of each basic freeway, freeway weaving, freeway merge, and freeway diverge segment to be estimated. It is highly unlikely that every segment of a facility will have the same roadway, traffic, and control conditions and even less likely that they will have the same capacity.

Conceptual Approach to the Capacity of a Freeway Facility

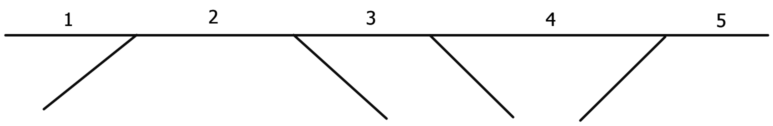
Consider the example shown in Exhibit 10-4. It illustrates five consecutive segments that are to be analyzed as one "freeway facility." Demand flow rates v_d, capacities c, and actual flow rates v_a are shown, as are the resulting v_d/c and v_a/c ratios. A lane is added in Segment 3 (even though this segment begins with an off-ramp), providing higher capacities for Segments 3, 4, and 5 than in Segments 1 and 2. The example analyzes three scenarios.

In Scenario 1, none of the demand flow rates exceeds the capacities of the segments that make up the facility. Thus, no breakdowns occur, and the actual flow rates are the same as the demand flow rates (i.e., $v_d = v_a$ for this scenario). None of the v_d/c or v_a/c ratios exceeds 1.00, although the highest ratios (0.978) occur in Segment 5.

Scenario 2 adds 200 vehicles per hour (veh/h) of demand to each segment (essentially another 200 veh/h of through freeway vehicles). In this case, Segment 5 will experience a breakdown—that is, the demand flow rate will exceed the capacity. In this segment, demand flow rate v_d differs from the actual flow rate v_a, as the actual flow rate v_a can never exceed the capacity c.

In Scenario 3, all demand flow rates are increased by 10%, which, in effect, keeps the relative values of the segment demand flow rates constant. In this case, demand flow rate will exceed capacity in Segments 4 and 5. Again, the demand flow rates and actual flow rates will differ in these segments.

Exhibit 10-4
Example of the Effect of Segment Capacity on a Freeway Facility



Scenario	Performance Measures	Freeway Segment 1	2	3	4	5
Scenario 1 (stable flow)	Demand v_d, veh/h	3,400	3,500	3,400	4,200	4,400
	Capacity c, veh/h	4,000	4,000	4,500	4,500	4,500
	Volume v_a, veh/h	3,400	3,500	3,400	4,200	4,400
	v_d/c ratio	0.850	0.875	0.756	0.933	0.978
	v_a/c ratio	0.850	0.875	0.756	0.933	0.978
Scenario 2 (add 200 veh/h to each segment)	Demand v_d, veh/h	3,600	3,700	3,600	4,400	4,600
	Capacity c, veh/h	4,000	4,000	4,500	4,500	4,500
	Volume v_a, veh/h	3,600	3,700	3,600	4,400	4,500
	v_d/c ratio	0.900	0.925	0.800	0.978	1.022
	v_a/c ratio	0.900	0.925	0.800	0.978	1.000
Scenario 3 (increase demand by 10% in all segments)	Demand v_d, veh/h	3,740	3,850	3,740	4,840	5,060
	Capacity c, veh/h	4,000	4,000	4,500	4,500	4,500
	Volume v_a, veh/h	3,740	3,850	3,740	4,500	4,500
	v_d/c ratio	0.935	0.963	0.831	1.078	1.120
	v_a/c ratio	0.935	0.963	0.831	1.000	1.000

Note: Shaded cells indicate segments where demand exceeds capacity.

This example highlights a number of points that make the analysis of freeway facilities very complicated:

1. It is critical to this methodology that the difference between demand flow rate v_d and actual flow rate v_a be highlighted and that both values be clearly and appropriately labeled.
2. In Scenarios 2 and 3, the analysis of Exhibit 10-4 is inadequate and misleading. In Scenario 2, when Segment 5 breaks down, queues begin to form and to propagate upstream. Thus, even though the demands in Segments 1 through 4 are less than the capacity of those segments, the queues generated by Segment 5 over time will propagate through Segments 1 through 4 and significantly affect their operation. In Scenario 3, Segments 4 and 5 fail, and queues are generated, which also propagate upstream over time.
3. It might be argued that the analysis of Scenario 1 is sufficient to understand the facility operation as long as all segments are undersaturated (i.e., all segment v_d/c ratios are less than or equal to 1.00). However, when any segment v_d/c ratio exceeds 1.00, such a simple analysis ignores the spreading impact of breakdowns in space and time.
4. In Scenarios 2 and 3, the segments downstream of Segment 5 will also be affected, as demand flow is prevented from reaching those segments by the Segment 5 (and Segment 4 in Scenario 3) breakdowns and queues.
5. In this example, it is also important to note that the segment(s) that break down first do not have the lowest capacities. Segments 1 and 2, with lower capacities, do not break down in any of the scenarios. Breakdown occurs first in Segment 5, which has one of the higher capacities.

Considering all these complications, the capacity of a freeway facility is defined as follows:

Freeway facility capacity is the capacity of the critical segment among those segments composing the defined facility. This capacity must, for analysis purposes, be compared with the demand flow rate on the critical segment.

The *critical segment* is defined as the segment that will break down first, given that all traffic, roadway, and control conditions do not change, including the spatial distribution of demands on each component segment. This definition is not a simple one. It depends on the relative demand characteristics and can change over time as the demand pattern changes. Facility capacity may be more than the capacity of the component segment with the lowest capacity. Therefore, it is important that individual segment demands and capacities be evaluated. The fact that one of these segments will be the critical one and will define the facility capacity does not diminish the importance of the capacities of other segments in the defined facility.

Base Capacity of Freeway Facilities

In the methodologies of Chapters 11, 12, and 13, a base capacity is used. The base capacity represents the capacity of the facility, assuming that there are no heavy vehicles in the traffic stream and that all drivers are regular users of the segment. The base capacity for all freeway segments varies with the free-flow speed, as indicated in Exhibit 10-5.

Exhibit 10-5
Free-Flow Speed vs. Base Capacity for Freeways

Free-Flow Speed (mi/h)	Base Capacity (pc/h/ln)
75	2,400
70	2,400
65	2,350
60	2,300
55	2,250

The equation given in Chapter 11, Basic Freeway Segments, for estimating the free-flow speed of a segment is as shown in Equation 10-1:

Equation 10-1

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\ TRD^{0.84}$$

where

FFS = free-flow speed (mi/h),

f_{LW} = adjustment for lane width (mi/h),

f_{LC} = adjustment for lateral clearance (mi/h), and

TRD = total ramp density (ramps/mi).

The process for determining the value of adjustment factors is described in Chapter 11.

Because the base capacity of a freeway segment is directly related to the free-flow speed, it is possible to construct a relationship between base capacity and the lane width, lateral clearance, and total ramp density of the segment. If the lane width and lateral clearance are taken to be their base values (12 and 6 ft, respectively), a relationship between base capacity and total ramp density emerges, as shown in Exhibit 10-6.

Base capacity is expressed as a flow rate for a 15-min analysis period, not a full-hour volume. It also represents a flow rate in pc/h, with no heavy vehicles, and a driver population familiar with the characteristics of the analysis segment.

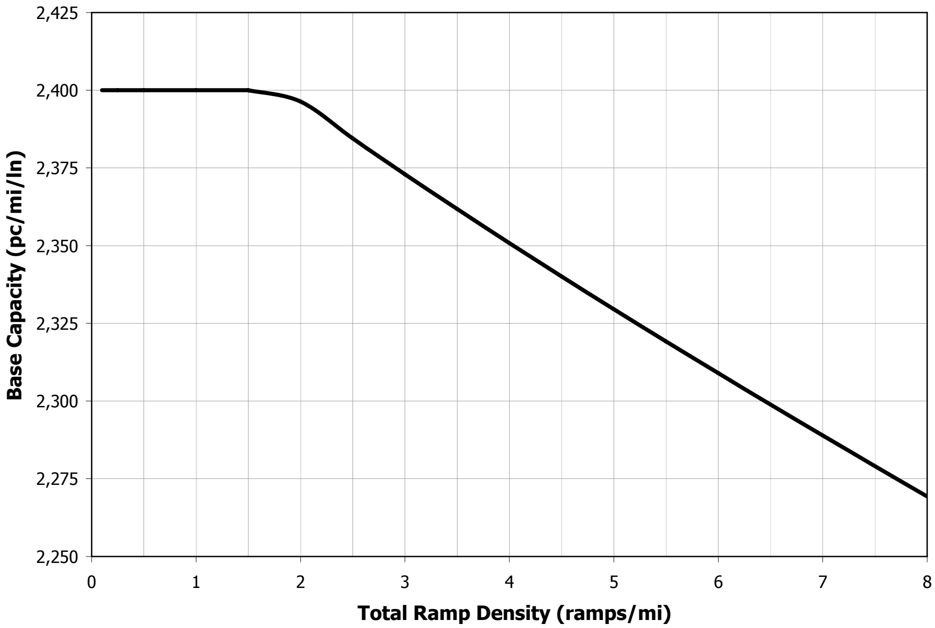


Exhibit 10-6
Base Capacity vs. Total Ramp Density

Segment Capacity vs. Facility Capacity

Free-flow speed is a characteristic of a length of freeway extending 3 mi upstream and 3 mi downstream of the center point of an analysis segment. The segment may be a basic freeway segment, a weaving segment, a merge segment, or a diverge segment. In essence, it is a measure of the impact of overall facility characteristics on the operation of the individual analysis segment centered in the defined 6-mi range.

This concept can be somewhat generalized where freeway facility analysis is involved. If conditions (particularly ramp density) are similar along a greater length of freeway, it is acceptable to compute the total ramp density for the greater length and apply it to all segments within the analysis length. This process assumes that moving the "center" of a 6-mi length for each component segment will not result in a significant change in the free-flow speed.

The capacity of a nearly homogeneous freeway facility is, for all practical purposes, the same as the capacity of a basic freeway segment with the same roadway and traffic characteristics. Consider the following:

- Merge and diverge segments have the same capacity as a similar basic freeway segment. As discussed in Chapter 13, the presence of merge and diverge segments on a freeway may affect operating characteristics, generally reducing speeds and increasing densities, but does not reduce capacity.
- Weaving segments often have per lane capacities that are less than those of the entering and leaving basic freeway segments. In almost all cases, however, weaving segments have more lanes than the entering and

leaving basic freeway segments. Thus, the impact on the capacity of the mainline freeway most often is negligible.

This does not mean, however, that the capacity of each component segment of a facility is the same. Each segment has its own demand and demand characteristics. Demand flow rate can change at every entry and exit point along the freeway, and the percent of heavy vehicles can change too. Terrain also can change at various points along the freeway.

Changes in heavy vehicle presence can change the capacity of individual segments within a defined facility. Changes in the split of movements in a weaving segment can change its capacity. In the same way, changes in the relative demand flows at on- and off-ramps can change the location of the critical segment within a defined facility and its capacity.

As noted previously, the capacity of a freeway facility is defined as the capacity of its critical segment.

LOS: COMPONENT SEGMENTS AND THE FREEWAY FACILITY

LOS of Component Segments

Chapters 11, 12, and 13 provide methodologies to determine the LOS in basic, weaving, merge, and diverge segments. In all cases, LOS F is identified when v_d/c is greater than 1.00. Such breakdowns are easily identified, and users are referred to this chapter.

This chapter's methodology provides an analysis of breakdown conditions, including the spatial and time impacts of a breakdown. Thus, in the performance of a facility-level analysis, LOS F in a component segment can be identified (*a*) when the segment v_d/c is greater than 1.00 and (*b*) when a queue from a downstream breakdown extends into an upstream segment. The latter cannot be done by using the individual segment analysis procedures of Chapters 11, 12, and 13.

Thus, when facility-level analysis is undertaken by using the methodology of this chapter, LOS F for a component segment will be identified in two different ways:

- When v_d/c is greater than 1.00, or
- When the density is greater than 45 pc/mi/ln for basic freeway segments or 43 pc/mi/ln for weaving, merge, or diverge segments.

The latter identifies segments in which queues have formed as a result of downstream breakdowns.

LOS for a Freeway Facility

Because LOS for basic, weaving, merge, and diverge segments on a freeway is defined in terms of density, LOS for a freeway facility is also defined on the basis of density.

A facility analysis will result in a density determination and LOS for each component segment. The facility LOS will be based on the weighted average density for all segments within the defined facility. Weighting is done on the basis of segment length and the number of lanes in each segment, as shown in Equation 10-2:

$$D_F = \frac{\sum_{i=1}^{n} D_i \times L_i \times N_i}{\sum_{i=1}^{n} L_i \times N_i}$$

Equation 10-2

where

D_F = average density for the facility (pc/mi/ln),

D_i = density for segment *i* (pc/mi/ln),

L_i = length of segment *i* (ft),

N_i = number of lanes in segment *i*, and

n = number of segments in the defined facility.

The LOS criteria for a freeway facility are shown in Exhibit 10-7. They are the same criteria used for basic freeway segments.

Exhibit 10-7
LOS Criteria for Freeway Facilities

Level of Service	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	>45 or any component v_d/c ratio > 1.00

Use of a LOS descriptor for the overall freeway facility must be done with care. It is critical that the LOS for individual segments composing the facility also be reported. Because the overall LOS is an average, it may mask serious problems in individual segments of the facility.

This is particularly important if one or more of the component segments are operating at LOS F. As described in this chapter's methodology section, the freeway facility methodology applies models to estimate the propagation of the effects of a breakdown in time and space. Where breakdowns exist in one or more segments of a facility, the average LOS is of limited use. The average LOS applies to a specific time period, usually 15 min.

While LOS A through D are defined by using the same densities that apply to basic freeway segments, LOS F for a facility is defined as a case in which any component segment of the freeway exceeds a v_d/c ratio of 1.00 or the average density over the defined facility exceeds 45 pc/mi/ln. In such a case, this chapter's methodology allows the analyst to map the impacts of this breakdown in time and space, and close attention to the individual LOS of component segments is necessary.

SERVICE FLOW RATES, SERVICE VOLUMES, AND DAILY SERVICE VOLUMES FOR A FREEWAY FACILITY

Just as each segment of a freeway facility has its own capacity, each segment also has a set of service flow rates SF_i for each LOS. A service flow rate is the maximum directional rate of flow that can be sustained in a given segment without violating the criteria for LOS *i*. Service flow rates are stated in vehicles per hour under prevailing roadway, traffic, and control conditions. By definition, the service flow rate for LOS E is synonymous with capacity for all uninterrupted-flow facilities and their component segments.

Chapters 11, 12, and 13 provide complete discussions of how to determine service flow rates for basic, weaving, merge, and diverge freeway segments.

A service volume SV_i is the maximum hourly directional volume that can be sustained in a given segment without violating the criteria for LOS *i* during the worst 15 min of the hour (period with the highest density) under prevailing roadway, traffic, and control conditions. Once a set of service flow rates has been established for a segment, the service volume is found from Equation 10-3:

Equation 10-3

$$SV_i = SF_i \times PHF$$

where

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

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

PHF = peak hour factor.

A daily service volume DSV_i is the maximum total daily volume in both directions that can be sustained in a given segment without violating the criteria for LOS *i* in the peak direction in the worst 15 min of the peak hour under prevailing roadway, traffic, and control conditions. Given a set of service volumes for a segment, the daily service volume is found from Equation 10-4:

Equation 10-4

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

where

DSV_i = daily service volume (veh/day),

K = proportion of daily traffic occurring in the peak hour of the day, and

D = proportion of traffic in the peak direction during the peak hour of the day.

The capacity of a freeway facility has been defined as the capacity (under prevailing conditions) of the critical segment. For consistency, therefore, other service flow rates must also be applied to the critical segment.

For an overall understanding of the freeway facility, the LOS and service flow rates (or service volumes or daily service volumes) of the individual component segments must be considered along with the overall average LOS for the defined facility and its service flow rate.

GENERALIZED DAILY SERVICE VOLUMES FOR FREEWAY FACILITIES

Generalized daily service volume tables provide a means to assess all freeways in a region or jurisdiction quickly to determine which segments need to be assessed more carefully (using operational analysis) to ameliorate existing or pending problems.

To generate a generalized daily service volume table for freeway facilities, several simplifying assumptions must be made. The assumptions made here include the following:

1. All segments of the freeway have the same basic number of lanes (two, three, or four in each direction).
2. Lane widths are 12 ft, and lateral clearances are 6 ft.
3. All on-ramps and off-ramps handle the same percentage of freeway traffic. This setup maintains a reasonably consistent demand flow rate on each segment of the facility.
4. The first ramp on the defined freeway facility is an off-ramp. This assumption is necessary to implement Item 5, below.
5. Given the demand characteristics of Items 2 and 3, all daily service volumes are stated in terms of the demand *entering* the defined freeway facility at its upstream boundary.
6. The terrain is the same in all segments of the facility.
7. The heavy vehicle percentage is the same in all segments of the facility.

On the basis of these assumptions, generalized daily service-volume tables are shown in Exhibit 10-8 (for urban freeways) and Exhibit 10-9 (for rural freeways).

Generalized service volumes are provided for level and rolling terrain; for four-lane, six-lane, and eight-lane freeways (both directions); and for a variety of combinations of the *K*-factor and *D*-factor. To use the table, analysts must select a combination of *K* and *D* appropriate for their state or region. Additional assumptions made for urban and rural freeways are listed here.

Assumptions for urban freeways:

- Total ramp density = 3.00 ramps/mi (i.e., ⅓-mi average spacing between ramps);
- 5% trucks, no recreational vehicles (RVs), and no buses;
- *PHF* = 0.95; and
- f_p = 1.00.

Assumptions for rural freeways:

- Total ramp density = 0.20 ramp/mi (i.e., 5-mi average spacing between ramps);
- 12% trucks, no RVs, and no buses;
- *PHF* = 0.88; and
- f_p = 0.85.

Generalized daily service volumes are based on the maximum service flow rate values for basic freeway segments. Exhibit 11-17 (Chapter 11) shows maximum service flow rates *MSF* for basic freeway segments. They are converted to service flow rates under prevailing conditions by multiplying by the number of lanes in one direction N, the heavy-vehicle adjustment factor f_{HV}, and the driver-population adjustment factor f_p. Equation 10-3 and Equation 10-4 are then used to convert the service flow rate *SF* to a service volume *SV* and a daily service volume *DSV*.

By combining these equations, the daily service volumes *DSV* of Exhibit 10-8 and Exhibit 10-9 are estimated from Equation 10-5:

Equation 10-5

$$DSV_i = \frac{MSF_i \times N \times f_{HV} \times f_p \times PHF}{K \times D}$$

where all variables are as previously defined.

In applying Equation 10-5, the values of *MSF* are selected from Exhibit 11-17 (Chapter 11), and values for the heavy vehicle and driver population adjustment factors are computed in accordance with the methodology of Chapter 11. The *MSF* for LOS E, which is capacity, may be taken directly from Exhibit 10-5, based on the total ramp density, as lane widths and lateral clearances are standard and have no effect on the *FFS* and thus no effect on the resulting capacities.

Exhibit 10-8 and Exhibit 10-9 are provided for general planning use and should *not* be used to analyze any specific freeway or to make final decisions on important design features. A full operational analysis using this chapter's methodology is required for such specific applications.

The exhibits are useful, however, in evaluating the overall performance of many freeways within a jurisdiction, as a first pass in determining where problems might exist or arise, and in deciding where improvements might be needed. Any freeways identified as likely to experience problems or to need improvement, however, should be subjected to a full operational analysis before any detailed decisions on implementing specific improvements are made.

Daily service volumes are heavily affected by the *K*- and *D*-factors chosen as typical for the analysis. It is important that the analyst use values that are reasonable for the facilities under study. Also, if any characteristic differs significantly from the typical values used to develop Exhibit 10-8 and Exhibit 10-9, the values taken from these exhibits will not be representative of the study facilities.

Exhibit 10-8
Generalized Daily Service Volumes for Urban Freeway Facilities (1,000 veh/day)

***K*-Factor**	***D*-Factor**	**Four-Lane Freeways**				**Six-Lane Freeways**				**Eight-Lane Freeways**			
		LOS B	**LOS C**	**LOS D**	**LOS E**	**LOS B**	**LOS C**	**LOS D**	**LOS E**	**LOS B**	**LOS C**	**LOS D**	**LOS E**
Level Terrain													
0.08	0.50	54.2	75.5	94.1	108.9	81.3	113.3	141.1	163.4	108.4	151.1	188.1	217.8
	0.55	49.3	68.7	85.5	99.0	73.9	103.0	128.3	148.5	98.6	137.3	171.0	198.0
	0.60	45.2	62.9	78.4	90.8	67.8	94.4	117.6	136.1	90.4	125.9	156.8	181.5
	0.65	41.7	58.1	72.4	83.8	62.6	87.2	108.5	125.7	83.4	116.2	144.7	167.5
0.09	0.50	48.2	67.1	83.6	96.8	72.3	100.7	125.4	145.2	96.4	134.3	167.2	193.6
	0.55	43.8	61.0	76.0	88.0	65.7	91.6	114.0	132.0	87.6	122.1	152.0	176.0
	0.60	40.2	56.0	69.7	80.7	60.2	83.9	104.5	121.0	80.3	111.9	139.4	161.3
	0.65	37.1	51.6	64.3	74.5	55.6	77.5	96.5	111.7	74.1	103.3	128.6	148.9
0.10	0.50	43.4	60.4	75.3	87.1	65.1	90.6	112.9	130.7	86.8	120.9	150.5	174.2
	0.55	39.4	54.9	68.4	79.2	59.1	82.4	102.6	118.8	78.9	109.9	136.8	158.4
	0.60	36.1	50.4	62.7	72.6	54.2	75.5	94.1	108.9	72.3	100.7	125.4	145.2
	0.65	33.4	46.5	57.9	67.0	50.0	69.7	86.8	100.5	66.7	93.0	115.8	134.0
0.11	0.50	39.4	54.9	68.4	79.2	59.1	82.4	102.6	118.8	78.9	109.9	136.8	158.4
	0.55	35.8	49.9	62.2	72.0	53.8	74.9	93.3	108.0	71.7	99.9	124.4	144.0
	0.60	32.9	45.8	57.0	66.0	49.3	68.7	85.5	99.0	65.7	91.6	114.0	132.0
	0.65	30.3	42.3	52.6	60.9	45.5	63.4	78.9	91.4	60.7	84.5	105.3	121.8
Rolling Terrain													
0.08	0.50	51.7	72.0	89.7	103.8	77.5	108.0	134.5	155.8	103.4	144.0	179.4	207.7
	0.55	47.0	65.5	81.5	94.4	70.5	98.2	122.3	141.6	94.0	131.0	163.1	188.8
	0.60	43.1	60.0	74.7	86.5	64.6	90.0	112.1	129.8	86.2	120.0	149.5	173.1
	0.65	39.8	55.4	69.0	79.9	59.7	83.1	103.5	119.8	79.5	110.8	138.0	159.7
0.09	0.50	46.0	64.0	79.7	92.3	68.9	96.0	119.6	138.4	91.9	128.0	159.5	184.6
	0.55	41.8	58.2	72.5	83.9	62.7	87.3	108.7	125.9	83.6	116.4	145.0	167.8
	0.60	38.3	53.4	66.4	76.9	57.4	80.0	99.7	115.4	76.6	106.7	132.9	153.8
	0.65	35.3	49.2	61.3	71.0	53.0	73.9	92.0	106.5	70.7	98.5	122.7	142.0
0.10	0.50	41.4	57.6	71.8	83.1	62.0	86.4	107.6	124.6	82.7	115.2	143.5	166.1
	0.55	37.6	52.4	65.2	75.5	56.4	78.6	97.9	113.3	75.2	104.8	130.5	151.0
	0.60	34.5	48.0	59.8	69.2	51.7	72.0	89.7	103.8	68.9	96.0	119.6	138.4
	0.65	31.8	44.3	55.2	63.9	47.7	66.5	82.8	95.8	63.6	88.6	110.4	127.8
0.11	0.50	37.6	52.4	65.2	75.5	56.4	78.6	97.9	113.3	75.2	104.8	130.5	151.0
	0.55	34.2	47.6	59.3	68.7	51.3	71.4	89.0	103.0	68.4	95.2	118.6	137.3
	0.60	31.3	43.7	54.4	62.9	47.0	65.5	81.5	94.4	62.7	87.3	108.7	125.9
	0.65	28.9	40.3	50.2	58.1	43.4	60.4	75.3	87.1	57.8	80.6	100.4	116.2

Note: Assumptions include the following: 5% trucks, 0% buses, 0% RVs, 0.95 *PHF*, 3 ramps/mi, f_p = 1.00, 12-ft lanes, and 6-ft lateral clearance. Values do not represent specific segment characteristics.

Exhibit 10-9
Generalized Daily Service Volumes for Rural Freeway Facilities (1,000 veh/day)

K-Factor	D-Factor	Four-Lane Freeways				Six-Lane Freeways				Eight-Lane Freeways			
		LOS B	LOS C	LOS D	LOS E	LOS B	LOS C	LOS D	LOS E	LOS B	LOS C	LOS D	LOS E
Level Terrain													
0.09	0.50	41.1	54.9	66.2	75.3	61.6	82.3	99.3	112.9	82.2	109.8	132.4	150.5
	0.55	37.4	49.9	60.2	68.4	56.0	74.8	90.2	102.6	74.7	99.8	120.3	136.9
	0.60	34.2	45.7	55.1	62.7	51.4	68.6	82.7	94.1	68.5	91.5	110.3	125.5
	0.65	31.6	42.2	50.9	57.9	47.4	63.3	76.4	86.9	63.2	84.4	101.8	115.8
0.10	0.50	37.0	49.4	59.6	67.7	55.5	74.1	89.3	101.6	74.0	98.8	119.1	135.5
	0.55	33.6	44.9	54.1	61.6	50.4	67.4	81.2	92.4	67.2	89.8	108.3	123.2
	0.60	30.8	41.2	49.6	56.5	46.2	61.7	74.4	84.7	61.6	82.3	99.3	112.9
	0.65	28.4	38.0	45.8	52.1	42.7	57.0	68.7	78.2	56.9	76.0	91.6	104.2
0.11	0.50	33.6	44.9	54.1	61.6	50.4	67.4	81.2	92.4	67.2	89.8	108.3	123.2
	0.55	30.6	40.8	49.2	56.0	45.8	61.2	73.8	84.0	61.1	81.6	98.4	112.0
	0.60	28.0	37.4	45.1	51.3	42.0	56.1	67.7	77.0	56.0	74.8	90.2	102.6
	0.65	25.9	34.5	41.6	47.4	38.8	51.8	62.5	71.1	51.7	69.1	83.3	94.7
0.12	0.50	30.8	41.2	49.6	56.5	46.2	61.7	74.4	84.7	61.6	82.3	99.3	112.9
	0.55	28.0	37.4	45.1	51.3	42.0	56.1	67.7	77.0	56.0	74.8	90.2	102.6
	0.60	25.7	34.3	41.4	47.0	38.5	51.5	62.0	70.6	51.4	68.6	82.7	94.1
	0.65	23.7	31.7	38.2	43.4	35.6	47.5	57.3	65.1	47.4	63.3	76.4	86.9
Rolling Terrain													
0.09	0.50	36.9	49.3	59.4	67.6	55.4	74.0	89.2	101.4	73.8	98.6	118.9	135.2
	0.55	33.6	44.8	54.0	61.5	50.3	67.2	81.1	92.2	67.1	89.6	108.1	122.9
	0.60	30.8	41.1	49.5	56.3	46.1	61.6	74.3	84.5	61.5	82.2	99.1	112.7
	0.65	28.4	37.9	45.7	52.0	42.6	56.9	68.6	78.0	56.8	75.9	91.5	104.0
0.10	0.50	33.2	44.4	53.5	60.9	49.8	66.6	80.3	91.3	66.4	88.7	107.0	121.7
	0.55	30.2	40.3	48.6	55.3	45.3	60.5	73.0	83.0	60.4	80.7	97.3	110.6
	0.60	27.7	37.0	44.6	50.7	41.5	55.5	66.9	76.1	55.4	74.0	89.2	101.4
	0.65	25.6	34.1	41.2	46.8	38.3	51.2	61.7	70.2	51.1	68.3	82.3	93.6
0.11	0.50	30.2	40.3	48.6	55.3	45.3	60.5	73.0	83.0	60.4	80.7	97.3	110.6
	0.55	27.5	36.7	44.2	50.3	41.2	55.0	66.3	75.4	54.9	73.3	88.4	100.6
	0.60	25.2	33.6	40.5	46.1	37.7	50.4	60.8	69.2	50.3	67.2	81.1	92.2
	0.65	23.2	31.0	37.4	42.6	34.8	46.5	56.1	63.8	46.5	62.1	74.8	85.1
0.12	0.50	27.7	37.0	44.6	50.7	41.5	55.5	66.9	76.1	55.4	74.0	89.2	101.4
	0.55	25.2	33.6	40.5	46.1	37.7	50.4	60.8	69.2	50.3	67.2	81.1	92.2
	0.60	23.1	30.8	37.2	42.3	34.6	46.2	55.7	63.4	46.1	61.6	74.3	84.5
	0.65	21.3	28.4	34.3	39.0	31.9	42.7	51.4	58.5	42.6	56.9	68.6	78.0

Note: Assumptions include the following: 12% trucks, 0% buses, 0% RVs, 0.88 *PHF*, 0.2 ramp/mi, f_p = 0.85, 12-ft lanes, and 6-ft lateral clearance. Values do not represent specific segment characteristics.

ACTIVE TRAFFIC MANAGEMENT AND OTHER MEASURES TO IMPROVE PERFORMANCE

Active traffic management (ATM) consists of the dynamic and continuous monitoring and control of traffic operations on a facility to improve its performance. Examples of ATM measures include congestion pricing, ramp metering, changeable message signs, incident response programs, and speed harmonization (variable speed limits).

ATM measures can influence both the nature of demand for the facility and the ability of the facility to deliver the capacity tailored to serve the demand. ATM measures can improve facility performance, sometimes significantly.

Other advanced design and management measures, not specifically included in the definition of ATM, can also significantly improve facility performance. These measures include auxiliary lanes, narrow lanes, high-occupancy vehicle (HOV) lanes, temporary use of shoulders, and designated truck lanes and ramps.

This methodology does not reflect all these measures. However, ramp metering can be taken into account by altering on-ramp demands in accordance with metering rates. Auxiliary lanes and narrow lanes are taken into account in the segment methodologies for basic freeway segments and weaving segments.

Other measures are not accounted for in this methodology. Chapter 35 provides a more detailed discussion of ATM and other advanced design and management strategies and insight into how their impacts may be evaluated.

2. METHODOLOGY

The methodology presented in this chapter provides for the integrated analysis of a freeway facility composed of connected segments. The methodology builds on the models and procedures for individual segments, as described in Chapter 11, Basic Freeway Segments; Chapter 12, Freeway Weaving Segments; and Chapter 13, Freeway Merge and Diverge Segments.

SCOPE OF THE METHODOLOGY

Because the freeway facility methodology builds on the segment methodologies of Chapters 11, 12, and 13, it incorporates all aspects of those chapters' methodologies. This methodology adds the ability to consider a number of linked segments over a number of time periods and to determine some overall operational parameters that allow for the assessment of a facility LOS and capacity.

This methodology also adds the ability to analyze operations when LOS F exists on one or more segments of the defined facility. In Chapters 11, 12, and 13, the existence of a breakdown (LOS F) is identified for a given segment, as appropriate. The segment methodologies do not, however, provide tools for analyzing the impacts of such breakdowns over time and space.

The methodology analyzes a set of connected segments over a set of sequential 15-min periods. In deciding which segments and time periods to analyze, two principles should be observed:

1. The first and last segments of the defined facility should *not* operate at LOS F.
2. The first and last time periods of the analysis should *not* include any segments that operate at LOS F.

When the first segment operates at LOS F, there is a queue extending upstream that is not included in the facility definition and that therefore cannot be analyzed. When the last segment operates at LOS F, there may be a downstream bottleneck outside the facility definition. Again, the impacts of this congestion cannot be evaluated when it is not fully contained within the defined facility. LOS F in either the first or last time period creates similar problems with regard to time. If the first time period is at LOS F, then LOS F may exist in previous time periods as well. If the last time period is at LOS F, subsequent periods may be at LOS F as well. The impacts of a breakdown cannot be fully analyzed unless it is fully contained within the defined facility and defined total analysis period. The same problems would exist if the analysis were conducted by using simulation.

There is no limit to the number of time periods that can be analyzed. The length of the freeway should be less than the distance a vehicle traveling at the average speed can achieve in 15 min. This specification generally results in a maximum facility length between 9 and 12 mi.

This methodology is based on research sponsored by the Federal Highway Administration (*1*).

LIMITATIONS OF THE METHODOLOGY

The methodology has the following limitations:

1. The methodology does not account for the delays caused by vehicles using alternative routes or vehicles leaving before or after the analysis period.
2. Multiple overlapping breakdowns or bottlenecks are difficult to analyze and cannot be fully evaluated by this methodology. Other tools may be more appropriate for specific applications beyond the capabilities of the methodology. Consult Chapter 6, HCM and Alternative Analysis Tools, for a discussion of simulation and other models.
3. Spatial, temporal, modal, and total demand responses to traffic management strategies are not automatically incorporated into the methodology. On viewing the facility traffic performance results, the analyst can modify the demand input manually to analyze the effect of user-demand responses and traffic growth. The accuracy of the results depends on the accuracy of the estimation of user-demand responses.
4. The methodology can address local oversaturated flow but cannot directly address systemwide oversaturation flow conditions.
5. The completeness of the analysis will be limited if freeway segments in the first time interval, the last time interval, and the first freeway segment (in all time periods) have demand-to-capacity ratios greater than 1.00. The rationale for these limitations is discussed in the section on demand-to-capacity ratio.
6. The existence of HOV lanes on freeways raises the issues of the operating characteristics of such lanes and their effect on operating characteristics on the remainder of the freeway. The methodology does not directly address separated HOV facilities and does not account for the interactions between HOV lanes and mixed-flow lanes and the weaving that may be produced.
7. The method does not address conditions in which off-ramp capacity limitations result in queues that extend onto the freeway or affect the behavior of off-ramp vehicles.
8. The method does not address toll plaza operations or their effect on freeway facility operations.

Given enough time, the analyst can analyze a completely undersaturated time–space domain manually, although it is very difficult and time-consuming. It is not expected that analysts will ever manually analyze a time–space domain that includes oversaturation. FREEVAL-2010 is a computational engine that can be used to implement the methodology, regardless of whether the time–space domain contains oversaturated segments and time periods. It is available in the Technical Reference Library section of Volume 4 of the *Highway Capacity Manual* (HCM).

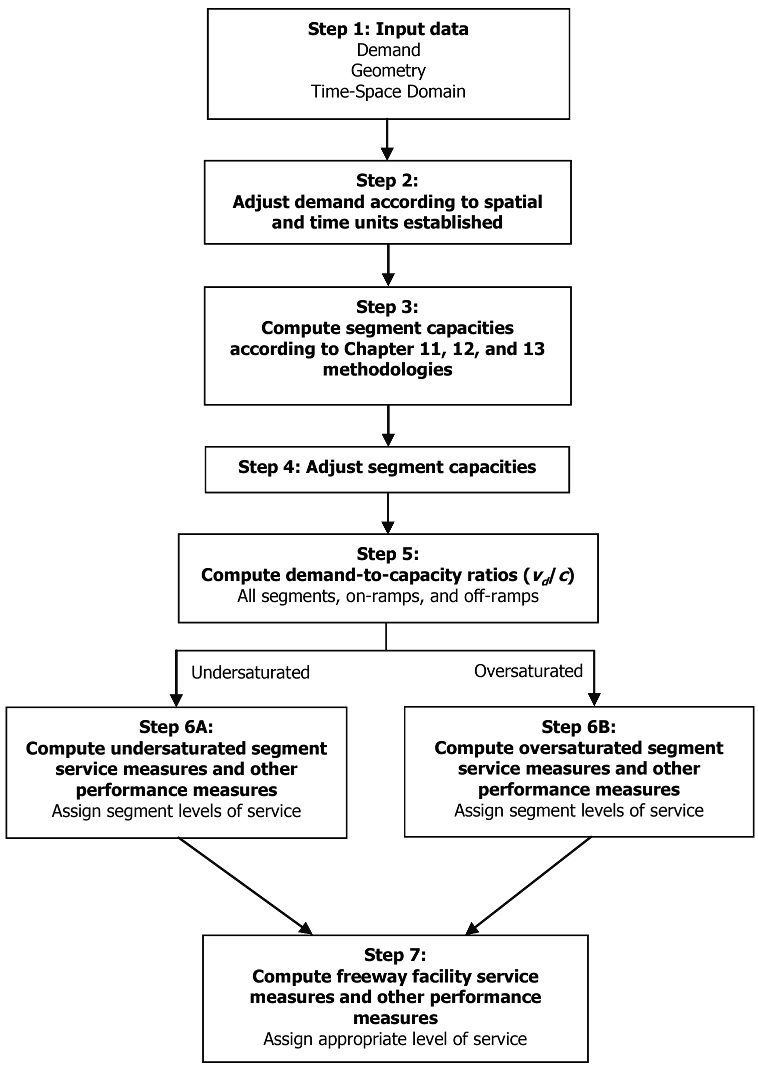
Because this chapter's methodology incorporates the methodologies for basic, weaving, merging, and diverging freeway segments, the limitations of those procedures also apply here.

The method does not include analysis of the street-side terminals of freeway on- and off-ramps. The methodologies of Chapters 18, 19, 20, and 21 should be used for intersections that are signalized, two-way STOP-controlled, all-way STOP-controlled, and roundabouts, respectively. Chapter 22, Interchange Ramp Terminals, provides a more comprehensive analysis of freeway interchanges where the street-side ramp terminals are signalized intersections or roundabouts.

OVERVIEW

Exhibit 10-10 summarizes the methodology for analyzing freeway facilities. The methodology adjusts vehicle speeds appropriately to account for the effects in adjacent segments. The methodology can analyze freeway traffic management strategies only in cases for which 15-min intervals are appropriate and for which reliable data for estimated capacity and demand exist.

Exhibit 10-10
Freeway Facility Methodology



COMPUTATIONAL STEPS

The purpose of this section is to describe the methodology's computational modules. To simplify the presentation, the focus is on the function of, and rationale for, each module. Chapter 25 presents an expanded version of this section, including all the supporting analytical models and equations.

Step 1: Input Data

Data concerning demand, geometry, and the time–space domain must be specified. As the methodology builds on segment analysis, all data for each segment and each time period must be provided, as indicated in Chapter 11 for basic freeway segments, Chapter 12 for weaving segments, and Chapter 13 for merge and diverge segments.

Demand

Demand flow rates must be specified for each segment and time period. Because analysis of multiple time periods is based on consecutive 15-min periods, the demand flow rates for each period must be provided. This condition is in addition to the requirements for isolated segment analyses.

Demand flow rates must be specified for the entering freeway mainline flow and for each on-ramp and off-ramp within the defined facility. The following information is needed for each time period to determine the demand flow rate:

- Demand flow rate (veh/h),
- Percent trucks (%),
- Percent RVs (%), and
- Driver population factor (f_p).

For weaving segments, demand flow rates must be identified by component movement: freeway to freeway, ramp to freeway, freeway to ramp, and ramp to ramp. Where this level of detail is not available, the following procedure may be used to estimate the component flows. It is not recommended, however, as weaving segment performance is sensitive to the split of demand flows.

- *Ramp-weave segments:* Assume that the ramp-to-ramp flow is 0. The ramp-to-freeway flow is then equal to the on-ramp flow; the freeway-to-ramp flow is then equal to the off-ramp flow.
- *Major weave segments:* On-ramp flow is apportioned to the two exit legs (freeway and ramp) in the same proportion as the total flow on the exit legs (freeway and ramp).

The driver population factor is normally 1.00, unless the driver population is dominated by unfamiliar users, in which case a value between 0.85 and 1.00 is assigned, on the basis of local characteristics and knowledge.

Geometry

All geometric features for each segment of the facility must be specified, including the following:

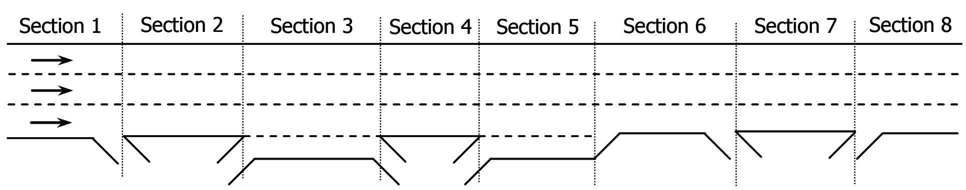
- Number of lanes;
- Average lane width;
- Right-side lateral clearance;
- Terrain;
- Free-flow speed; and
- Location of merge, diverge, and weaving segments, with all internal geometry specified, including the number of lanes on ramps and at ramp–freeway junctions or within weaving segments, lane widths, existence and length of acceleration or deceleration lanes, distances between merge and diverge points, and the details of lane configuration where relevant.

Geometry does not change by time period, so this information is given only once, regardless of the number of time periods under study.

Time–Space Domain

A time–space domain for the analysis must be established. The domain consists of a specification of the freeway *sections* included in the defined facility and an identification of the time intervals for which the analysis is to be conducted. A typical time–space domain is shown in Exhibit 10-11.

Exhibit 10-11
Example Time–Space Domain for Freeway Facility Analysis



Time Step	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8
1								
2								
3								
4								
5								
6								
7								
8								

The horizontal scale indicates the distance along the freeway facility. A freeway *section* boundary occurs where there is a change in demand—that is, at each on-ramp or off-ramp or where a lane is added or dropped. These areas are referred to as *sections*, because adjustments will be made within the procedure to determine where *segment* boundaries should be for analysis. This process relies on the influence areas of merge, diverge, and weaving segments, discussed earlier in this chapter, and on variable length limitations specified in Chapter 12 for weaving segments and in Chapter 13 for merge and diverge segments.

The vertical scale indicates the study time duration. Time extends down the time–space domain, and the scale is divided into 15-min intervals. In the example shown, there are 8 sections and 8 time steps, yielding 8 × 8 = 64 time–space cells, each of which will be analyzed within the methodology.

The boundary conditions of the time–space domain are extremely important. The time–space domain will be analyzed as an independent freeway facility having no interactions with upstream or downstream portions of the freeway, or any connecting facilities, including other freeways and surface facilities. Therefore, no congestion should occur along the four boundaries of the time–space domain. The cells located along the four boundaries should all have demands less than capacity and should contain undersaturated flow conditions. A proper analysis of congestion within the time–space domain can occur only if the congestion is limited to internal cells not along the time–space boundaries.

Converting the Horizontal Scale from Sections to Analysis Segments

The sections of the defined freeway facility are established by using points where demand changes or where lanes are added or subtracted. This, however, does *not* fully describe individual *segments* for analysis within the methodology. The conversion from sections to analysis segments can be done manually by applying the principles discussed here.

Chapter 13, Freeway Merge and Diverge Segments, indicates that each merge segment extends from the merge point to a point 1,500 ft downstream of it. Each diverge segment extends from the diverge point to a point 1,500 ft upstream of it. This allows for a number of scenarios affecting the definition of analysis segments within the defined freeway.

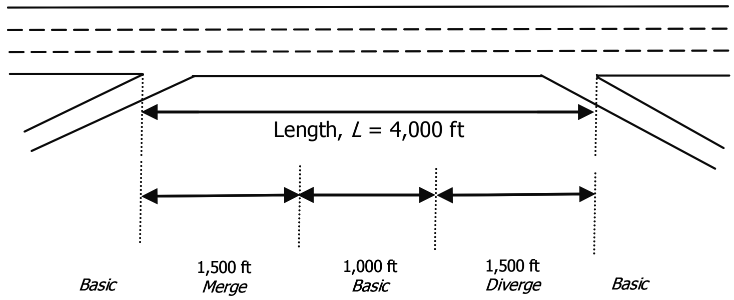
Consider the illustration of Exhibit 10-12. It shows a one-lane on-ramp followed by a one-lane off-ramp with no auxiliary lane between them. The illustration assumes that there are no upstream or downstream ramps or weaving segments that impinge on this section.

In Exhibit 10-12(a), there are 4,000 ft between the two ramps. Therefore, the merge segment extends 1,500 ft downstream, and the diverge segment extends 1,500 ft upstream, which leaves a 1,000-ft basic freeway segment between them.

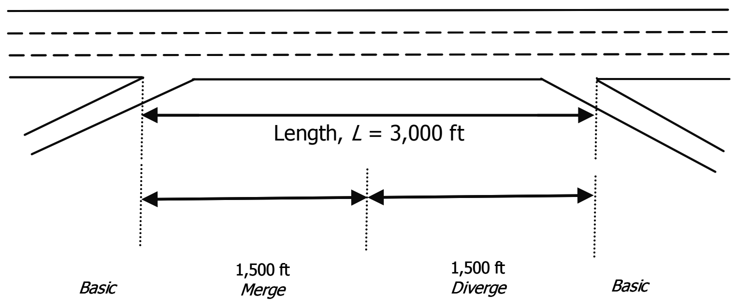
In Exhibit 10-12(b), there are 3,000 ft between the two ramps. The two 1,500-ft ramp influence areas define the entire length. Therefore, there is no basic freeway segment between the merge and diverge segments.

In Exhibit 10-12(c), the situation is more complicated. With only 2,000 ft between the ramps, the merge and diverge influence areas overlap for a distance of 1,000 ft.

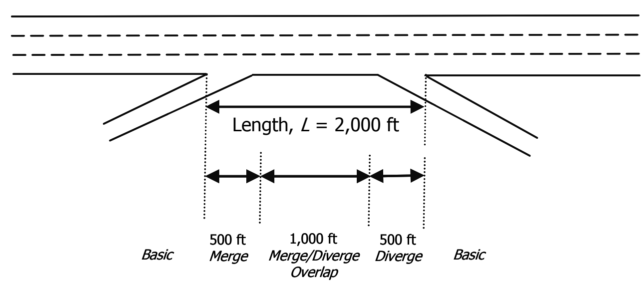
Exhibit 10-12
Defining Analysis Segments for a Ramp Configuration



(a) Length between ramps = 4,000 ft



(b) Length between ramps = 3,000 ft



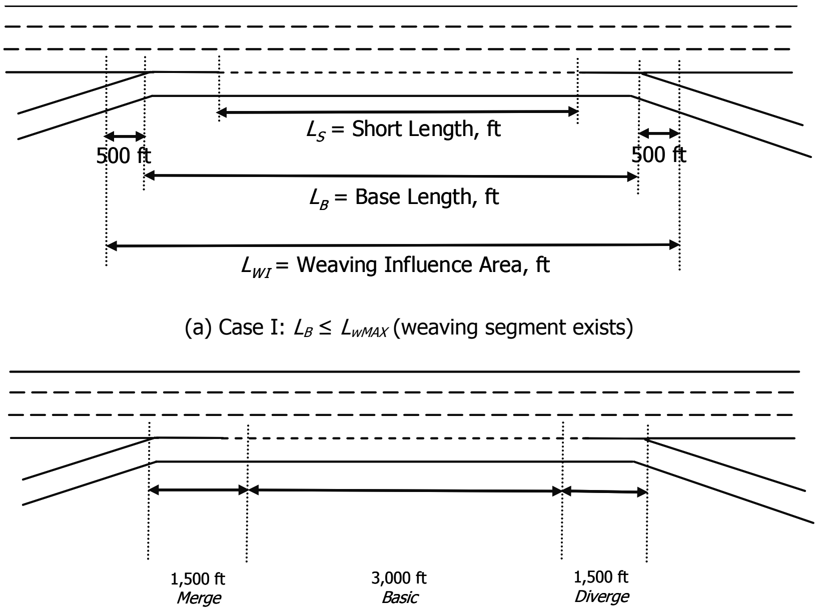
(c) Length between ramps = 2,000 ft

Chapter 13, Freeway Merge and Diverge Segments, covers this situation. Where ramp influence areas overlap, the analysis is conducted for each ramp separately. The analysis producing the worst LOS (or service measure value if the LOS is equivalent) is used to define operations in the overlap area.

The facility methodology goes through the logic of distances and segment definitions to convert section boundaries to segment boundaries for analysis. If the distance between an on-ramp and off-ramp is less than the full influence area of 1,500 ft, the worst case is applied to the distance between the ramps, while basic segment criteria are applied to segments upstream of the on-ramp and downstream of the off-ramp.

A similar situation can arise where weaving configurations exist. Exhibit 10-13 illustrates a weaving configuration within a defined freeway facility. In this case, the distance between the merge and diverge ends of the configuration must be compared with the maximum length of a weaving segment, L_{wMAX}. If the distance between the merge and diverge points is less than or equal to L_{wMAX}, then the entire segment is analyzed as a weaving segment, as shown in Exhibit 10-13(a).

Exhibit 10-13
Defining Analysis Segments for a Weaving Configuration



(a) Case I: $L_B \leq L_{wMAX}$ (weaving segment exists)

(b) Case II: $L_B > L_{wMAX}$ (isolated merge and diverge exists)

Three lengths are involved in analyzing a weaving segment:

- The base length of the segment, measured from the points where the edges of the travel lanes of the merging and diverging roadways converge (L_B);
- The influence area of the weaving segment (L_{WI}), which includes 500 ft upstream and downstream of L_B; and
- The short length of the segment, defined as the distance over which lane changing is not prohibited or dissuaded by markings (L_S).

The latter is the length that is used in all the predictive models for weaving segment analysis. The results of these models, however, apply to a distance of L_B + 500 ft upstream and L_B + 500 ft downstream. For further discussion of the various lengths applied to weaving segments, consult Chapter 12.

If the distance between the merge and diverge points is greater than L_{wMAX}, then the merge and diverge segments are too far apart to form a weaving segment. As shown in Exhibit 10-13(b), the merge and diverge segments are treated separately, and any distance remaining between the merge and diverge influence areas is treated as a basic freeway segment.

In the Chapter 12 weaving methodology, the value of L_{wMAX} depends on a number of factors, including the split of component flows, demand flows, and other traffic factors. A weaving configuration could therefore qualify as a weaving segment in some analysis periods and as separate merge, diverge, and possibly basic segments in others.

In segmenting the freeway facility for analysis, merge, diverge, and weaving segments are identified as illustrated in Exhibit 10-12 and Exhibit 10-13. All segments not qualifying as merge, diverge, or weaving segments are basic freeway segments.

However, a long basic freeway section may have to be divided into multiple segments. This situation occurs when there is a sharp break in terrain within the section. For example, a 5-mi section may have a constant demand and a constant number of lanes. If there is a 2-mi level terrain portion followed by a 4% grade that is 3 mi long, then the level terrain portion and the specific grade portion would be established as two separate, consecutive basic freeway segments.

Step 2: Adjust Demand According to Spatial and Time Units Established

Traffic counts taken at each entrance to and exit from the defined freeway facility (including the mainline entrance and mainline exit) for each time interval serve as inputs to the methodology. While entrance counts are considered to represent the current entrance demands for the freeway facility (provided that there is not a queue on the freeway entrance), the exit counts may not represent the current exit demands for the freeway facility because of congestion within the defined facility.

For planning applications, estimated traffic demands at each entrance to and exit from the freeway facility for each time interval serve as input to the methodology. The sum of the input demands must equal the sum of the output demands in every time interval.

Once the entrance and exit demands are calculated, the demands for each cell in every time interval can be estimated. The segment demands can be thought of as filtering across the time–space domain and filling each cell of the time–space matrix.

Demand estimation is needed if the methodology uses actual freeway counts. If demand flows are known or can be projected, they are used directly without modification.

The methodology includes a demand estimation model that converts the input set of freeway exit 15-min counts to a set of vehicle flows that desire to exit the freeway in a given 15-min period. This demand may not be the same as the 15-min exit count because of upstream congestion within the defined freeway facility.

The procedure sums the freeway entrance demands along the entire directional freeway facility, including the entering mainline segment, and compares this sum with the sum of freeway exit counts along the directional freeway facility, including the departing mainline segment. This procedure is repeated for each time interval. The ratio of the total facility entrance counts to total facility exit counts is called the *time interval scale factor* and should approach 1.00 when the freeway exit counts are, in fact, freeway exit demands.

Scale factors greater than 1.00 indicate increasing levels of congestion within the freeway facility, with exit counts underestimating the actual freeway exit demands. To provide an estimate of freeway exit demand, each freeway exit count is multiplied by the time interval scale factor.

Equation 10-6 and Equation 10-7 summarize this process.

$$f_{TISi} = \frac{\sum_j V_{ON15ij}}{\sum_j V_{OFF15ij}}$$

Equation 10-6

$$V_{dOFF15ij} = V_{OFF15ij} \times f_{TISi}$$

Equation 10-7

where

f_{TISi} = time-interval scale factor for time period *i*,

V_{ON15ij} = 15-min entering count for time period *i* and entering location *j* (veh),

$V_{OFF15ij}$ = 15-min exit count for time period *i* and exiting location *j* (veh), and

$V_{dOFF15ij}$ = adjusted 15-min exit demand for time period *i* and exiting location *j* (veh).

Once the entrance and exit demands are determined, the traffic demands for each section and each time period can be calculated. On the time–space domain, section demands can be viewed as projecting horizontally across Exhibit 10-11, with each cell containing an estimate of its 15-min demand.

Because each time period is separately balanced, it is advisable to limit the total length of the defined facility to a distance that can be traversed within 15 min. In practical terms, this practice limits the length of the facility to 9 to 12 mi.

Step 3: Compute Segment Capacities According to Chapter 11, 12, and 13 Methodologies

Segment capacity estimates are determined by the methodologies of Chapter 11 for basic freeway segments, Chapter 12 for weaving segments, and Chapter 13 for merge and diverge segments. All estimates of segment capacity should be carefully reviewed and compared with local knowledge and available traffic information for the study site, particularly where known bottlenecks exist.

On-ramp and off-ramp roadway capacities are also determined in this step with the Chapter 13 methodology. On-ramp demands may exceed on-ramp capacities and limit the traffic demand entering the facility. Off-ramp demands may exceed off-ramp capacities and cause congestion on the freeway, although that impact is not accounted for in this methodology.

All capacity results are stated in vehicles per hour under prevailing roadway and traffic conditions.

The effect of a predetermined ramp-metering plan can be evaluated in this methodology by overriding the computed ramp roadway capacities. The capacity of each entrance ramp in each time interval is changed to reflect the specified ramp-metering rate. This feature not only allows for evaluating a prescribed ramp-metering plan but also permits the user to improve the ramp-metering plan through experimentation.

Freeway design improvements can be evaluated with this methodology by modifying the design features of any portion of the freeway facility. For example, the effects of adding auxiliary lanes at critical locations and full lanes over multiple segments can be assessed.

Step 4: Adjust Segment Capacities

Segment capacities can be affected by a number of conditions not normally accounted for in the segment methodologies of Chapters 11, 12, and 13. These reductions include the effects of short-term and long-term lane closures for construction or major maintenance operations, the effects of adverse weather conditions, and the effects of other environmental factors.

At lane drops, permanent reductions in capacity occur. They are included in the base methodology, which automatically accounts for the capacity of segments on the basis of the number of lanes in the segment and other prevailing conditions.

Capacity Reductions due to Construction and Major Maintenance Operations

Capacity reductions due to construction activities can be divided into short-term work-zone lane closures, typically for maintenance, and long-term lane closures, typically for construction. A primary distinction between short-term work zones and long-term construction zones is the nature of the barriers used to demarcate the work area. Long-term construction zones generally use portable concrete barriers, while short-term work zones use standard channeling devices (e.g., traffic cones, drums) in accordance with the *Manual on Uniform Traffic Control Devices for Streets and Highways* (*2*). Capacity reductions due to long-term construction or major maintenance operations generally last several weeks, months, or even years, depending on the nature of the work. Short-term closures generally last a few hours.

Short-Term Work Zones

Research (*3*) suggests that a capacity of 1,600 pc/h/ln be used for short-term freeway work zones, regardless of the lane-closure configuration. However, for some types of closures, a higher value could be appropriate.

This base value should be adjusted for other conditions, as follows:

1. *Intensity of work activity:* The intensity of work activity refers to the number of workers on the site, the number and size of work vehicles in use, and the proximity of the work activity to the travel lanes. Unusual types of work also contribute to intensity in terms of rubbernecking by drivers passing through the site. Research (*3*) suggests that the base value of 1,600 pc/h/ln be adjusted by as much as ±10% for work activity that is more or less intensive than normal. It does not, however, define what constitutes "normal" intensity, so this factor should be applied on the basis of professional judgment and local experience.

6. *Effects of heavy vehicles:* Because the base value is given in terms of pc/h/ln, it is recommended that the heavy vehicle adjustment factor (f_{HV}) be applied. A complete discussion of the heavy vehicle adjustment factor and its determination are included in Chapter 11, Basic Freeway Segments. Equation 10-8 shows how the factor is determined.

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

Equation 10-8

where

f_{HV} = heavy-vehicle adjustment factor,

P_T = proportion of trucks and buses in the traffic stream,

P_R = proportion of RVs in the traffic stream,

E_T = passenger-car equivalent for trucks and buses, and

E_R = passenger-car equivalent for RVs.

Passenger-car equivalents for trucks and buses and for RVs may be found in Chapter 11, Basic Freeway Segments.

7. *Presence of ramps:* If there is an entrance ramp within the taper area approaching the lane closure or within 500 ft downstream of the beginning of the full lane closure, the ramp will have a noticeable effect on the capacity of the work zone for handling mainline traffic. This situation arises in two ways: (*a*) the ramp traffic generally forces its way in, so it directly reduces the amount of mainline traffic that can be handled, and (*b*) the added turbulence in the merge area may slightly reduce capacity (even though such turbulence does *not* reduce capacity on a normal freeway segment without lane closures). If at all possible, on-ramps should be located at least 1,500 ft upstream of the beginning of the full lane closure to maximize the total work zone throughput. If that cannot be done, then either the ramp volume should be added to the mainline volume to be served or the capacity of the work zone should be decreased by the ramp volume (up to a maximum of one-half of the capacity of one lane) on the assumption that, at very high volumes, mainline and ramp vehicles will alternate.

Equation 10-9 is used to estimate the resulting reduced capacity in vehicles per hour.

$$c_a = \{[(1{,}600 + I) \times f_{HV}] \times N\} - R$$

Equation 10-9

where

c_a = adjusted mainline capacity (veh/h);

I = adjustment factor for type, intensity, and proximity of work activity, pc/h/ln (ranges between ±160 pc/h/ln);

f_{HV} = heavy-vehicle adjustment factor;

N = number of lanes open through the work zone; and

R = manual adjustment for on-ramps (veh/h).

Long-Term Construction Zones

There have been many studies of long-term construction zone capacities. They are summarized in Exhibit 10-14.

Exhibit 10-14
Capacity of Long-Term Construction Zones (veh/h/ln)

State	Normal Lanes to Reduced Lanes: 2 to 1	3 to 2	3 to 1	4 to 3	4 to 2	4 to 1	Source
TX	1,340		1,170				(*4*)
NC	1,690		1,640				(*5*)
CT	1,500–1,800		1,500–1,800				(*6*)
MO	1,240	1,430	960	1,480	1,420		(*7*)
NV	1,375–1,400		1,375–1,400				(*6*)
OR	1,400–1,600		1,400–1,600				(*6*)
SC	950		950				(*6*)
WA	1,350		1,450				(*6*)
WI	1,560–1,900		1,600–2,000		1,800–2,100		(*6, 8*)
FL	1,800		1,800				(*9*)
VA	1,300	1,300	1,300	1,300	1,300	1,300	(*10*)
IA	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	(*11*)
MA	1,340	1,490	1,170	1,520	1,480	1,170	(*12*)
Default	**1,400**	**1,450**	**1,450**	**1,500**	**1,450**	**1,350**	

Source: Adapted from Chatterjee et al. (*13*).

It is easy to see from Exhibit 10-14 that capacities through long-term construction zones are highly variable and depend on many site-specific characteristics. Therefore, it is better to base this adjustment on local data and experience. If such data do not exist and cannot be reasonably acquired, the default values of Exhibit 10-14 may be used to provide an approximate estimate of construction zone capacity.

Lane-Width Consideration

The impact of lane width on general freeway operations is incorporated into the methodology of Chapter 11, Basic Freeway Segments, for determining free-flow speed. As free-flow speed affects capacity, it follows that restricted lane widths will negatively affect capacity.

As free-flow speeds are not estimated specifically for work or construction zones, it is appropriate to add an adjustment factor for the effect of lane widths narrower than 12 ft in a work or construction zone. The factor f_{LW} would be added to Equation 10-9, as shown in Equation 10-10:

Equation 10-10

$$c'_a = c_a \times f_{LW}$$

where c'_a is the adjusted capacity of the work or construction zone reflecting the impact of restricted lane width, in vehicles per hour, and all other variables are as previously defined.

The value of the adjustment factor f_{LW} is 1.00 for 12-ft lanes, 0.91 for lanes between 10.0 and 11.9 ft, and 0.86 for lanes between 9.0 and 9.9 ft. If lanes narrower than 9.0 ft are in use, local observations should be made to calibrate an appropriate adjustment.

Capacity Reductions due to Weather and Environmental Conditions

A number of studies have attempted to address the impacts of adverse weather and environmental conditions on the capacity of freeways. Comprehensive results for a range of conditions in Iowa, summarized in Exhibit 10-15, are provided elsewhere (*14*).

Exhibit 10-15
Capacity Reductions due to Weather and Environmental Conditions in Iowa

Type of Condition	Intensity of Condition	Percent Reduction in Capacity Average	Percent Reduction in Capacity Range
Rain	>0 ≤ 0.10 in./h	2.01	1.17–3.43
	>0.10 ≤ 0.25 in./h	7.24	5.67–10.10
	>0.25 in./h	14.13	10.72–17.67
Snow	>0 ≤ 0.05 in./h	4.29	3.44–5.51
	>0.05 ≤ 0.10 in./h	8.66	5.48–11.53
	>0.10 ≤ 0.50 in./h	11.04	7.45–13.35
	>0.50 in./h	22.43	19.53–27.82
Temperature	<50°F ≥ 34°F	1.07	1.06–1.08
	<34°F ≥ –4°F	1.50	1.48–1.52
	<–4°F	8.45	6.62–10.27
Wind	>10 ≤ 20 mi/h	1.07	0.73–1.41
	>20 mi/h	1.47	0.74–2.19
Visibility	<1 ≥ 0.50 mi	9.67	One site
	<0.50 ≤ 0.25 mi	11.67	One site
	<0.25 mi	10.49	One site

Source: Adapted from Agarwal et al. (*14*).

Additional information is available in the literature. Additional data and information on the impacts of rain on freeway capacity are provided elsewhere (*15, 16*), as are information on the effects of snow (*16*) and insights and information on the effects of fog (*17, 18*).

A study of capacity on German autobahns provides data on the difference between daytime and nighttime conditions on wet or dry pavements (*19*). Exhibit 10-16 summarizes these results.

Exhibit 10-16
Capacities on German Autobahns Under Various Conditions (veh/h/ln)

Freeway Lanes	Weekday or Weekend	Daylight Dry	Dark Dry	Daylight Wet	Dark Wet
6	Weekday (% change*)	1,489	1,299 (13%)	1,310 (12%)	923 (38%)
6	Weekend (% change*)	1,380	1,084 (21%)	1,014 (27%)	— —
4	Weekday (% change*)	1,739	1,415 (19%)	1,421 (18%)	913 (47%)
4	Weekend (% change*)	1,551	1,158 (25%)	1,104 (29%)	— —

Note: *Percent change from daylight, dry conditions for the same day of week.
Source: Adapted from Brilon and Ponzlet (*19*).

This exhibit is interesting in that the daylight, dry capacities of German autobahns are somewhat less than might be expected on U.S. freeways. This situation could be due to the higher speeds that prevail on the autobahns and heavy-vehicle presence, which are not reflected in these veh/h/ln statistics.

The daylight wet versus dry capacity reductions are greater in Exhibit 10-16 than those shown in Exhibit 10-15, which may again be a reflection of different driver behavior characteristics in Germany and the United States. Darkness alone has a significant impact on autobahn capacities. Since winter peak hours occur when it is dark in many areas of the country, such reductions are important to recognize.

The difference between weekday and weekend capacities is also interesting and is on the order of 7% to 10% in Exhibit 10-16. This impact is generally reflected in the use of a driver-population factor f_p (see Chapter 11). Weekend driving populations may not be as familiar with the facility as weekday commuters. Even familiar users may not drive as aggressively on weekend recreational or other trips when the pressure of a specific schedule may be less than is present during the week.

Capacity Reductions due to Traffic Accidents or Vehicular Breakdowns

Capacity reductions due to traffic accidents or other incidents are generally short-lived, ranging from less than 1 h before they can be cleared to as long as 12 h for an accident involving severe injuries, fatalities, hazardous materials cleanup, or cleanup of other materials from vehicles involved in accidents.

One study (*20*) reported the mean duration of a traffic incident to be 37 min, with more than half the incidents lasting 30 min or less and 82% lasting less than 1 h.

Exhibit 10-17 summarizes the results of two studies (*21*, *22*) on the capacity impacts of lane blockages due to incidents, including accidents. An incident's effect on capacity depends on the proportion of the traveled roadway that is blocked and on the number of lanes on the freeway at that point.

Exhibit 10-17
Proportion of Freeway Segment Capacity Available Under Incident Conditions

Number of Lanes (One Direction)	Shoulder Disablement	Shoulder Accident	One Lane Blocked	Two Lanes Blocked	Three Lanes Blocked
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.26
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

In a blocked lane, the loss of capacity is likely to be greater than the proportion of the roadway that is blocked. A one-lane blockage on a two-lane directional freeway segment (50% of the roadway blocked) reduces capacity to 35% of the original value, for example. The added loss of capacity arises because drivers slow to look at the incident while they are abreast of it and are slow to react to the possibility of speeding up to move through the incident area.

The "rubbernecking" factor is also responsible for a reduction in capacity in the direction of travel opposite to that in which the accident or incident occurred. While no quantitative studies of this impact have been conducted, experience suggests that the severity of the accident or incident plays a significant role in the impact of rubbernecking. The reduction in capacity may range from 5% for a single-vehicle accident with one emergency vehicle present to as high as 25% for a multivehicle accident with several emergency vehicles.

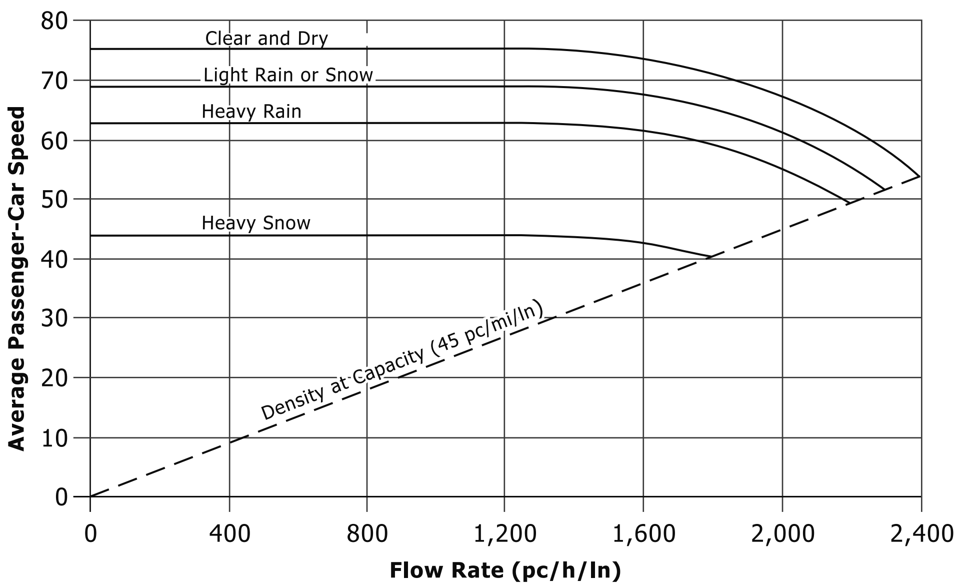
Applying Capacity Reductions

There are several ways to use the information on reduced capacities discussed in this section.

Quick approximations simply require that the capacity of each freeway facility segment (as estimated by using the methodologies of Chapters 11, 12, and 13) be reduced by all the impacts of work zones, weather, environment, and accidents or incidents that are present, in accord with the information provided here. The methodology continues using these reduced capacities.

If speed information is available, then the free-flow speed through the restricted capacity area can be used to select an appropriate speed–flow curve for analysis (from Chapter 11). The reduced free-flow speed results in a reduced capacity. An example of this approach is illustrated in Exhibit 10-18, which is based on speed data presented elsewhere (*16, 19*).

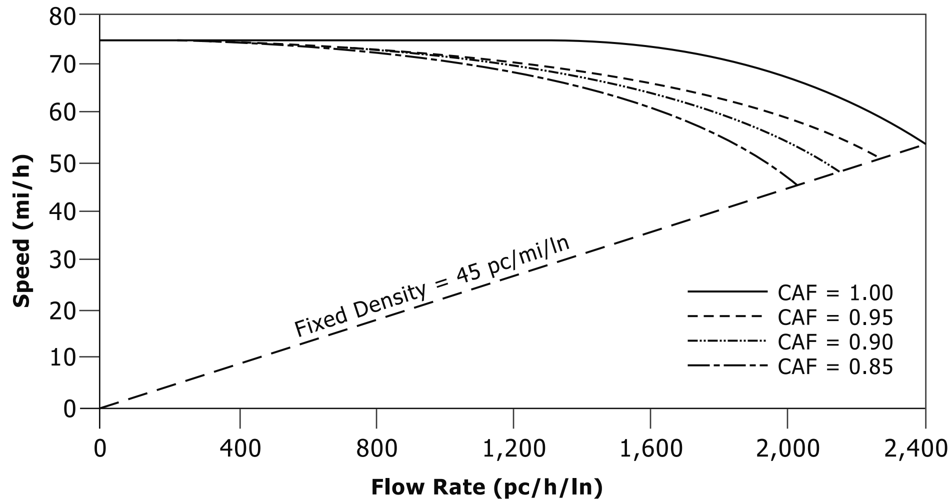
Exhibit 10-18
Illustration of Speed–Flow Curves for Different Weather Conditions



Note: Free-flow speed = 75 mi/h (base conditions).

For most temporary capacity reductions, the only information available relates to capacity. In most of these cases, speed conditions can be reasonably estimated. For example, in construction zones, a reduced speed limit is usually posted, and lower speeds can be expected to occur, particularly when actual construction operations are taking place. Likewise, for incidents, traffic naturally slows as drivers pass the incident site, where rubbernecking takes place. Exhibit 10-19 shows an example of modeling such cases on the basis of a downward-shifted speed–flow curve.

Exhibit 10-19
Illustration of Adjusted Speed–Flow Curves for Indicated Capacity Reductions



Note: Free-flow speed = 75 mi/h (base conditions); CAF = capacity adjustment factor (proportion of available capacity).

If the analyst has no interest in speeds, the capacity reduction could be modeled by using a fractional number of lanes that would reflect the new capacity of the roadway rather than the actual number of lanes present. For example, in the case of a four-lane directional freeway segment with two lanes blocked, Exhibit 10-17 indicates that only 25% of capacity would be available. This segment could be modeled as if only one lane were available through the incident (even though two are actually in use).

Some of the performance measures that result from this methodology, however, rely on speed. A simple approach that does not deal with speed consequences would result in an incomplete analysis. Consequently, an approach that uses modified speed–flow curves, as illustrated here, is recommended.

Step 5: Compute Demand-to-Capacity Ratios

Each cell of the time–space domain now contains an estimate of demand and capacity. A demand-to-capacity ratio can be calculated for each cell. The cell values must be carefully reviewed to determine whether all boundary cells have v_d/c ratios of 1.00 or less and to determine whether any cells in the interior of the time–space domain have v_d/c values greater than 1.00.

If any boundary cells have a v_d/c ratio greater than 1.00, further analysis may be significantly flawed:

1. If any cell in the first time interval has a v_d/c ratio greater than 1.00, there may have been oversaturated conditions in earlier time intervals without transfer of unsatisfied demand into the time–space domain of the analysis.
2. If any cell in the last time interval has a v_d/c ratio greater than 1.00, the analysis will be incomplete because the unsatisfied demand in the last time interval cannot be transferred to later time intervals.
3. If any cell in the last downstream segment has a v_d/c ratio greater than 1.00, there may be downstream bottlenecks that should be checked before

proceeding with the analysis. If any cell in the first segment has a v_d/c ratio greater than 1.00, then oversaturation will extend upstream of the defined freeway facility, but its effects will not be analyzed within the time–space domain.

These checks do not guarantee that the boundary cells will not show v_d/c ratios greater than 1.00 later in the analysis. If these initial checks reveal boundary cells with v_d/c ratios greater than 1.00, then the time–space domain of the analysis should be adjusted to eliminate the problem.

As the analysis of the time–space domain proceeds, subsequent demand shifts may cause some boundary cell v_d/c ratios to exceed 1.00. In these cases, the problem should be reformulated or alternative tools applied. Most alternative tools will have the same problem if the boundary conditions experience congestion.

Another important check is to observe whether any cell in the interior of the time–space domain has a v_d/c ratio greater than 1.00. There are two possible outcomes:

1. If all cells have v_d/c ratios of 1.00 or less, then the entire time–space domain contains undersaturated flow, and the analysis is greatly simplified.
2. If any cell in the time–space domain has a v_d/c ratio greater than 1.00, then the time–space domain will contain both undersaturated and oversaturated cells. Analysis of oversaturated conditions is much more complex because of the interactions between freeway segments and the shifting of demand in both time and space.

If Case 1 exists, the analysis moves to Step 6A. If Case 2 exists, the analysis moves to Step 6B.

The v_d/c ratio for all on-ramps and off-ramps should also be examined. If an on-ramp demand exceeds the on-ramp capacity, the ramp demand flow rates should be adjusted to reflect capacity. Off-ramps generally fail because of deficiencies at the ramp–street junction. They may be analyzed by procedures in Chapters 18–22, depending on the type of traffic control used at the ramp–street junction. These checks are done manually, and inputs to this methodology must be revised accordingly.

Steps 6A and 6B: Compute Undersaturated (6A)/Oversaturated (6B) Service Measures and Other Performance Measures

The analysis begins in the first cell in the upper-left corner of the time–space domain (the first segment in the first time interval) and continues downstream along the freeway facility for each segment in the first time interval. The analysis then returns to the first upstream segment in the second time interval and continues downstream along the freeway for each segment in the second time interval. This process continues until all cells in the time–space domain have been analyzed.

As each cell is analyzed in turn, its v_d/c ratio is checked. If the v_d/c ratio is 1.00 or less, the cell is not a bottleneck and is able to handle all traffic demand that wishes to enter. The process is continued in the order noted in the previous paragraph until a cell with a v_d/c ratio greater than 1.00 is encountered. Such a cell is labeled as a bottleneck. Because it cannot handle a flow greater than its capacity, the following impacts will occur:

1. The v_d/c ratio of the bottleneck cell will be exactly 1.00, as the cell processes a flow rate equal to its capacity.
2. Flow rates for all cells downstream of the bottleneck must be adjusted downward to reflect the fact that not all the demand flow at the bottleneck gets through. Downstream cells are subject to demand starvation due to the bottleneck.
3. The unsatisfied demand at the bottleneck cell must be stored in the upstream segments. Flow conditions and performance measures in these upstream cells are affected. Shock wave analysis is applied to estimate these impacts.
4. The unsatisfied demand stored upstream of the bottleneck cell must be transferred to the next time interval. This transfer is accomplished by adding the unsatisfied demand by desired destination to the origin–destination table of the next time interval.

This four-step process is implemented for each bottleneck encountered, following the specified sequence of cell analysis. If no bottlenecks are identified, the entire domain is undersaturated, and the sequence of steps for oversaturated conditions is not applied.

If a bottleneck is severe, the storage of unsatisfied demand may extend beyond the upstream boundary of the freeway facility or beyond the last time interval of the time–space domain. In such cases, the analysis will be flawed, and the time–space domain should be reconstituted.

After all demand shifts (in the case of one or more oversaturated cells) are estimated, each cell is analyzed by the methodologies of Chapter 11, Basic Freeway Segments; Chapter 12, Freeway Weaving Segments; and Chapter 13, Freeway Merge and Diverge Segments. Facility service and performance measures may then be estimated.

Undersaturated Conditions

For undersaturated conditions, the process is straightforward. Because there are no cells with v_d/c ratios greater than 1.00, the flow rate in each cell, v_a, is equal to the demand flow rate, v_d. Each segment analysis using the methodologies of Chapters 11, 12, and 13 will result in estimating a density D and a space mean speed S.

When the analysis moves from isolated segments to a system, additional constraints may be necessary. A maximum-achievable-speed constraint is imposed to limit the prediction of speeds in segments downstream of a segment experiencing low speeds. This constraint prevents large speed fluctuations from segment to segment when the segment methodologies are directly applied. This process results in some changes in the speeds and densities predicted by the segment methodologies.

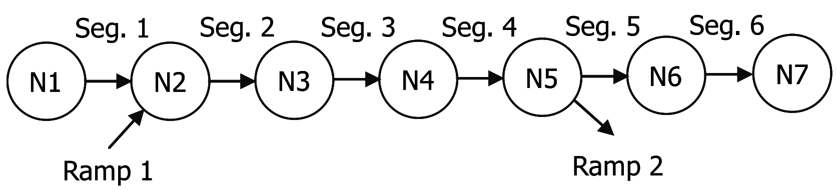
For each time interval, Equation 10-2 is used to estimate the average density for the defined freeway facility. This result is compared with the criteria of Exhibit 10-7 to determine the facility LOS for the time period. Each time period will have a separate LOS. Although LOS is not averaged over time intervals, if desired, density can be averaged over time intervals.

Oversaturated Conditions

Once oversaturation is encountered, the methodology changes its temporal and spatial units of analysis. The spatial units become nodes and segments, and the temporal unit moves from a time interval of 15 min to smaller time periods, as recommended in Chapter 25, Freeway Facilities: Supplemental.

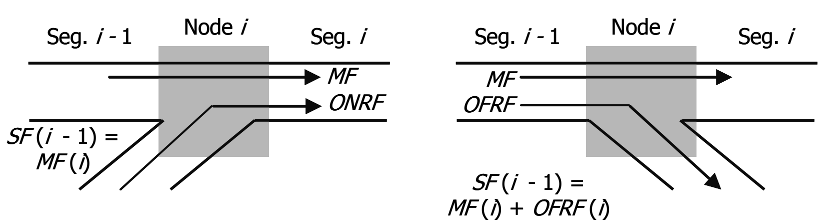
Exhibit 10-20 illustrates the node–segment concept. A node is defined as the junction of two segments. Given that there is a node at the beginning and end of the freeway facility, there will always be one more node than the number of segments on the facility.

Exhibit 10-20
Node–Segment Representation of a Freeway Facility



The numbering of nodes and segments begins at the upstream end of the defined freeway facility and moves to the downstream end. The segment upstream of node i is numbered $i - 1$, and the downstream segment is numbered i, as shown in Exhibit 10-21.

Exhibit 10-21
Mainline and Segment Flow at On- and Off-Ramps



Note: *SF* = segment flow, *MF* = mainline flow, *ONRF* = on-ramp flow, and *OFRF* = off-ramp flow.

The oversaturated analysis moves from the first node to each downstream node for a time step. After the analysis for the first time step is complete, the same nodal analysis is performed for each subsequent time step.

When oversaturated conditions exist, many flow variables must be adjusted to reflect the upstream and downstream effects of bottlenecks. These adjustments are explained in general terms in the sections that follow and are fully detailed in Chapter 25.

Flow Fundamentals

As noted previously, segment flow rates must be calculated for each time step. They are used to estimate the number of vehicles on each segment at the end of every time step. The number of vehicles on each segment is used to track queue accumulation and discharge and to estimate the average segment density.

The conversion from standard 15-min time intervals to time steps (of lesser duration) occurs during the first oversaturated interval. Time steps are then used until the analysis is complete. This transition to time steps is critical because, at certain points in the methodology, future performance is estimated from past performance of an individual variable. Use of time steps also allows for a more accurate estimation of queues.

Service and other performance measures for oversaturated conditions use a simplified, linear flow–density relationship, as detailed in Chapter 25.

Segment Initialization

To estimate the number of vehicles on each segment for each time step under oversaturated conditions, it is necessary to begin the process with the appropriate number of vehicles in each segment. Determining this number is referred to as *segment initialization.*

A simplified queuing analysis is initially performed to account for the effects of upstream bottlenecks. The bottlenecks limit the number of vehicles that can proceed downstream.

To obtain the proper number of vehicles on each segment, the expected demand is calculated from the demands for and capacities of the segment, including the effects of all upstream segments. The expected demand represents the flow that would arrive at each segment if all queues were stacked vertically (i.e., as if the queues had no upstream impacts). For all segments upstream of a bottleneck, the expected demand will equal the actual demand.

For the bottleneck segment and all further downstream segments, a capacity restraint is applied at the bottleneck when expected demand is computed. From the expected segment demand, the background density can be obtained for each segment by using the appropriate estimation algorithms from Chapters 11, 12, and 13.

Mainline Flow Calculation

Flows analyzed in oversaturated conditions are calculated for every time step and are expressed in vehicles per time step. They are analyzed separately on the basis of the origin and destination of the flow across the node. The following flows are defined:

1. The flow from the mainline upstream segment $i - 1$ to the mainline downstream segment i is the mainline flow MF.
2. The flow from the mainline to an off-ramp is the off-ramp flow $OFRF$.
3. The flow from an on-ramp to the mainline is the on-ramp flow $ONRF$.

Each of these flows is illustrated in Exhibit 10-21.

Mainline Input

The mainline input is the number of vehicles that wish to travel through a node during the time step. The calculation includes the effects of bottlenecks upstream of the subject node. The effects include the metering of traffic during queue accumulation and the presence of additional vehicles during queue discharge.

The mainline input is calculated by taking the number of vehicles entering the node upstream of the analysis node, adding on-ramp flows or subtracting off-ramp flows, and adding the number of unserved vehicles on the upstream segment. The result is the maximum number of vehicles that desire to enter a node during a time step.

Mainline Output

The mainline output is the maximum number of vehicles that can exit a node, constrained by downstream bottlenecks or by merging traffic. Different constraints on the output of a node result in three different types of mainline outputs (MO1, MO2, and MO3).

- *Mainline output from ramps (MO1):* MO1 is the constraint caused by the flow of vehicles from an on-ramp. The capacity of an on-ramp flow is shared by two competing flows: flow from the on-ramp and flow from the mainline. The total flow that can pass the node is estimated as the minimum of the segment *i* capacity and the mainline outputs (MO2 and MO3) calculated in the preceding time step.
- *Mainline output from segment storage (MO2):* The output of mainline flow through a node is also constrained by the growth of queues on the downstream segment. The presence of a queue limits the flow into the segment once the queue reaches its upstream end. The queue position is calculated by shock wave analysis. The MO2 limitation is determined first by calculating the maximum number of vehicles allowed on a segment at a given queue density. The maximum flow that can enter a queued segment is the number of vehicles leaving the segment plus the difference between the maximum number of vehicles allowed on a segment and the number of vehicles already on the segment. The queue density is determined from the linear congested portion of the density–flow relationship shown in Chapter 25.
- *Mainline output from front-clearing queue (MO3):* The final limitation on exiting mainline flows at a node is caused by front-clearing downstream queues. These queues typically occur when temporary incidents clear. Two conditions must be satisfied: (*a*) the segment capacity (minus the on-ramp demand if present) for the current time interval must be greater than the segment capacity (minus on-ramp demand) in the preceding time interval, and (*b*) the segment capacity minus the ramp demand for the current time interval must be greater than the segment demand in the same time interval. Front-clearing queues do not affect the segment throughput (which is limited by queue throughput) until the recovery wave has reached the upstream end of the segment. The shock wave speed is estimated from the slope of the line connecting the bottleneck throughput and the segment capacity points.

Mainline Flow

The mainline flow across node *i* is the minimum of the following variables:

- Node *i* mainline input,
- Node *i* MO2,
- Node *i* MO3,
- Segment *i* – 1 capacity, and
- Segment *i* capacity.

Determining On-Ramp Flow

The on-ramp flow is the minimum of the on-ramp input and output. Ramp input in a time step is the ramp demand plus any unserved ramp vehicles from a previous time step.

On-ramp output is limited by the ramp roadway capacity and the ramp-metering rate. It is also affected by the volumes on the mainline segments. The latter is a very complex process that depends on the various flow combinations on the segment, the segment capacity, and the ramp roadway volumes. Details of the calculations are presented in Chapter 25.

Determining Off-Ramp Flow

The off-ramp flow is determined by calculating a diverge percentage based on the segment and off-ramp demands. The diverge percentage varies only by time interval and remains constant for vehicles that are associated with a particular time interval. If there is an upstream queue, then traffic to this off-ramp may be metered. This will cause a decrease in the off-ramp flow. When vehicles that were metered arrive in the next time interval, they use the diverge percentage associated with the preceding time interval. This methodology ensures that all off-ramp vehicles prevented from exiting during the presence of a bottleneck are appropriately discharged in later time intervals.

Determining Segment Flow

Segment flow is the number of vehicles that flow out of a segment during the current time step. These vehicles enter the current segment either to the mainline or to an off-ramp at the current node as shown in Exhibit 10-20. The number of vehicles on each segment in the current time step is calculated with the following information:

- The number of vehicles that were in the segment in the previous time step,
- The number of vehicles that entered the segment in the current time step, and
- The number of vehicles that can leave the segment in the current time step.

Because the number of vehicles that leave a segment must be known, the number of vehicles on the current segment cannot be determined until the upstream segment is analyzed.

The number of unserved vehicles stored on a segment is calculated as the difference between the number of vehicles on the segment and the number of vehicles that would be on the segment at the background density.

Determining Segment Service Measures

In the last time step of a time interval, the segment flows in each time step are averaged over the time interval, and the service measures for each segment are calculated. If there were no queues on a particular segment during the entire time interval, then the performance measures are calculated from Chapters 11, 12, and 13 as appropriate.

If there was a queue on the current segment during the time interval, then the performance measures are calculated in four steps:

1. The average number of vehicles over a time interval is calculated for each segment.
2. The average segment density is calculated by taking the average number of vehicles in all time steps (in the time interval) and dividing it by the segment length.
3. The average speed on the current segment during the current time interval is calculated as the ratio of segment flow to density.
4. The final segment performance measure is the length of the queue at the end of the time interval (if one exists), which is calculated by using shock wave theory.

On-ramp queue lengths can also be calculated. A queue will form on the on-ramp roadway only if the flow is limited by a meter or by freeway traffic in the gore area. If the flow is limited by the ramp roadway capacity, unserved vehicles will be stored on a facility upstream of the ramp roadway, most likely a surface street. The methodology does not account for this delay. If the queue is on a ramp roadway, its length is calculated by using the difference in background and queue densities.

Step 7: Compute Freeway Facility Service Measures and Other Performance Measures by Time Interval

The previously discussed traffic performance measures can be aggregated over the length of the defined freeway facility for each time interval. Aggregations over the entire time–space domain of the analysis are also mathematically possible, although LOS is defined only for 15-min time intervals.

Freeway facility LOS is defined for each time interval included in the analysis. An average density for each time interval, weighted by length of segments and numbers of lanes in segments, is calculated (with Equation 10-2) and used to compare with the criteria of Exhibit 10-7.

3. APPLICATIONS

Specific computational steps for the freeway facility methodology were conceptually discussed and presented in this chapter's methodology section. Additional computational details are provided in Chapter 25, Freeway Facilities: Supplemental.

This chapter's methodology is sufficiently complex to require software for its application. Even for fully undersaturated analyses, the number and complexity of computations make it difficult and extremely time-consuming to analyze a case manually. Oversaturated analyses are considerably more complex, and manual solutions would be impractical. The computational engine for this methodology is FREEVAL-2010. A complete user's guide and executable spreadsheet are available in the Technical Reference Library in Volume 4.

OPERATIONAL ANALYSIS

The only mode in which the methodology can be directly implemented is operational analysis—that is, given a complete description of a freeway facility, its component segment geometries, and all relevant demand flow rates, a complex analysis is conducted of each segment, and of the freeway facility, by time interval. Outputs will include segment flow rates, densities, and average speeds as well as average facility density and speed for each time interval. By using the estimated facility density for each time interval, a facility LOS can be assigned.

Exhibit 10-22 shows the data inputs that are required for an operational analysis of a freeway facility.

Exhibit 10-22
Required Input Data for Freeway Facility Analysis

Geometric Data for Each Section
• Section length (ft) • Mainline number of lanes • Mainline average lane width (ft) • Mainline lateral clearance (ft) • Terrain (level, rolling, or mountainous), or specific grade (% grade, length in mi) • Ramp number of lanes • Ramp acceleration or deceleration lane length (ft) • Existence of independent HOV lane
Traffic Characteristic Data for Each Segment
• Mainline free-flow speed (mi/h), optional • Vehicle occupancy (passengers/veh) • Percent trucks and buses (%) • Percent RVs (%) • Driver population (commuter or recreational) • Ramp free-flow speeds (mi/h)
Demand Data for Each Segment
• Mainline entry demand for each time interval (veh/h) • On-ramp demands for each time interval (veh/h) • Off-ramp demands for each time interval (veh/h) • Weaving demand on weaving segments, by movement (veh/h) • HOV lane demand (veh/h), if present

Where all data are not readily available or collectable, the analysis may be supplemented by using consistent default values for each segment. Lists and discussions of default values are found in Chapter 11, Basic Freeway Segments;

Chapter 12, Freeway Weaving Segments; and Chapter 13, Freeway Merge and Diverge Segments.

Performance measures output by the methodology for individual segments and the facility (for a given time interval) include the following:

- Average speed (mi/h),
- Average density (pc/mi/ln),
- Vehicle miles of travel,
- Vehicle hours of travel, and
- Travel time (min/veh).

Chapter 25 details facilitywide performance measure calculations by time interval.

PLANNING, PRELIMINARY ENGINEERING, AND DESIGN ANALYSIS

This methodology cannot be directly used in planning, preliminary engineering, and design applications. However, for generalized planning, Exhibit 10-8 (urban freeways) and Exhibit 10-9 (rural freeways) provide daily-service-volume tables for a variety of typical freeway conditions. These tables may be applied for general evaluations of a number of freeway facilities in a specified region. They should not be used for directly evaluating a specific freeway facility or for developing detailed facility improvement plans. A full operational analysis would normally be applied to any freeway facility identified as potentially needing improvement.

Preliminary engineering and design applications of the methodology are possible by using the segment procedures described in Chapters 11, 12, and 13. Various geometric scenarios can be evaluated and compared by using a travel demand matrix and the facility methodology on the basis of the segment results.

TRAFFIC MANAGEMENT STRATEGIES

The freeway facilities methodology has incorporated procedures for assessing a variety of traffic management strategies. The methodology permits modifying previously calculated cell demands or capacities (or both) within the time–space domain to assess a traffic management strategy or a combination of strategies.

1. A growth factor parameter has been incorporated to evaluate traffic performance when traffic demands are higher or lower than the demand calculated from the traffic counts. This parameter would be used to undertake a sensitivity analysis of the effect of demand on freeway performance and to evaluate future scenarios. In these cases, all cell demand estimates are multiplied by the growth factor parameter.
2. The effect of a predetermined ramp-metering plan can be evaluated by modifying the ramp roadway capacities. The capacity of each entrance ramp in each time interval is changed to the desired metering rate. This feature permits evaluating a predetermined ramp-metering plan and experimenting to obtain an improved ramp-metering plan.

3. Freeway design improvements can be evaluated with this methodology by modifying the design features of any portion of the freeway facility. For example, the effect of adding an auxiliary lane at a critical location or adding merging or diverging lanes can be assessed.
4. Reduced-capacity situations can be investigated. The capacity in any cell or cells of the time–space domain can be reduced to represent situations such as construction and maintenance activities, adverse weather, and traffic accidents and vehicle breakdowns.
5. User demand responses such as spatial, temporal, modal, and total demand responses caused by a traffic management strategy are not automatically incorporated into the methodology. On viewing the new freeway traffic performance results, the user can modify the demand input manually to evaluate the effect of anticipated demand responses.

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 freeway facilities. Additional information on this topic may be found in Chapter 25, Freeway Facilities: Supplemental.

Strengths of the HCM Procedure

This chapter's procedures were based on extensive research supported by a significant quantity of field data. They have evolved over a number of years and represent a consensus of experts. Specific strengths of the HCM freeway facilities procedures include the following:

- They provide more detailed algorithms for considering geometric elements of the facility (such as lane and shoulder width).
- They provide capacity estimates for each segment of the facility, which simulation tools do not provide directly (and in some cases may require as an input).
- The capacity can be explicitly adjusted to account for weather conditions, lighting conditions, work zone setup and activity, and incidents.
- The calculation of key performance measures, such as speed and density, is transparent. Simulation tools often use statistics accumulated over the simulation period to derive various link or time-period-specific results, and the derivation of these results may not be obvious. Thus, the user of a simulation tool must know exactly which measure is being reported (e.g., space mean speed versus time mean speed). Furthermore, simulation tools may apply these measures in ways different from the HCM to arrive at other measures.

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

Freeway facilities can be analyzed with a variety of stochastic and deterministic simulation tools. 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.

Exhibit 10-23 provides a list of the limitations stated earlier in this chapter, along with their potential for improved treatment by alternative tools.

Exhibit 10-23
Limitations of the HCM Freeway Facilities Analysis Procedure

Limitation	Potential for Improved Treatment by Alternative Tools
Changes in travel time caused by vehicles using alternate routes	Modeled explicitly by dynamic traffic assignment tools
Multiple overlapping bottlenecks	Modeled explicitly by simulation tools
User-demand responses (spatial, temporal, modal)	Modeled explicitly by dynamic traffic assignment tools
Systemwide oversaturated flow conditions	Modeled explicitly by simulation tools
First/last time interval or first/last segment demand-to-capacity ratio > 1.0	Modeled explicitly by simulation tools, except that a simulation analysis may also be inaccurate if it does not fully account for a downstream bottleneck that causes congestion in the last segment during the last time period
Interaction between managed lanes and mixed-flow lanes	Modeled explicitly by some simulation tools

Additional Features and Performance Measures Available from Alternative Tools

This chapter provides a methodology for estimating a variety of performance measures for individual segments along a freeway facility, and the entire facility, given each segment's traffic demand and characteristics. The following performance measures are reported by the freeway facilities procedure:

- Travel time,
- Free-flow travel time,
- Traffic delay,
- Vehicle miles of travel,
- Person miles of travel,
- Speed, and
- Density (segment only).

Alternative tools can offer additional performance measures, such as queue lengths, fuel consumption, vehicle emissions, and operating costs. As with most other procedural chapters in the HCM, simulation outputs—especially graphics-based presentations—may provide details on point problems that might go unnoticed with a macroscopic analysis.

Development of HCM-Compatible Performance Measures Using Alternative Tools

LOS for all types of freeway segments is estimated by the density of traffic (pc/mi/ln) on each segment. The guidance provided in Chapter 11, Basic Freeway

Segments, for developing compatible density estimates applies to freeway facilities as well.

With the exception of free-flow travel time, the additional performance measures listed above that are produced by the procedures in this chapter are also produced by typical simulation tools. For the most part, the definitions are compatible, and, subject to the precautions and calibration requirements that follow, the performance measures from alternative tools may be considered equivalent to those that are produced by the procedures in this chapter.

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

To better determine when simulation of a freeway facility may be more appropriate than an HCM analysis, the fundamental differences between the two approaches must be understood. The HCM and simulation analysis approaches are reviewed in the following subsections.

HCM Approach

The HCM analysis procedure uses one of two approaches—one for undersaturated conditions and one for oversaturated conditions. For undersaturated conditions—that is, v_d/c is less than 1.0 for all segments and time periods—the approach is generally disaggregate. In other words, the facility is subdivided into segments corresponding to basic freeway, weaving, and merge/diverge segments, and the LOS results are reported for individual segments on the basis of the analysis procedures of Chapters 11, 12, and 13, respectively. However, LOS results are not reported for the facility as a whole.

For oversaturated conditions, the facility is analyzed in a different manner. First, the facility is considered in its entirety rather than at the individual segment level. Second, the analysis time interval, typically 15 min, is subdivided into time steps of 15 to 60 s, depending on the length of the shortest segment. This approach is necessary so that flows can be reduced to capacity levels at bottleneck locations and queues can be tracked in space and time. For oversaturated segments, the average segment density is calculated by dividing the average number of vehicles for all time steps (in the time interval) by the segment length. The average segment speed is calculated by dividing the average segment flow rate by the average segment density. Facilitywide performance measures are calculated by aggregating segment performance measures across space and time, as outlined in Chapter 25. A LOS for the facility is assigned on the basis of density for each time interval.

When the oversaturation analysis procedure is applied, if any segment is undersaturated for an entire time interval, its performance measures are calculated according to the appropriate procedure in Chapters 11, 12, and 13.

Simulation Approach

Simulation tools model the facility in its entirety and from that perspective have some similarity to the oversaturated analysis approach of the HCM. Microscopic simulation tools operate similarly under both saturated and undersaturated conditions, tracking each vehicle through time and space and generally handling the accumulation and queuing of vehicles in saturated conditions in a realistic manner. Macroscopic simulation tools vary in their treatment of saturated conditions. Some tools do not handle oversaturated conditions at all, while others may queue vehicles in the vertical, rather than horizontal, dimension. These tools may still provide reasonably accurate results under slightly oversaturated conditions, but the results will clearly be invalid for heavily congested conditions.

The treatment of oversaturated conditions is a fundamental issue that must be understood when considering whether to apply simulation in lieu of the HCM for analysis of congested conditions. A review of simulation modeling approaches is beyond the scope of this document. More detailed information on the topic may be found in the Technical Reference Library in Volume 4.

Adjustment of Simulation Parameters to the HCM Results

Some calibration is generally required before an alternative tool can be used effectively to supplement or replace the HCM procedure. The following subsections discuss key variables that should be checked for consistency with the HCM procedure values.

Capacity

In the HCM, capacity is a function of the specified free-flow speed (which can be adjusted by lane width, shoulder width, and ramp density). In a simulation tool, capacity is typically a function of the specified minimum vehicle entry headway (into the system) and car-following parameters (assuming microscopic simulation).

While the determination of capacity for a basic freeway segment is clearly described in Chapter 11, this chapter does not offer specific guidance on determining the appropriate capacity for different segment types within a facility, other than to refer the reader to the individual chapters (basic segments, weaving segments, merge segments, diverge segments) for appropriate capacity values. The HCM specifies the capacity of a freeway facility in units of veh/h rather than pc/h.

In macroscopic simulation tools, capacity is generally an input. Thus, for this situation, it is straightforward to match the simulation capacity to the HCM capacity. Microscopic simulation tools, however, do not have an explicit capacity input. Most microscopic tools provide an input that affects the minimum separation for the generation of vehicles into the system. Therefore, specifying a value of 1.5 s for this input will result in a maximum vehicle entry rate of 2,400 (3,600/1.5) veh/h/ln. Once vehicles enter the system, vehicle headways are governed by the car-following model. Thus, given other factors and car-following model constraints, the maximum throughput on any one segment may not reach this value. Consequently, some experimenting is usually necessary to find the right minimum entry separation value to achieve a capacity value comparable with that in the HCM. Again, the analyst needs to be careful of the units being used for capacity in making comparisons.

The other issue to be aware of is that, while geometric factors such as lane and shoulder width affect the free-flow speed (which in turn affects capacity) in the HCM procedure, some simulation tools do not account for these effects, or they may account for other factors, such as horizontal curvature, that the HCM procedure does not consider.

Lane Distribution

In the HCM procedure, there is an implicit assumption that, for any given vehicle demand, the vehicles are evenly distributed across all lanes of a basic freeway segment. For merge and diverge segments, the HCM procedure includes calculations to determine how vehicles are distributed across lanes as a result of merging or diverging movements. For weaving segments, there is not an explicit determination of flow rates in particular lanes, but consideration of weaving and nonweaving flows and the number of lanes available for each is an essential element of the analysis procedure.

In simulation tools, the distribution of vehicles across lanes is typically specified only for the entry point of the network. Once vehicles have entered the network, they are distributed across lanes according to car-following and lane-changing logic. This input value should reflect field data if they are available. If field data indicate an imbalance of flows across lanes, this situation may lead to a difference between the HCM and simulation results. If field data are not available, specifying an even distribution of traffic across all lanes is probably reasonable for networks that begin with a long basic segment. If there is a ramp junction within a short distance downstream of the entry point of the network, setting the lane distribution values to be consistent with those from Chapter 13 of the HCM will likely yield more consistent results.

Traffic Stream Composition

The HCM deals with the presence of non–passenger car vehicles in the traffic stream by applying passenger car equivalent values. These values are based on the percentage of trucks, buses, and RVs in the traffic stream as well as type of terrain (grade profile and its length). Thus, the traffic stream is converted into some equivalent number of passenger cars only, and the analysis results are based on flow rates in these units.

In the case of stochastic-based simulators, the generated vehicle type percentages may only approximate the specified percentages.

Simulation tools deal with the traffic stream composition just as it is specified; that is, the specific percentages of each vehicle type are generated into and moved through the system according to their specific vehicle attributes (e.g., acceleration and deceleration capabilities). Thus, simulation, particularly microscopic simulation, results likely better reflect the effects of non–passenger car vehicles on the traffic stream. Although in some instances the passenger car equivalent values contained in the HCM were developed from simulation data, simplifying assumptions made to make them implementable in an analytical procedure result in some loss of fidelity in the treatment of different vehicle types.

Furthermore, it should be recognized that the HCM procedures do not explicitly account for differences in driver types. Microscopic simulation tools explicitly provide for a range of driver types and allow a number of factors related to driver type to be modified (e.g., free-flow speed, gap acceptance threshold). However, it should also be recognized that the empirical data some HCM procedures are based on include the effects of the various driver types present in traffic streams.

Free-Flow Speed

In the HCM, free-flow speed is either measured in the field or estimated with calibrated predictive algorithms. In simulation, free-flow speed is almost always an input value. Where field measurements are not available, simulation users may wish to use the HCM predictive algorithms to estimate free-flow speed.

Step-by-Step Recommendations for Applying Alternative Tools

General guidance for applying alternative tools is provided in Chapter 6, HCM and Alternative Analysis Tools. The chapters that cover specific types of freeway segments offer more detailed step-by-step guidance specific to those segments. All the segment-specific guidance applies to freeway facilities, which are configured as combinations of different segments.

The first step is to determine whether the facility can be analyzed satisfactorily by the procedures described in this chapter. If the facility contains geometric or operational elements beyond the scope of these procedures, then an alternative tool should be selected. The steps involved in the application will depend on the reason(s) for choosing an alternative tool. In some cases, the step-by-step segment guidance will cover the situation adequately. In more complex cases (e.g., those that involve integrated analysis of a freeway corridor), more comprehensive guidance from one or more documents in the Technical Reference Library in Volume 4 may be needed.

Sample Calculations Illustrating Alternative Tool Applications

The limitations of this chapter's procedures are mainly related to the lack of a comprehensive treatment of the interaction between segments and facilities. Many of these limitations can be addressed by simulation tools, which generally take a more integrated approach to the analysis of complex networks of freeways, ramps, and surface street facilities. Supplemental examples illustrating interactions between segments are presented in Chapter 26, Freeway and Highway Segments: Supplemental, and Chapter 34, Interchange Ramp Terminals: Supplemental. A comprehensive example of the application of simulation tools to a major freeway reconstruction project is presented as Case Study 6 in the HCM Applications Guide located in Volume 4.

4. EXAMPLE PROBLEMS

Exhibit 10-24
List of Example Problems

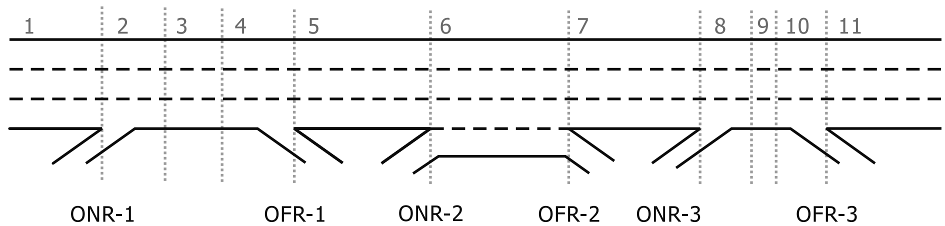
Example Problem	Description	Application
1	Evaluation of an undersaturated facility	Operational analysis
2	Evaluation of an oversaturated facility	Operational analysis
3	Capacity improvements to an oversaturated facility	Operational analysis

EXAMPLE PROBLEM 1: EVALUATION OF AN UNDERSATURATED FACILITY

The Facility

The subject of this operational analysis is an urban freeway facility 6 mi long and composed of 11 individual analysis segments, as shown in Exhibit 10-25.

Exhibit 10-25
Freeway Facility in Example Problem 1



The facility has three on-ramps and three off-ramps. Geometric details are given in Exhibit 10-26.

Exhibit 10-26
Geometry of Directional Freeway Facility for Example Problem 1

Segment No.	1	2	3	4	5	6	7	8	9	10	11
Segment type	B	ONR	B	OFR	B	B or W	B	ONR	R	OFR	B
Segment length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280
No. of lanes	3	3	3	3	3	4	3	3	3	3	3

Note: B = basic freeway segment, W = weaving segment, ONR = on-ramp (merge) segment, OFR = off-ramp (diverge) segment, R = overlapping ramp segment.

The on- and off-ramps in Segment 6 are connected by an auxiliary lane and the segment may therefore operate as a weaving segment, depending on traffic patterns. The separation of the on-ramp in Segment 8 and the off-ramp in Segment 10 is less than 3,000 ft. Since the ramp influence area of on-ramps and off-ramps is 1,500 ft, according to Chapter 13, the segment affected by both ramps is analyzed as a separate overlapping ramp segment (Segment 9), labeled "R."

The analysis question at hand is the following: What is the operational performance and LOS of the directional freeway facility shown in Exhibit 10-25?

The Facts

In addition to the information contained in Exhibit 10-25 and Exhibit 10-26, the following characteristics of the freeway facility are known:

Heavy vehicles = 5% trucks, 0% RVs (all movements);

Driver population = regular commuters;

FFS = 60 mi/h (all mainline segments);

Ramp *FFS* = 40 mi/h (all ramps);

Acceleration lane length = 500 ft (all ramps);

Deceleration lane length = 500 ft (all ramps);

D_{jam} = 190 pc/mi/ln;

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

L_s = 1,640 ft (for Weaving Segment 6);

TRD = 1.0 ramp/mi;

Terrain = level; and

Analysis duration = 75 min (divided into five 15-min intervals).

Comments

The facility was segmented into analysis segments on the basis of the guidance given in this chapter. The facility shown in Exhibit 10-25 initially depicts seven freeway *sections* (measured between ramps) that are divided into 11 analysis *segments.* The facility contains each of the possible segment types for illustrative purposes, including basic segment (B), weaving segment (W), merge segment (ONR), diverge segment (OFR), and overlapping ramp segment (R). The input data contain the required information needed for each of the segment methodologies.

The classification of the weave in Segment 6 is preliminary until it is determined whether the segment operates as a weave. For this purpose, the short length must be compared with the maximum length for weaving analysis to determine whether the Chapter 12, Weaving Segments, methodology or the Chapter 11, Basic Freeway Segments, methodology is applicable. The short length of the weaving segment used for calculation is shorter than the weaving influence area over which the calculated speed and density measures are applied.

Chapter 11 must be consulted to find appropriate values for the heavy vehicle adjustment factor f_{HV} and the driver population adjustment factor f_p. FREEVAL-2010 automatically determines these adjustment factors for general terrain conditions, but user input is needed for specific upgrades and composite grades.

All input parameters have been specified, so default values are not needed. Fifteen-minute demand flow rates are given in vehicles per hour under prevailing conditions. These demands must be converted to passenger cars per hour under equivalent ideal conditions for use in the parts of the methodology related to segment LOS estimation.

Step 1: Input Data

Traffic demand inputs for all 11 segments and five analysis intervals are given in Exhibit 10-27.

Exhibit 10-27
Demand Inputs for Example Problem 1

Time Step (15 min)	Entering Flow Rate (veh/h)	Ramp Flow Rates by Time Period (veh/h)						Exiting Flow Rate (veh/h)
		ONR1	ONR2*	ONR3	OFR1	OFR2	OFR3	
1	4,505	450	540 (50)	450	270	360	270	5,045
2	4,955	540	720 (100)	540	360	360	270	5,765
3	5,225	630	810 (150)	630	270	360	450	6,215
4	4,685	360	360 (80)	450	270	360	270	4,955
5	3,785	180	270 (50)	270	270	180	180	3,875

* Numbers in parentheses indicate ONR-2 to OFR-2 demand flow rates in Weaving Segment 6.

The volumes in Exhibit 10-27 represent the 15-min demand flow rates on the facility as determined from field observations or other sources. The actual volume served in each segment will be determined by the methodology. The demand flows are given for the extended time–space domain, consistent with this chapter's recommendations. Peaking occurs in the third 15-min period. Since inputs are in the form of 15-min flow rates, no peak hour factor adjustment is necessary. Additional geometric and traffic-related inputs are as specified in Exhibit 10-25 and the facts section of the problem statement.

Step 2: Demand Adjustments

The traffic flows in Exhibit 10-27 are already given in the form of actual demands. Therefore, no additional demand adjustment is necessary, since the flows represent true demand. Demand adjustment is necessary only if field-measured volumes are used that may be affected by upstream congestion (bottleneck) on the facility. The methodology (and FREEVAL-2010) assume that the user inputs true demand flows.

Step 3: Compute Segment Capacities

Segment capacities are determined by using the methodologies of Chapter 11 for basic freeway segments, Chapter 12 for weaving segments, and Chapter 13 for merge and diverge segments. The resulting capacities are shown in Exhibit 10-28. Since the capacity of a weaving segment depends on traffic patterns, including the weaving ratio, it varies by time period. The remaining segment capacities are constant in all five time intervals. The capacities for Segments 1–5 and 7–11 are the same, since the segments have the same basic cross section. The units shown are in vehicles per hour.

Exhibit 10-28
Segment Capacities for Example Problem 1

Time Step	Capacities (veh/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1						8,252					
2						8,261					
3	6,732	6,732	6,732	6,732	6,732	8,303	6,732	6,732	6,732	6,732	6,732
4						8,382					
5						8,442					

Step 4: Adjust Segment Capacities

This step typically allows the user to adjust capacities of specific segments or time periods to model the effects of short-term work zones, long-term construction, inclement weather conditions, or incidents. Since it is the base scenario in this sequence of example problems, no additional capacity adjustments are performed.

Step 5: Compute Demand-to-Capacity Ratios

The demand-to-capacity ratios are calculated from the demand flows in Exhibit 10-27 and from the segment capacities in Exhibit 10-28.

Exhibit 10-29
Segment Demand-to-Capacity Ratios for Example Problem 1

Time Step	Demand-to-Capacity Ratios by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	0.67	0.74	0.74	0.74	0.70	0.63	0.72	0.79	0.79	0.79	0.75
2	0.74	0.82	0.82	0.82	0.76	0.71	0.82	0.90	0.90	0.90	0.86
3	0.78	0.87	0.87	0.87	0.83	0.77	0.90	0.99	0.99	0.99	0.92
4	0.70	0.75	0.75	0.75	0.71	0.61	0.71	0.78	0.78	0.78	0.74
5	0.56	0.59	0.59	0.59	0.55	0.47	0.56	0.60	0.60	0.60	0.58

The computed demand-to-capacity ratio matrix in Exhibit 10-29 shows no segments with a v_d/c ratio greater than 1.0 in any time interval. Consequently, the facility is categorized as *globally undersaturated* and the analysis proceeds with computing the undersaturated service measures in Step 6a. Further, it is expected that no queuing will occur on the facility and that the volume served in each segment is identical to the input demand flows. Consequently, the matrix of volume-to-capacity ratios would be identical to the demand-to-capacity ratios in Exhibit 10-29. The resulting matrix of volumes served by segment and time interval is shown in Exhibit 10-30.

Exhibit 10-30
Volume-Served Matrix for Example Problem 1

Time Step	Volumes Served (veh/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	4,505	4,955	4,955	4,955	4,685	5,225	4,865	5,315	5,315	5,315	5,045
2	4,955	5,495	5,495	5,495	5,135	5,855	5,495	6,035	6,035	6,035	5,765
3	5,225	5,855	5,855	5,855	5,585	6,395	6,035	6,665	6,665	6,665	6,215
4	4,685	5,045	5,045	5,045	4,775	5,135	4,775	5,225	5,225	5,225	4,955
5	3,785	3,965	3,965	3,965	3,695	3,965	3,785	4,055	4,055	4,055	3,875

Step 6a: Compute Undersaturated Segment Service Measures

Since the facility is globally undersaturated, the methodology proceeds to calculate service measures for each segment and each time period, starting with the first segment in Time Step 1. The computational details for each segment type are exactly as described in Chapters 11, 12, and 13. The weaving methodology in Chapter 13 checks whether the weaving short length L_S is less than or equal to the maximum weaving length L_{max}. It is assumed that, for any time interval where L_S is longer than L_{max}, the weaving segment will operate as a basic freeway segment.

The basic performance measures computed for each segment and each time step are the segment speed (Exhibit 10-31), density (Exhibit 10-32), and LOS (Exhibit 10-33).

Exhibit 10-31
Speed Matrix for Example Problem 1

Time Step	Speed (mi/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	60.0	53.9	59.7	56.1	60.0	48.0	59.9	53.4	53.4	56.0	59.7
2	59.8	53.2	58.6	55.8	59.6	46.7	58.6	52.2	52.2	55.6	57.5
3	59.4	52.5	57.1	55.7	58.3	46.1	56.1	50.6	50.6	55.2	55.0
4	60.0	53.8	59.7	56.1	60.0	49.7	60.0	53.5	53.5	56.0	59.8
5	60.0	54.9	59.8	56.3	60.0	52.5	60.0	54.8	54.8	56.5	60.0

Exhibit 10-32
Density Matrix for Example Problem 1

Time Step	Density (veh/mi/ln) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	25.0	30.7	27.7	29.4	26.0	27.2	27.1	33.2	33.2	31.7	28.2
2	27.6	34.5	31.3	32.8	28.7	31.3	31.3	38.5	38.5	36.2	33.4
3	29.3	37.2	34.2	35.0	31.9	34.6	35.8	43.9	43.9	40.3	37.7
4	26.0	31.3	28.2	30.0	26.5	25.8	26.5	32.5	32.5	31.1	27.6
5	21.0	24.1	22.1	23.5	20.5	18.9	21.0	24.7	24.7	23.9	21.5

Exhibit 10-33
LOS Matrix for Example Problem 1

Time Step	LOS by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	C	C	D	C	D	C	D	D	D	D	D
2	D	D	D	D	D	D	D	D	D	D	D
3	D	D	D	D	D	E	E	E	E	E	E
4	D	C	D	D	D	C	D	D	D	D	D
5	C	C	C	C	C	B	C	C	C	C	C

Step 7: Compute Facility Service Measures and Determine LOS

In the final analysis step, facilitywide performance and service measures are calculated for each time step. Example calculations are provided for the first time step only; summary results are shown for all five time steps.

First, the facility space mean speed S is calculated for time interval $t = 1$ from the 11 individual segment flows $SF(i, t)$, segment lengths $L(i)$, and space mean speeds in each segment and time period $U(i, t)$.

$$S(t=1) = \frac{\sum_{i=1}^{11} SF(i,1) \times L(i)}{\sum_{i=1}^{11} SF(i,1) \times \frac{L(i)}{U(i,1)}}$$

$\sum_{i=1}^{11} SF(i,1) \times L(i)$

= 4,505×5,280 + 4,955×1,500 + 4,955×2,280 + 4,955×1,500
+ 4,685×5,280 + 5,225×2,640 + 4,865×5,280 + 5,315×1,140
+ 5,315×360 + 5,315×1,140 + 5,045×5,280
= 154,836,000 veh-ft

$\sum_{i=1}^{11} SF(i,1) \times \frac{L(i)}{U(i,1)}$

= (4,505×5,280/60.00) + (4,955×1,500/53.9)
+ (4,955×2,280/59.70) + (4,955×1,500/56.10)
+ (4,685×5,280/60.00) + (5,225×2,640/48.00)
+ (4,865×5,280/59.90) + (5,315×1,140/53.40)
+ (5,315×360/53.40) + (5,315×1,140/56.00)
+ (5,045×5,280/59.70)
= 2,688,024 veh-ft/mi/h

$$S(t=1) = \frac{154{,}836{,}000}{2{,}688{,}024} = 57.6 \text{ mi/h}$$

Second, the average facility density is calculated for Time Step 1 from the individual segment densities *D*, segment lengths *L*, and number of vehicles in each segment *N*:

$$D(t=1)=\frac{\sum_{i=1}^{11} D(i,1)\times L(i)\times N(i,1)}{\sum_{i=1}^{11} L(i)N(i,1)}$$

$\sum_{i=1}^{11} D(i,1)\times L(i)\times N(i,1)$ = (25.0×5,280×3) + (30.7×1,500×3) + (27.7×2,280×3) + (29.4×1,500×3) + (26.0×5,280×3) + (27.2×2,640×4) + (27.1×5,280×3) + (33.2×1,140×3) + (33.2×360×3) + (31.7×1,140×3) + (28.2×5,280×3)
= 2,687,957 (veh/mi/ln)(ln-ft)

$\sum_{i=1}^{11} L(i)N(i,1)$ = (5,280×3) + (1,500×3) + (2,280×3) + (1,500×3) + (5,280×3) + (2,640×4) + (5,280×3) + (1,140×3) + (360×3) + (1,140×3) + (5,280×3)
= 97,680 ln-ft

$$D(t=1)=\frac{2{,}687{,}957}{97{,}680}=27.5\text{ veh/mi/ln}$$

These calculations are repeated for all five time steps. The overall space mean speed across all time intervals is calculated as follows:

$$S(p=5)=\frac{\sum_{p=1}^{5}\sum_{i=1}^{11} SF(i,p)L(i)}{\sum_{p=1}^{5}\sum_{i=1}^{11} SF(i,p)\frac{L(i)}{U(i,p)}}$$

The overall average density across all time intervals is calculated as follows:

$$D(p=5)=\frac{\sum_{p=1}^{5}\sum_{i=1}^{11} D(i,p)\times L(i)\times N(i,p)}{\sum_{p=1}^{5}\sum_{i=1}^{11} L(i)N(i,p)}$$

The resulting performance and service measures for Time Steps 1–5 and the facility totals are shown in Exhibit 10-34. The LOS for each time interval is determined directly from the average density for each time interval by using Exhibit 10-7. No LOS is defined for the average across all time intervals.

Exhibit 10-34
Facility Performance Measure Summary for Example Problem 1

Time Step	Performance Measures: Space Mean Speed (mi/h)	Performance Measures: Average Density (veh/mi/ln)	LOS
1	57.6	27.5	D
2	56.6	31.3	D
3	55.1	34.8	E
4	57.9	27.5	D
5	58.4	21.4	C
Total	**56.9**	**28.5**	—

Discussion

This facility turned out to be globally undersaturated. Consequently, the facility-aggregated performance measures could be calculated directly from the individual segment performance measures. An assessment of the segment service measures across the time–space domain can begin to highlight areas of potential congestion. Visually, this process can be facilitated by plotting the v_d/c, v_a/c, speed, or density matrices in contour plots.

EXAMPLE PROBLEM 2: EVALUATION OF AN OVERSATURATED FACILITY

The Facility

The facility used in Example Problem 2 is identical to the one in Example Problem 1, which is shown in Exhibit 10-25 and Exhibit 10-26.

The Facts

In addition to the information in Exhibit 10-25 and Exhibit 10-26, the following characteristics of the freeway facility are known:

Heavy vehicles = 5% trucks, 0% RVs (all movements);

Driver population = regular commuters;

FFS = 60 mi/h (all mainline segments);

Ramp *FFS* = 40 mi/h (all ramps);

Acceleration lane length = 500 ft (all ramps);

Deceleration lane length = 500 ft (all ramps);

D_{jam} = 190 pc/mi/ln;

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

L_s = 1,640 ft (for Weaving Segment 6);

TRD = 1.0 ramp/mi;

Terrain = level;

Analysis duration = 75 min (divided into five 15-min time steps); and

Demand adjustment = +11% increase in demand volumes across all segments and time steps compared with Example Problem 1.

Comments

The facility and all geometric inputs are identical to Example Problem 1. The same general comments apply. The results of Example Problem 1 suggested a globally undersaturated facility, but some segments were close to their capacity (v_d/c ratios approaching 1.0). In the second example, a facilitywide demand increase of 11% is applied to all segments and all time periods. Consequently, it is expected that parts of the facility may become oversaturated and that queues may form on the facility.

Step 1: Input Data

The revised traffic demand inputs for all 11 segments and five analysis intervals are shown in Exhibit 10-35.

Exhibit 10-35
Demand Inputs for Example Problem 2

Time Step (15 min)	Entering Flow Rate (veh/h)	Ramp Flow Rates by Time Period (veh/h)						Exiting Flow Rate (veh/h)
		ONR1	ONR2*	ONR3	OFR1	OFR2	OFR3	
1	5,001	500	599 (56)	500	600	400	300	5,600
2	5,500	599	799 (111)	599	400	400	300	6,399
3	5,800	699	899 (167)	699	300	400	500	6,899
4	5,200	400	400 (89)	500	300	400	300	5,500
5	4,201	200	300 (56)	300	300	200	200	4,301

* Numbers in parentheses indicate ONR-2 to OFR-2 demand flow rates in Weaving Segment 6.

The values in Exhibit 10-35 represent the adjusted demand flows on the facility as determined from field observations or demand projections. The actual volume served in each segment will be determined during application of the methodology and is expected to be less downstream of a congested segment. The demand flows are given for the extended time–space domain, consistent with this chapter's methodology. Peaking occurs in the third 15-min period. Since inputs are in the form of 15-min observations, no peak hour factor adjustment is necessary. Additional geometric and traffic-related inputs are as specified in Exhibit 10-25 and the facts section of the problem statement.

Step 2: Demand Adjustments

The traffic flows in Exhibit 10-35 have already been given in the form of actual demands and no further demand adjustments are necessary.

Step 3: Compute Segment Capacities

Since no changes to segment geometry were made, the segment capacities for basic and ramp segments are consistent with Example Problem 1 and Exhibit 10-28. Capacities for weaving segments are a function of weaving flow patterns, and the increased demand flows resulted in slight changes as shown in Exhibit 10-36.

Exhibit 10-36
Segment Capacities for Example Problem 2

Time Step	Capacities (veh/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1						8,253					
2						8,260					
3	6,732	6,732	6,732	6,732	6,732	8,303	6,732	6,732	6,732	6,732	6,732
4						8,382					
5						8,443					

Step 4: Adjust Segment Capacities

No capacity adjustments are made in this example.

Step 5: Compute Demand-to-Capacity Ratios

The demand-to-capacity ratios in Exhibit 10-37 are calculated from the demand flows in Exhibit 10-35 and from the segment capacities in Exhibit 10-36.

Exhibit 10-37
Segment Demand-to-Capacity Ratios for Example Problem 2

Time Step	Demand-to-Capacity Ratios by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	0.74	0.82	0.82	0.82	0.77	0.70	0.80	0.88	0.88	0.88	0.83
2	0.82	0.91	0.91	0.91	0.85	0.79	0.91	1.00	1.00	1.00	0.95
3	0.86	0.97	0.97	0.97	0.92	0.85	1.00	**1.10**	**1.10**	**1.10**	**1.02**
4	0.77	0.83	0.83	0.83	0.79	0.68	0.79	0.86	0.86	0.86	0.82
5	0.62	0.65	0.65	0.65	0.61	0.52	0.62	0.67	0.67	0.67	0.64

The computed v_d/c matrix in Exhibit 10-37 shows that Segments 8–11 now have v_d/c ratios greater than 1.0 (bold values). Consequently, the facility is categorized as *oversaturated* and the analysis proceeds with computing the oversaturated service measures in Step 6b. Further, it is expected that queuing will occur on the facility upstream of the congested segments and that the volume served in each segment downstream of the congested segments will be less than the demand. This residual demand will be served in later time intervals, provided that upstream demand drops and queues are allowed to clear.

Step 6b: Compute Oversaturated Segment Service Measures

The oversaturated computations apply to any segment with a v_d/c ratio greater than 1.0 as well as any segments upstream of those segments that experience queuing as a result of the bottleneck. All remaining segments are analyzed by using the individual segment methodologies of Chapters 11, 12, and 13, as applicable, with the caveat that volumes served may differ from demand flows.

Similar to Example Problem 1, the methodology calculates performance measures for each segment and each time period, starting with the first segment in Time Step 1. The computations are repeated for all segments for Time Steps 1 and 2 without encountering a segment with $v_d/c > 1.0$. Once the methodology enters Time Period 3 and Segment 8, the oversaturated computational module is invoked.

As the first active bottleneck, the v_a/c ratio for Segment 8 will be exactly 1.0 and will process traffic at its capacity. Consequently, demand for all downstream segments will be metered by that bottleneck. The unsatisfied demand is stored in upstream segments, which causes queuing in Segment 7 and perhaps further upstream segments depending on the level of excess demand. The rate of growth of the vehicle queue (wave speed) is estimated from shock wave theory, as discussed in detail in Chapter 25, Freeway Facilities: Supplemental. The performance measures (speed and density) of any segment with queuing are recomputed as discussed in Chapter 25, and the newly calculated values override the results from the segment-specific procedures.

Any unsatisfied demand is serviced in later time periods. As a result, volumes served in later time periods may be higher than the period demand flows. The resulting matrix of volumes served for Example Problem 2 is shown in Exhibit 10-38. The table emphasizes cells where volumes served are less than demand flows (in **bold)** and where volumes served are greater than demand flows (*italicized).*

Exhibit 10-38
Volume-Served Matrix for Example Problem 2

Time Step	Volumes Served (veh/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	5,001	5,500	5,500	5,500	5,200	5,800	5,400	5,900	5,900	5,900	5,600
2	5,500	6,099	6,099	6,099	5,700	6,400	6,099	6,699	6,699	6,699	6,399
3	5,800	6,499	6,499	6,499	**6,111**	**6,625**	**6,032**	**6,732**	**6,732**	**6,732**	**6,277**
4	5,200	5,600	5,600	5,600	*5,389*	*6,173*	*5,967*	*6,466*	*6,466*	*6,466*	*6,121*
5	4,201	4,401	4,401	4,401	4,101	4,401	4,201	4,501	4,501	4,501	4,301

As a result of the bottleneck activation in Segment 8 in Time Period 3, queues form in upstream Segments 7, 6, and 5. The queuing is associated with reduced speeds and increased densities in those segments. Details on how these measures are calculated for oversaturated segments are given in Chapter 25. The results in this chapter were obtained from the FREEVAL-2010 engine. The resulting performance measures computed for each segment and time interval are the speed (Exhibit 10-39), density (Exhibit 10-40), and LOS (Exhibit 10-41).

Exhibit 10-39
Speed Matrix for Example Problem 2

Time Step	Speed (mi/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	59.8	53.1	58.6	55.9	59.4	46.8	58.9	52.5	52.5	55.7	58.2
2	58.6	52.1	55.7	55.5	57.8	45.4	55.7	50.5	50.5	55.3	53.8
3	57.4	51.0	53.0	55.4	53.6	28.2	34.8	50.2	50.2	55.1	54.6
4	59.4	53.0	58.2	55.8	49.9	39.2	53.9	51.2	51.2	55.3	55.6
5	60.0	54.5	59.7	56.2	60.0	51.7	60.0	54.4	54.4	56.3	60.0

Exhibit 10-40
Density Matrix for Example Problem 2

Time Step	Density (veh/mi/ln) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	27.9	34.5	31.3	32.8	29.2	31.0	30.6	37.5	37.5	35.3	32.1
2	31.3	39.0	36.5	36.7	32.9	35.8	36.5	44.2	44.2	40.4	39.7
3	33.7	42.5	40.9	39.1	38.0	**58.8**	**57.7**	44.7	44.7	40.7	38.3
4	29.2	35.2	32.1	33.4	36.0	39.4	36.9	42.1	42.1	38.9	36.7
5	23.3	26.9	24.6	26.1	22.8	21.3	23.3	27.6	27.6	26.6	23.9

Exhibit 10-41
Expanded LOS Matrix for Example Problem 2

Time Step	Density-Based LOS by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	D	D	D	D	D	D	D	D	D	D	D
2	D	D	E	D	D	E	E	E	E	E	E
3	D	D	E	D	E	**F**	**F**	E	E	E	E
4	D	D	D	D	E	E	E	D	D	D	E
5	C	C	C	C	C	C	C	C	C	C	C
Time Step	**Demand-Based LOS by Segment**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1											
2											
3								**F**	**F**	**F**	**F**
4											
5											

The LOS table for oversaturated facilities (Exhibit 10-41) distinguishes between the conventional density-based LOS and a segment demand-based LOS. The density-based stratification strictly depends on the prevailing average density on each segment. Segments downstream of the bottleneck, whose capacities are greater than or equal to the bottleneck capacity, operate at LOS E (or better), even though their v_d/c ratios were greater than 1.0. The demand-based LOS identifies those segments with demand-to-capacity ratios exceeding 1.0 as if they had been evaluated in isolation (i.e., using methodologies of Chapters 11, 12, and 13). By contrasting the two parts of the LOS table, the analyst can develop an understanding of the metering effect of the bottleneck.

Step 7: Compute Facility Service Measures and Determine LOS

In the final analysis step, facilitywide performance and service measures are calculated for each time interval (Exhibit 10-42), consistent with Example Problem 1. Only summary results are shown in this case, since the computations have already been shown. The facility operates at LOS F in Time Period 3, since one or more individual segments have *d/c* ratios ≥ 1.0, even though the average facility density is below the LOS F threshold.

Exhibit 10-42
Facility Performance Measure Summary for Example Problem 2

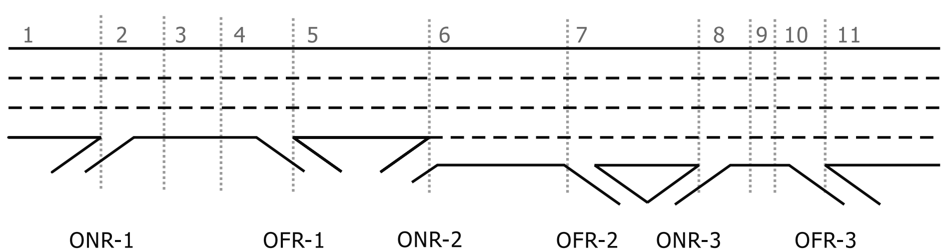
Time Interval	Performance Measure: Space Mean Speed (mi/h)	Performance Measure: Average Density (veh/mi/ln)	LOS
1	56.7	31.0	D
2	54.5	36.1	E
3	46.3	43.7	F
4	52.8	35.4	E
5	58.2	23.8	C
Total	**52.9**	**34.0**	**—**

EXAMPLE PROBLEM 3: CAPACITY IMPROVEMENTS TO AN OVERSATURATED FACILITY

The Facility

In this example, portions of the congested facility in Example Problem 2 are being improved in an attempt to alleviate the congestion resulting from the Segment 8 bottleneck. Exhibit 10-43 shows the upgraded facility geometry.

Exhibit 10-43
Freeway Facility in Example Problem 3



The modified geometry of the 6-mi directional freeway facility is reflected in Exhibit 10-44.

Exhibit 10-44
Geometry of Directional Freeway Facility in Example Problem 3

Segment No.	1	2	3	4	5	6	7	8	9	10	11
Segment type	B	ONR	B	OFR	B	B or W	B	ONR	R	OFR	B
Segment length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280
No. of lanes	3	3	3	3	3	4	**4**	**4**	**4**	**4**	**4**

Note: B = basic freeway segment, W = weaving segment, ONR = on-ramp (merge) segment, OFR = off-ramp (diverge) segment, R = overlapping ramp segment.
Bold type indicates geometry changes from Example Problems 1 and 2.

The facility improvements consisted of adding a lane to Segments 7–11 to give the facility a continuous four-lane cross section starting in Segment 6. While the active bottleneck in Example Problem 2 was in Segment 8, the prior analysis showed that other segments (Segments 9–11) showed similar demand-to-capacity ratios greater than 1.0. Consequently, any capacity improvements that are limited to Segment 8 would have merely moved the spatial location of the bottleneck further downstream rather than improving the overall facility. Segments 9–11 may also be referred to as "hidden" or "inactive" bottlenecks, because their predicted congestion is mitigated by the upstream metering of traffic.

The Facts

In addition to the information contained in Exhibit 10-43 and Exhibit 10-44, the following characteristics of the freeway facility are known:

Heavy vehicles = 5% trucks, 0% RVs (all movements);
Driver population = regular commuters;
FFS = 60 mi/h (all mainline segments);
Ramp *FFS* = 40 mi/h (all ramps);
Acceleration lane length = 500 ft (all ramps);
Deceleration lane length = 500 ft (all ramps);
D_{jam} = 190 pc/mi/ln;
c_{IFL} = 2,300 pc/h/ln (for *FFS* = 60 mi/h);
L_s = 1,640 ft (for Weaving Segment 6);
TRD = 1.0 ramp/mi;
Terrain = level;
Analysis duration = 75 min (divided into five 15-min intervals); and
Demand adjustment = +11% (all segments and all time intervals).

Comments

The traffic demand flow inputs are identical to those in Example Problem 2, which reflected an 11% increase in traffic applied to all segments and all time periods. In an attempt to solve the congestion effect found in the earlier example, the facility was widened in Segments 7 and 11. This change directly affects the capacities of those segments.

In a more subtle way, the proposed modifications also change some of the defining parameters of Weaving Segment 6 as well. With the added continuous lane downstream of the segment, the required number of lane changes from the ramp to the freeway is reduced from one to zero, following the guidelines in Chapter 12. These changes need to be considered when the undersaturated performance of that segment is evaluated. The weaving segment's capacity is unchanged relative to Example Problem 2, since, even with the proposed improvements, the number of weaving lanes remains two.

Step 1: Input Data

Traffic demand inputs for all 11 segments and five analysis intervals are identical to those in Example Problem 2 as shown in Exhibit 10-35. The values in Exhibit 10-35 represent the adjusted demand flows on the facility as determined from field observations or other sources. The actual volume served in each segment will be determined during the methodologies and is expected to be less downstream of a congested segment. Additional geometric and traffic-related inputs are as specified in Exhibit 10-44 and the facts section of the problem statement.

Step 2: Demand Adjustments

The traffic flows in Exhibit 10-35 have already been given in the form of actual demands and no further demand adjustments are necessary.

Step 3: Compute Segment Capacities

Segment capacities are determined by using the methodologies of Chapter 11 for basic freeway segments, Chapter 12 for weaving segments, and Chapter 13 for merge and diverge segments. The resulting capacities are shown in Exhibit 10-45. Since the capacity of a weaving segment depends on traffic patterns, it varies by time period. The remaining capacities are constant for all five time steps. The capacities for Segments 1–5 and for Segments 7–11 are the same, since the segments have the same basic cross section.

Exhibit 10-45
Segment Capacities for Example Problem 3

Time Step	Capacities (veh/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1						8,253					
2						8,260					
3	6,732	6,732	6,732	6,732	6,732	8,303	8,976	8,976	8,976	8,976	8,976
4						8,382					
5						8,443					

Step 4: Adjust Segment Capacities

No additional capacity adjustments are made in this example.

Step 5: Compute Demand-to-Capacity Ratios

The demand-to-capacity ratios are calculated from the demand flows in Exhibit 10-35 and segment capacities in Exhibit 10-45.

Exhibit 10-46
Segment Demand-to-Capacity Ratios for Example Problem 3

Time Step	Demand-to-Capacity Ratio by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	0.74	0.82	0.82	0.82	0.77	0.70	0.60	0.66	0.66	0.66	0.62
2	0.82	0.91	0.91	0.91	0.85	0.79	0.68	0.75	0.75	0.75	0.71
3	0.86	0.97	0.97	0.97	0.92	0.85	0.75	0.82	0.82	0.82	0.77
4	0.77	0.83	0.83	0.83	0.79	0.68	0.59	0.65	0.65	0.65	0.61
5	0.62	0.65	0.65	0.65	0.61	0.52	0.47	0.50	0.50	0.50	0.48

The demand-to-capacity ratio matrix for Example Problem 3 (Exhibit 10-46) shows that the capacity improvements successfully reduced all the previously congested segments to $v_d/c < 1.0$. Therefore, it is expected that the facility will operate as *globally undersaturated* and that all segment performance measures can be directly computed by using the methodologies in Chapters 11, 12, and 13 in Step 6a.

Step 6a: Compute Undersaturated Segment Service Measures

Since the facility is globally undersaturated, the methodology proceeds to calculate performance and service measures for each segment and each time step, starting with the first segment in Time Interval 1. The computational details for each segment type are exactly as described in Chapters 11, 12, and 13. The weaving methodology in Chapter 13 checks whether the weaving short length L_S is less than or equal to the maximum weaving length L_{max}. It is assumed that, for any time interval where L_S is longer than L_{max}, the weaving segment will operate as a basic freeway segment.

The basic performance service measures computed for each segment and each time interval include the segment speed (Exhibit 10-47), density (Exhibit 10-48), and LOS (Exhibit 10-49).

Exhibit 10-47
Speed Matrix for Example Problem 3

Time Step	Speed (mi/h) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	59.8	53.1	58.6	55.9	59.4	50.4	60.0	54.9	54.9	58.1	60.0
2	58.6	52.1	55.7	55.5	57.8	50.0	60.0	54.3	54.3	57.7	60.0
3	57.4	51.0	53.0	55.4	55.1	49.7	59.8	53.6	53.6	57.2	59.5
4	59.4	53.0	58.2	55.8	59.2	50.7	60.0	55.0	55.0	58.1	60.0
5	60.0	54.5	59.7	56.2	60.0	53.4	60.0	55.9	55.9	58.8	60.0

Exhibit 10-48
Density Matrix for Example Problem 3

Time Step	Density (veh/mi/ln) by Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	27.9	34.5	31.3	32.8	29.2	28.8	22.5	26.9	26.9	25.4	23.3
2	31.3	39.0	36.5	36.7	32.9	32.5	25.4	30.9	30.9	29.0	26.7
3	33.7	42.5	40.9	39.1	37.5	35.7	28.0	34.5	34.5	32.4	29.0
4	29.2	35.2	32.1	33.4	29.8	28.1	22.1	26.4	26.4	24.9	22.9
5	23.3	26.9	24.6	26.1	22.8	20.6	17.5	20.1	20.1	19.1	17.9

Exhibit 10-49
LOS Matrix for Example Problem 3

Time Step	LOS for Segment										
	1	2	3	4	5	6	7	8	9	10	11
1	D	D	D	D	D	D	C	C	C	C	C
2	D	D	E	D	D	D	D	C	C	C	D
3	D	D	E	D	E	E	D	D	D	D	D
4	D	D	D	D	D	D	C	C	C	C	C
5	C	C	C	C	C	C	B	B	B	B	C

Step 7: Compute Facility Service Measures and Determine LOS

In the final analysis step, facilitywide performance and service measures are calculated for each time step (Exhibit 10-50), consistent with Example Problem 2. Only summary results are shown in this case, since the computations have already been shown. The improvement has been able to restore the facility LOS to the values experienced in the original pregrowth scenario shown in Exhibit 10-34.

Exhibit 10-50
Facility Performance Measure Summary for Example Problem 3

Time Step	Performance Measure: Space Mean Speed (mi/h)	Performance Measure: Average Density (veh/mi/ln)	LOS
1	57.9	26.8	D
2	57.1	30.4	D
3	56.0	33.5	D
4	57.8	26.9	D
5	58.6	20.8	C
Total	**57.3**	**27.7**	**—**

5. REFERENCES

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