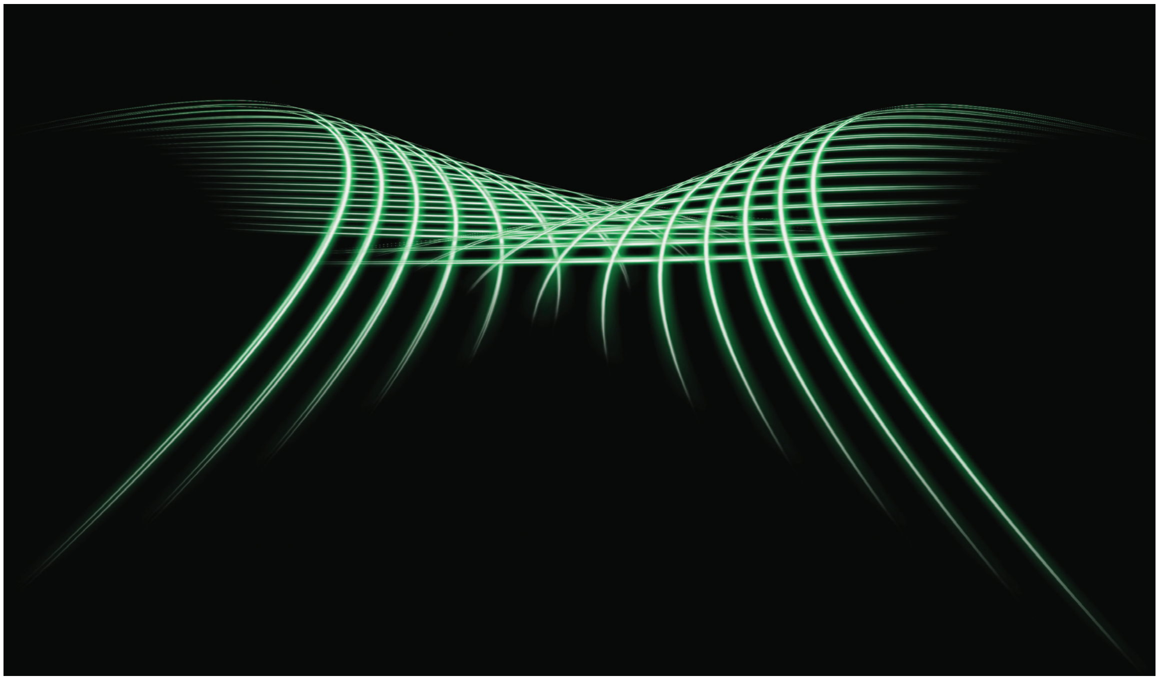
HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 11

BASIC FREEWAY SEGMENTS

TRB TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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HCM2010

HIGHWAY CAPACITY MANUAL

The HCM 2010 significantly enhances how engineers and planners assess the traffic and environmental effects of highway projects by

- Providing an integrated multimodal approach to the analysis and evaluation of urban streets from the points of view of automobile drivers, transit passengers, bicyclists, and pedestrians;
- Addressing the proper application of microsimulation analysis and the evaluation of the results;
- Examining active traffic management in relation to demand and capacity; and
- Exploring specific tools and generalized service volume tables to assist planners in quickly sizing future facilities.

The HCM 2010 consists of four volumes:

Volume 1: Concepts;
Volume 2: Uninterrupted Flow;
Volume 3: Interrupted Flow; and
Volume 4: Applications Guide (electronic only).

The four-volume format provides information at several levels of detail, to help users more easily apply and understand the concepts, methodologies, and potential applications.

Volumes 1, 2, and 3 are issued as a boxed set. Volume 4 is electronic only, accessible to registered HCM users via the Internet, and includes four types of content: supplemental chapters on methodological details and emerging issues; interpretations, clarifications, and corrections; comprehensive case studies; and a technical reference library.

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CHAPTER 11
BASIC FREEWAY SEGMENTS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Basic freeway segments are defined as those freeway segments that are outside the influence of merging, diverging, or weaving maneuvers. In general, this means that lane-changing activity is not significantly influenced by the presence of ramps and weaving segments. Lane-changing activity primarily reflects the normal desire of drivers to optimize their efficiency through lane-changing and passing maneuvers.

A complete discussion of influence areas is included in Chapter 10, Freeway Facilities, with additional discussion in Chapters 12, Freeway Weaving Segments, and 13, Freeway Merge and Diverge Segments. In general terms, the influence area of merge (on-ramp) segments extends for 1,500 ft downstream of the merge point; the influence area of diverge (off-ramp) segments extends for 1,500 ft upstream of the diverge point; and the influence area of weaving segments extends 500 ft upstream and downstream of the segment itself. This description is not to suggest that the influence of these segments cannot extend over a broader range, particularly under breakdown conditions. Under stable operations, however, these distances define the areas most affected by merge, diverge, and weaving movements. The impact of breakdowns in any type of freeway segment on adjacent segments can be addressed by using the methodology of Chapter 10, Freeway Facilities.

Chapter 11, Basic Freeway Segments, provides a methodology for analyzing the capacity and level of service (LOS) of existing or planned basic freeway segments. The methodology can also be used for design applications, where the number of lanes needed to provide a target LOS for an existing or projected demand flow rate can be found.

Analysis segments must have uniform geometric and traffic conditions, including demand flow rates.

Such analyses are applied to basic freeway segments with uniform characteristics. Uniform segments must have the same geometric and traffic characteristics, including a constant demand flow rate.

BASE CONDITIONS

Base conditions include good weather and visibility and no incidents or accidents. These conditions are always assumed to exist.

The base conditions under which the full capacity of a basic freeway segment is achieved include good weather, good visibility, no incidents or accidents, no work zone activity, and no pavement deterioration serious enough to affect operations. This chapter's methodology assumes that these conditions exist. If any of these conditions do not exist, the speed, LOS, and capacity of the freeway segment can be expected to be worse than those predicted by this methodology.

Base conditions also include the following conditions, which can be adjusted as the methodology is applied to address situations in which these conditions do not exist:

Base conditions also include 0% heavy vehicles, a driver population composed of regular users of the freeway, and 12-ft lane widths and minimum 6-ft right-side clearances.

The methodology provides adjustments for situations when these conditions do not apply.

- No heavy vehicles [trucks, buses, recreational vehicles (RVs)] in the traffic stream;
- A driver population composed primarily of regular users who are familiar with the facility; and
- Minimum 12-ft lane widths and 6-ft right-side clearances.

FLOW CHARACTERISTICS UNDER BASE CONDITIONS

Traffic flow within basic freeway segments can be highly varied depending on the conditions constricting flow at upstream and downstream bottleneck locations. Such bottlenecks can be created by merging, diverging, or weaving traffic; lane drops; maintenance and construction activities; traffic accidents or incidents; objects in the roadway; or all of the foregoing. Bottlenecks can exist even when a lane is not fully blocked. Partial blockages will cause drivers to slow and divert their paths. In addition, the practice of rubbernecking near roadside incidents or accidents can cause functional bottlenecks.

Types of Flow

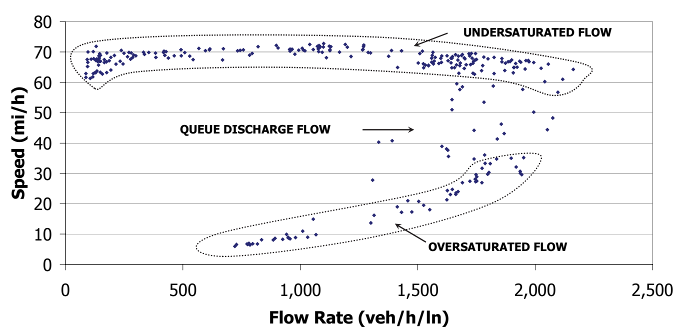
Chapter 2 describes in more detail the types of traffic flow on basic freeway segments.

As was discussed in more detail in Chapter 2, Applications, traffic flow within a basic freeway segment can be categorized as one of three general types: undersaturated, queue discharge, and oversaturated.

- *Undersaturated flow* represents conditions under which the traffic stream is unaffected by upstream or downstream bottlenecks.
- *Queue discharge flow* represents traffic flow that has just passed through a bottleneck and is accelerating back to drivers' desired speeds for the prevailing conditions. As long as another downstream bottleneck does not exist, queue discharge flow is relatively stable until the queue is fully discharged.
- *Oversaturated flow* represents the conditions within a queue that has backed up from a downstream bottleneck. These flow conditions do not reflect the prevailing conditions of the site itself, but rather the consequences of a downstream problem. All oversaturated flow is considered to be congested.

An example of each of the three types of flow discussed is illustrated in Exhibit 11-1, using data from a freeway in California.

Exhibit 11-1
Three Types of Freeway Flow



Note: I-405, Los Angeles, Calif.
Source: California Department of Transportation, 2008.

The basic freeway segment methodology is based on undersaturated flow conditions.

The analysis methodology for basic freeway segments is based entirely on calibrations of the speed–flow relationships under base conditions with undersaturated flow. The methodology identifies cases in which failure has occurred but does not attempt to describe operating conditions when a segment has failed. The methodology of Chapter 10, Freeway Facilities, should be used for oversaturated conditions.

Speed–Flow Curves for Base Conditions

A set of speed–flow curves for basic freeway segments operating under base conditions is shown in Exhibit 11-2. There are five curves, one for each of five levels of free-flow speed (FFS): 75 mi/h, 70 mi/h, 65 mi/h, 60 mi/h, and 55 mi/h. Technically speaking, the FFS is the speed at the y-intercept of each curve. In practical terms, there are two ranges in the shape of the curves:

- For each curve, a range of flows exists from 0 pc/h/ln to a breakpoint in which speed remains constant at the FFS. The ranges vary for each of the curves as follows:

  FFS = 75 mi/h: 0–1,000 pc/h/ln;

  FFS = 70 mi/h: 0–1,200 pc/h/ln;

  FFS = 65 mi/h: 0–1,400 pc/h/ln;

  FFS = 60 mi/h: 0–1,600 pc/h/ln;

  FFS = 55 mi/h: 0–1,800 pc/h/ln.

- At flow rates above the breakpoint of each curve, speeds decline at an increasing rate until capacity is reached.

Exhibit 11-2
Speed–Flow Curves for Basic Freeway Segments Under Base Conditions

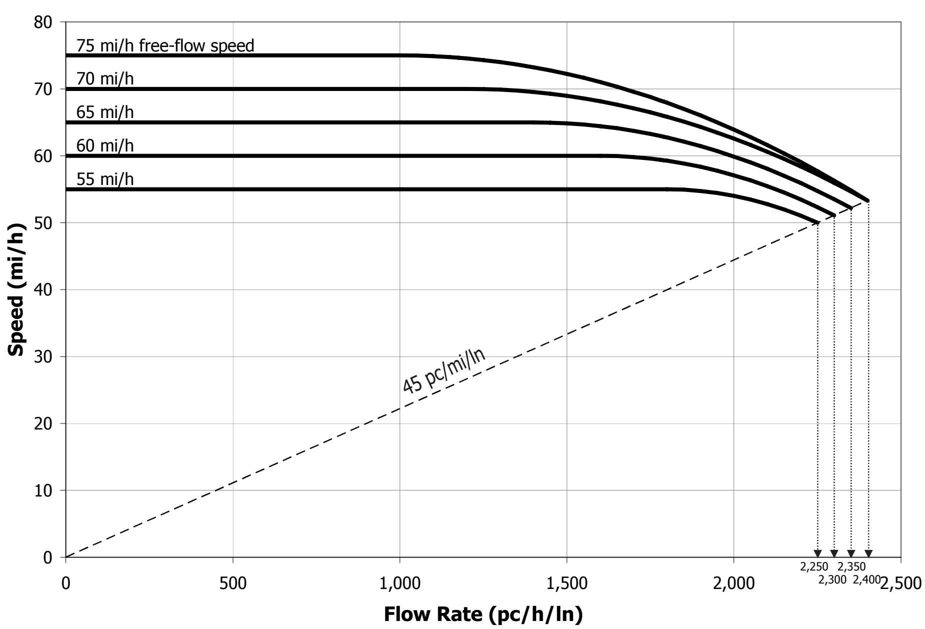


Exhibit 11-3 shows the equations that define each of the curves in Exhibit 11-2. Because estimating or measuring FFS is difficult, and there is considerable variation in observed and predicted values, no attempt should be made to

FFS should be rounded to the nearest 5 mi/h.

interpolate between the basic curves. FFS should be rounded to the nearest 5 mi/h as follows:

- ≥72.5 mi/h < 77.5 mi/h: use FFS = 75 mi/h,
- ≥67.5 mi/h < 72.5 mi/h: use FFS = 70 mi/h,
- ≥62.5 mi/h < 67.5 mi/h: use FFS = 65 mi/h,
- ≥57.5 mi/h < 62.5 mi/h: use FFS = 60 mi/h,
- ≥52.5 mi/h < 57.5 mi/h: use FFS = 55 mi/h.

Exhibit 11-3
Equations Describing Speed–Flow Curves in Exhibit 11-2 (Speeds in mi/h)

FFS (mi/h)	Breakpoint (pc/h/ln)	Flow Rate Range ≥0 ≤ Breakpoint	Flow Rate Range >Breakpoint ≤ Capacity
75	1,000	75	$75 - 0.00001107\,(v_p - 1{,}000)^2$
70	1,200	70	$70 - 0.00001160\,(v_p - 1{,}200)^2$
65	1,400	65	$65 - 0.00001418\,(v_p - 1{,}400)^2$
60	1,600	60	$60 - 0.00001816\,(v_p - 1{,}600)^2$
55	1,800	55	$55 - 0.00002469\,(v_p - 1{,}800)^2$

Notes: FFS = free-flow speed, v_p = demand flow rate (pc/h/ln) under equivalent base conditions.
Maximum flow rate for the equations is capacity: 2,400 pc/h/ln for 70- and 75-mph FFS; 2,350 pc/h/ln for 65-mph FFS; 2,300 pc/h/ln for 60-mph FFS; and 2,250 pc/h/ln for 55-mph FFS.

The research leading to these curves (*1, 2*) found that several factors affect the FFS of a basic freeway segment, including the lane width, right-shoulder clearance, and ramp density. Ramp density is the average number of on-ramps plus off-ramps in a 6-mi range, 3 mi upstream and 3 mi downstream of the midpoint of the study segment. Many other factors are likely to influence FFS: horizontal and vertical alignment, posted speed limits, level of speed enforcement, lighting conditions, and weather. Although these factors may affect FFS, little information is available that would allow their quantification.

CAPACITY UNDER BASE CONDITIONS

The capacity of a basic freeway segment under base conditions varies with the FFS. For 70- and 75-mi/h FFS, the capacity is 2,400 pc/h/ln. For lesser levels of FFS, capacity diminishes slightly. For 65-mi/h FFS, the capacity is 2,350 pc/h/ln; for 60-mi/h FFS, 2,300 pc/h/ln; and for 55-mi/h FFS, 2,250 pc/h/ln.

Base capacity values refer to the average flow rate across all lanes. Individual lanes could have stable flows in excess of these values.

Since freeways usually do not operate under base conditions, observed capacity values will typically be lower than the base capacity values.

Chapter 10, Freeway Facilities, contains information that would allow these values to be reduced to reflect long- and short-term construction and maintenance activities, adverse weather conditions, and accidents or incidents.

These values represent national norms. It should be remembered that capacity varies stochastically and that any given location could have a larger or smaller value. It should also be remembered that capacity refers to the *average flow rate across all lanes*. Thus, a three-lane basic freeway segment with a 70-mi/h FFS would have an expected base capacity of 3 × 2,400 = 7,200 pc/h. This flow would not be uniformly distributed across all lanes. Thus, one or two lanes could have stable base flows in excess of 2,400 pc/h/ln.

As shown in Exhibit 11-2, it is believed that basic freeway segments reach capacity at a density of approximately 45 passenger cars per mile per lane (pc/mi/ln), which may vary slightly from location to location. At this density, vehicles are too closely spaced to dampen the impact of any perturbation in flow, such as a lane change or a vehicle entering the freeway, without causing a disruption that propagates upstream.

LOS FOR BASIC FREEWAY SEGMENTS

LOS for basic freeway segments is defined by density.

LOS on a basic freeway segment is defined by density. Although speed is a major concern of drivers as related to service quality, it would be difficult to describe LOS by using speed, since it remains constant up to flow rates of 1,000 to 1,800 pc/h/ln, depending on the FFS. Density describes the proximity to other vehicles and is related to the freedom to maneuver within the traffic stream. Unlike speed, however, density is sensitive to flow rates throughout the range of flows.

Exhibit 11-4 visually demonstrates the six LOS defined for basic freeway segments. LOS are defined to represent reasonable ranges in the three critical flow variables: speed, density, and flow rate.

Exhibit 11-4
LOS Examples

LOS A | LOS B | LOS C | LOS D | LOS E | LOS F

Freeway LOS Described

LOS A describes free-flow operations. FFS prevails on the freeway, and vehicles are almost completely unimpeded in their ability to maneuver within the traffic stream. The effects of incidents or point breakdowns are easily absorbed.

LOS B represents reasonably free-flow operations, and FFS on the freeway is maintained. The ability to maneuver within the traffic stream is only slightly restricted, and the general level of physical and psychological comfort provided to drivers is still high. The effects of minor incidents and point breakdowns are still easily absorbed.

LOS C provides for flow with speeds near the FFS of the freeway. Freedom to maneuver within the traffic stream is noticeably restricted, and lane changes require more care and vigilance on the part of the driver. Minor incidents may still be absorbed, but the local deterioration in service quality will be significant. Queues may be expected to form behind any significant blockages.

LOS D is the level at which speeds begin to decline with increasing flows, with density increasing more quickly. Freedom to maneuver within the traffic stream is seriously limited and drivers experience reduced physical and psychological comfort levels. Even minor incidents can be expected to create queuing, because the traffic stream has little space to absorb disruptions.

LOS E describes operation at capacity. Operations on the freeway at this level are highly volatile because there are virtually no usable gaps within the traffic stream, leaving little room to maneuver within the traffic stream. Any disruption to the traffic stream, such as vehicles entering from a ramp or a vehicle changing lanes, can establish a disruption wave that propagates throughout the upstream traffic flow. At capacity, the traffic stream has no ability to dissipate even the most minor disruption, and any incident can be expected to produce a serious breakdown and substantial queuing. The physical and psychological comfort afforded to drivers is poor.

LOS F describes breakdown, or unstable flow. Such conditions exist within queues forming behind bottlenecks. Breakdowns occur for a number of reasons:

- Traffic incidents can temporarily reduce the capacity of a short segment, so that the number of vehicles arriving at a point is greater than the number of vehicles that can move through it.
- Points of recurring congestion, such as merge or weaving segments and lane drops, experience very high demand in which the number of vehicles arriving is greater than the number of vehicles that can be discharged.
- In analyses using forecast volumes, the projected flow rate can exceed the estimated capacity of a given location.

Breakdown (LOS F) occurs whenever the demand-to-capacity ratio exceeds 1.00.

In all cases, breakdown occurs when the ratio of existing demand to actual capacity, or of forecast demand to estimated capacity, exceeds 1.00. Operations immediately downstream of, or even at, such a point, however, are generally at or near LOS E, and downstream operations improve (assuming that there are no additional downstream bottlenecks) as discharging vehicles move away from the bottleneck.

The effects of a breakdown may extend upstream for a considerable distance.

LOS F operations within a queue are the result of a breakdown or bottleneck at a downstream point. In practical terms, the point of the breakdown has a *v*/*c* ratio greater than 1.00, and is also labeled LOS F, although actual operations at the breakdown point and immediately downstream may actually reflect LOS E conditions. Whenever queues due to a breakdown exist, they have the potential to extend upstream for considerable distances.

LOS Criteria

A basic freeway segment can be characterized by three performance measures: density in passenger cars per mile per lane (pc/mi/ln), space mean speed in miles per hour (mi/h), and the ratio of demand flow rate to capacity (*v*/*c*). Each of these measures is an indication of how well traffic is being accommodated by the basic freeway segment.

Because speed is constant through a broad range of flows and the *v*/*c* ratio is not directly discernible to road users (except at capacity), the service measure for basic freeway segments is density. Exhibit 11-5 shows the criteria.

Exhibit 11-5
LOS Criteria for Basic Freeway Segments

LOS	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	Demand exceeds capacity >45

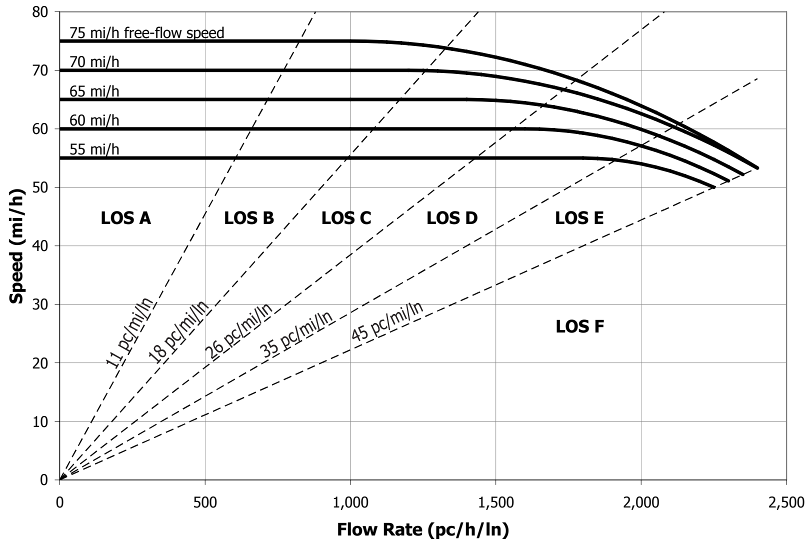
For all LOS, the density boundaries on basic freeway segments are the same as those for surface multilane highways, except at the LOS E–F boundary. Traffic characteristics are such that the maximum flow rates at any given LOS are lower on multilane highways than on similar basic freeway segments.

The specification of maximum densities for LOS A to D is based on the collective professional judgment of the members of the Transportation Research Board's Highway Capacity and Quality of Service Committee. The upper value shown for LOS F (45 pc/mi/ln) is the maximum density at which sustained flows at capacity are expected to occur. In effect, as indicated in the speed–flow curves of Exhibit 11-2, when a density of 45 pc/mi/ln is reached, flow is at capacity, and the *v*/*c* ratio is 1.00.

In the application of this chapter's methodology, however, LOS F is identified when demand exceeds capacity because the analytic methodology *does not allow* the determination of density when demand exceeds capacity. Although the density will be greater than 45 pc/h/ln, the methodology of Chapter 10, Freeway Facilities, must be applied to determine a more precise density for such cases.

Exhibit 11-6 illustrates the defined LOS on the base speed–flow curves. On a speed–flow plot, density is a line of constant slope beginning at the origin. The LOS boundaries were defined to produce reasonable ranges within each LOS on these speed–flow relationships.

Exhibit 11-6
LOS for Basic Freeway Segments



REQUIRED INPUT DATA

The analysis of a basic freeway segment requires details concerning the geometric characteristics of the segment and the demand characteristics of the users of the segment. This section presents the required input data for the basic freeway segment methodology; specifics about individual parameters are given in the Methodology section.

Freeway Data

The following information on the segment's geometric features is needed to conduct an analysis (typical ranges for these parameters are shown):

1. FFS: 55 to 75 mi/h;
2. Number of mainline freeway lanes (one direction): at least two;
3. Lane width: 10 ft to 12 ft or more;
4. Right-side lateral clearance: 0 ft to more than 6 ft;
5. Total ramp density: 0 to 6 ramps/mi; and
6. Terrain: level, rolling, or mountainous, or specific length and percent grade.

Demand Data

The following information on the segment's users is required:

1. Demand during the analysis hour or daily demand and *K*- and *D*-factors;
2. Heavy-vehicle presence (proportion of trucks, buses, and RVs): 0 to 100% in general terrain, or 0 to 25% or more for specific grades;
3. Peak-hour factor (PHF): up to 1.00; and
4. Driver population factor: 0.85 to 1.00.

Length of Analysis Period

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

2. METHODOLOGY

This chapter's methodology can be used to analyze the capacity, LOS, lane requirements, and effects of design features on the performance of basic freeway segments. The methodology is based on the results of an NCHRP study (*1*), which has been partially updated (*2*). A number of significant publications were also used in the development of the methodology (*3–12*).

LIMITATIONS OF METHODOLOGY

This chapter's methodology does not apply to or take into account (without modification by the analyst) the following:

- Special lanes reserved for a single vehicle type, such as high-occupancy-vehicle (HOV) lanes, truck lanes, and climbing lanes;
- Lane control (to restrict lane changing);
- Extended bridge and tunnel segments;
- Segments near a toll plaza;
- Facilities with FFS less than 55 mi/h or more than 75 mi/h;
- The influence of downstream queuing on a segment;
- Posted speed limit and enforcement practices;
- Presence of intelligent transportation systems (ITS) related to vehicle or driver guidance;
- Capacity-enhancing effects of ramp metering;
- Operational effects of oversaturated conditions; and
- Operational effects of construction operations.

In most of the cases just cited, the analyst would have to utilize alternative tools or draw on other research information and develop special-purpose modifications of this methodology to incorporate the effects of any of the cited conditions. Operational effects of oversaturated conditions, incidents, work zones, and weather and lighting conditions can be evaluated with the methodology of Chapter 10, Freeway Facilities. Operational effects of active traffic management measures are discussed in Chapter 35.

Active traffic management measures for freeways discussed in Chapter 35 consist of
- *Dynamic demand metering,*
- *Congestion pricing,*
- *Traveler information systems,*
- *Dynamic lane and shoulder management,*
- *Speed harmonization,*
- *Incident management, and*
- *Work zone traffic management.*

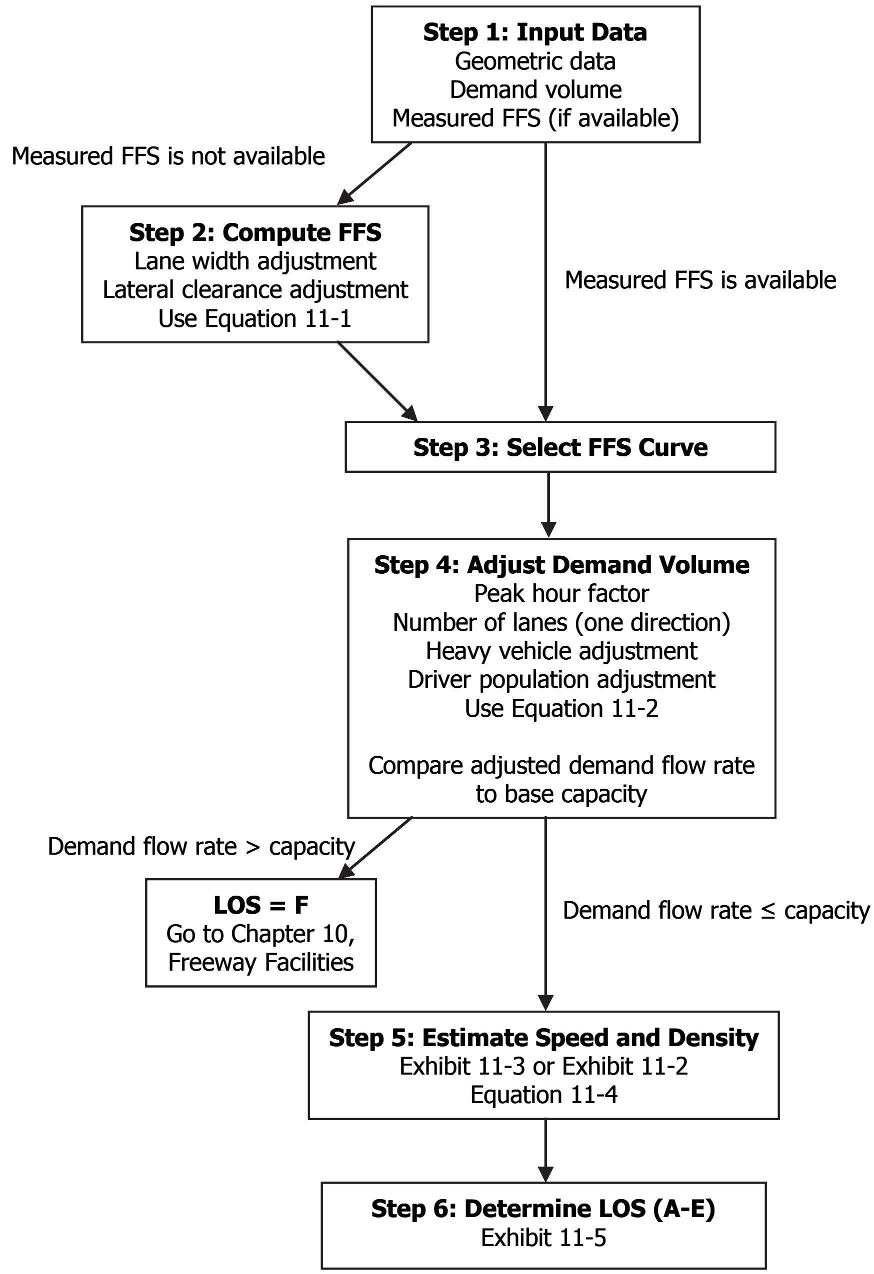
OVERVIEW OF METHODOLOGY

The methodology of this chapter is for the analysis of basic freeway segments. A method for analysis of extended lengths of freeway composed of a combination of basic freeway segments, weaving segments, and merge or diverge segments is found in Chapter 10, Freeway Facilities.

Exhibit 11-7 illustrates the basic methodology used in operational analysis. The methodology can also be directly applied to determine the number of lanes required to provide a target LOS for a given demand volume.

Exhibit 11-7
Overview of Operational Analysis Methodology for Basic Freeway Segments

Exhibit 11-7 illustrates the methodology for operational analysis. Other types of analysis are described in the Applications section.



COMPUTATIONAL STEPS

Step 1: Input Data

For a typical operational analysis, as noted previously, the analyst would have to specify (with either site-specific or default values) demand volume, number and width of lanes, right-side lateral clearance, total ramp density, percent of heavy vehicles (trucks, buses, and RVs), PHF, terrain, and the driver population factor.

Step 2: Compute FFS

FFS can be determined directly from field measurements or can be estimated as described below.

Field Measurement of FFS

FFS is the mean speed of passenger cars during periods of low to moderate flow.

FFS is the mean speed of passenger cars measured during periods of low to moderate flow (up to 1,000 pc/h/ln). For a specific freeway segment, average speeds are virtually constant in this range of flow rates. If the FFS can be field measured, this is the preferable way to make the determination. If the FFS is measured directly, no adjustments are applied to the measured value.

The speed study should be conducted at a location that is representative of the segment at a time when flow rates are less than 1,000 pc/h/ln. The speed study should measure the speeds of all passenger cars or use a systematic sample (e.g., every tenth car in each lane). A sample of at least 100 passenger-car speeds should be obtained. Any speed measurement technique that has been found acceptable for other types of traffic engineering applications may be used. Further guidance on the conduct of speed studies is provided in standard traffic engineering publications, such as the Institute of Transportation Engineers *Manual of Traffic Engineering Studies* (*11*).

Estimating FFS

It is not possible to make field measurements for future facilities, and field measurement may not be possible or practical in all existing cases. In such cases, the segment's FFS may be estimated by using Equation 11-1, which is based on the physical characteristics of the segment under study:

Equation 11-1

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

where

FFS = FFS of basic freeway segment (mi/h),

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

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

TRD = total ramp density (ramps/mi).

Base FFS

This methodology covers basic freeway segments with FFSs ranging from 55 mi/h to 75 mi/h. Thus, the predictive algorithm must start with a base speed of 75 mi/h or higher. A value of 75.4 mi/h was chosen, since it resulted in the most accurate predictions versus data collected in 2008.

Adjustment for Lane Width

The base condition for lane width is 12 ft or greater. When the average lane width across all lanes is less than 12 ft, the FFS is negatively affected. Adjustments to reflect the effect of narrower average lane width are shown in Exhibit 11-8.

Exhibit 11-8
Adjustment to FFS for Average Lane Width

Average Lane Width (ft)	Reduction in FFS, f_{LW} (mi/h)
≥12	0.0
≥11–12	1.9
≥10–11	6.6

Adjustment for Lateral Clearance

The base condition for right-side lateral clearance is 6 ft or greater. The lateral clearance is measured from the right edge of the travel lane to the nearest lateral obstruction. Care must be taken to identify a "lateral obstruction." Some obstructions may be continuous, such as retaining walls, concrete barriers, guardrails, or barrier curbs. Others may be periodic, such as light supports or bridge abutments. In some cases, drivers may become accustomed to certain types of obstructions, often making their influence on traffic negligible.

Exhibit 11-9 shows the adjustments to the base FFS due to the existence of obstructions closer than 6 ft to the right travel lane edge. Median clearances of 2 ft or more generally have little impact on traffic. No adjustments are available to reflect the presence of left-side lateral obstructions closer than 2 ft to the left travel lane edge. Such situations are, however, quite rare on modern freeways, except in constrained work zones.

Exhibit 11-9
Adjustment to FFS for Right-Side Lateral Clearance, f_{LC} (mi/h)

Right-Side Lateral Clearance (ft)	Lanes in One Direction			
	2	3	4	≥5
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

The impact of a right-side lateral clearance restriction depends on both the distance to the obstruction and the number of lanes in one direction on the basic freeway segment. A lateral clearance restriction causes vehicles in the right lane to move somewhat to the left. This movement, in turn, affects vehicles in the next lane. As the number of lanes increases, the overall effect on freeway operations decreases.

Total Ramp Density

Equation 11-1 includes a term that accounts for the impact of total ramp density on FFS. Total ramp density is defined as the number of ramps (on and off, one direction) located between 3 mi upstream and 3 mi downstream of the midpoint of the basic freeway segment under study, divided by 6 mi. The total ramp density has been found to be a measure of the impact of merging and diverging vehicles on FFS.

Step 3: Select FFS Curve

As noted previously, once the FFS of the basic freeway segment is determined, one of the five base speed–flow curves (Exhibit 11-2) is selected for use in the analysis. Interpolation between curves is not recommended. Criteria for selecting an appropriate curve were given in the text following Exhibit 11-2.

Step 4: Adjust Demand Volume

Since the basic speed–flow curves of Exhibit 11-2 are based on flow rates in equivalent passenger cars per hour, with the driver population dominated by regular users of the basic freeway segment, demand volumes expressed as vehicles per hour under prevailing conditions must be converted to this basis. Equation 11-2 is used for this adjustment:

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

Equation 11-2

where

v_p = demand flow rate under equivalent base conditions (pc/h/ln),

V = demand volume under prevailing conditions (veh/h),

PHF = peak-hour factor,

N = number of lanes in analysis direction,

f_{HV} = adjustment factor for presence of heavy vehicles in traffic stream, and

f_p = adjustment factor for unfamiliar driver populations.

Peak Hour Factor

The PHF represents the variation in traffic flow within an hour. Observations of traffic flow consistently indicate that the flow rates found in the peak 15 min within an hour are not sustained throughout the entire hour. The application of the PHF in Equation 11-2 accounts for this phenomenon.

On freeways, typical PHFs range from 0.85 to 0.98 (*13*). Lower values within that range are typical of lower-volume conditions. Higher values within that range are typical of urban and suburban peak-hour conditions. Field data should be used if possible to develop PHFs that represent local conditions.

Adjustment for Heavy Vehicles

A heavy vehicle is defined as any vehicle with more than four wheels on the ground during normal operation. Such vehicles are generally categorized as trucks, buses, or RVs. Trucks cover a wide variety of vehicles, from single-unit trucks with double rear tires to triple-unit tractor–trailer combinations. Small panel or pickup trucks with only four wheels are, however, classified as passenger cars. Buses include intercity buses, public transit buses, and school buses. Because buses are in many ways similar to single-unit trucks, both types of vehicles are considered in one category. RVs include a wide variety of vehicles from self-contained motor homes to cars and small trucks with trailers (for boats, all-terrain vehicles, or other conveyances). It should be noted that most sport-utility vehicles have only four wheels and are thus categorized as passenger cars. The heavy-vehicle adjustment factor f_{HV} is computed as follows:

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

Equation 11-3

where

f_{HV} = heavy-vehicle adjustment factor,

P_T = proportion of trucks and buses in traffic stream,

P_R = proportion of RVs in traffic stream,

E_T = passenger-car equivalent (PCE) of one truck or bus in traffic stream, and

E_R = PCE of one RV in traffic stream.

The adjustment factor is found in a two-step process. First, the PCE for each truck or bus and RV is found for the prevailing conditions under study. These equivalency values represent the number of passenger cars that would use the same amount of freeway capacity as one truck or bus or RV under the prevailing conditions. Second, Equation 11-3 is used to convert the PCE values to the adjustment factor.

In many cases, trucks will be the only heavy-vehicle type present in the traffic stream. In others, the percentage of RVs will be small in comparison with trucks and buses. If the ratio of trucks and buses to RVs is 5:1 or greater, all heavy vehicles may be (but do not have to be) considered to be trucks.

The effect of heavy vehicles on traffic flow depends on terrain and grade conditions as well as traffic composition. PCEs can be selected for one of three conditions:

- Extended freeway segments in general terrain,
- Specific upgrades, or
- Specific downgrades.

Each of these conditions is more precisely defined and discussed next.

Equivalents for General Terrain Segments

General terrain refers to extended lengths of freeway containing a number of upgrades and downgrades where no one grade is long enough or steep enough to have a significant impact on the operation of the overall segment. As a guideline for this determination, extended segment analysis can be applied where grades are ≤2% and ≤0.25 mi long, or where grades between 2% and 3% are ≤0.50 mi long. For this determination, each upgrade and downgrade is considered to be a single grade, even if the grade is not uniform. The total length of the upgrade or downgrade is used with the steepest grade it contains. There are three categories of general terrain:

- *Level terrain*: Any combination of grades and horizontal or vertical alignment that permits heavy vehicles to maintain the same speed as passenger cars. This type of terrain typically contains short grades of no more than 2%.
- *Rolling terrain*: Any combination of grades and horizontal or vertical alignment that causes heavy vehicles to reduce their speed substantially below those of passenger cars but that does not cause heavy vehicles to operate at crawl speeds for any significant length

of time or at frequent intervals. *Crawl speed* is the maximum sustained speed that trucks can maintain on an extended upgrade of a given percent. If the grade is long enough, trucks will be forced to decelerate to the crawl speed, which they can maintain for extended distances. Appendix A contains truck-performance curves illustrating crawl speed and length of grade.

- *Mountainous terrain*: Any combination of grades and horizontal and vertical alignment that causes heavy vehicles to operate at crawl speed for significant distances or at frequent intervals.

The mountainous terrain category is rarely used, because individual grades will typically be longer, steeper, or both, than the criteria for general terrain analysis.

Mountainous terrain is relatively rare. Generally, in segments severe enough to cause the type of operation described for mountainous terrain, individual grades will be longer or steeper, or both, than the criteria for general terrain analysis.

Exhibit 11-10 shows PCEs for trucks and buses and RVs in general terrain segments.

Exhibit 11-10
PCEs for Heavy Vehicles in General Terrain Segments

Vehicle	PCE by Type of Terrain: Level	Rolling	Mountainous
Trucks and buses, E_T	1.5	2.5	4.5
RVs, E_R	1.2	2.0	4.0

Equivalents for Specific Upgrades

Any freeway grade between 2% and 3% and longer than 0.5 mi or 3% or greater and longer than 0.25 mi should be considered a separate segment. The analysis of such segments must consider the upgrade conditions and the downgrade conditions separately, as well as whether the grade is a single, isolated grade of constant percentage or part of a series forming a composite grade. The analysis of composite grades is discussed in Appendix A.

Several studies have shown that freeway truck populations have an average weight-to-horsepower ratio between 125 and 150 lb/hp. This methodology adopts PCEs that are calibrated for a mix of trucks and buses in this range. RVs vary considerably in both type and characteristics and include everything from cars with trailers to self-contained mobile campers. In addition to the variability of vehicle characteristics, RV drivers are typically not professionals, and their degree of skill in handling such vehicles also varies widely. Typical RV weight-to-horsepower ratios range from 30 to 60 lb/hp.

Exhibit 11-11 and Exhibit 11-12 give values of E_T for trucks and buses and E_R for RVs, respectively. These factors vary with the percent of grade, length of grade, and the proportion of heavy vehicles in the traffic stream. Maximum values occur when there are only a few heavy vehicles in the traffic stream. The equivalents decrease as the number of heavy vehicles increases because these vehicles tend to form platoons. Because heavy vehicles have more uniform operating characteristics, fewer large gaps are created in the traffic stream when they platoon, and the impact of a single heavy vehicle in a platoon is less severe than that of a single heavy vehicle in a stream of primarily passenger cars. The aggregate impact of heavy vehicles on the traffic stream, however, increases as numbers and percentages of heavy vehicles increase.

The grade length should include 25% of the length of the vertical curves at the start and end of the grade.

With two consecutive upgrades, 50% of the length of the vertical curve joining them should be included.

The point of interest is usually the spot where heavy vehicles would have the greatest impact on operations: the top of a grade, the top of the steepest grade in a series, or a ramp junction, for example.

The length of the grade is generally taken from a highway profile. It typically includes the straight portion of the grade plus some portion of the vertical curves at the beginning and end of the grade. It is recommended that 25% of the length of the vertical curves at both ends of the grade be included in the length. Where two consecutive upgrades are present, 50% of the length of the vertical curve joining them is included in the length of each grade.

In the analysis of upgrades, the point of interest is generally at the end of the grade, where heavy vehicles would have the maximum effect on operations. However, if a ramp junction is being analyzed, for example, the length of the grade to the merge or diverge point would be used.

On composite grades, the relative steepness of segments is important. If a 5% upgrade is followed by a 2% upgrade, for example, the maximum impact of heavy vehicles is most likely at the end of the 5% segment. Heavy vehicles would be expected to accelerate after entering the 2% segment.

Exhibit 11-11
PCEs for Trucks and Buses (E_T) on Upgrades

Upgrade (%)	Length (mi)	Proportion of Trucks and Buses								
		2%	4%	5%	6%	8%	10%	15%	20%	≥25%
≤2	All	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
>2–3	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.50–0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.75–1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>1.00–1.50	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>1.50	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
>3–4	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50–0.75	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	>0.75–1.00	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	>1.00–1.50	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	>1.50	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
>4–5	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.50–0.75	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	>0.75–1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	>1.00	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
>5–6	0.00–0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.30	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.30–0.50	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	>0.50–0.75	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0
	>0.75–1.00	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	>1.00	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
>6	0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	1.0
	>0.25–0.30	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	>0.30–0.50	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	>0.50–0.75	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	>0.75–1.00	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	>1.00	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

Note: Interpolation for percentage of trucks and buses is recommended to the nearest 0.1.

Exhibit 11-12
PCEs for RVs (E_R) on Upgrades

Upgrade (%)	Length (mi)	Proportion of RVs								
		2%	4%	5%	6%	8%	10%	15%	20%	≥25%
≤2	All	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
>2–3	0.00–0.50	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.50	3.0	1.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2
>3–4	0.00–0.25	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.25–0.50	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
>4–5	0.00–0.25	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0
	>0.50	4.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0
>5	0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5
	>0.25–0.50	6.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0
	>0.50	6.0	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.0

Note: Interpolation for percentage of RVs is recommended to the nearest 0.1.

Equivalents for Specific Downgrades

Knowledge of specific impacts of heavy vehicles on operating conditions on downgrades is limited. In general, if the downgrade is not severe enough to cause trucks to shift into a lower gear (to engage engine braking), heavy vehicles may be treated as if they were on level terrain segments. Where a downgrade is severe, trucks must often use low gears to avoid gaining too much speed and running out of control. In such cases, their effect on operating conditions is more significant than on level terrain. Exhibit 11-13 gives values of E_T for this situation.

Exhibit 11-13
PCEs for Trucks and Buses (E_T) on Specific Downgrades

Downgrade (%)	Length of Grade (mi)	Proportion of Trucks and Buses			
		5%	10%	15%	≥20%
<4	All	1.5	1.5	1.5	1.5
4–5	≤4	1.5	1.5	1.5	1.5
	>4	2.0	2.0	2.0	1.5
>5–6	≤4	1.5	1.5	1.5	1.5
	>4	5.5	4.0	4.0	3.0
>6	≤4	1.5	1.5	1.5	1.5
	>4	7.5	6.0	5.5	4.5

On downgrades, RVs are always treated as if they were on level terrain; E_R is therefore always 1.2 on downgrades regardless of the length or severity of the downgrade or the percentage of RVs in the traffic stream.

E_R is always 1.2 on downgrades.

Equivalents for Composite Grades

The vertical alignment of most freeways results in a continuous series of grades. It is often necessary to determine the effect of a series of grades in succession. The most straightforward technique is to compute the average grade from the beginning of the composite grade to the point of interest. The average grade is defined as the total rise from the beginning of the composite grade to the point in question divided by the length of the grade (to the point of interest).

The average-grade technique is an acceptable approach for grades in which all subsections are less than 4% or the total length of the grade is less than 4,000 ft. For more severe composite grades, a detailed technique is presented in Appendix A. This technique uses vehicle performance curves and equivalent speeds to determine the equivalent simple grade for analysis.

The average grade can be used when all component grades are <4% or the total length of the grades is <4,000 ft.

Appendix A provides a method for addressing more severe composite grades.

Adjustment for Driver Population

The base traffic stream characteristics for basic freeway segments are representative of traffic streams composed primarily of commuters, or drivers who are familiar with the facility. It is generally accepted that traffic streams with different characteristics (e.g., recreational drivers) use freeways less efficiently. Although data are sparse and reported results vary substantially, significantly lower capacities have been reported on weekends, particularly in recreational areas. It may generally be assumed that the reduction in capacity (LOS E) extends to service flow rates and service volumes for other LOS as well.

An f_p-value of 1.00 should generally be used, reflective of drivers who are regular users of the freeway.

The adjustment factor f_p is used to reflect the effect of driver population. The values of f_p range from 0.85 to 1.00 in most cases, although lower values have been observed in isolated cases. In general, the analyst should use a value of 1.00, which reflects commuters or otherwise-accustomed drivers, unless there is sufficient evidence that a lower value should be used. Where greater accuracy is needed, comparative field studies of commuter and recreational traffic flow and speeds are recommended.

Does LOS F Exist?

At this point, the demand volume has been converted to a demand flow rate in passenger cars per hour per lane under equivalent base conditions. This demand rate must be compared with the base capacity of the basic freeway segment (2,400 pc/h/ln for FFS = 75 mi/h and 70 mi/h; 2,350 pc/h/ln for FFS = 65 mi/h; 2,300 pc/h/ln for FFS = 60 mi/h; 2,250 pc/h/ln for FFS = 55 mi/h).

If the demand exceeds capacity, the LOS is F, and a breakdown has been identified. To analyze the impacts of such a breakdown, the methodology of Chapter 10, Freeway Facilities, must be used. No further analysis using the methodology of the current chapter is possible.

If the demand is less than or equal to capacity, the analysis continues to Step 5.

Step 5: Estimate Speed and Density

At this point in the methodology, the following have been determined: (*a*) the FFS and appropriate FFS curve for use in the analysis, and (*b*) the demand flow rate expressed in passenger cars per hour per lane under equivalent base conditions. With this information, the estimated speed and density of the traffic stream may be determined.

With the equations specified in Exhibit 11-3, the expected mean speed of the traffic stream can be computed. A graphical solution with Exhibit 11-2 can also be performed.

With the estimated speed determined, Equation 11-4 is used to estimate the density of the traffic stream:

$$D = \frac{v_p}{S}$$

Equation 11-4

where

D = density (pc/mi/ln),

v_p = demand flow rate (pc/h/ln), and

S = mean speed of traffic stream under base conditions (mi/h).

As has been noted, Equation 11-4 is only used when the v_p/c is less than or equal to 1.00. All cases in which this ratio is greater than 1.00 are LOS F. In these cases, the speed S will be outside the range of Exhibit 11-3 and Exhibit 11-4, and no speed can be estimated.

Where LOS F exists, the analyst is urged to consult Chapter 10, Freeway Facilities, which allows an analysis of the time and spatial impacts of a breakdown, including its effects on upstream and downstream segments.

Step 6: Determine LOS

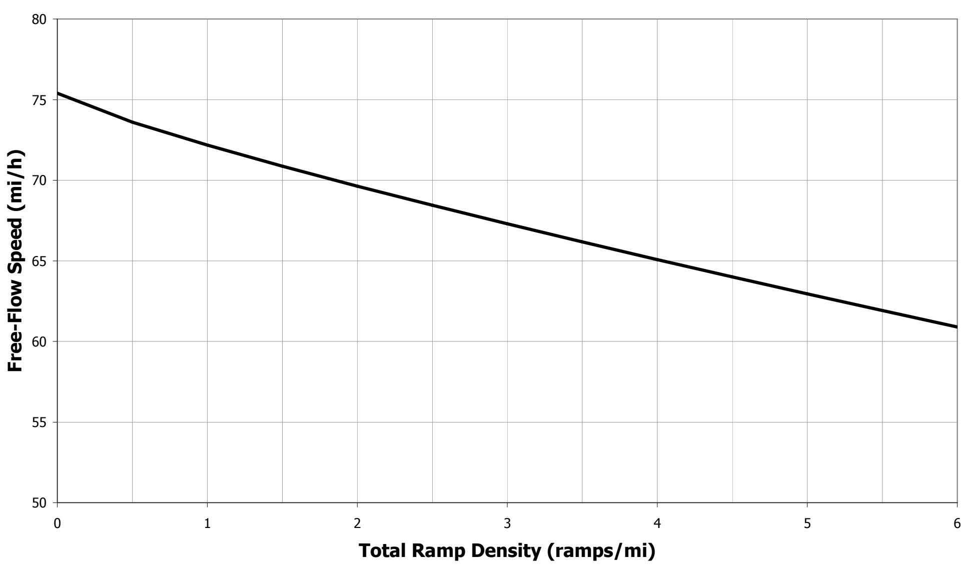
Exhibit 11-5 is entered with the density obtained from Equation 11-4 to determine the expected prevailing LOS.

SENSITIVITY OF RESULTS

The freeway FFS is most sensitive to the total ramp density.

The FFS of basic freeway segments is most sensitive to the total ramp density. Exhibit 11-14 illustrates the resulting FFS when total ramp density varies from 0 ramps/mi to 6 ramps/mi. Standard lane widths and right-side clearances are assumed. A freeway with 0 ramps/mi represents a case in which there are no ramps within 3 mi on either side of the study location. This situation occurs primarily in rural areas, where interchanges may be 10 or more miles apart. In rare cases, ramp densities in excess of 6 ramps/mi may exist, particularly in dense urban areas.

Exhibit 11-14
Sensitivity of FFS to Total Ramp Density



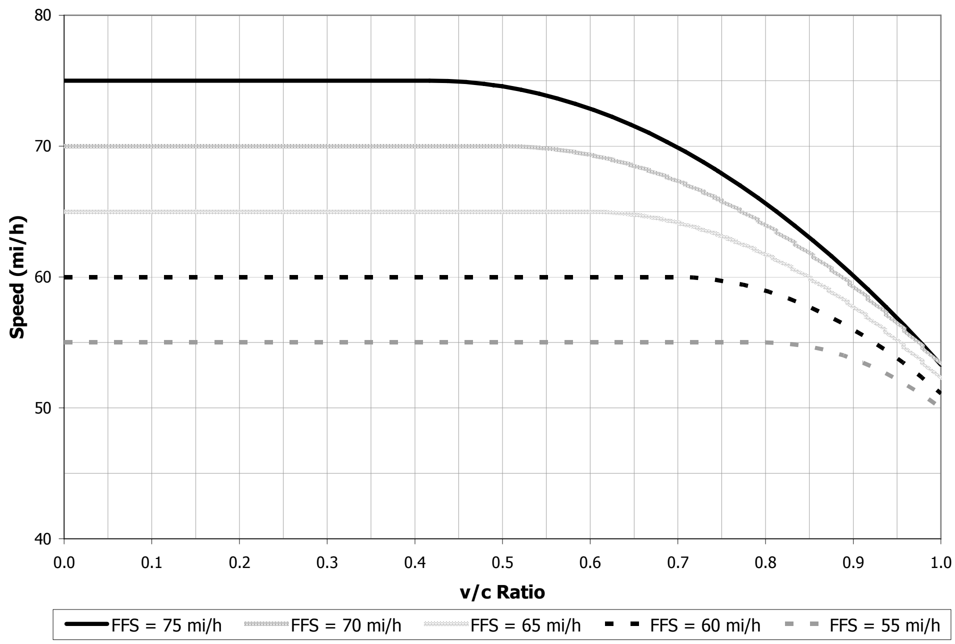
Each on- and off-ramp in the direction of travel is counted when total ramp density is determined.

Higher total ramp densities represent suburban and urban situations as well as the type of interchanges present. Most interchanges involve two to four ramps. A full cloverleaf, for example, has four ramps: two on-ramps and two off-ramps in each direction. A diamond interchange has two ramps in each direction: one on-ramp and one off-ramp. Thus, a freeway with two cloverleaf interchanges fully contained within 1 mi would have a total ramp density of 8 ramps/mi. A freeway with two diamond interchanges fully contained within 1 mi would have a total density of 4 ramps/mi. This finding suggests that in any given situation (with comparable demand flows), cloverleaf interchanges will have a greater negative impact on FFS than diamond interchanges.

Although Exhibit 11-14 is not a straight line, the slope is relatively constant. On average, an increase of 2 ramps/mi in total ramp density causes a drop in FFS of approximately 5 mi/h. A reduction in FFS, of course, implies reductions in capacity and service volumes.

Exhibit 11-15 shows the relationship between speed and *v/c* ratio. Not unexpectedly, the shapes of these curves are similar to the basic speed–flow curves of Exhibit 11-2. Speed does not begin to decline until a *v/c* ratio of 0.42 to 0.80 is reached, depending on the FFS.

Exhibit 11-15
Speed Versus *v/c* Ratio



3. APPLICATIONS

The methodology in this chapter is relatively straightforward, so it can be directly used in any one of four applications:

1. *Operational analysis*: All traffic and roadway conditions are specified for an existing facility or a future facility with forecast conditions. The existing or expected LOS is determined.
2. *Design analysis*: A forecast demand volume is used, and key design parameters are specified (e.g., lane width and lateral clearance). The number of lanes required to deliver a target LOS is determined.
3. *Planning and preliminary engineering*: The basic scenario is the same as that for design analysis, except that the analysis is conducted at a much earlier stage of the development process. Inputs include default values, and the demand volume is usually stated as an annual average daily traffic (AADT) value.
4. *Service flow rates and service volumes*: The service flow rate, service volume, or daily service volume, or all three, are estimated for each LOS for an existing or future facility. All traffic and roadway conditions must be specified for this type of analysis.

Because the methodology and its algorithms are simple and do not involve iterations, all of the types of analysis cited can be done without the trial-and-error approach required by many other *Highway Capacity Manual* (HCM) methodologies.

DEFAULT VALUES

In using this chapter's methodology, a range of input data is needed. Most of these data should be field-measured or estimated values for the specific segment under consideration. When some of the data are not available, default values may be used. However, the use of default values will affect the accuracy of the output. Exhibit 11-16 shows the data that are required to conduct an operational analysis and the recommended default values when site-specific data are unavailable (*13*).

Exhibit 11-16
Required Input Data and Default Values for Basic Freeway Segments

Required Data	Default Values
Geometric Data	
Number of lanes in one direction	No default, must have site-specific value
Lane width (ft)	12 ft
Right-side lateral clearance (ft)	10 ft
Ramp density (ramps/mi)	No default, must have site-specific value
Terrain or specific grade (%, length)	No default, must have site-specific value
FFS (mi/h)	Urban, 70 mi/h; rural, 75 mi/h
Demand Data	
Length of analysis period (min)	15 min
PHF	0.94
Proportion of heavy vehicles (%)	Urban, 5%; rural, 12%*
Driver population factor	1.00

* Alternative state-specific default values for percentage of heavy vehicles are given in Chapter 26.

The analyst may also replace the default values of Exhibit 11-16 with defaults that have been locally calibrated.

Research into the percentage of heavy vehicles on uninterrupted-flow facilities (*13*) found a wide range of average values from state to state. Chapter 26 provides alternative default values for percentage of heavy vehicles by state and area population on the basis of data from the 2004 Highway Performance Monitoring System. Where states or local jurisdictions have developed their own values, these may be substituted. Analysts may also wish to develop their own default values based on more recent data.

ESTABLISH ANALYSIS BOUNDARIES

Determining capacity or LOS requires uniform traffic and roadway conditions on the analysis segment. Thus, any point where roadway or traffic conditions change must mark a boundary of the analysis segment.

At every ramp–freeway junction, the demand volume changes (as some vehicles enter or leave the traffic stream). Thus, any ramp junction should mark a boundary between adjacent basic freeway segments.

Ramp junctions, grade changes of 2% or more, changes in the freeway's geometric characteristics, and changes in speed limit are places where basic freeway segment boundaries should be established.

In addition to ramp–freeway junctions, the following conditions generally dictate that a boundary should be established between basic freeway segments:

- Change in the number of lanes (cross section),
- Changes in lane width or lateral clearance,
- Grade change of 2% or more on a specific or composite grade,
- Change in terrain category (for general terrain segments), or
- Change in posted speed limit.

The last is not directly involved in the analysis of a basic freeway segment but would probably reflect changes in ramp density or other freeway features.

TYPES OF ANALYSIS

Operational Analysis

Operational analyses find the expected LOS for specified roadway and traffic conditions.

The operational analysis application was fully specified in the Methodology section of this chapter. Operational analysis begins with all input parameters specified and is used to find the expected LOS that would result from the prevailing roadway and traffic conditions.

Design Analysis

Design analyses find the number of lanes required for a target LOS, given a specified demand volume.

In design analysis, a known demand volume is used to determine the number of lanes needed to deliver a target LOS. Two modifications are required to the operational analysis methodology. First, since the number of lanes is to be determined, the demand volume is converted to a demand flow rate in passenger cars per hour, not per lane, using Equation 11-5 instead of Equation 11-2:

Equation 11-5

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

where v is the demand flow rate in passenger cars per hour and all other variables are as previously defined.

Second, a maximum service flow rate for the target LOS is then selected from Exhibit 11-17. These values are selected from the base speed–flow curves of Exhibit 11-6 for each LOS.

Exhibit 11-17
Maximum Service Flow Rates in Passenger Cars per Hour per Lane for Basic Freeway Segments Under Base Conditions

FFS (mi/h)	Target Level of Service				
	A	B	C	D	E
75	820	1,310	1,750	2,110	2,400
70	770	1,250	1,690	2,080	2,400
65	710	1,170	1,630	2,030	2,350
60	660	1,080	1,560	2,010	2,300
55	600	990	1,430	1,900	2,250

Note: All values rounded to the nearest 10 pc/h/ln.

Next the number of lanes required to deliver the target LOS can be found from Equation 11-6:

Equation 11-6

$$N = \frac{v}{MSF_i}$$

where N is the number of lanes required and MSF_i is the maximum service flow rate for LOS i from Exhibit 11-17. Equation 11-5 and Equation 11-6 can be conveniently combined as Equation 11-7:

Equation 11-7

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

where all variables are as previously defined.

All fractional values of N must be rounded up.

The value of N resulting from Equation 11-6 or Equation 11-7 will most likely be fractional. Since only integer numbers of lanes can be constructed, the result is always rounded to the next-higher value. Thus, if the result is 3.2 lanes, 4 must be provided. The 3.2 lanes is, in effect, the minimum number of lanes needed to provide the target LOS. If the result were rounded to 3, a poorer LOS than the target value would result.

Because only whole lanes can be built, it may not be possible to achieve the target LOS for a given demand volume.

This rounding-up process will occasionally produce an interesting result: it is possible that a target LOS (for example, LOS C) cannot be achieved for a given demand volume. If 2.1 lanes are required to produce LOS C, providing 2 lanes would drop the LOS, most likely to D. However, if three lanes are provided, the LOS might actually improve to B. Thus, some judgment may be required to interpret the results. In this case, two lanes might be provided even though they would result in a borderline LOS D. Economic considerations might lead a decision maker to accept a slightly lower operating condition than that originally targeted.

Planning and Preliminary Engineering

Planning and preliminary engineering applications also find the number of lanes required to deliver a target LOS but provide more generalized input values to the methodology.

The objective of planning or preliminary engineering is to get a general idea of the number of lanes that will be required to deliver a target LOS. The primary differences are that many default values will be used and the demand volume will be usually expressed as an AADT. Thus, a planning and preliminary engineering analysis starts by converting the demand expressed as an AADT to an estimate of the directional peak-hour demand volume (DDHV) with Equation 11-8:

Equation 11-8

$$V = DDHV = AADT \times K \times D$$

where K is the proportion of AADT occurring during the peak hour and D is the proportion of peak-hour volume traveling in the peak direction; all other variables are as previously defined.

Chapter 3 provides additional guidance on K- and D-factors.

On urban freeways, the typical range of K-factors is from 0.08 to 0.10. On rural freeways, values typically range between 0.09 and 0.13. Directional distributions also vary, as was illustrated in Chapter 3, Modal Characteristics, but a typical value for both urban and rural freeways is 0.55. As with all default values, locally or regionally calibrated values are preferred and yield more accurate results. Both the K-factor and the D-factor have a significant impact on the estimated hourly demand volume.

Once the hourly demand volume is estimated, the methodology follows the same path as that for design analysis.

Service Flow Rates, Service Volumes, and Daily Service Volumes

This chapter's methodology can be easily manipulated to produce service flow rates, service volumes, and daily service volumes for a basic freeway segment.

Exhibit 11-17 gave values of the maximum service flow rates, MSF_i, for each LOS for freeways of various FFSs. These values are given in terms of passenger cars per hour per lane under equivalent base conditions. A service flow rate, SF_i, is the maximum rate of flow that can exist while LOS i is maintained during the 15-min analysis period under prevailing conditions. It can be computed from the maximum service flow rate by using Equation 11-9:

Equation 11-9

$$SF_i = MSF_i \times N \times f_{HV} \times f_p$$

where all variables are as previously defined.

A service flow rate can be converted to a service volume, SV_i, by applying a PHF, as shown in Equation 11-10. A service volume is the maximum hourly volume that can exist while LOS i is maintained during the worst 15-min period of the analysis hour.

Equation 11-10

$$SV_i = SF_i \times PHF$$

where all variables are as previously defined.

A daily service volume, DSV_i, is the maximum AADT that can be accommodated by the facility under prevailing conditions while LOS i is maintained during the worst 15-min period of the analysis day. It is estimated from Equation 11-11:

Equation 11-11

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

where all variables are as previously defined.

Service flow rates *SF* and service volumes *SV* are stated for a single direction of the freeway. Daily service volumes *DSV* are stated as total volumes in *both* directions of the freeway.

USE OF ALTERNATIVE TOOLS

General guidance for the use of alternative traffic analysis tools for capacity and LOS analysis is provided in Chapter 6, HCM and Alternative Analysis Tools. This section contains specific guidance for the application of alternative tools to the analysis of basic freeway segments. Additional information on this topic may be found in Chapter 26, Basic Freeway Segments: Supplemental.

Strengths of HCM Procedure

This chapter's procedures were developed on the basis of extensive research supported by a significant quantity of field data. They have evolved over a number of years and represent a body of expert consensus.

The HCM methodology provides FFS as an output, incorporates geometric characteristics, provides explicit capacity estimates, and produces a single deterministic estimate of traffic density.

Specific strengths of the HCM basic freeway segment methodology include the following:

- It provides a detailed methodology for obtaining FFS. This methodology is based on various geometric characteristics. In simulation packages FFS (or an equivalent, such as desired speed) is an input.
- It considers geometric characteristics (such as lane widths), which are rarely, if ever, incorporated into simulation algorithms.
- It provides explicit capacity estimates. Simulation packages do not provide capacity estimates directly. Capacity estimates can only be obtained from simulators through multiple runs with oversaturated conditions. The user can modify simulated capacities by modifying specific input values such as the minimum acceptable headway.
- It produces a single deterministic estimate of traffic density, which is important for some purposes such as development impact review.

Limitations of HCM Procedures That Might Be Addressed by Alternative Tools

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

Deterministic models yield the same results for the same inputs each time they are implemented; stochastic models incorporate statistical variability. The same inputs yield different results in each use. For such models, an average result of X usages is employed as output.

Exhibit 11-18 tabulates the HCM limitations for basic freeway segments along with the potential for improved treatment by alternative tools.

Additional Features and Performance Measures Available from Alternative Tools

This chapter provides a methodology for estimating the capacity, speed, and density of a basic freeway segment, given the segment's traffic demand and characteristics. Alternative tools offer additional performance measures, including delay, stops, queue lengths, fuel consumption, pollution, and operating costs.

Exhibit 11-18
Limitations of HCM Basic Freeway Segments Procedure

Limitation	Potential for Improved Treatment by Alternative Tools
Special lanes reserved for a single vehicle type, such as HOV, truck, and climbing lanes	Modeled explicitly by simulation
Extended bridge and tunnel segments	Can be approximated by using assumptions related to desired speed and number of lanes along each segment
Segments near a toll plaza	Can be approximated by using assumptions related to discharge at toll plaza
Facilities with FFS less than 55 mi/h or more than 75 mi/h	Modeled explicitly by simulation
Oversaturated conditions (refer to Chapters 10 and 26 for further discussion)	Modeled explicitly by simulation
Influence of downstream blockages or queuing on a segment	Modeled explicitly by simulation
Posted speed limit and extent of police enforcement	Can be approximated by using assumptions related to desired speed along a given segment
Presence of ITS features related to vehicle or driver guidance	Several features modeled explicitly by simulation; others may be approximated by using assumptions (for example, by modifying origin–destination demands by time interval)

As with most other procedural chapters in the HCM, simulation outputs, especially graphics-based presentations, can provide details on point problems that might otherwise go unnoticed with a macroscopic analysis that yields only segment-level measures. The effect of downstream conditions on lane utilization and backup beyond the segment boundary is a good example of a situation that can benefit from the increased insight offered by a microscopic model.

Development of HCM-Compatible Performance Measures Using Alternative Tools

The LOS for basic freeway segments is based on traffic density expressed in passenger cars per mile per lane. The HCM methodology estimates density by dividing the flow rate by the average passenger-car speed. Simulation models typically estimate density by dividing the average number of vehicles in the segment by the area of the segment (in lane miles). The result is vehicles per lane mile. This measurement corresponds to density based on space mean speed. The HCM-reported density is also based on space mean speed, but because there is no variability in the speeds, the space mean speed is equal to the time mean speed. Generally, increased speed variability in driver behavior (which simulators usually include) results in lower average space mean speed and higher density.

In obtaining density from alternative models, it is important to take into account the following:

- The vehicles included in the density estimation (for example, whether only the vehicles that have exited the link are considered);
- The manner in which auxiliary lanes are considered;

- The units used for density, since a simulation package would typically provide density in units of vehicles rather than passenger cars; converting the simulation outputs to passenger cars with the HCM PCE values is typically not appropriate, given that the simulation should already account for the effects of heavy vehicles on a microscopic basis—with heavy vehicles operating at lower speeds and at longer headways—thus making any additional adjustments duplicative;
- The units used in the reporting of density (e.g., whether it is reported per lane mile);
- The homogeneity of the analysis segment, since the HCM does not use the segment length as an input (unless it is a specific upgrade or downgrade segment, where the length is used to estimate the PCE values), and conditions are assumed to be homogeneous for the entire segment; and
- The driver variability assumed in the simulation package, since increased driver variability will generally increase the average density.

Regarding capacity, the HCM provides capacity estimates in passenger cars per hour per lane as a function of FFS. To compare the HCM's estimates with capacity estimates from a simulation package, the following should be considered:

- The manner in which a simulation package provides the number of vehicles exiting a segment; in some cases it may be necessary to provide virtual detectors at a specific point on the simulated segment so that the maximum throughput can be obtained;
- The units used to specify maximum throughput, since a simulation package would do this in units of vehicles rather than passenger cars; converting these to passenger cars by using the HCM PCE values is typically not appropriate, since differences between automobile and heavy-vehicle performance should already be accounted for microscopically within a simulation; and
- The incorporation of other simulation inputs, such as the "minimum separation of vehicles," that affect the capacity result.

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

The HCM's methodology is based on the relationship between speed and flow for various values of FFS. One fundamental potential difference between the HCM and other models is this relationship. For example, the HCM assumes a constant speed for a broad range of flows. However, this is not necessarily the case for any given simulation package, some of which assume a continuously decreasing speed with increasing flow. Furthermore, in some simulation packages, that relationship changes when certain parameters are modified. Therefore, if performance measures are compatible between the HCM and an alternative model for a given set of flows, this will not necessarily be the case for all other sets of flows.

Adjustment of Simulation Parameters to HCM Results

The most important elements to be adjusted when a basic freeway segment is analyzed are the speed–flow relationship or the capacity, or both. The speed–flow relationship should be examined as a function of the given FFS. That FFS should match the field- or HCM-estimated value. Some tools only accept integer values of FFS, whereas the HCM may provide a fractional value as an intermediate calculation result.

Step-by-Step Recommendations for Applying Alternative Tools

This section provides recommendations specifically for freeway segments (general guidance on selecting and applying simulation packages is provided in Chapter 6, HCM and Alternative Analysis Tools). To apply an alternative tool to the analysis of basic freeway segments, the following steps should be taken:

1. Determine whether the chosen tool can provide density and capacity for a basic freeway segment and the approach used to obtain those values. Once the analyst is satisfied that density and capacity can be obtained and that values compatible with those of the HCM can also be obtained, proceed with the analysis.
2. Determine the FFS of the study site, either from field data or by estimating it according to this chapter's methodology.
3. Enter all available geometric and traffic characteristics into the simulation package and install virtual detectors along the study segment, if necessary, to obtain speeds and flows.
4. By loading the study network over capacity, obtain the maximum throughput and compare it with the HCM estimate. Calibrate the simulation package by modifying parameters related to the minimum time headway, so that the capacity obtained by the simulator closely matches the HCM estimate. Estimate the required number of runs to be conducted so that the comparison is statistically valid.
5. If the analysis requires evaluating various different demand conditions for the segment, plot the simulator's speed–flow curve and compare it with the HCM relationship. Attempt to calibrate the simulation package by modifying parameters related to driver behavior, such as the distribution of driver types. It is possible that the simulation cannot be calibrated to match the HCM speed–flow relationship. In that case, the results should be viewed with caution in terms of their compatibility with the HCM methods.

Sample Calculations Illustrating Alternative Tool Applications

Chapter 26, in Volume 4 of the HCM, provides two supplemental problems that examine situations beyond the scope of this chapter's methodology by using a typical microsimulation-based tool. Both problems are based on Example Problem 3 (found in the next section of this chapter), which analyzes a six-lane freeway segment in a growing urban area. The first supplemental problem evaluates the facility when an HOV lane is added, and the second problem analyzes operations with an incident within the segment.

4. EXAMPLE PROBLEMS

Exhibit 11-19
List of Example Problems

Example Problem	Description	Application
1	Four-lane freeway LOS	Operational analysis
2	Number of lanes required for target LOS	Design analysis
3	Six-lane freeway LOS and capacity	Operational and planning analysis
4	LOS on upgrades and downgrades	Operational analysis
5	Design-hour volume and number of lanes	Planning analysis
6	Service flow rates and service volumes	Planning analysis

EXAMPLE PROBLEM 1: FOUR-LANE FREEWAY LOS

The Facts

- Four-lane freeway (two lanes in each direction);
- Lane width = 11 ft;
- Right-side lateral clearance = 2 ft;
- Commuter traffic (regular users);
- Peak-hour, peak-direction demand volume = 2,000 veh/h;
- Traffic composition: 5% trucks, 0% RVs;
- PHF = 0.92;
- One cloverleaf interchange per mile; and
- Rolling terrain.

Comments

The task is to find the expected LOS for this freeway during the worst 15 min of the peak hour. With one cloverleaf interchange per mile, the total ramp density will be 4 ramps/mi.

Step 1: Input Data

All input data are specified above.

Step 2: Compute FFS

The FFS of the freeway is estimated as follows:

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

The adjustment for lane width is selected from Exhibit 11-8 for 11-ft lanes (1.9 mi/h). The adjustment for right-side lateral clearance is selected from Exhibit 11-9 for a 2-ft clearance on a freeway with two lanes in one direction (2.4 mi/h). The total ramp density is 4 ramps/mi. Then

$$FFS = 75.4 - 1.9 - 2.4 - 3.22\left(4^{0.84}\right) = 60.8 \text{ mi/h}$$

Step 3: Select FFS Curve

As the FFS calculated in Step 2 is greater than or equal to 57.5 and less than 62.5 mi/h, the 60-mi/h speed–flow curve will be used for this analysis.

Step 4: Adjust Demand Volume

The demand volume must be adjusted to a flow rate that reflects passenger cars per hour per lane under equivalent base conditions by using Equation 11-2:

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

The demand volume is given as 2,000 veh/h. The PHF is specified to be 0.92, and there are two lanes in each direction. The driver population factor is 1.00, since regular users (commuters) are also specified. Trucks make up 5% of the traffic stream, so a heavy-vehicle adjustment factor must be determined.

From Exhibit 11-10, the PCE for trucks is 2.5 for rolling terrain. The heavy-vehicle adjustment factor is then computed by using Equation 11-3:

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

$$f_{HV} = \frac{1}{1 + 0.05\left(2.5 - 1\right) + 0} = 0.930$$

Then

$$v_p = \frac{2{,}000}{0.92 \times 2 \times 0.93 \times 1.00} = 1{,}169 \text{ pc/h/ln}$$

Since this value is less than the base capacity of 2,300 pc/h/ln for a freeway with FFS = 60 mi/h, LOS F does not exist, and the analysis continues to Step 5.

Step 5: Estimate Speed and Density

The FFS of the basic freeway segment is now estimated along with the demand flow rate in passenger cars per hour per lane under equivalent base conditions. From Exhibit 11-3, the equation for estimating the speed of the traffic stream is selected for a 60-mi/h FFS, with a flow rate less than 1,600 pc/h/ln. This is the constant-speed portion of the curve, so S = 60 mi/h. The density of the traffic stream may now be computed as

$$D = \frac{v_p}{S} = \frac{1{,}169}{60} = 19.5 \text{ pc/mi/ln}$$

Step 6: Determine LOS

From Exhibit 11-5, a density of 19.5 pc/mi/ln corresponds to LOS C but is close to the boundary for LOS B, which is a maximum of 18 pc/mi/ln. This solution could also be calculated graphically by using Exhibit 11-6 as a base (Exhibit 11-20).

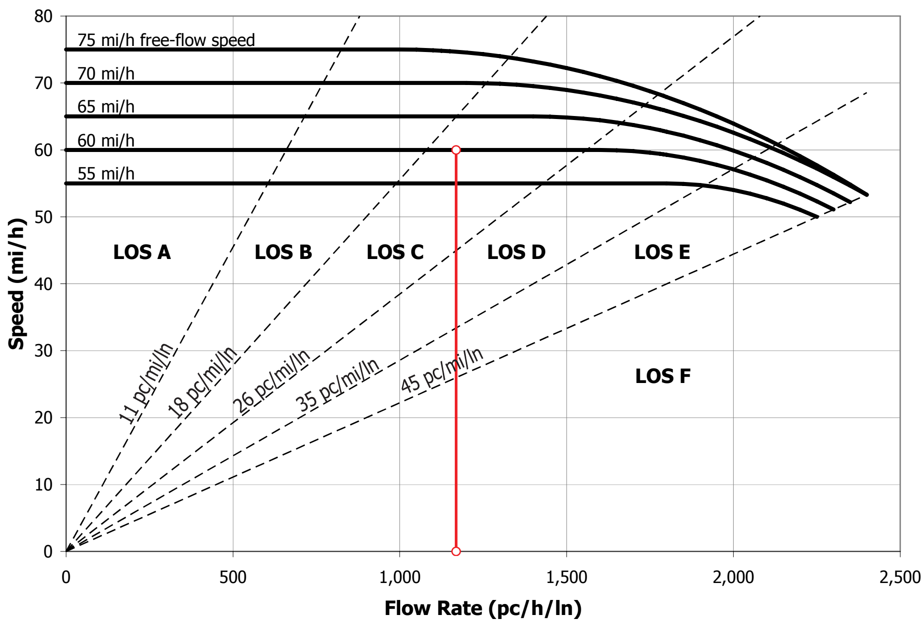


Exhibit 11-20
Graphical Solution for Example Problem 1

Discussion

This basic freeway segment of a four-lane freeway is expected to operate at LOS C during the worst 15 min of the peak hour. It is important to note that the operation, although at LOS C, is close to the LOS B boundary. In most jurisdictions, this operation would be considered to be quite acceptable; therefore, no remediation would normally be required.

EXAMPLE PROBLEM 2: NUMBER OF LANES REQUIRED FOR TARGET LOS

The Facts

- Demand volume = 4,000 veh/h (one direction);
- Level terrain;
- Traffic composition: 15% trucks, 3% RVs;
- Provision of 12-ft lanes;
- Provision of 6-ft right-side lateral clearance;
- Commuter traffic (regular users);
- PHF = 0.85;
- Ramp density = 3 ramps/mi; and
- Target LOS = D.

Comments

This is a classic design application of the methodology. The number of lanes needed to provide LOS D during the worst 15 min of the peak hour is to be determined.

Step 1: Input Data

All input data were specified previously.

Step 2: Compute FFS

The FFS is estimated by using Equation 11-1. Because the lane width and lateral clearance to be provided on the new freeway will be 12 ft and 6 ft, respectively, there are no adjustments for these features. The total ramp density is given as 3 ramps/mi. Then

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

$$FFS = 75.4 - 0.0 - 0.0 - 3.22\left(3^{0.84}\right) = 67.3 \text{ mi/h}$$

Step 3: Select FFS Curve

Since the FFS calculated in Step 2 is greater than or equal to 62.5 and less than 67.5 mi/h, the 65-mi/h speed–flow curve will be used for this analysis.

Step 4: Estimate Number of Lanes Needed

Because this is a design analysis, Step 4 of the operational analysis methodology is modified. Equation 11-7 may be used directly to determine the number of lanes needed to provide for at least LOS D:

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

A value of the maximum service flow rate must be selected from Exhibit 11-17 for a FFS of 65 mi/h and LOS D. This value is 2,030 pc/h/ln. The PHF is given as 0.85. The driver population factor is 1.00, since commuters are involved. A heavy-vehicle factor for 15% trucks and 3% RVs must be determined by using Exhibit 11-10 for level terrain. The PCEs of trucks and RVs in level terrain are 1.5 and 1.2, respectively. Then

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

$$f_{HV} = \frac{1}{1 + 0.15(1.5 - 1) + 0.03(1.2 - 1)} = 0.925$$

and

$$N = \frac{4{,}000}{2030 \times 0.85 \times 0.925 \times 1.00} = 2.51 \text{ lanes}$$

It is not possible to build 2.51 lanes. To provide a minimum of LOS D, it will be necessary to provide three lanes in each direction, or a six-lane freeway.

At this point, the design application ends. It is possible, however, to consider what speed, density, and LOS will prevail when three lanes are actually provided. Therefore, the example problem continues with Steps 5 and 6.

Step 5: Estimate Speed and Density

In pursuing additional information, the problem now reverts to an operational analysis of a three-lane basic freeway segment with a demand volume of 4,000 pc/h.

Equation 11-2 is used to compute the actual demand flow rate per lane under equivalent base conditions:

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

$$v_p = \frac{4{,}000}{0.85 \times 3 \times 0.925 \times 1.00} = 1{,}696 \text{ pc/h/ln}$$

The expected speed of the traffic stream may be estimated either by using Exhibit 11-6 (for a graphical solution) or by selecting the appropriate equation from Exhibit 11-3—in this case, using FFS = 65 mi/h and a demand flow rate over 1,400 pc/h/ln. With the latter approach,

$$S = 65 - 0.00001418\left(v_p - 1{,}400\right)^2$$

$$S = 65 - 0.00001418\left(1{,}696 - 1{,}400\right)^2 = 63.8 \text{ mi/h}$$

The density may now be computed:

$$D = \frac{v_p}{S} = \frac{1{,}696}{63.8} = 26.6 \text{ pc/mi/ln}$$

Step 6: Determine LOS

Entering Exhibit 11-5 with a density of 26.6 pc/mi/ln, the LOS is D but is very close to the boundary of LOS C, which is 26 pc/mi/ln.

Discussion

The resulting LOS is D, which was the target for the design. Although the minimum number of lanes needed was 2.51, which would have provided for a minimal LOS D, providing three lanes yields a density that is close to the LOS C boundary. In any event, the target LOS of the design will be met by providing a six-lane basic freeway segment.

EXAMPLE PROBLEM 3: SIX-LANE FREEWAY LOS AND CAPACITY

The Facts

- Volume of 5,000 veh/h (one direction, existing);
- Volume of 5,600 veh/h (one direction, in 3 years);
- Traffic composition: 10% trucks, no RVs;
- Level terrain;
- Three lanes in each direction;
- FFS = 70 mi/h (measured);
- PHF = 0.95;
- Commuter traffic (regular users); and
- Traffic growth after 3 years = 4% per year.

Comments

This example consists of two operational analyses, one for the present demand volume of 5,000 pc/h and one for the demand volume of 5,600 pc/h expected in 3 years. In addition, a planning element is introduced: Assuming that traffic grows as expected, when will the capacity of the roadway be exceeded? This analysis requires that capacity be determined in addition to the normal output of operational analyses.

Step 1: Input Data

All input data were given previously.

Step 2: Compute FFS

Step 2 is not needed since a measured FFS is given (70 mi/h).

Step 3: Select FFS Curve

Step 3 is not needed. The FFS curve for 70 mi/h will be used, based on the measured value.

Step 4: Adjust Demand Volume

In this case, two demand volumes will be adjusted by using Equation 11-2:

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

The PHF is given as 0.95, and there are three lanes in each direction. The driver population adjustment factor will be 1.00, for regular users. The heavy-vehicle factor must reflect 10% trucks in level terrain. From Exhibit 11-10, the PCE for trucks in level terrain is 1.5. Equation 11-3 then gives the following:

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

$$f_{HV} = \frac{1}{1 + 0.10(1.5 - 1) + 0} = 0.952$$

Two values of v_p will be computed: one for present conditions and one for conditions in 3 years:

$$v_p\ (\text{present}) = \frac{5{,}000}{0.95 \times 3 \times 0.952 \times 1.00} = 1{,}843\ \text{pc/h}$$

$$v_p\ (\text{future}) = \frac{5{,}600}{0.95 \times 3 \times 0.952 \times 1.00} = 2{,}064\ \text{pc/h}$$

Step 5: Estimate Speed and Density

Two values of speed and density will be estimated, one each for the present and future conditions stated. The equations of Exhibit 11-3 will be used to estimate speeds. One equation applies to both cases, a 70-mi/h FFS with a flow rate over 1,200 pc/h/ln:

$$S(\text{present}) = 70 - 0.00001160\left(v_p - 1{,}200\right)^2$$

$$S(\text{present}) = 70 - 0.00001160(1{,}843 - 1{,}200)^2 = 65.2 \text{ mi/h}$$

$$S(\text{future}) = 70 - 0.00001160\left(v_p - 1{,}200\right)^2$$

$$S(\text{future}) = 70 - 0.00001160(2{,}064 - 1{,}200)^2 = 61.3 \text{ mi/h}$$

The corresponding densities may now be estimated as follows:

$$D = \frac{v_p}{S}$$

$$D(\text{present}) = \frac{1{,}843}{65.2} = 28.3 \text{ pc/mi/ln}$$

$$D(\text{future}) = \frac{2{,}064}{61.3} = 33.7 \text{ pc/mi/ln}$$

Step 6: Determine LOS

From Exhibit 11-5, the LOS for the present situation is D, and the LOS for the future scenario (in 3 years) is also D, despite the increase in density.

Step 7: When Will Capacity Be Reached?

Step 7 is an additional step for this problem. To answer the question, the capacity of the basic freeway segment must be estimated. From Exhibit 11-17, the maximum service flow rate for LOS E on a basic freeway segment with a 70-mi/h FFS is 2,400 pc/h/ln. This flow rate is synonymous with capacity.

The analyst must be sure that the capacity and demand flow rates compared in Step 7 are on the same basis. The 2,400 pc/h/ln is a flow rate under equivalent base conditions. The demand flow rate in 3 years was estimated to be 2,064 pc/h/ln on this basis. These two values, therefore, may be compared. As an alternative, the capacity could be computed for prevailing conditions:

$$SF_E = MSF_E \times N \times f_{HV} \times f_p$$

$$SF_E = 2{,}400 \times 3 \times 0.952 \times 1.00 = 6{,}854 \text{ veh/h}$$

This capacity, however, is stated as a *flow rate*. The demand volume is stated as an hourly volume. Thus, a *service volume* for LOS E is needed:

$$SV_E = SF_E \times PHF = 6{,}854 \times 0.95 = 6{,}511 \text{ veh/h}$$

The problem may be solved either by comparing the demand volume of 5,600 veh/h (in 3 years) with the hourly capacity of 6,511 veh/h or by comparing the demand flow rate under equivalent base conditions of 2,064 pc/h/ln with the base capacity of 2,400 pc/h/ln. With the hourly demand volume and hourly capacity,

$$6{,}511 = 5{,}600(1.04)^n$$
$$n = 3.85 \text{ years}$$

On the basis of the forecasts of traffic growth, the basic freeway segment described will reach capacity within 7 years (the demand of 5,600 veh/h occurs 3 years from the present).

Discussion

The LOS on this segment will remain D within 3 years despite the increase in density. The demand is expected to exceed capacity within 7 years. Given the normal lead times for planning, design, and approvals before the start of construction, it is probable that planning and preliminary design for an improvement should be started immediately.

EXAMPLE PROBLEM 4: LOS ON UPGRADES AND DOWNGRADES

The Facts

- Demand volume = 2,300 veh/h (one direction);
- Traffic composition: 15% trucks, no RVs;
- PHF = 0.90;
- FFS = 70 mi/h upgrade, 75 mi/h downgrade (measured);
- Unfamiliar drivers (f_p = 0.95); and
- Composite grade: 3,000 ft at 3%, followed by 2,600 ft at 5%.

Comments

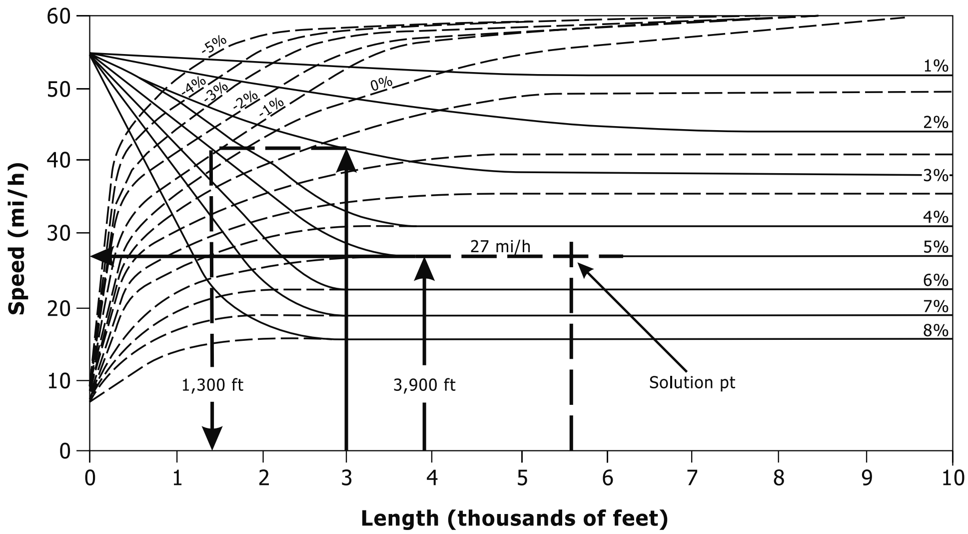
This is a typical operational analysis. The expected outcome is an assessment of the LOS on both the upgrade and the downgrade. However, the problem deals with a specific grade and a composite grade. Because there is a segment of the grade that is greater than 4% and the total length of the composite grade exceeds 4,000 ft, the special procedure in Appendix A must be applied. That procedure will yield an equivalent constant-percent grade of 3,000 + 2,600 = 5,600 ft (1.06 mi), which has the same impact on heavy vehicles as the composite grade described.

Composite Grade

Exhibit 11-21 shows the conversion of the composite grade to a grade of constant percent 5,600 ft long. At the end of such a grade, the final speed of heavy vehicles is approximately the same as that on the composite grade.

A vertical line enters the truck performance curves at 3,000 ft extending to the +3% grade curve, indicating that the speed of trucks after 3,000 ft of +3% grade is approximately 42 mi/h. This is also the speed at which the truck enters the +5% grade; it corresponds to the same speed as that of a truck on a +5% grade after 1,300 ft. The truck travels another 2,600 ft (to 3,900 ft) on the +5% curve, where a final speed of 27 mi/h is reached. The intersection of a horizontal drawn at 27 mi/h and a vertical drawn at a total length of grade of 5,600 ft yields the equivalent of +5%. In effect, because trucks on this grade are at crawl speed, it does not matter how long the grade is: 27 mi/h can be maintained indefinitely.

Exhibit 11-21
Determination of Composite Grade Equivalents for Example Problem 4



The equivalent grade is 5%, 5,600 ft. This equivalent should be applied to *both the upgrade and the downgrade*, even though it is developed specifically for the upgrade.

Although the truck acceleration curves of Appendix A could be used to develop a separate downgrade composite equivalent, it would be very misleading. The truck performance curves assume a maximum speed of 60 mi/h. On a long, steep downgrade, trucks will achieve much higher speeds.

It is highly likely that trucks will be forced to use a low gear to apply engine braking on the grade described. Thus, PCEs for the downgrade will be selected from Exhibit 11-13.

Step 1: Input Data

All input data were specified previously.

Step 2: Compute FFS

FFSs were measured in the field. The upgrade FFS is 70 mi/h; the downgrade FFS is 75 mi/h.

Step 3: Select FFS Curve

The 70-mi/h curve will be used for the upgrade; the 75-mi/h curve will be used for the downgrade.

Step 4: Adjust Demand Volume

The demand flow rates in passenger cars per hour per lane for the upgrade and downgrade are estimated by using Equation 11-2:

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

The PHF is 0.90, there are two lanes on the upgrade and two lanes on the downgrade, and f_p is specified as 0.95. Heavy-vehicle adjustment factors, however, must be determined separately for the upgrade and the downgrade.

The PCE for trucks (E_T) on the upgrade is selected from Exhibit 11-11 for a grade of 5%, >1.00 mi long, with 15% trucks: 3.0. The PCE for the trucks on the downgrade is selected from Exhibit 11-13 for a grade of 4% to 5%, ≤4 mi long: 1.5.

The heavy-vehicle adjustment factors, f_{HV}, are computed by using Equation 11-3:

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

$$f_{HV}\,(\text{upgrade}) = \frac{1}{1 + 0.15(3-1) + 0} = 0.769$$

$$f_{HV}\left(\text{downgrade}\right) = \frac{1}{1 + 0.15(1.5-1) + 0} = 0.930$$

Then

$$v_p\left(\text{upgrade}\right) = \frac{2{,}300}{0.90 \times 2 \times 0.769 \times 0.95} = 1{,}749 \text{ pc/h/ln}$$

$$v_p\left(\text{downgrade}\right) = \frac{2{,}300}{0.90 \times 2 \times 0.930 \times 0.95} = 1{,}446 \text{ pc/h/ln}$$

Since neither of these values exceeds the base capacity of a freeway with FFS = 75 mi/h (downgrade) or FFS = 70 mi/h (upgrade), LOS F does not exist, and the analysis continues to Step 5.

Step 5: Estimate Speed and Density

With the FFS and the demand flow rate determined for both the upgrade and the downgrade, the expected speed and density on each may now be estimated. Speed is estimated by using the equations of Exhibit 11-3.

For the upgrade, the FFS is 70 mi/h, and the demand flow rate is greater than 1,200 pc/h/ln. Then

$$S = 70 - 0.00001160\left(v_p - 1{,}200\right)^2$$

$$S = 70 - 0.00001160\,(1{,}749 - 1{,}200)^2 = 66.5\,\text{mi/h}$$

For the downgrade, the FFS is 75 mi/h, and the demand flow rate is greater than 1,000 pc/h/ln. Then

$$S = 75 - 0.00001107\left(v_p - 1{,}000\right)^2$$

$$S = 75 - 0.00001107\,(1{,}446 - 1{,}000)^2 = 72.8 \text{ mi/h}$$

Densities may now be estimated from the demand flow rates and estimated speeds:

$$D = \frac{v_p}{S}$$

$$D(\text{upgrade}) = \frac{1{,}749}{66.5} = 26.3 \text{ pc/mi/ln}$$

$$D(\text{downgrade}) = \frac{1{,}446}{72.8} = 19.9 \text{ pc/mi/ln}$$

Step 6: Determine LOS

As shown in Exhibit 11-5, the upgrade LOS is D; the downgrade LOS is C. Both levels, however, are close to the boundaries for better operations—the upgrade is close to the boundary for LOS C (D = 26 pc/mi/ln) and the downgrade is close to the boundary for LOS B (D = 18 pc/mi/ln).

Discussion

Both the upgrade and the downgrade are operating at what would generally be called acceptable levels. If traffic grows over time, the addition of a truck climbing lane on the upgrade might be considered.

EXAMPLE PROBLEM 5: DESIGN-HOUR VOLUME AND NUMBER OF LANES

The Facts

- Demand volume = 75,000 veh/day,
- Proportion of AADT in the peak hour: 0.09,
- Directional distribution: 55/45,
- Rolling terrain, and
- Target LOS = D.

Comments

In this planning and preliminary engineering application, several input variables are not specified, so default values will have to be used. With knowledge of local conditions and freeway design standards, the following default values will be used in the solution: FFS = 65 mi/h; 5% trucks, no RVs; PHF = 0.95; and f_p = 1.00.

Determining Opening-Day Directional Design-Hour Volume

Because the demand volume is given as an AADT, it must be converted to a directional design-hour volume (DDHV) by using Equation 11-8:

$$V = DDHV = AADT \times K \times D$$

$$V = DDHV = 75{,}000 \times 0.09 \times 0.55 = 3{,}713 \text{ veh/h}$$

Step 1: Input Data

All input data were specified.

Step 2: Compute FFS

A default value of 65 mi/h will be used in this problem.

Step 3: Select FFS Curve

The 65-mi/h speed–flow curve will be used in this problem.

Step 4: Determine Number of Lanes Required

After estimating the demand volume on an hourly basis, the remainder of this solution follows the design application. The number of lanes needed is estimated by using Equation 11-7:

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

The maximum service flow rate is selected from Exhibit 11-17 for LOS D on a 65-mi/h basic freeway segment: 2,030 pc/h/ln. The PHF is a default value: 0.95. The driver population factor is also a default value: 1.00. The freeway is in rolling terrain and is expected to have 5% trucks (another default value). From Equation 11-10, for rolling terrain, $E_T = 2.5$. Then

$$f_{HV} = \frac{1}{1 + 0.05(2.5 - 1) + 0} = 0.930$$

$$N = \frac{3{,}713}{2{,}030 \times 0.95 \times 0.93 \times 1.00} = 2.07 \text{ lanes}$$

Because fractional lanes cannot be built, three lanes will have to be provided in each direction to ensure that LOS D is provided during the worst 15 min of the peak hour. Therefore, the resulting LOS may be better than the design target.

Step 5: Estimate Speed and Density

In order to determine the likely LOS resulting from a six-lane freeway, the speed and density should be estimated. Equation 11-2 is used to determine the actual demand flow rate for three lanes:

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

$$v_p = \frac{3{,}713}{0.95 \times 3 \times 0.93 \times 1.00} = 1{,}401 \text{ pc/h/ln}$$

From Exhibit 11-3, for a 65-mi/h basic freeway segment with more than 1,400 pc/h/ln, the expected speed is

$$S = 65 - 0.00001418\left(v_p - 1{,}400\right)^2$$

$$S = 65 - 0.00001418(1{,}401 - 1{,}400)^2 = 65.0 \text{ mi/h}$$

and the density is

$$D = \frac{v_p}{S} = \frac{1{,}401}{65.0} = 21.6 \text{ pc/mi/ln}$$

Step 6: Determine LOS

As shown in Exhibit 11-5, the expected LOS is C.

Discussion

This problem illustrates an interesting point: given the parameters of this example problem, the target LOS of D cannot be achieved on opening day. If a four-lane freeway (two lanes in each direction) is built, LOS E will result. If a six-lane freeway (three lanes in each direction) is built, LOS C will result.

EXAMPLE PROBLEM 6: SERVICE FLOW RATES AND SERVICE VOLUMES

The Facts

- Eight-lane freeway;
- FFS = 70 mi/h (measured);
- Traffic composition: 8% trucks, 1% RVs;
- Rolling terrain;
- PHF = 0.87;
- Driver population factor f_p = 1.00;
- Proportion of AADT in peak hour (*K*-factor): 0.08; and
- Directional distribution (*D*-factor): 60/40.

Comments

In this problem, the service flow rate, service volume, and daily service volume for each LOS will be computed. These values could then be compared with any existing or forecast demand volumes to determine the LOS.

Step 1: Input Data

All input data were specified.

Step 2: Compute FFS

The FFS has been field-measured as 70 mi/h.

Step 3: Select FFS Curve

The curve for FFS = 70 mi/h will be used.

Step 4: Compute Service Flow Rates, *SF*

For a 70-mi/h basic freeway segment, maximum service flow rates, *MSF*, can be selected from Exhibit 11-17. These are the maximum service flow rates that can be sustained while a given LOS is maintained. They are stated as flow rates in passenger cars per hour per lane for equivalent base conditions. The values are

- MSF_A = 770 pc/h/ln,
- MSF_B = 1,250 pc/h/ln,
- MSF_C = 1,690 pc/h/ln,
- MSF_D = 2,080 pc/h/ln, and
- MSF_E = 2,400 pc/h/ln.

Service flow rates, SF, are estimated by using Equation 11-9:

$$SF_i = MSF_i \times N \times f_{HV} \times f_p$$

where the maximum service flow rates are as cited, N = 4 lanes in each direction, and the driver population factor f_p is 1.00. The heavy-vehicle adjustment factor must be determined for 8% trucks and 1% RVs in rolling terrain. From Exhibit 11-10, for rolling terrain, E_T = 2.5 and E_R = 2.0. Then

$$f_{HV} = \frac{1}{1 + 0.08(2.5-1) + 0.01(2.0-1)} = 0.885$$

Service flow rates may now be computed:

$$SF_A = 770 \times 4 \times 0.885 \times 1.00 = 2{,}726 \text{ veh/h}$$

$$SF_B = 1{,}250 \times 4 \times 0.885 \times 1.00 = 4{,}425 \text{ veh/h}$$

$$SF_C = 1{,}690 \times 4 \times 0.885 \times 1.00 = 5{,}983 \text{ veh/h}$$

$$SF_D = 2{,}080 \times 4 \times 0.885 \times 1.00 = 7{,}363 \text{ veh/h}$$

$$SF_E = 2{,}400 \times 4 \times 0.885 \times 1.00 = 8{,}496 \text{ veh/h}$$

Service flow rates are the maximum rates of flow that may exist in the worst 15-min period of the peak hour while the stated LOS is maintained.

Step 5: Compute Service Volumes, *SV*

Equation 11-10 is used to convert service flow rates to service volumes. The conversion multiplies the service flow rates by the PHF to produce maximum hourly volumes that can be accommodated while the given LOS is maintained during the worst 15 min of the hour.

$$SV_i = SF_i \times PHF$$

$$SV_A = 2{,}726 \times 0.87 = 2{,}372 \text{ veh/h}$$

$$SV_B = 4{,}425 \times 0.87 = 3{,}850 \text{ veh/h}$$

$$SV_C = 5{,}983 \times 0.87 = 5{,}205 \text{ veh/h}$$

$$SV_D = 7{,}363 \times 0.87 = 6{,}406 \text{ veh/h}$$

$$SV_E = 8{,}496 \times 0.87 = 7{,}392 \text{ veh/h}$$

Step 6: Compute Daily Service Volumes, *DSV*

Equation 11-11 is used to convert service volumes to daily service volumes. Daily service volumes are the maximum AADTs that can be accommodated while the given LOS is maintained during the worst 15 min of the peak hour in the peak direction of flow.

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

$$DSV_A = \frac{2{,}372}{0.08 \times 0.60} = 49{,}417 \text{ veh/day}$$

$$DSV_B = \frac{3{,}850}{0.08 \times 0.60} = 80{,}208 \text{ veh/day}$$

$$DSV_C = \frac{5{,}205}{0.08 \times 0.60} = 108{,}438 \text{ veh/day}$$

$$DSV_D = \frac{6{,}406}{0.08 \times 0.60} = 133{,}458 \text{ veh/day}$$

$$DSV_E = \frac{7{,}392}{0.08 \times 0.60} = 154{,}000 \text{ veh/day}$$

Discussion

These results can be conveniently shown in the form of a table, as illustrated in Exhibit 11-22. Given the approximate nature of these computations and the default values used, it is appropriate to round the DSV values to the nearest 100 veh/day, and SF and SV values to the nearest 10 veh/h.

Exhibit 11-22
Service Flow Rates, Service Volumes, and Daily Service Volumes for Example Problem 6

LOS	*SF* (veh/h)	*SV* (veh/h)	*DSV* (veh/day)
A	2,730	2,370	49,400
B	4,430	3,850	80,200
C	5,980	5,210	108,400
D	7,360	6,410	133,500
E	8,500	7,390	154,000

Exhibit 11-22, of course, applies only to the basic freeway segment as described. Should any of the prevailing conditions change, the values in the exhibit would also change. However, for a given segment, forecast demand volumes, whether given as flow rates, hourly volumes, or AADTs, could be compared with the criteria in Exhibit 11-22 to determine the likely LOS immediately. For example, if the 10-year forecast AADT for this segment is 125,000 veh/day, the expected LOS would be D.

5. REFERENCES

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

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6. Banks, J. H. Flow Processes at a Freeway Bottleneck. In *Transportation Research Record 1287*, Transportation Research Board, National Research Council,Washington, D.C., 1990, pp. 20–28.
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13. Zegeer, J. D., M. A. Vandehey, M. Blogg, K. Nguyen, and M. Ereti. *NCHRP Report 599: Default Values for Highway Capacity and Level of Service Analyses.* Transportation Research Board of the National Academies, Washington, D.C., 2008.

APPENDIX A: COMPOSITE GRADES

The composite grade procedure should be used for a series of grades that are ≥4,000 ft in length and that have a portion of the grade steeper than 4%.

The procedure finds the equivalent single grade that results in the same final truck speed as the series of grades would.

In a basic freeway segment analysis, an overall average grade can be substituted for a series of grades if no single portion of the grade is steeper than 4% or the total length of the grade is less than 4,000 ft. For grades outside these limits (i.e., a portion of the grade is greater than 4% *and* the total length of the grade is greater than or equal to 4,000 ft), the composite grade procedure presented in this appendix is recommended. The composite grade procedure is used to determine an equivalent grade that will result in the same final speed of trucks as would the series of grades making up the composite.

The acceleration and deceleration curves presented here are for vehicles with an average weight-to-horsepower ratio of 200 lb/hp, heavier than typical trucks found on freeways, which range between 125 lb/hp and 150 lb/hp. This is done in recognition of the fact that heavier trucks will have more of an impact on the traffic stream than lighter trucks.

Exhibit 11-A1 shows typical acceleration (*dashed lines*) and deceleration (*solid lines*) performance for a truck with a ratio of 200 lb/hp. The curves are conservative in that they assume a maximum truck speed of 55 mi/h for trucks entering a grade and 60 mi/h for trucks accelerating on a grade.

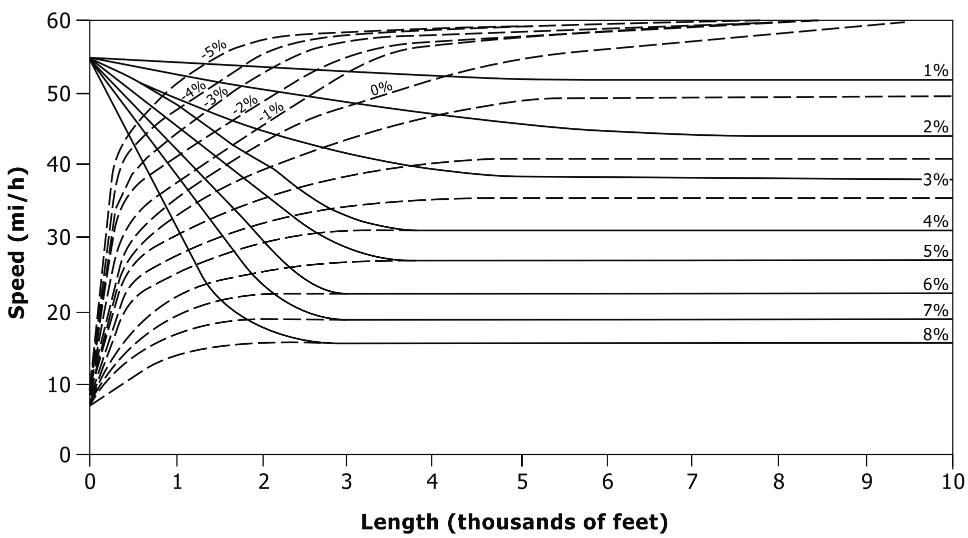


Exhibit 11-A1
Performance Curves for 200-lb/hp Truck

EXAMPLE PROBLEM

An example is provided to illustrate the process involved in determining an equivalent grade for a composite grade on a freeway. The example has two segments, but the procedure is valid for any number of segments. The composite grade is

- Upgrade of 2% for 5,000 ft, followed by
- Upgrade of 6% for 5,000 ft.

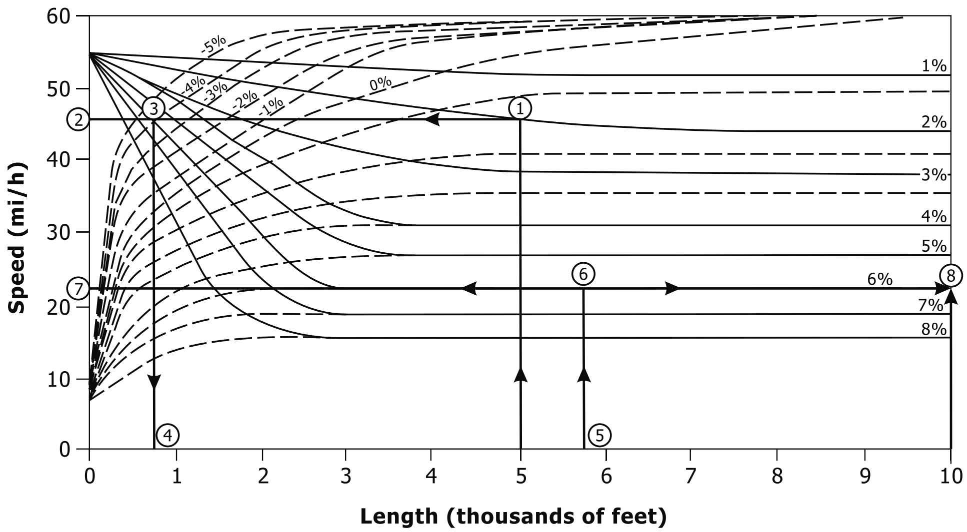
This grade should not be analyzed with an average grade approach, because one portion of the grade is steeper than 4% and the total length of the grade is in excess of 4,000 ft. As a comparison, application of the average grade approach in this case would yield the following:

- Total rise along composite: (5,000 × 0.02) + (5,000 × 0.06) = 400 ft.
- Average grade: 400/10,000 = 0.04, or 4%.

With the average grade approach, the composite would be analyzed as if it were a single upgrade of 4%, 10,000 ft (1.89 mi) long.

Exhibit 11-A2 illustrates the recommended solution.

Exhibit 11-A2
Solution Using Composite Grade Procedure



The flat portions of the upgrade curves indicate the truck crawl speed for that grade.

A vertical line is drawn at 5,000 ft to the intersection with the curve for the +2% grade (Point 1). A horizontal line is drawn from the intersection point to the *y*-axis (Point 2). This procedure indicates that after 5,000 ft of +2% upgrade, trucks will be operating at a speed of approximately 46 mi/h.

This speed is also the speed at which trucks enter the +6% segment of the composite grade. The intersection of the 46-mi/h horizontal line with the curve for the +6% grade (Point 3) is found. A vertical line is dropped from this point to the *x*-axis (Point 4). This procedure indicates that trucks enter the +6% segment of the composite as if they had already been on the +6% grade for approximately 800 ft. Trucks will travel another 5,000 ft along the +6% grade, starting from Point 4. A vertical line is drawn at a distance of 800 + 5,000 = 5,800 ft (Point 5) to the intersection with the curve for the +6% grade (Point 6). A horizontal line drawn from this point to the *y*-axis (Point 7) indicates that the speed of trucks at the end of the two-segment composite grade will be approximately 23 mi/h.

The solution point is found as the intersection of a vertical line drawn at 10,000 ft (the total length of the composite grade) and a horizontal line drawn at 23 mi/h. The solution is read as the percent grade on which the solution point lies (Point 8). In this case, the point lies exactly on the curve for the 6% grade. Interpolations between curves are permissible.

In this case, the grade that is equivalent to the composite grade is a single grade of 6%, 10,000 ft (1.89 mi) long. This grade is 2% higher than the 4% average grade. The appropriate equivalent grade is the same percentage as the second segment of the composite grade because trucks have already reached crawl speed. Once trucks hit crawl speed, it does not matter how far from the beginning of the grade they are; their speed will remain constant.

PROCEDURAL STEPS

The general steps taken in solving for a composite-grade equivalent are summarized as follows:

1. Enter Exhibit 11-A1 with the length of the first segment of the composite grade.
2. Find the truck speed at the end of the first segment of the grade.
3. Find the length along the second segment of the grade that results in the same speed as that found in Step 2.
4. Add the length of the Segment 2 grade to the length determined in Step 3.
5. Repeat Steps 2 through 4 for each subsequent grade segment.
6. Find the intersection of a vertical line drawn at the total length of the composite grade and a horizontal line drawn at the final speed of trucks at the end of the composite grade.
7. Determine the percent of grade for the solution point of Step 6.

DISCUSSION

In the analysis of composite grades, the point of interest is not always at the end of the grade. It is important to identify the point at which the speed of trucks is the lowest because this is where trucks will have the maximum impact on operating conditions. This point may be an intermediate point. If a +3% grade of 1,000 ft is followed by a +4% grade of 2,000 ft, then by a +2% grade of 1,500 ft, the speed of trucks will be slowest at the end of the +4% grade segment. Thus, a composite grade solution would be sought for the first two segments of the grade, with a total grade length of 1,000 + 2,000 = 3,000 ft.

The composite grade procedure is not applicable in all cases, especially if the first segment is a downgrade and the segment length is long or if the segments are too short. In the use of performance curves, cases that cannot be solved with this procedure will become apparent to the analyst because the line will not intersect or the points will fall outside the limits of the curves. In such cases, field measurements of speeds should be used as inputs to the selection of appropriate truck equivalency values.