CHAPTER 23

BASIC FREEWAY SEGMENTS

CONTENTS

EXHIBITS

I. INTRODUCTION

Background and concepts for this chapter are given in Chapter 13

The methodology in this chapter can be used to analyze the capacity, level of service (LOS), lane requirements, and effects of traffic and design features of basic freeway segments.

The methodology in this chapter is based on the results of an NCHRP study (*1*). The study used additional references to develop the methodology (*2–11*). Updates to the original methodology were subsequently developed (*12*).

BASE CONDITIONS FOR BASIC FREEWAY SEGMENTS

The base conditions under which the full capacity of a basic freeway segment is achieved are good weather, good visibility, and no incidents or accidents. For the analysis procedures in this chapter, these base conditions are assumed to exist. If any of these conditions fails to exist, the speed, LOS, and capacity of the freeway segment all tend to be reduced.

Base conditions for freeway flow

The specific speed-flow-density relationship of a basic freeway segment depends on prevailing traffic and roadway conditions. A set of base conditions for basic freeway segments has been established. These conditions serve as a starting point for the methodology in this chapter.

- Minimum lane widths of 3.6 m;
- Minimum right-shoulder lateral clearance between the edge of the travel lane and the nearest obstacle or object that influences traffic behavior of 1.8 m;
- Minimum median lateral clearance of 0.6 m;
- Traffic stream composed entirely of passenger cars;
- Five or more lanes for one direction (in urban areas only);
- Interchange spacing at 3 km or greater;
- Level terrain, with grades no greater than 2 percent; and
- A driver population composed principally of regular users of the facility.

These base conditions represent a high operating level, with a free-flow speed (FFS) of 110 km/h or greater.

LIMITATIONS OF THE METHODOLOGY

The methodology does not apply to or take into account (without modification by the analyst) the following:

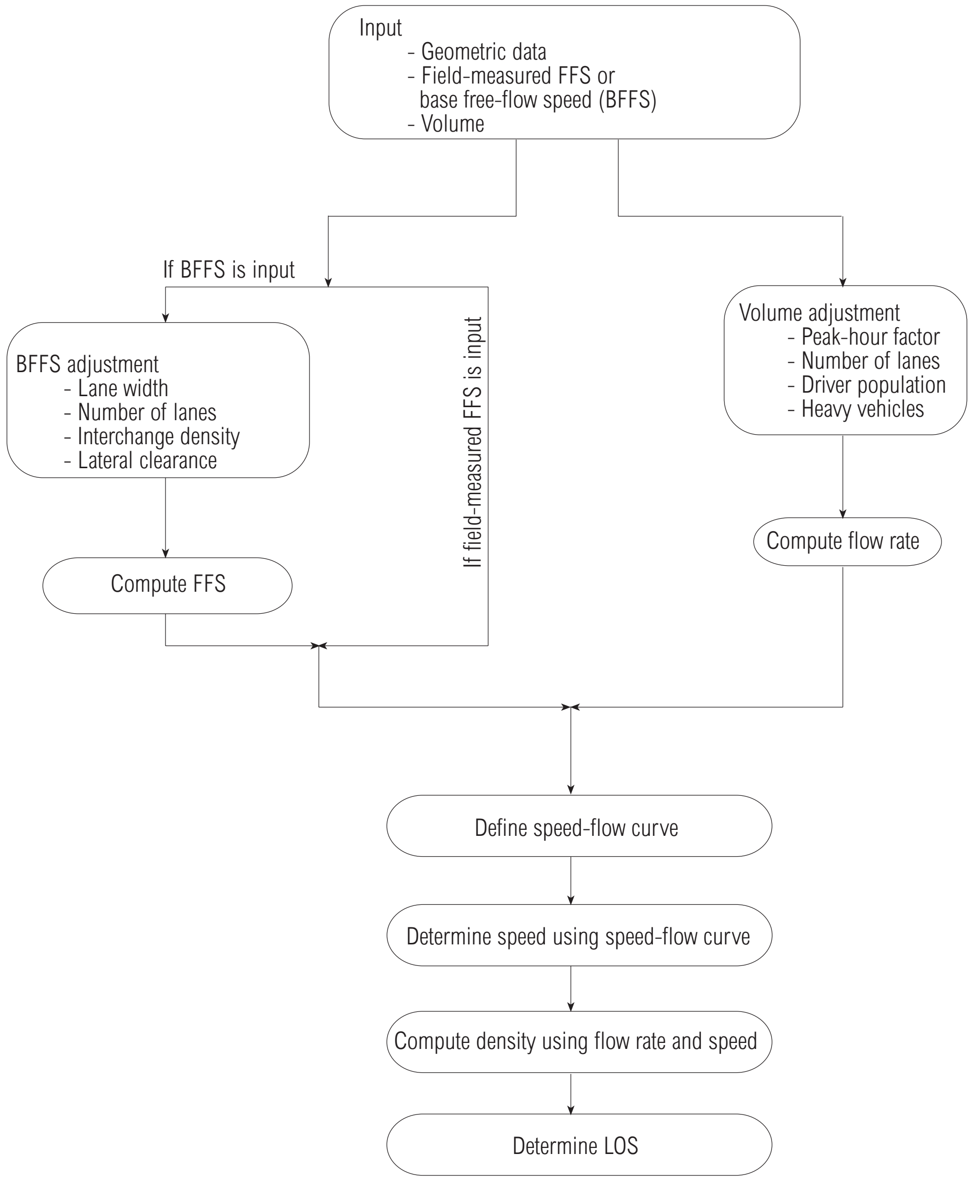
- Special lanes reserved for a single vehicle type, such as high-occupancy vehicle (HOV) lanes, truck lanes, and climbing lanes;
- Extended bridge and tunnel segments;
- Segments near a toll plaza;
- Facilities with free-flow speeds below 90 km/h or in excess of 120 km/h;
- Demand conditions in excess of capacity (refer to Chapter 22 for further discussion);
- The influence of downstream blockages or queuing on a segment;
- Posted speed limit, the extent of police enforcement, or the presence of intelligent transportation systems features related to vehicle or driver guidance; or
- Capacity-enhancing effects of ramp metering.

The analyst would have to draw on other research information and develop special-purpose modifications of this methodology to incorporate the effects of the above conditions.

II. METHODOLOGY

The methodology described in this chapter is for the analysis of basic freeway segments. A method for analysis of extended lengths of freeway that comprise a combination of basic segments, weaving segments, and ramp junctions is found in Chapter 22. Exhibit 23-1 illustrates input to and the basic computation order of the method for basic freeway segments. The primary output of the method is LOS.

EXHIBIT 23-1. BASIC FREEWAY SEGMENT METHODOLOGY



LOS

A basic freeway segment can be characterized by three performance measures: density in terms of passenger cars per kilometer per lane, speed in terms of mean passenger-car speed, and volume-to-capacity (v/c) ratio. Each of these measures is an indication of how well traffic flow is being accommodated by the freeway.

The measure used to provide an estimate of level of service is density. The three measures of speed, density, and flow or volume are interrelated. If values for two of these measures are known, the third can be computed.

Level-of-service thresholds for a basic freeway segment are summarized below.

Density is used to define LOS

LOS	Density Range (pc/km/ln)
A	0–7
B	> 7–11
C	> 11–16
D	> 16–22
E	> 22–28
F	> 28

Density greater than 28 pc/km/ln (LOS F) indicates a queue that extends into the segment

For any given level of service, the maximum allowable density is somewhat lower than that for the corresponding level of service on multilane highways. This reflects the higher quality of service drivers expect when using freeways as compared with surface multilane facilities. This does not imply that an at-grade multilane highway will perform better than a freeway with the same number of lanes under similar conditions. For any given density, a freeway will carry higher flow rates at higher speeds than will a comparable multilane highway.

The specification of maximum densities for LOS A through D is based on the collective professional judgment of the members of the Committee on Highway Capacity and Quality of Service of the Transportation Research Board. The upper value shown for LOS E (28 pc/km/ln) is the maximum density at which sustained flows at capacity are expected to occur.

LOS criteria for basic freeway segments are given in Exhibit 23-2 for free-flow speeds of 120 km/h or greater, 110 km/h, 100 km/h, and 90 km/h. To be within a given LOS, the density criterion must be met. In effect, under base conditions, these are the speeds and flow rates expected to occur at the density shown for each LOS.

EXHIBIT 23-2. LOS CRITERIA FOR BASIC FREEWAY SEGMENTS

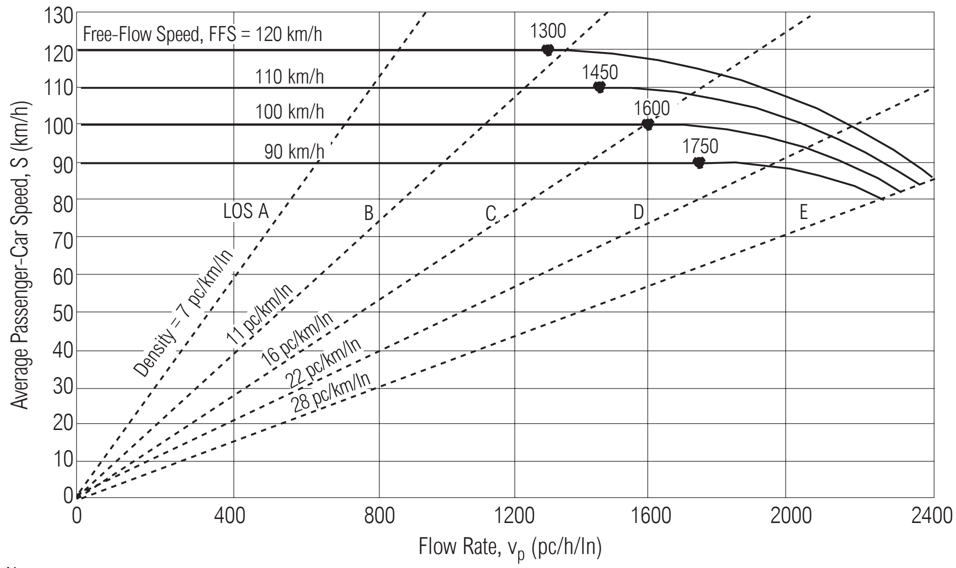
Criteria	LOS				
	A	B	C	D	E
FFS = 120 km/h					
Maximum density (pc/km/ln)	7	11	16	22	28
Minimum speed (km/h)	120.0	120.0	114.6	99.6	85.7
Maximum v/c	0.35	0.55	0.77	0.92	1.00
Maximum service flow rate (pc/h/ln)	840	1320	1840	2200	2400
FFS = 110 km/h					
Maximum density (pc/km/ln)	7	11	16	22	28
Minimum speed (km/h)	110.0	110.0	108.5	97.2	83.9
Maximum v/c	0.33	0.51	0.74	0.91	1.00
Maximum service flow rate (pc/h/ln)	770	1210	1740	2135	2350
FFS = 100 km/h					
Maximum density (pc/km/ln)	7	11	16	22	28
Minimum speed (km/h)	100.0	100.0	100.0	93.8	82.1
Maximum v/c	0.30	0.48	0.70	0.90	1.00
Maximum service flow rate (pc/h/ln)	700	1100	1600	2065	2300
FFS = 90 km/h					
Maximum density (pc/km/ln)	7	11	16	22	28
Minimum speed (km/h)	90.0	90.0	90.0	89.1	80.4
Maximum v/c	0.28	0.44	0.64	0.87	1.00
Maximum service flow rate (pc/h/ln)	630	990	1440	1955	2250

Note:
The exact mathematical relationship between density and v/c has not always been maintained at LOS boundaries because of the use of rounded values. Density is the primary determinant of LOS. The speed criterion is the speed at maximum density for a given LOS.

Failure, breakdown, congestion, and LOS F occur when queues begin to form on the freeway. Density tends to increase sharply within the queue and may be considerably higher than the maximum value of 28 pc/km/ln for LOS E. Further guidance on analysis of basic freeway segments with densities greater than 28 pc/km/ln is provided in Chapter 22.

Exhibit 23-3 shows the relationship between speed, flow, and density for basic freeway segments. It also shows the definition of the various LOS on the basis of density boundary values.

EXHIBIT 23-3. SPEED-FLOW CURVES AND LOS FOR BASIC FREEWAY SEGMENTS



Note:
Capacity varies by free-flow speed. Capacity is 2400, 2350, 2300, and 2250 pc/h/ln at free-flow speeds of 120, 110, 100, and 90 km/h, respectively.

For $90 \le FFS \le 120$ and for flow rate (v_p)
$(3100 - 15FFS) < v_p \le (1800 + 5FFS)$,

$$S = FFS - \left[\frac{1}{28}(23FFS - 1800)\left(\frac{v_p + 15FFS - 3100}{20FFS - 1300}\right)^{2.6}\right]$$

For $90 \le FFS \le 120$ and
$v_p \le (3100 - 15FFS)$,
$S = FFS$

DETERMINING FFS

Measure or estimate the FFS

FFS is the mean speed of passenger cars measured during low to moderate flows (up to 1,300 pc/h/ln). For a specific segment of freeway, speeds are virtually constant in this range of flow rates. Two methods can be used to determine the FFS of a basic freeway segment: field measurement and estimation with guidelines provided in this chapter. The field-measurement procedure is provided for users who prefer to gather these data directly. However, field measurements are not required for application of the method. If field-measured data are used, no adjustments are made to the free-flow speed.

Measurement of free-flow speed

The speed study should be conducted at a location that is representative of the segment when flows and densities are low (flow rates may be up to 1,300 pc/h/ln). Weekday off-peak hours are generally good times to observe low to moderate flow rates. The speed study should measure the speeds of all passenger cars or use a systematic sample (e.g., every 10th passenger car). The speed study should measure passenger-car speeds across all lanes. 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 speed studies may be used. Further guidance on the conduct of speed studies is found in standard traffic engineering publications, such as the *Manual of Traffic Engineering Studies* published by the Institute of Transportation Engineers.

The average of all passenger-car speeds measured in the field under low- to moderate-volume conditions can be used directly as the FFS of the freeway segment. This speed reflects the net effect of all conditions at the study site that influence speed, including those considered in this method (lane width, lateral clearance, interchange density, and number of lanes) as well as others such as speed limit and vertical and horizontal alignment. Speed data that include both passenger cars and heavy vehicles can be used for level terrain or moderate downgrades but should not be used for rolling or mountainous terrain.

Estimate free-flow speed if measurement is not possible

If field measurement of FFS is not possible, FFS can be estimated indirectly on the basis of the physical characteristics of the freeway segment being studied. The physical characteristics include lane width, number of lanes, right-shoulder lateral clearance, and interchange density. Equation 23-1 is used to estimate the free-flow speed of a basic freeway segment:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \qquad (23\text{-}1)$$

where

FFS = free-flow speed (km/h);
$BFFS$ = base free-flow speed, 110 km/h (urban) or 120 km/h (rural);
f_{LW} = adjustment for lane width from Exhibit 23-4 (km/h);
f_{LC} = adjustment for right-shoulder lateral clearance from Exhibit 23-5 (km/h);
f_N = adjustment for number of lanes from Exhibit 23-6 (km/h); and
f_{ID} = adjustment for interchange density from Exhibit 23-7 (km/h).

BFFS

Estimation of FFS for an existing or future freeway segment is accomplished by adjusting a base free-flow speed downward to reflect the influence of four factors: lane width, lateral clearance, number of lanes, and interchange density. Thus, the analyst is required to select an appropriate BFFS as a starting point.

Adjustment for Lane Width

The base condition for lane width is 3.6 m or greater. When the average lane width across all lanes is less than 3.6 m, the base free-flow speed (e.g., 120 km/h) is reduced. Adjustments to reflect the effect of narrower average lane width are given in Exhibit 23-4.

EXHIBIT 23-4. ADJUSTMENTS FOR LANE WIDTH

Lane Width (m)	Reduction in Free-Flow Speed, f_{LW} (km/h)
3.6	0.0
3.5	1.0
3.4	2.1
3.3	3.1
3.2	5.6
3.1	8.1
3.0	10.6

Adjustment for Lateral Clearance

Base lateral clearance is 1.8 m or greater on the right side and 0.6 m or greater on the median or left side, measured from the edge of the paved shoulder to the nearest edge of the traveled lane. When the right-shoulder lateral clearance is less than 1.8 m, the BFFS is reduced. Adjustments to reflect the effect of narrower right-shoulder lateral clearance are given in Exhibit 23-5. No adjustments are available to reflect the effect of median lateral clearance less than 0.6 m. Lateral clearance less than 0.6 m on either the right or left side of a freeway is considered rare. Considerable judgment must be used in determining whether objects or barriers along the right side of a freeway present a true obstruction. Such obstructions may be continuous, such as retaining walls, concrete barriers, or guardrails, or may be noncontinuous, such as light supports or bridge abutments. In some cases, drivers may become accustomed to certain types of obstructions, in which case their influence on traffic flow may be negligible.

Adjustment for lateral clearance reflects only the right-shoulder width

EXHIBIT 23-5. ADJUSTMENTS FOR RIGHT-SHOULDER LATERAL CLEARANCE

Right-Shoulder Lateral Clearance (m)	Reduction in Free-Flow Speed, f_{LC} (km/h)			
	Lanes in One Direction			
	2	3	4	≥ 5
≥ 1.8	0.0	0.0	0.0	0.0
1.5	1.0	0.7	0.3	0.2
1.2	1.9	1.3	0.7	0.4
0.9	2.9	1.9	1.0	0.6
0.6	3.9	2.6	1.3	0.8
0.3	4.8	3.2	1.6	1.1
0.0	5.8	3.9	1.9	1.3

Adjustment for Number of Lanes

Adjustment for number of lanes (not applicable to rural freeway segments)

Freeway segments with five or more lanes (in one direction) are considered as having base conditions with respect to number of lanes. When fewer lanes are present, the BFFS is reduced. Exhibit 23-6 provides adjustments to reflect the effect of number of lanes on BFFS. In determining number of lanes, only mainline lanes, both basic and auxiliary, should be considered. HOV lanes should not be included.

EXHIBIT 23-6. ADJUSTMENTS FOR NUMBER OF LANES

Number of Lanes (One Direction)	Reduction in Free-Flow Speed, f_N (km/h)
≥ 5	0.0
4	2.4
3	4.8
2	7.3

Note: For all rural freeway segments, f_N is 0.0.

The adjustments in Exhibit 23-6 are based exclusively on data collected on urban and suburban freeways and do not reflect conditions on rural freeways, which typically carry two lanes in each direction. In using Equation 23-1 to estimate the FFS of a rural freeway segment, the value of the adjustment for number of lanes, f_N, should be 0.0.

Adjustment for Interchange Density

A 10-km segment is used to determine interchange density

The base interchange density is 0.3 interchanges per kilometer, or 3.3-km interchange spacing. Base free-flow speed is reduced when interchange density becomes greater. Adjustments to reflect the effect of interchange density are provided in Exhibit 23-7. Interchange density is determined over a 10-km segment of freeway (5 km upstream and 5 km downstream) in which the freeway segment is located. An interchange is defined as having at least one on-ramp. Therefore, interchanges that have only off-ramps would not be considered in determining interchange density. Interchanges considered should include typical interchanges with arterials or highways and major freeway-to-freeway interchanges.

EXHIBIT 23-7. ADJUSTMENTS FOR INTERCHANGE DENSITY

Interchanges per Kilometer	Reduction in Free-Flow Speed, f_{ID} (km/h)
≤ 0.3	0.0
0.4	1.1
0.5	2.1
0.6	3.9
0.7	5.0
0.8	6.0
0.9	8.1
1.0	9.2
1.1	10.2
1.2	12.1

DETERMINING FLOW RATE

The hourly flow rate must reflect the influence of heavy vehicles, the temporal variation of traffic flow over an hour, and the characteristics of the driver population. These effects are reflected by adjusting hourly volumes or estimates, typically reported in vehicles per hour (veh/h), to arrive at an equivalent passenger-car flow rate in passenger cars per hour (pc/h). The equivalent passenger-car flow rate is calculated using the heavy-vehicle and peak-hour adjustment factors and is reported on a per lane basis (pc/h/ln). Equation 23-2 is used to calculate the equivalent passenger-car flow rate.

$$v_p = \frac{V}{PHF * N * f_{HV} * f_p} \tag{23-2}$$

Convert veh/h to pc/h using heavy-vehicle, peak-hour, and driver population factors

where

v_p = 15-min passenger-car equivalent flow rate (pc/h/ln),
V = hourly volume (veh/h),
PHF = peak-hour factor,
N = number of lanes,
f_{HV} = heavy-vehicle adjustment factor, and
f_p = driver population factor.

Peak-Hour Factor

The peak-hour factor (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 period within an hour are not sustained throughout the entire hour. The application of the peak-hour factor in Equation 23-2 accounts for this phenomenon.

On freeways, typical PHFs range from 0.80 to 0.95. Lower PHFs are characteristic of rural freeways or off-peak conditions. Higher factors are typical of urban and suburban peak-hour conditions. Field data should be used, if possible, to develop PHFs representative of local conditions.

Heavy-Vehicle Adjustments

Freeway traffic volumes that include a mix of vehicle types must be adjusted to an equivalent flow rate expressed in passenger cars per hour per lane. This adjustment is made using the factor f_{HV}. Once the values of E_T and E_R are found, the adjustment factor, f_{HV}, is determined by using Equation 23-3.

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \tag{23-3}$$

where

E_T, E_R = passenger-car equivalents for trucks/buses and recreational vehicles (RVs) in the traffic stream, respectively;

P_T, P_R = proportion of trucks/buses and RVs in the traffic stream, respectively; and

f_{HV} = heavy-vehicle adjustment factor.

Adjustments for heavy vehicles in the traffic stream apply for three vehicle types: trucks, buses, and RVs. There is no evidence to indicate distinct differences in performance between trucks and buses on freeways, and therefore trucks and buses are treated identically.

In many cases, trucks will be the only heavy-vehicle type present in the traffic stream to a significant degree. Where the percentage of RVs is small compared with the percentage of trucks, it is sometimes convenient to consider all heavy vehicles to be trucks. It is generally acceptable to do this where the percentage of trucks and buses is at least five times the percentage of RVs.

The factor f_{HV} is found using a two-step process. First, the passenger-car equivalent for each truck/bus and RV is found for the traffic and roadway conditions under study. These equivalency values, E_T and E_R, represent the number of passenger cars that would use the same amount of freeway capacity as one truck/bus or RV, respectively, under prevailing roadway and traffic conditions. Second, using the values of E_T and E_R and the proportion of each type of vehicle in the traffic stream (P_T and P_R), the adjustment factor f_{HV} is computed.

The effect of heavy vehicles on traffic flow depends on grade conditions as well as traffic composition. Passenger-car equivalents can be selected for one of three conditions: extended freeway segments, upgrades, and downgrades.

Extended Freeway Segments

Extended segment—use when no one grade (3 percent or greater) is longer than 0.5 km. Use when no one grade (less than 3 percent) is longer than 1 km.

It is often appropriate to consider an extended length of freeway containing a number of upgrades, downgrades, and level segments as a single uniform segment. This is possible where no one grade is long enough or steep enough to have a significant effect on the operation of the overall segment. As a guideline, extended segment analysis can be used where no one grade of 3 percent or greater is longer than 0.5 km or where no one grade of less than 3 percent is longer than 1.0 km.

Specific Grades

Any grade less than 3 percent that is longer than 1.0 km or any grade of 3 percent or more that is longer than 0.5 km must be analyzed as a separate segment because of its significant effect on traffic flow.

Equivalents for Extended Freeway Segments

Whenever extended segment analysis is used, the terrain of the freeway must be classified as level, rolling, or mountainous.

Level Terrain

Level terrain is 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 includes short grades of no more than 2 percent.

Rolling Terrain

Rolling terrain is any combination of grades and horizontal or vertical alignment that causes heavy vehicles to reduce their speeds 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 any grade is long enough, trucks will be forced to decelerate to the crawl speed, which they will then be able to maintain for extended distances. Appendix A contains truck performance curves illustrating crawl speed and length of grade.

Appendix A shows truck performance curves

Mountainous Terrain

Mountainous terrain is any combination of grades and horizontal or vertical alignment that causes heavy vehicles to operate at crawl speeds for significant distances or at frequent intervals.

Exhibit 23-8 gives passenger-car equivalents for extended freeway segments. Note that it is extremely difficult to have mountainous terrain as defined herein without violating the guidelines for using the general terrain methodology (i.e., having no grade greater than 3 percent longer than 0.5 km). To a lesser extent, the same statement may be made with respect to rolling terrain. The equivalence values shown in Exhibit 23-8 are most useful in the planning stage of analysis, when specific alignments are not known but approximate capacity computations are still needed.

EXHIBIT 23-8. PASSENGER-CAR EQUIVALENTS ON EXTENDED FREEWAY SEGMENTS

	Type of Terrain		
Factor	Level	Rolling	Mountainous
E_T (trucks and buses)	1.5	2.5	4.5
E_R (RVs)	1.2	2.0	4.0

Equivalents for Specific Grades

Any freeway grade of more than 1.0 km for grades less than 3 percent or 0.5 km for grades of 3 percent or more should be considered as a separate segment. Analysis of such segments must consider the upgrade and downgrade conditions and whether the grade is a single and isolated grade of constant percentage or part of a series forming a composite grade.

Several studies have indicated that freeway truck populations have an average weight-to-power ratio of between 75 and 90 kg/kW. These procedures adopt passenger-car equivalents calibrated for a mix of trucks/buses in this range. RVs vary considerably in both type and characteristics. These vehicles include everything from cars with trailers to self-contained mobile campers. In addition to the variability of the vehicles, the drivers are not professionals, and their degree of skill in handling such vehicles varies. Typical weight-to-power ratios of RVs range from 20 to 40 kg/kW.

Equivalents for Specific Upgrades

Exhibits 23-9 and 23-10 give values of E_T and E_R for upgrade segments. These factors vary with the percent of grade, length of grade, and the proportion of heavy vehicles in the traffic stream. The maximum values of E_T and E_R occur when there are only a few heavy vehicles. The equivalents decrease as the number of heavy vehicles increases, because these vehicles tend to form platoons and have operating characteristics that are more uniform as a group than those of passenger cars.

Establishing length of grade

The length of grade is generally taken from a profile of the highway in question and 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 percent of the length of the vertical curves at the beginning and end of the grade be included in the length of the grade. Where two consecutive upgrades are present, 50 percent of the length of the vertical curve between them is assigned to the length of each upgrade.

EXHIBIT 23-9. PASSENGER-CAR EQUIVALENTS FOR TRUCKS AND BUSES ON UPGRADES

Upgrade (%)	Length (km)	E_T Percentage 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	0.0–0.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.4–0.8	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.8–1.2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 1.2–1.6	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	> 1.6–2.4	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 2.4	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
> 3–4	0.0–0.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.4–0.8	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	> 0.8–1.2	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	> 1.2–1.6	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	> 1.6–2.4	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	> 2.4	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
> 4–5	0.0–0.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.4–0.8	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 0.8–1.2	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	> 1.2–1.6	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	> 1.6	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
> 5–6	0.0–0.4	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.4–0.5	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 0.5–0.8	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	> 0.8–1.2	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0
	> 1.2–1.6	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	> 1.6	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
> 6	0.0–0.4	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	> 0.4–0.5	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	> 0.5–0.8	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	> 0.8–1.2	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	> 1.2–1.6	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	> 1.6	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

EXHIBIT 23-10. PASSENGER-CAR EQUIVALENTS FOR RVS ON UPGRADES

Upgrade (%)	Length (km)	E_R Percentage 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	0.0–0.8	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	> 0.8	3.0	1.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2
> 3–4	0.0–0.4	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	> 0.4–0.8	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	> 0.8	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
> 4–5	0.0–0.4	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	> 0.4–0.8	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0
	> 0.8	4.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0
> 5	0.0–0.4	4.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5
	> 0.4–0.8	6.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0
	> 0.8	6.0	4.5	4.0	4.5	3.5	3.0	3.0	2.5	2.0

In analyzing upgrades, the point of interest is usually the end of the grade, where heavy vehicles presumably have the maximum effect on operations. This is not always the case, however. If a ramp junction is located midgrade, the point of the merge or diverge will also be a critical point for analysis. In the case of composite grades, the point at which heavy vehicles are traveling slowest is the critical point for analysis. If a 5 percent upgrade is followed by a 2 percent upgrade, it is reasonable to assume that the end of the 5 percent portion will be critical, since heavy vehicles would be expected to accelerate on the 2 percent portion of the grade.

Equivalents for Specific Downgrades

For RVs, downgrades may be treated as level terrain

There are few specific data on the effect of heavy vehicles on traffic flow on downgrades. In general, if the downgrade does not cause trucks to shift into a low gear, they may be treated as if they were level terrain segments, and passenger-car equivalents are selected accordingly. Where more severe downgrades occur, trucks must often use low gears to avoid gaining too much speed and running out of control. In such cases, their effect is greater than it would be on level terrain. Exhibit 23-11 gives values of E_T. For RVs, downgrades may be treated as level terrain.

EXHIBIT 23-11. PASSENGER-CAR EQUIVALENTS FOR TRUCKS AND BUSES ON DOWNGRADES

Downgrade (%)	Length (km)	E_T Percentage of Trucks 5	10	15	20
< 4	All	1.5	1.5	1.5	1.5
4–5	≤ 6.4	1.5	1.5	1.5	1.5
4–5	> 6.4	2.0	2.0	2.0	1.5
> 5–6	≤ 6.4	1.5	1.5	1.5	1.5
> 5–6	> 6.4	5.5	4.0	4.0	3.0
> 6	≤ 6.4	1.5	1.5	1.5	1.5
> 6	> 6.4	7.5	6.0	5.5	4.5

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 significant grades in succession. The most straightforward technique is to compute the average grade to the point in question. The average grade is defined as the total rise from the beginning of the composite grade divided by the length of the grade.

Appendix A gives a detailed composite grade technique

The average grade technique is an acceptable approach for grades in which all subsections are less than 4 percent or the total length of the composite grade is less than 1,200 m. 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.

Driver Population Factor

The traffic stream characteristics that are the basis of this methodology are representative of regular drivers in a substantially commuter traffic stream or in a stream in which most drivers are familiar with the facility. It is generally accepted that traffic streams with different characteristics (i.e., recreational drivers) use freeways less efficiently. Whereas 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 volumes for other levels of service as well.

The adjustment factor f_p is used to reflect this effect. The values of f_p range from 0.85 to 1.00. In general, the analyst should select 1.00, which reflects commuter traffic (i.e., familiar users), unless there is sufficient evidence that a lower value should be applied. Where greater accuracy is needed, comparative field studies of commuter and recreational traffic flow and speeds are recommended.

DETERMINING LOS

The first step in determining LOS of a basic freeway segment is to define and segment the freeway facility as appropriate. Second, on the basis of estimated or field-measured FFS, an appropriate speed-flow curve of the same shape as the typical curves (Exhibit 23-3) is constructed. On the basis of the flow rate, v_p, and the constructed speed-flow curve, an average passenger-car speed is read on the y-axis of Exhibit 23-3. The next step is to calculate density using Equation 23-4.

$$D = \frac{v_p}{S} \tag{23-4}$$

where

- D = density (pc/km/ln),
- v_p = flow rate (pc/h/ln), and
- S = average passenger-car speed (km/h).

LOS of the basic freeway segment is then determined by comparing the calculated density with the density ranges in Exhibit 23-2.

SENSITIVITY OF RESULTS TO INPUT VARIABLES

Downstream conditions may cause backups that result in low speeds and low volumes. The basic freeway segment methodology cannot be applied in such circumstances.

Analysts will note that there is no direct way to calibrate the estimated capacity of the basic freeway segment with field conditions. The analyst must instead calibrate the estimated free-flow speed and demand adjustments with field conditions. Field measurements of density can be used to determine LOS directly.

The FFS for urban freeways is sensitive to the average interchange spacing and the number of lanes in one direction. The sensitivity increases with the number of lanes. Exhibit 23-12 can be used to determine the FFS given the number of lanes in one direction and the average distance between freeway interchanges.

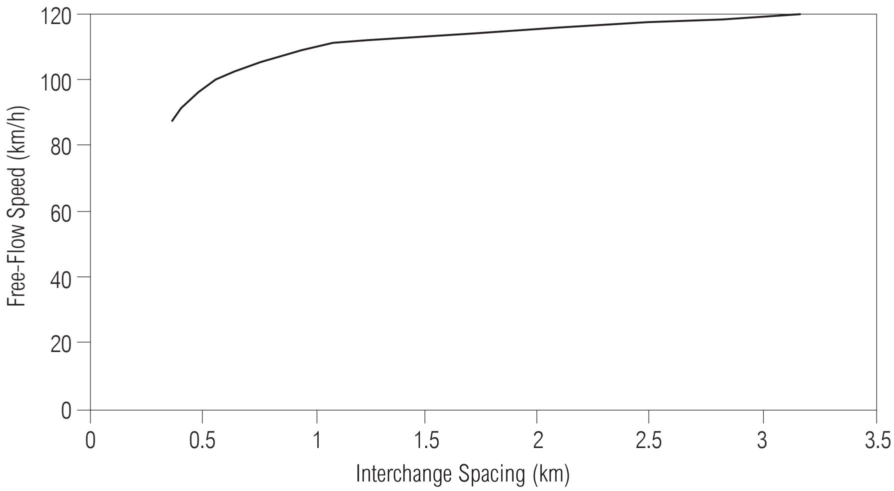
EXHIBIT 23-12. URBAN FREEWAY FFS AND INTERCHANGE SPACING
(SEE FOOTNOTE FOR ASSUMED VALUES)

	Free-Flow Speed (km/h)			
	Interchange Spacing (km)			
Number of Lanes	1.00	1.25	2.00	3.00
2	94	97	101	103
3	96	99	103	105
4	98	102	106	108
5	99	104	108	110

Note:
Assumptions: BFFS = 110 km/h, lane width = 3.6 m, lateral clearance = 1.8 m.

The FFS for rural freeways is sensitive to the average interchange spacing for spacing under 1.0 km. Exhibit 23-13 can be used to determine the FFS for rural freeways given the average interchange spacing.

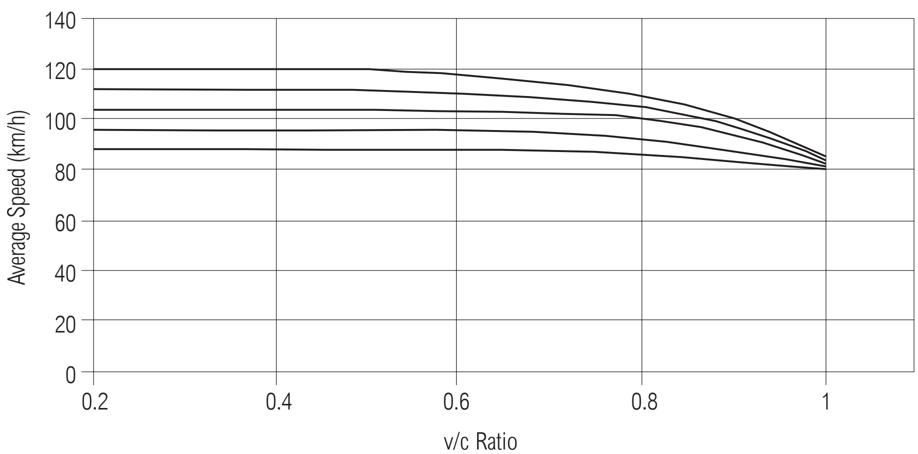
EXHIBIT 23-13. RURAL FREEWAY FFS
(SEE FOOTNOTE FOR ASSUMED VALUES)



Note:
Assumptions: BFFS = 120 km/h, lane width = 3.6 m, lateral clearance = 1.8 m.

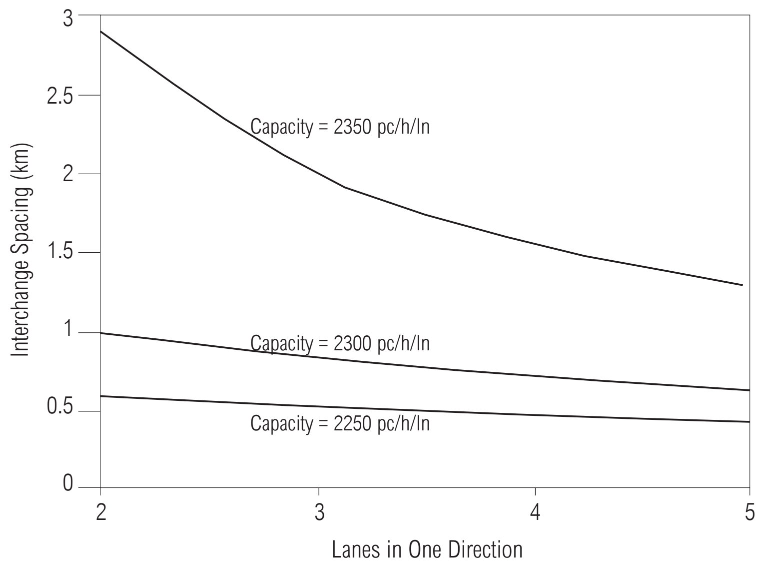
The v/c ratio has relatively little effect on speed until it exceeds 54 to 80 percent, depending on FFS. FFS (which is sensitive to lane width, shoulder width, number of lanes, and interchange spacing) has more effect on mean speed at low v/c ratios than the v/c ratio itself (see Exhibit 23-14).

EXHIBIT 23-14. FREEWAY SPEED-FLOW AND v/c RATIO



For a rural freeway, the capacity per lane is 2,400 pc/h/ln, based on the assumption that rural freeways have interchange spacing of greater than 3.0 km and two lanes in one direction. Exhibit 23-15 can be used to determine capacity for urban freeways with shorter interchange spacing or a different number of lanes.

EXHIBIT 23-15. URBAN FREEWAY CAPACITY AND INTERCHANGE SPACING



III. APPLICATIONS

Guidelines on required inputs and estimated values are given in Chapter 13, "Freeway Concepts"

The methodology of this chapter can be used to analyze the capacity and LOS of basic freeway segments. The analyst must address two fundamental questions. First, the primary output must be identified. Primary outputs typically solved for in a variety of applications include LOS, number of lanes required (N), and flow rate achievable (v_p). Performance measures related to density (D) and speed (S) are also achievable but are considered secondary outputs.

Second, the analyst must identify the default values or estimated values for use in the analysis. Basically, the analyst has three sources of input data:

1. Default values found in this manual,
2. Estimates and locally derived default values developed by the user, and
3. Values derived from field measurements and observation.

A value for each input variable must be supplied to calculate the outputs, both primary and secondary.

A common application of the method is to compute the LOS of an existing segment or a changed facility in the near term or distant future. This type of application is often termed operational, and its primary output is LOS, with secondary outputs for density and speed. Another application is to check the adequacy of or to recommend the number of lanes for a basic freeway segment given the volume or flow rate and LOS goal. This type of application is termed design, since its primary output is the number of lanes required to serve the assumed conditions. Other outputs from this application include speed and density. Finally, the achievable flow rate, v_p, can be calculated as a primary output. This analysis requires an LOS goal and a number of lanes as inputs and typically estimates the flow rate that will cause the highway to operate at an unacceptable LOS.

Another general type of analysis can be termed planning. This type of analysis uses estimates, HCM default values, and local default values as inputs in the calculation. LOS, number of lanes, or flow rate can be determined as outputs along with the secondary outputs of density and speed. The difference between planning analysis and operational or design analysis is that most or all of the input values in planning analysis come from estimates or default values, but the operational and design analyses tend to use field measurements or known values for most or all of the input variables. Note that for each of the analyses, FFS, either measured or estimated, is required as an input in the computation.

SEGMENTING THE FREEWAY

Capacity or LOS analysis requires that the freeway segment have uniform traffic conditions and roadway characteristics. Thus, a point at which there is a change in either the traffic or roadway conditions typically represents an endpoint of the analysis segment.

A number of locations on a freeway form natural boundaries of uniform segments. Any on-ramp or off-ramp is such a boundary, since the volume of freeway traffic changes. The beginning and end of simple or composite grades also act as boundaries. Any point at which the traffic or roadway conditions change should be used as a boundary between uniform segments, each of which should be analyzed separately.

In addition to the natural boundaries created by on-ramps and off-ramps, the following conditions generally dictate that the freeway segment under analysis be segmented:

- Change in the number of lanes,
- Change in the right-shoulder lateral clearance,
- Grade change of 2 percent or more or constant upgrade longer than 1200 m, and
- Change in speed limit.

COMPUTATIONAL STEPS

The basic freeway segments worksheet for computations is shown in Exhibit 23-16. The analyst provides general information and site information for all applications.

Operational (LOS)

For operational (LOS) analysis, all speed and flow data are entered as inputs. Equivalent flow is then computed with the aid of the exhibits for passenger-car equivalents. FFS is estimated by adjusting a base FFS. Finally, LOS is determined by entering (with v_p) the speed-flow graph at the top of the worksheet and intersecting the specific curve that has been selected or constructed for the freeway segment.

This point of intersection identifies the LOS and (on the vertical axis of the graph) the estimated speed, S. If the analyst requires a value for density (D), it is calculated as v_p/S.

Design (N)

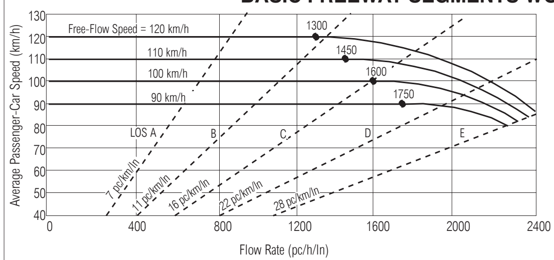
The key to design analysis for number of lanes (N) is establishing an hourly volume. All information, with the exception of number of lanes, can be entered in the flow input and speed input portion of the worksheet (see Exhibit 23-16). An FFS, either computed or measured directly, is entered on the worksheet. The appropriate curve representing the FFS is established on the graph. The required or desired LOS is also entered. Then the analyst assumes N and computes flow, v_p, with the aid of the exhibits for passenger-car equivalents. LOS is determined by entering the speed-flow graph with v_p at the top of the worksheet. Then, the derived LOS is compared with the desired LOS. This process is then repeated, adding one lane to the previously assumed number of lanes, until the determined LOS matches or is better than the desired LOS. Density is calculated using v_p and S.

Design (v_p)

The objective of design analysis for flow rate, v_p, is to estimate the flow rate in passenger cars per hour per lane given a set of traffic, roadway, and FFS conditions. A desired LOS is entered on the worksheet. Then, the FFS of the segment is established using either the BFFS and the four adjustment factors or an FFS measured in the field. Once this facility speed-flow curve is established, the analyst can determine what flow rate is achievable with the given LOS. This would be considered the maximum flow rate achievable or allowable for the given level. The average passenger-car speed is also directly available from the graph. Finally, if required, a value for density can be directly calculated, using the flow rate and the average speed.

EXHIBIT 23-16. BASIC FREEWAY SEGMENTS WORKSHEET

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information

Analyst ____________
Agency or Company ____________
Date Performed ____________
Analysis Time Period ____________

Site Information

Highway/Direction of Travel ____________
From/To ____________
Jurisdiction ____________
Analysis Year ____________

❑ Operational (LOS) ❑ Design (N) ❑ Design (v_p) ❑ Planning (LOS) ❑ Planning (N) ❑ Planning (v_p)

Flow Inputs

Volume, V ____________ veh/h
Annual avg. daily traffic, AADT ____________ veh/day
Peak-hour proportion of AADT, K ____________
Peak-hour direction proportion, D ____________
DDHV = AADT * K * D ____________ veh/h
Driver type ❑ Commuter/Weekday ❑ Recreational/Weekend

Peak-hour factor, PHF ____________
% Trucks and buses, P_T ____________
% RVs, P_R ____________
General terrain
❑ Level ❑ Rolling ❑ Mountainous
Grade Length ________ km Up/Down ________ %

Calculate Flow Adjustments

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

Speed Inputs

Lane width ____________ m
Rt.-shoulder lateral clearance ____________ m
Interchange density ____________ I/km
Number of lanes, N ____________
FFS (measured) ____________ km/h
Base free-flow speed, BFFS ____________ km/h

Calculate Speed Adjustments and FFS

f_{LW} ____________ km/h
f_{LC} ____________ km/h
f_{ID} ____________ km/h
f_N ____________ km/h
$FFS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N$ ____________ km/h

LOS and Performance Measures

Operational (LOS) or Planning (LOS)

$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$ ____________ pc/h/ln
S ____________ km/h
$D = v_p / S$ ____________ pc/km/ln
LOS ____________

Design (v_p) or Planning (v_p)

LOS ____________
v_p ____________ pc/h/ln
$V = v_p * PHF * N * f_{HV} * f_p$ ____________ veh/h
S ____________ km/h
$D = v_p / S$ ____________ pc/km/ln

Design (N) or Planning (N) 1st Iteration

N ____________ assumed
$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$ ____________ pc/h/ln
LOS ____________

Design (N) or Planning (N) 2nd Iteration

N ____________ assumed
$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$ ____________ pc/h/ln
S ____________ km/h
$D = v_p / S$ ____________ pc/km/ln
LOS ____________

Glossary

N - Number of lanes
V - Hourly volume
v_p - Flow rate
LOS - Level of service
DDHV - Directional design-hour volume
S - Speed
D - Density
FFS - Free-flow speed
BFFS- Base free-flow speed

Factor Location

E_R - Exhibits 23-8, 23-10
E_T - Exhibits 23-8, 23-9, 23-11
f_p - Page 23-12
LOS, S, FFS, v_p - Exhibits 23-2, 23-3
f_{LW} - Exhibit 23-4
f_{LC} - Exhibit 23-5
f_N - Exhibit 23-6
f_{ID} - Exhibit 23-7

PLANNING APPLICATIONS

Planning (LOS)
Planning (v_p)
Planning (N)

The three planning applications—planning for LOS, flow rate (v_p), and number of lanes (N)—correspond directly to the procedures described for operations and design. The primary criterion categorizing these as planning applications is the use of estimates, HCM default values, and local default values as inputs into the calculations. The use of annual average daily traffic (AADT) to estimate directional design-hour volume (DDHV) also characterizes a planning application. (For guidelines on computing DDHV, refer to Chapter 8.)

To perform planning applications, the analyst typically has few, if any, of the required input values. Chapter 13 contains more information on the use of default values.

ANALYSIS TOOLS

The basic freeway segments worksheet shown in Exhibit 23-16 and provided in Appendix B can be used to perform all applications, including operational for LOS; design for flow rate, v_p, and number of lanes, N; and planning for LOS, v_p, and N.

IV. EXAMPLE PROBLEMS

Problem No.	Description	Application
1	Find LOS for an existing four-lane freeway	Operational (LOS)
2	Find number of lanes for a suburban freeway	Design (N)
3	Find LOS for an existing six-lane urban freeway, and find LOS that occurs in 3 years. Also find when the freeway will exceed capacity	Operational (LOS), Planning (LOS), and Planning (N)
4	Find LOS for an upgrade and a downgrade on an existing four-lane freeway	Operational (LOS)
5	Find opening-day demand volumes and number of lanes for a new urban freeway facility	Planning (LOS) and Planning (v_p)

EXAMPLE PROBLEM 1

The Freeway Existing four-lane freeway, rural area, very restricted geometry, rolling terrain, 110-km/h speed limit.

The Question What is the LOS during the peak hour?

The Facts

- √ Two lanes in each direction,
- √ 3.3-m lane width,
- √ 0.6-m lateral clearance,
- √ Commuter traffic,
- √ 2,000-veh/h peak-hour volume (one direction),
- √ 5 percent trucks,
- √ 0.92 PHF,
- √ 0.6 interchanges per kilometer, and
- √ Rolling terrain.

Comments

- √ Assume 0 percent buses and RVs since none are indicated.
- √ Assume BFFS of 120 km/h for rural areas.
- √ Assume that the number of lanes does not affect free-flow speed, since the freeway is in a rural area.
- √ Assume $f_p = 1.00$ for commuter traffic.

Outline of Solution All input parameters are known. Demand is computed in terms of passenger cars per hour per lane, an FFS is estimated, and the LOS is determined from the speed-flow graph. An estimate of passenger-car speed is determined from the graph, and a value of density is calculated using speed and flow rate. The calculation of speed is based on the equation found in Exhibit 23-3.

Steps

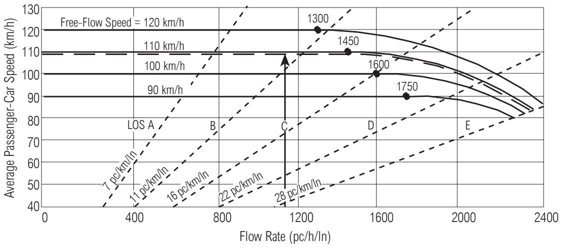
1. Convert volume (veh/h) to flow rate (pc/h/ln) (use Equation 23-2).	$v_p = \frac{V}{(PHF)(N)(f_{HV})(f_p)}$ $v_p = \frac{2,000}{(0.92)(2)(f_{HV})(1.00)}$
2. Find f_{HV} (use Exhibit 23-8 and Equation 23-3).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV} = \frac{1}{1 + 0.05(2.5 - 1) + 0}$ $f_{HV} = 0.930$
3. Find v_p (use Equation 23-2).	$v_p = \frac{2,000}{(0.92)(2)(0.930)(1.00)}$ = 1,169 pc/h/ln
4. Compute free-flow speed (use Exhibits 23-4, 23-5, 23-6, 23-7, and Equation 23-1).	$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$ FFS = 120 – 3.1 – 3.9 – 0.0 – 3.9 FFS = 109.1 km/h
5. Determine level of service (use Exhibit 23-2).	LOS B

The Results

LOS = B,
Speed = 109 km/h, and
Density = 11 pc/km/ln.

Example Problem 1

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information

Analyst: WLL
Agency or Company: CEI
Date Performed: 4/12/99
Analysis Time Period: ______

Site Information

Highway/Direction of Travel: ______
From/To: ______
Jurisdiction: ______
Analysis Year: 1999

☒ Operational (LOS) ☐ Design (N) ☐ Design (v_p) ☐ Planning (LOS) ☐ Planning (N) ☐ Planning (v_p)

Flow Inputs

Volume, V: 2000 veh/h
Annual avg. daily traffic, AADT: ______ veh/day
Peak-hour proportion of AADT, K: ______
Peak-hour direction proportion, D: ______
DDHV = AADT * K * D: ______ veh/h
Driver type ☒ Commuter/Weekday ☐ Recreational/Weekend

Peak-hour factor, PHF: 0.92
% Trucks and buses, P_T: 5
% RVs, P_R: 0
General terrain
☐ Level ☒ Rolling ☐ Mountainous
Grade Length ______ km Up/Down ______ %

Calculate Flow Adjustments

f_p: 1.00
E_T: 2.5
E_R: 2.0
$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$: 0.930

Speed Inputs

Lane width: 3.3 m
Rt.-shoulder lateral clearance: 0.6 m
Interchange density: 0.6 I/km
Number of lanes, N: 2
FFS (measured): ______ km/h
Base free-flow speed, BFFS: 120 km/h

Calculate Speed Adjustments and FFS

f_{LW}: 3.1 km/h
f_{LC}: 3.9 km/h
f_{ID}: 3.9 km/h
f_N: 0.0 km/h
$FFS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N$: 109.1 km/h

LOS and Performance Measures

Operational (LOS) or Planning (LOS)

$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$: 1169 pc/h/ln
S: 109.1 km/h
$D = v_p / S$: 10.7 pc/km/ln
LOS: B

Design (v_p) or Planning (v_p)

LOS: ______
v_p: ______ pc/h/ln
$V = v_p * PHF * N * f_{HV} * f_p$: ______ veh/h
S: ______ km/h
$D = v_p / S$: ______ pc/km/ln

Design (N) or Planning (N) 1st Iteration

N: ______ assumed
$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$: ______ pc/h/ln
LOS: ______

Design (N) or Planning (N) 2nd Iteration

N: ______ assumed
$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$: ______ pc/h/ln
S: ______ km/h
$D = v_p / S$: ______ pc/km/ln
LOS: ______

Glossary

N - Number of lanes
V - Hourly volume
v_p - Flow rate
LOS - Level of service
DDHV - Directional design-hour volume
S - Speed
D - Density
FFS - Free-flow speed
BFFS- Base free-flow speed

Factor Location

E_R - Exhibits 23-8, 23-10
E_T - Exhibits 23-8, 23-9, 23-11
f_p - Page 23-12
LOS, S, FFS, v_p - Exhibits 23-2, 23-3
f_{LW} - Exhibit 23-4
f_{LC} - Exhibit 23-5
f_N - Exhibit 23-6
f_{ID} - Exhibit 23-7

EXAMPLE PROBLEM 2

The Freeway New suburban freeway is being designed.

The Question How many lanes are needed to provide LOS D during the peak hour?

The Facts

- √ 4,000 veh/h (one direction),
- √ Level terrain,
- √ 15 percent trucks,
- √ 3.6-m lane width,
- √ 0.85 PHF,
- √ 0.9 interchanges per kilometer,
- √ 3 percent RVs, and
- √ 1.8-m lateral clearance.

Comments

- √ Assume commuter traffic. Thus, $f_p = 1.00$.
- √ Assume BFFS of 120 km/h.
- √ Assume that the number of lanes affects free-flow speed, since the freeway is being designed in a suburban area.

Outline of Solution All input parameters are known. Flow rate, speed, density, and LOS are calculated starting with a four-lane freeway and then increasing the number of lanes to six, eight, and so forth until LOS D is achieved. The calculation of speed is based on the equation found in Exhibit 23-3.

Steps

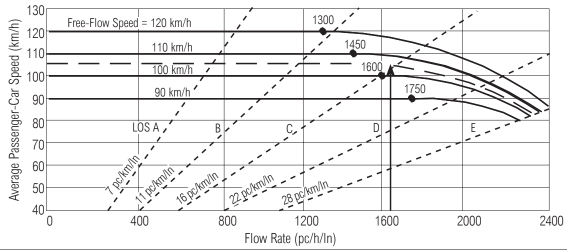
1. Convert volume (veh/h) to flow rate (pc/h/ln) (use Equation 23-2).	$v_p = \dfrac{V}{(PHF)(N)(f_{HV})(f_p)}$
2. Find f_{HV} (use Exhibit 23-8 and Equation 23-3).	$f_{HV} = \dfrac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV} = \dfrac{1}{1 + (0.15)(1.5 - 1) + 0.03(1.2 - 1)}$ $f_{HV} = 0.925$
3. For four-lane option (use Equation 23-2).	$v_p = \dfrac{4{,}000}{(0.85)(2)(0.925)(1.00)} = 2{,}544$ pc/h/ln
4. The four-lane option is not acceptable since 2544 pc/h/ln exceeds capacity of 2400 pc/h/ln.	
5. For six-lane option (use Equation 23-2).	$v_p = \dfrac{4{,}000}{(0.85)(3)(0.925)(1.00)} = 1{,}696$ pc/h/ln
6. Compute free-flow speed for a six-lane freeway (use Exhibits 23-4, 23-5, 23-6, 23-7, and Equation 23-1).	$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$ $FFS = 120 - 0.0 - 0.0 - 4.8 - 8.1$ $FFS = 107.1$ km/h
7. Determine level of service (use Exhibit 23-2).	LOS C

The Results

Six lanes are needed,
LOS = C,
Speed = 107 km/h, and
Density = 16 pc/km/ln.

Example Problem 2

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information

Analyst: JMYE
Agency or Company: CEI
Date Performed: 4/14/99
Analysis Time Period: ______

Site Information

Highway/Direction of Travel: ______
From/To: ______
Jurisdiction: ______
Analysis Year: 1999

☐ Operational (LOS) ☒ Design (N) ☐ Design (v_p) ☐ Planning (LOS) ☐ Planning (N) ☐ Planning (v_p)

Flow Inputs

Volume, V	4000 veh/h	Peak-hour factor, PHF	0.85
Annual avg. daily traffic, AADT	______ veh/day	% Trucks and buses, P_T	15
Peak-hour proportion of AADT, K	______	% RVs, P_R	3
Peak-hour direction proportion, D	______	General terrain	
DDHV = AADT * K * D	______ veh/h	☒ Level ☐ Rolling ☐ Mountainous	
Driver type ☒ Commuter/Weekday ☐ Recreational/Weekend		Grade Length ______ km Up/Down ______ %	

Calculate Flow Adjustments

f_p	1.00	E_R	1.2
E_T	1.5	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$	0.925

Speed Inputs

Lane width	3.6 m
Rt.-shoulder lateral clearance	1.8 m
Interchange density	0.9 I/km
Number of lanes, N	2/3
FFS (measured)	______ km/h
Base free-flow speed, BFFS	120 km/h

Calculate Speed Adjustments and FFS

f_{LW}	0.0 km/h
f_{LC}	0.0 km/h
f_{ID}	8.1 km/h
f_N	7.3/4.8 km/h
$FFS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N$	104.6/107.1 km/h

LOS and Performance Measures

Operational (LOS) or Planning (LOS)

$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$	______ pc/h/ln
S	______ km/h
$D = v_p / S$	______ pc/km/ln
LOS	______

Design (v_p) or Planning (v_p)

LOS	______
v_p	______ pc/h/ln
$V = v_p * PHF * N * f_{HV} * f_p$	______ veh/h
S	______ km/h
$D = v_p / S$	______ pc/km/ln

Design (N) or Planning (N) 1st Iteration

N	2 assumed
$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$	2544 pc/h/ln
LOS	oversaturated

Design (N) or Planning (N) 2nd Iteration

N	3 assumed
$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$	1696 pc/h/ln
S	106.5 km/h
$D = v_p / S$	15.9 pc/km/ln
LOS	C

Glossary

N - Number of lanes
V - Hourly volume
v_p - Flow rate
LOS - Level of service
DDHV - Directional design-hour volume
S - Speed
D - Density
FFS - Free-flow speed
BFFS - Base free-flow speed

Factor Location

E_R - Exhibits 23-8, 23-10
E_T - Exhibits 23-8, 23-9, 23-11
f_p - Page 23-12
LOS, S, FFS, v_p - Exhibits 23-2, 23-3
f_{LW} - Exhibit 23-4
f_{LC} - Exhibit 23-5
f_N - Exhibit 23-6
f_{ID} - Exhibit 23-7

EXAMPLE PROBLEM 3

The Freeway Existing six-lane freeway in a growing urban area.

The Question What is the current LOS during the peak hour? What LOS will occur in 3 years? When should a fourth lane be added in each direction to avoid an excess of demand over capacity?

The Facts

- √ 5,000 veh/h (one direction, existing);
- √ Level terrain;
- √ 5,600 veh/h (one direction, in 3 years);
- √ Beyond 3 years, traffic grows at 4 percent per year;
- √ 6 lanes;
- √ 10 percent trucks;
- √ 0.95 PHF; and
- √ FFS = 110 km/h (measured in field).

Comments

- √ Since no information is given on possible changes over time, assume that 10 percent trucks, PHF, and FFS remain constant.
- √ This problem deals with a variety of demand levels and can most easily be solved by computing the maximum volume that can be accommodated for each level of service.
- √ Assume 0 percent buses and RVs.
- √ Assume commuter traffic.

Outline of Solution The maximum volume (veh/h) for each LOS is computed, the demand volumes are compared, and a level of service is estimated.

Steps

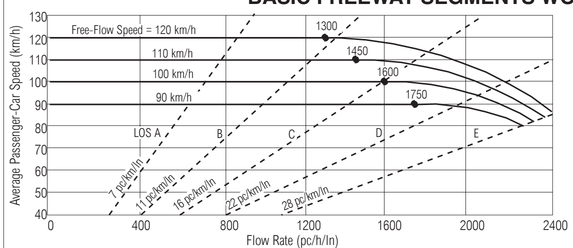
1. Convert the maximum service flow rate (pc/h/ln) for each LOS to veh/h (use Equation 23-2).	$v_p = \dfrac{V}{(PHF)(N)(f_{HV})(f_p)}$ $V = v_p(PHF)(N)(f_{HV})(f_p)$
2. Find f_{HV} (use Equation 23-3 and Exhibit 23-8).	$f_{HV} = \dfrac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV} = \dfrac{1}{1 + 0.10(1.5 - 1) + 0}$ $f_{HV} = 0.952$
3. Find maximum v_p for each LOS (use Exhibit 23-2).	LOS A, v_p = 770 pc/h/ln LOS B, v_p = 1,210 LOS C, v_p = 1,740 LOS D, v_p = 2,135 LOS E, v_p = 2,350
4. Compute V (veh/h) (use equation from Step 1 with f_p = 1.00).	LOS A, V = 2,089 veh/h LOS B, V = 3,283 LOS C, V = 4,721 LOS D, V = 5,793 LOS E, V = 6,376
5. Compare 5,000 veh/h and 5,600 veh/h with above, determine LOS.	
6. When traffic exceeds 6,376 veh/h, a fourth lane in each direction will be needed. A compounding equation is used.	$5{,}600(1.04^n) = 6{,}376$ $n = 3.3$ years

The Results

LOS D (existing),
LOS D (in 3 years), and
A fourth lane will be needed in 3.3 years beyond the end of the first 3 years.

Example Problem 3

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information

Analyst	JMYE
Agency or Company	CEI
Date Performed	4/15/99
Analysis Time Period	

Site Information

Highway/Direction of Travel	
From/To	
Jurisdiction	
Analysis Year	1999/2002

☒ Operational (LOS) ☐ Design (N) ☐ Design (v_p) ☒ Planning (LOS) ☐ Planning (N) ☐ Planning (v_p)

Flow Inputs

Volume, V	5000/5600 veh/h	Peak-hour factor, PHF	0.95
Annual avg. daily traffic, AADT	veh/day	% Trucks and buses, P_T	10
Peak-hour proportion of AADT, K		% RVs, P_R	0
Peak-hour direction proportion, D		General terrain	
DDHV = AADT * K * D	veh/h	☒ Level ☐ Rolling ☐ Mountainous	
Driver type ☒ Commuter/Weekday ☐ Recreational/Weekend		Grade Length ____ km Up/Down ____ %	

Calculate Flow Adjustments

f_p	1.00	E_R	
E_T	1.5	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$	0.952

Speed Inputs

Lane width	m
Rt.-shoulder lateral clearance	m
Interchange density	I/km
Number of lanes, N	3
FFS (measured)	110 km/h
Base free-flow speed, BFFS	km/h

Calculate Speed Adjustments and FFS

f_{LW}	km/h
f_{LC}	km/h
f_{ID}	km/h
f_N	km/h
FFS = BFFS – f_{LW} – f_{LC} – f_{ID} – f_N	km/h

LOS and Performance Measures

Operational (LOS) or Planning (LOS)

$v_p = \frac{V \text{ or DDHV}}{PHF * N * f_{HV} * f_p}$	pc/h/ln
S	km/h
D = v_p /S	pc/km/ln
LOS	D (existing)/D (in 3 years)

Design (v_p) or Planning (v_p)

LOS	C/D/E
v_p	1740/2135/2350 pc/h/ln
V = v_p * PHF * N * f_{HV} * f_p	4721/5793/6376 veh/h
S	km/h
D = v_p /S	pc/km/ln

Design (N) or Planning (N) 1st Iteration

N	assumed
$v_p = \frac{V \text{ or DDHV}}{PHF * N * f_{HV} * f_p}$	pc/h/ln
LOS	

Design (N) or Planning (N) 2nd Iteration

N	assumed
$v_p = \frac{V \text{ or DDHV}}{PHF * N * f_{HV} * f_p}$	pc/h/ln
S	km/h
D = v_p /S	pc/km/ln
LOS	

Glossary

N - Number of lanes
V - Hourly volume
v_p - Flow rate
LOS - Level of service
DDHV - Directional design-hour volume
S - Speed
D - Density
FFS - Free-flow speed
BFFS - Base free-flow speed

Factor Location

E_R - Exhibits 23-8, 23-10
E_T - Exhibits 23-8, 23-9, 23-11
f_p - Page 23-12
LOS, S, FFS, v_p - Exhibits 23-2, 23-3
f_{LW} - Exhibit 23-4
f_{LC} - Exhibit 23-5
f_N - Exhibit 23-6
f_{ID} - Exhibit 23-7

EXAMPLE PROBLEM 4

The Freeway Existing four-lane freeway in a rural area.

The Question What is the LOS for both the upgrade and the downgrade directions during the peak hour?

The Facts

- √ 2 lanes in each direction,
- √ 15 percent trucks,
- √ 0.90 PHF,
- √ Segment 2, 800 m at 5 percent grade,
- √ FFS = 115 km/h (measured in field, upgrade direction),
- √ 2,300 veh/h peak-hour volume (one direction),
- √ Segment 1, 900 m at 3 percent grade, and
- √ FFS = 120 km/h (measured in field, downgrade direction).

Comments

- √ Assume 0 percent buses and RVs since none are indicated.
- √ The precise procedure for composite grades is used because there is a segment steeper than 4 percent and the total length is greater than 1200 m.
- √ Assume f_p = 0.95 because drivers are generally unfamiliar with the area.

Outline of Solution The truck performance curves in Appendix A are used to develop an equivalent grade (i.e., a constant grade that has the same effect on heavy vehicles as does the composite grade). Demand is computed in terms of passenger cars per hour per lane, and LOS is determined from the speed-flow graph. The calculation of speed is based on the equation found in Exhibit 23-3.

Steps

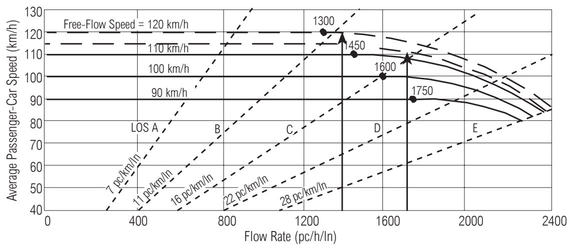
1. Determine equivalent constant grade (use Exhibit A23-2).	Using Appendix A, enter 900 m. Speed at top of 3 percent grade is 68 km/h. Intersection of horizontal at 68 km/h and 5 percent curve implies trucks have been on 5 percent for 375 m. A vertical is drawn at 1175 m to the 5 percent deceleration curve, and a horizontal shows a final truck speed of 42 km/h. A horizontal line at a speed of 42 km/h and a vertical line at 1700 m intersect at a composite grade of 5 percent. Similarly, the composite grade for the downgrade is computed as –1 percent.
2. Convert volume (veh/h) to flow rate (pc/h/ln) (use Equation 23-2).	$v_p = \frac{V}{(PHF)(N)(f_{HV})(f_p)}$
3. Find f_{HV} (upgrade) (Exhibit 23-9 and Equation 23-3).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV} = \frac{1}{1 + 0.15(3.0 - 1) + 0} = 0.769$
4. Find f_{HV} (downgrade) (use Exhibit 23-11 and Equation 23-3).	$f_{HV} = \frac{1}{1 + 0.15(1.5 - 1) + 0} = 0.930$
5. Find v_p (upgrade) (use Equation 23-2).	$v_p = \frac{2,300}{(0.90)(2)(0.769)(0.95)} = 1,749$ pc/h/ln
6. Find v_p (downgrade) (use Equation 23-2).	$v_p = \frac{2,300}{(0.90)(2)(0.930)(0.95)} = 1,446$ pc/h/ln
7. Determine LOS (use Exhibit 23-2).	LOS C (upgrade and downgrade)

The Results

Upgrade	Downgrade
LOS C,	LOS C,
Speed = 113 km/h, and	Speed = 120 km/h, and
Density = 15 pc/km/ln.	Density = 12 pc/km/ln.

Example Problem 4

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information

Analyst: JMYE
Agency or Company: CEI
Date Performed: 5/16/99
Analysis Time Period: ______

Site Information

Highway/Direction of Travel: ______
From/To: ______
Jurisdiction: ______
Analysis Year: 1999

☒ Operational (LOS) ❑ Design (N) ❑ Design (v_p) ❑ Planning (LOS) ❑ Planning (N) ❑ Planning (v_p)

Flow Inputs

Volume, V: 2300 veh/h
Annual avg. daily traffic, AADT: ______ veh/day
Peak-hour proportion of AADT, K: ______
Peak-hour direction proportion, D: ______
DDHV = AADT * K * D: ______ veh/h
Driver type ❑ Commuter/Weekday ❑ Recreational/Weekend

Peak-hour factor, PHF: 0.90
% Trucks and buses, P_T: 15
% RVs, P_R: 0
General terrain ❑ Level ❑ Rolling ❑ Mountainous
Grade Length 1.7 km Up/Down 5/-1 %

Calculate Flow Adjustments

f_p: 0.95
E_T: 3.0/1.5
E_R: ______
$f_{HV} = \dfrac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$: 0.769/0.930

Speed Inputs

Lane width: ______ m
Rt.-shoulder lateral clearance: ______ m
Interchange density: ______ I/km
Number of lanes, N: 2
FFS (measured): 115/120 km/h
Base free-flow speed, BFFS: ______ km/h

Calculate Speed Adjustments and FFS

f_{LW}: ______ km/h
f_{LC}: ______ km/h
f_{ID}: ______ km/h
f_N: ______ km/h
$FFS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N$: ______ km/h

LOS and Performance Measures

Operational (LOS) or Planning (LOS)

$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$: 1749/1446 pc/h/ln
S: 112.7/119.8 km/h
$D = v_p/S$: 15.5/12.1 pc/km/ln
LOS: C/C

Design (v_p) or Planning (v_p)

LOS: ______
v_p: ______ pc/h/ln
$V = v_p * PHF * N * f_{HV} * f_p$: ______ veh/h
S: ______ km/h
$D = v_p/S$: ______ pc/km/ln

Design (N) or Planning (N) 1st Iteration

N: ______ assumed
$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$: ______ pc/h/ln
LOS: ______

Design (N) or Planning (N) 2nd Iteration

N: ______ assumed
$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$: ______ pc/h/ln
S: ______ km/h
$D = v_p/S$: ______ pc/km/ln
LOS: ______

Glossary

N - Number of lanes
V - Hourly volume
v_p - Flow rate
LOS - Level of service
DDHV - Directional design-hour volume
S - Speed
D - Density
FFS - Free-flow speed
BFFS - Base free-flow speed

Factor Location

E_R - Exhibits 23-8, 23-10
E_T - Exhibits 23-8, 23-9, 23-11
f_p - Page 23-12
LOS, S, FFS, v_p - Exhibits 23-2, 23-3
f_{LW} - Exhibit 23-4
f_{LC} - Exhibit 23-5
f_N - Exhibit 23-6
f_{ID} - Exhibit 23-7

EXAMPLE PROBLEM 5

The Freeway New urban facility being planned with a forecast opening-day AADT of 75,000 veh/day.

The Question What is the minimum number of lanes needed to provide at least LOS D during the peak hour on opening day? What are the speed and density of traffic for the proposed number of lanes?

The Facts
- √ 75,000 veh/day,
- √ K = 0.090,
- √ Directional split = 55/45, and
- √ Rolling terrain.

Comments
- √ Several input variables (FFS, PHF, percent trucks) are not given. Reasonable default values are selected as FFS = 110 km/h (in lieu of field measurement), PHF = 0.90, 10 percent trucks, and 0 percent RVs.
- √ Assume commuter traffic (f_p = 1.00).

Outline of Solution Flow rate, speed, density, and LOS are calculated starting with a four-lane freeway and then increasing the number of lanes to six, eight, and so forth until LOS D is achieved. The calculation of speed is based on the equation found in Exhibit 23-3.

Steps

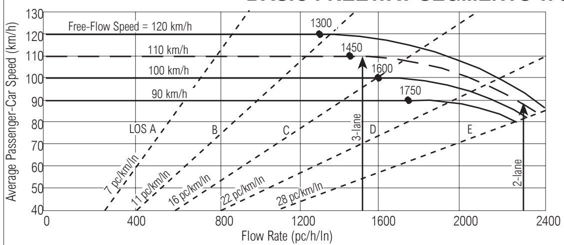
1. Convert AADT to design-hour volume.	DDHV = AADT * K * D DDHV = 75,000 * 0.090 * 0.55 DDHV = 3,713 veh/h
2. Find f_{HV} (use Exhibit 23-8 and Equation 23-3).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV} = \frac{1}{1 + 0.10(2.5 - 1) + 0}$ $f_{HV} = 0.870$
3. For four-lane option (use Equation 23-2).	$v_p = \frac{3{,}713}{(0.90)(2)(0.870)(1.00)} = 2{,}371$ pc/h/ln
4. Determine level of service (use Exhibit 23-2).	LOS F
5. For six-lane option (use Equation 23-2).	$v_p = \frac{3{,}713}{(0.90)(3)(0.870)(1.00)}$ v_p = 1,581 pc/h/ln
6. Determine level of service (use Exhibit 23-2).	LOS C
7. Calculate speed and density	S = 109.8 km/h D = 14.4 pc/km/ln

The Results

Six lanes are needed,
LOS = C,
Speed = 110 km/h, and
Density = 14 pc/km/ln.

Example Problem 5

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information / Site Information

General Information		Site Information	
Analyst	JMYE	Highway/Direction of Travel	
Agency or Company	CEI	From/To	
Date Performed	4/15/99	Jurisdiction	
Analysis Time Period		Analysis Year	1999

❑ Operational (LOS) ❑ Design (N) ❑ Design (v_p) ❑ Planning (LOS) ☒ Planning (N) ❑ Planning (v_p)

Flow Inputs

Volume, V	veh/h	Peak-hour factor, PHF	0.90
Annual avg. daily traffic, AADT	75,000 veh/day	% Trucks and buses, P_T	10
Peak-hour proportion of AADT, K	0.090	% RVs, P_R	0
Peak-hour direction proportion, D	0.55	General terrain	
DDHV = AADT * K * D	3713 veh/h	❑ Level ☒ Rolling ❑ Mountainous	
Driver type ☒ Commuter/Weekday ❑ Recreational/Weekend		Grade Length ____ km Up/Down ____ %	

Calculate Flow Adjustments

f_p	1.00	E_R	
E_T	2.5	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$	0.870

Speed Inputs / Calculate Speed Adjustments and FFS

Speed Inputs		Calculate Speed Adjustments and FFS	
Lane width	m	f_{LW}	km/h
Rt.-shoulder lateral clearance	m	f_{LC}	km/h
Interchange density	I/km	f_{ID}	km/h
Number of lanes, N		f_N	km/h
FFS (measured)	110 km/h	FFS = BFFS – f_{LW} – f_{LC} – f_{ID} – f_N	km/h
Base free-flow speed, BFFS	km/h		

LOS and Performance Measures

Operational (LOS) or Planning (LOS)		Design (N) or Planning (N) 1st Iteration	
$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$	pc/h/ln	N	2 assumed
S	km/h	$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$	2371 pc/h/ln
D = v_p /S	pc/km/ln	LOS	F
LOS			
Design (v_p) or Planning (v_p)		**Design (N) or Planning (N) 2nd Iteration**	
LOS		N	3 assumed
v_p	pc/h/ln	$v_p = \frac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$	1581 pc/h/ln
V = v_p * PHF * N * f_{HV} * f_p	veh/h	S	109.8 km/h
S	km/h	D = v_p /S	14.4 pc/km/ln
D = v_p /S	pc/km/ln	LOS	C

Glossary / Factor Location

Glossary		Factor Location	
N - Number of lanes	S - Speed	E_R - Exhibits 23-8, 23-10	f_{LW} - Exhibit 23-4
V - Hourly volume	D - Density	E_T - Exhibits 23-8, 23-9, 23-11	f_{LC} - Exhibit 23-5
v_p - Flow rate	FFS - Free-flow speed	f_p - Page 23-12	f_N - Exhibit 23-6
LOS - Level of service	BFFS - Base free-flow speed	LOS, S, FFS, v_p - Exhibits 23-2, 23-3	f_{ID} - Exhibit 23-7
DDHV - Directional design-hour volume			

V. REFERENCES

1. Schoen, J., A. May, W. Reilly, and T. Urbanik. *Speed-Flow Relationships for Basic Freeway Sections*. Final Report, NCHRP Project 3-45. JHK & Associates, Tucson, Ariz., May 1995.
2. Reilly, W., D. Harwood, J. Schoen, et al. *Capacity and Level of Service Procedures for Multilane Rural and Suburban Highways*. Final Report, NCHRP Project 3-33. JHK & Associates, Tucson, Ariz., 1988.

3. Basic Freeway Sections (Chapter 3). In *Special Report 209: Highway Capacity Manual* (third edition), TRB, National Research Council, Washington, D.C., 1994.
4. Hall, F. L., V. F. Hurdle, and J. H. Banks. Synthesis of Recent Work on the Nature of Speed-Flow and Flow-Occupancy (or Density) Relationships on Freeways. In *Transportation Research Record 1365*, TRB, National Research Council, Washington, D.C., 1992, pp. 12–18.
5. Urbanik, T., II, W. Hinshaw, and K. Barnes. Evaluation of High-Volume Urban Texas Freeways. In *Transportation Research Record 1320*, TRB, National Research Council, Washington, D.C., 1991, pp. 110–118.
6. Banks, J. H. Flow Processes at a Freeway Bottleneck. In *Transportation Research Record 1287*, TRB, National Research Council, Washington, D.C., 1990, pp. 20–28.
7. Hall, F. L., and L. M. Hall. Capacity and Speed-Flow Analysis of the Queen Elizabeth Way in Ontario. In *Transportation Research Record 1287*, TRB, National Research Council, Washington, D.C., 1990, pp. 108–118.
8. Hall, F. L., and K. Agyemang-Duah. Freeway Capacity Drop and the Definition of Capacity. In *Transportation Research Record 1320*, TRB, National Research Council, Washington, D.C., 1991, pp. 91–98.
9. Chin, H. C., and A. D. May. Examination of the Speed-Flow Relationship at the Caldecott Tunnel. In *Transportation Research Record 1320*, TRB, National Research Council, Washington, D.C., 1991, pp. 75–82.
10. Banks, J. *Evaluation of the Two-Capacity Phenomenon as a Basis for Ramp Metering*. Final Report, San Diego State University, San Diego, Calif., 1991.
11. *Manual of Traffic Engineering Studies*. Institute of Transportation Engineers, Arlington, Va., 1976.
12. Webster, N., and L. Elefteriadou. A Simulation Study of Truck Passenger Car Equivalents (PCE) on Basic Freeway Sections. *Transportation Research B,* Vol. 33, No. 5, 1999, pp. 323–336.

APPENDIX A. COMPOSITE GRADE

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 percent or the total length of the grade is less than 1200 m. For grades outside these limits (i.e., grades having either a total length greater than 1200 m or portions steeper than 4 percent, or both), the composite grade procedure is recommended. The composite grade procedure is used to determine an equivalent grade that will result in the same final truck speed as would a series of varying grades.

As noted in the chapter, the acceleration/deceleration curves presented here are for vehicles with an average weight-to-power ratio of 120 kg/kW, heavier than typical trucks found on freeways. Typical trucks, which average between 80 and 90 kg/kW, are used to determine passenger-car equivalents.

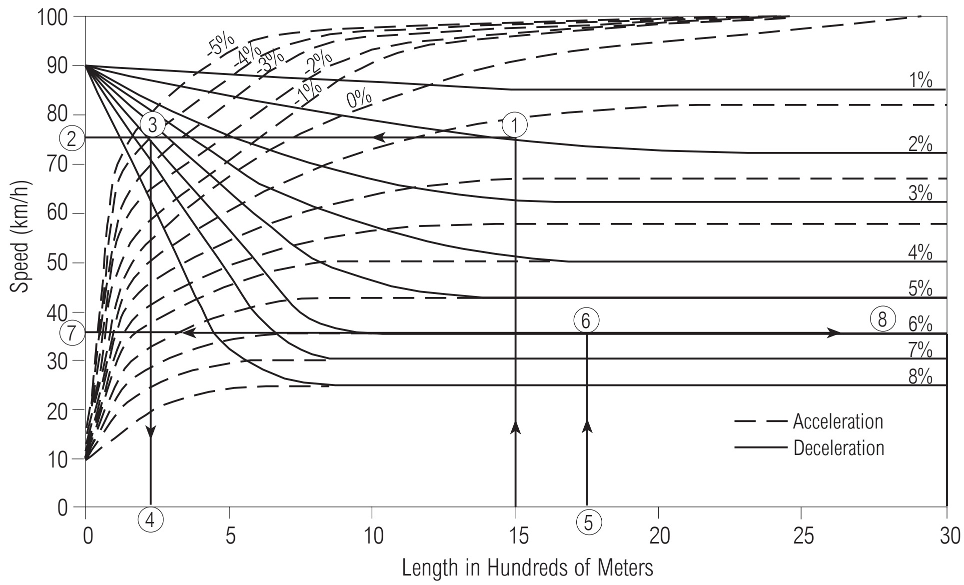
An example is provided to illustrate the process involved in determining an equivalent grade on a freeway with two segments. Segment 1 is 1500 m long with a 2 percent upgrade, and Segment 2 is 1500 m long with a 6 percent upgrade. If the average grade procedure were used (not valid in this case), the result would be as follows:

Total rise = $(1500 * 0.02) + (1500 * 0.06) = 120$ m

Average grade = $120/3000 = 0.04$ or 4 percent

The solution for the same freeway conditions using the composite grade procedure is illustrated in Exhibit A23-1. A vertical line is drawn at 1500 m to intersect with the 2 percent deceleration curve, Point 1. The truck speed at this point is determined by drawing a horizontal line to intersect with the vertical axis, Point 2. The speed is 75 km/h, which is the speed the truck exits Segment 1 and enters Segment 2.

EXHIBIT A23-1. SAMPLE SOLUTION FOR COMPOSITE GRADE



The intersection of the horizontal line with the 6 percent deceleration curve is Point 3. A vertical line is drawn at this point to intersect with the horizontal axis, Point 4. Point 4 indicates that 75 km/h is the speed as if the truck has traveled 225 m on a 6 percent upgrade from level terrain.

Because the truck travels another 1500 m on a 6 percent grade, 1500 m is added to 225 m, and Point 5 is found at 1725 m. A vertical line is drawn from Point 5 to intersect with the 6 percent deceleration curve, Point 6. A horizontal line is drawn at Point 6 to intersect with the vertical axis. The final truck speed is found to be 36 km/h, Point 7.

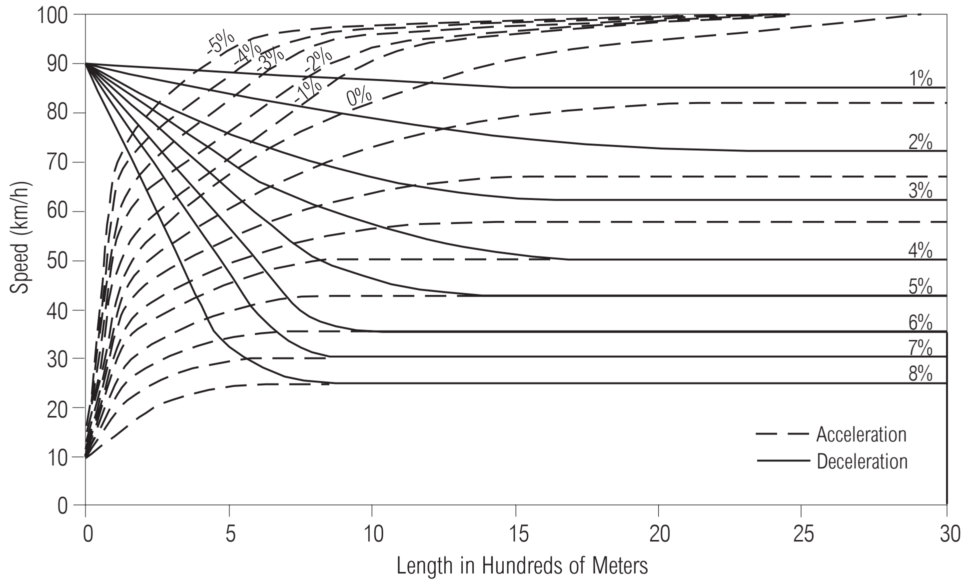
The equivalent grade can now be determined by intersecting a horizontal line drawn at 36 km/h with a vertical line drawn at 3000 m, Point 8. The equivalent grade is found to be 6 percent, instead of 4 percent as previously calculated by the average grade technique. The value of E_T can now be determined on the basis of a 6 percent grade and the length of 3000 m.

The general steps taken in solving the problem are summarized as follows.

1. Enter Exhibit A23-2 with an initial grade and length. Find the truck speed at the end of the first segment.
2. Find the length along the second grade that results in the same truck speed. This point is used as the starting point for the subsequent segment.
3. Add the length of Segment 2 to the length computed in Step 2. Then determine the final truck speed.
4. For each additional segment, repeat Steps 1 through 3.
5. Enter Exhibit A23-2 with the final truck speed and the total segment length to find the equivalent composite grade.

In the analysis, it is important to identify the point at which the truck speed is the lowest, because its effect on traffic flow is the most severe at that point. Thus, the appropriate point to evaluate truck speed may not always be the segment endpoint. For example, if a 4 percent upgrade of 2 km is followed by 1 km of 2 percent upgrade, the point of minimum truck speed will be the end of the first segment, not the end of the following segment.

EXHIBIT A23-2. PERFORMANCE CURVES FOR TRUCKS (120 kg/kW)

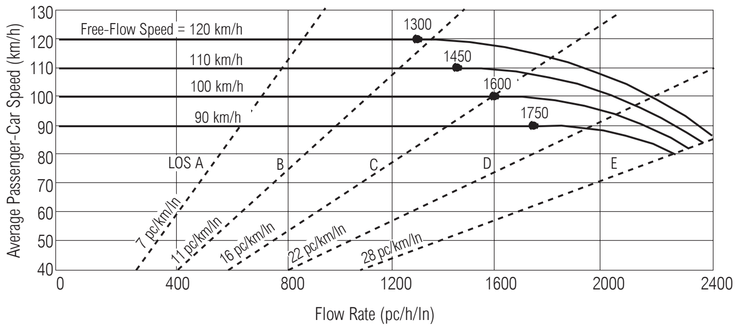


The composite grade procedure is not applicable in all cases, especially if the first segment is downgrade and the segment length is long, or the segments are too short. In using the performance curves, cases that cannot be solved with this procedure will become apparent to the analyst because lines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

APPENDIX B. WORKSHEET

BASIC FREEWAY SEGMENTS WORKSHEET

BASIC FREEWAY SEGMENTS WORKSHEET



Application	Input	Output
Operational (LOS)	FFS, N, v_p	LOS, S, D
Design (N)	FFS, LOS, v_p	N, S, D
Design (v_p)	FFS, LOS, N	v_p, S, D
Planning (LOS)	FFS, N, AADT	LOS, S, D
Planning (N)	FFS, LOS, AADT	N, S, D
Planning (v_p)	FFS, LOS, N	v_p, S, D

General Information

Analyst ____________
Agency or Company ____________
Date Performed ____________
Analysis Time Period ____________

Site Information

Highway/Direction of Travel ____________
From/To ____________
Jurisdiction ____________
Analysis Year ____________

❑ Operational (LOS) ❑ Design (N) ❑ Design (v_p) ❑ Planning (LOS) ❑ Planning (N) ❑ Planning (v_p)

Flow Inputs

Volume, V ____________ veh/h
Annual avg. daily traffic, AADT ____________ veh/day
Peak-hour proportion of AADT, K ____________
Peak-hour direction proportion, D ____________
DDHV = AADT * K * D ____________ veh/h
Driver type ❑ Commuter/Weekday ❑ Recreational/Weekend

Peak-hour factor, PHF ____________
% Trucks and buses, P_T ____________
% RVs, P_R ____________
General terrain
❑ Level ❑ Rolling ❑ Mountainous
Grade Length ________ km Up/Down ________ %

Calculate Flow Adjustments

f_p ____________
E_T ____________

E_R ____________

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

Speed Inputs

Lane width ____________ m
Rt.-shoulder lateral clearance ____________ m
Interchange density ____________ I/km
Number of lanes, N ____________
FFS (measured) ____________ km/h
Base free-flow speed, BFFS ____________ km/h

Calculate Speed Adjustments and FFS

f_{LW} ____________ km/h
f_{LC} ____________ km/h
f_{ID} ____________ km/h
f_N ____________ km/h
$FFS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N$ ____________ km/h

LOS and Performance Measures

Operational (LOS) or Planning (LOS)

$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$ ____________ pc/h/ln
S ____________ km/h
$D = v_p / S$ ____________ pc/km/ln
LOS ____________

Design (v_p) or Planning (v_p)

LOS ____________
v_p ____________ pc/h/ln
$V = v_p * PHF * N * f_{HV} * f_p$ ____________ veh/h
S ____________ km/h
$D = v_p / S$ ____________ pc/km/ln

Design (N) or Planning (N) 1st Iteration

N ____________ assumed
$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$ ____________ pc/h/ln
LOS ____________

Design (N) or Planning (N) 2nd Iteration

N ____________ assumed
$v_p = \dfrac{V \text{ or } DDHV}{PHF * N * f_{HV} * f_p}$ ____________ pc/h/ln
S ____________ km/h
$D = v_p / S$ ____________ pc/km/ln
LOS ____________

Glossary

N - Number of lanes
V - Hourly volume
v_p - Flow rate
LOS - Level of service
DDHV - Directional design-hour volume
S - Speed
D - Density
FFS - Free-flow speed
BFFS - Base free-flow speed

Factor Location

E_R - Exhibits 23-8, 23-10
E_T - Exhibits 23-8, 23-9, 23-11
f_p - Page 23-12
LOS, S, FFS, v_p - Exhibits 23-2, 23-3
f_{LW} - Exhibit 23-4
f_{LC} - Exhibit 23-5
f_N - Exhibit 23-6
f_{ID} - Exhibit 23-7