CHAPTER 25

RAMPS AND RAMP JUNCTIONS

CONTENTS

EXHIBITS

I. INTRODUCTION

Background and concepts for this chapter are in Chapter 13, "Freeway Concepts"

A ramp is a length of roadway providing an exclusive connection between two highway facilities. The facilities connected by a ramp may consist of freeways, multilane highways, two-lane highways, suburban streets, and urban streets.

A ramp may consist of up to three geometric elements of interest:

- Ramp-freeway junction,
- Ramp roadway, and
- Ramp-street junction.

SCOPE OF THE METHODOLOGY

This chapter focuses on the operation of ramp-freeway junctions and on the characteristics of ramp roadways themselves. These procedures may be applied, in an approximate manner, to completely uncontrolled ramp terminals on other types of facilities such as multilane and two-lane highways.

Procedures in this chapter allow for the identification of likely congestion at ramp-freeway terminals [level of service (LOS) F] and for the analysis of operations at ramp-freeway junctions and on ramp roadways at LOS A through E. Chapter 22, "Freeway Facilities," provides procedures for the analysis of oversaturated flow as well as special applications, including ramps on five-lane (one-direction) freeway segments, two-lane ramps, major merge areas, and major diverge areas.

For additional discussion of the general concepts and principles affecting ramp junction operation, consult Chapter 13, "Freeway Concepts."

This edition of ramp-freeway terminal analysis procedures results primarily from studies conducted under National Cooperative Highway Research Program Project 3-37 (*1*). Some special applications resulted from adaptations of procedures developed in the 1970s (*2*). AASHTO policies (*3*) contain additional material on the geometric design and geometric design criteria for ramps.

LIMITATIONS OF THE METHODOLOGY

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

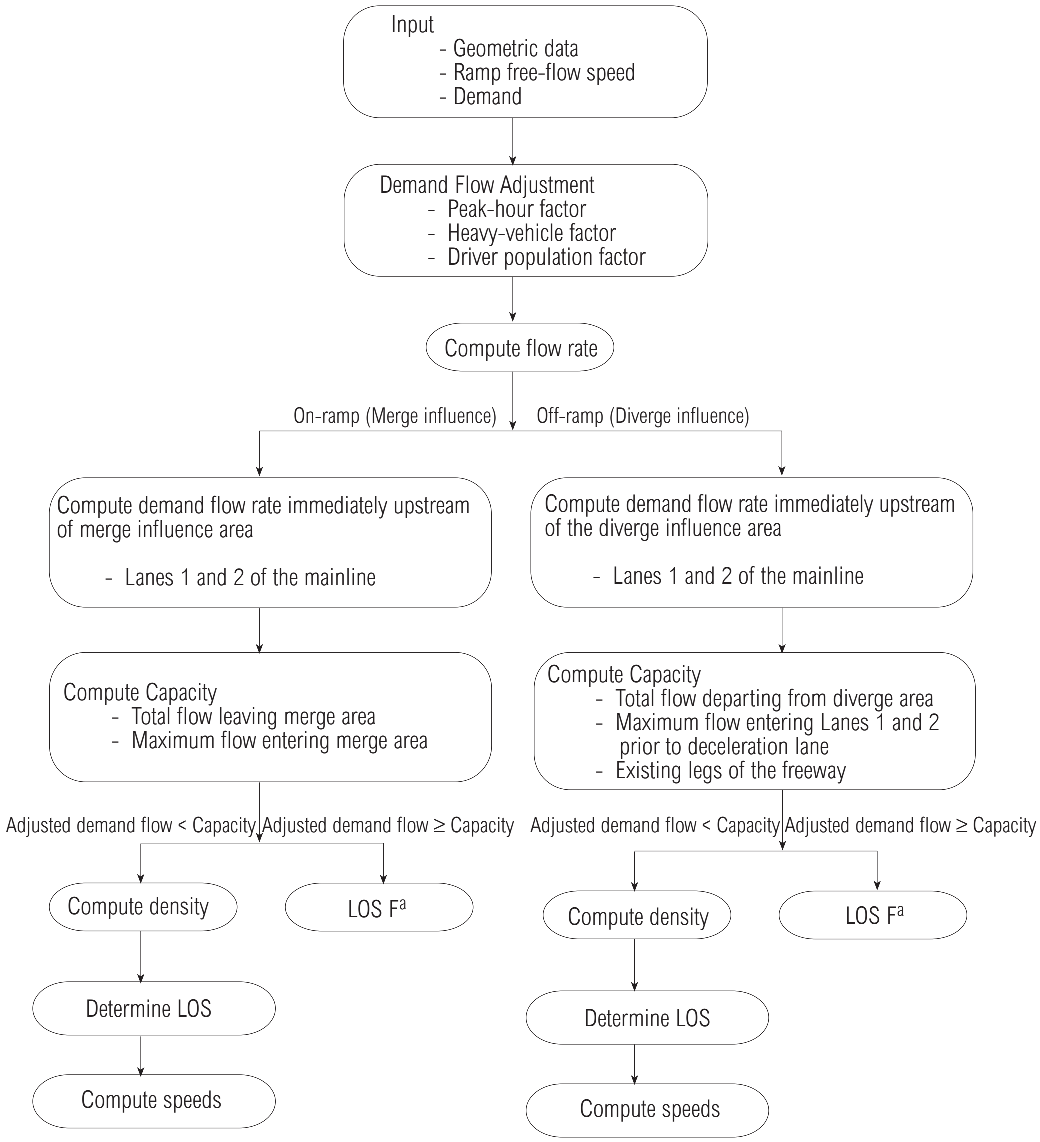
- Special lanes, such as high-occupancy vehicle (HOV) lanes, as ramp entrance lanes;
- Ramp metering;
- Oversaturated conditions;
- Posted speed limit, and extent of police enforcement; and
- Presence of intelligent transportation system (ITS) features.

II. METHODOLOGY

Exhibit 25-1 illustrates input to and the basic computation order for the method for ramps and ramp junctions. The primary outputs of the method are LOS and capacity.

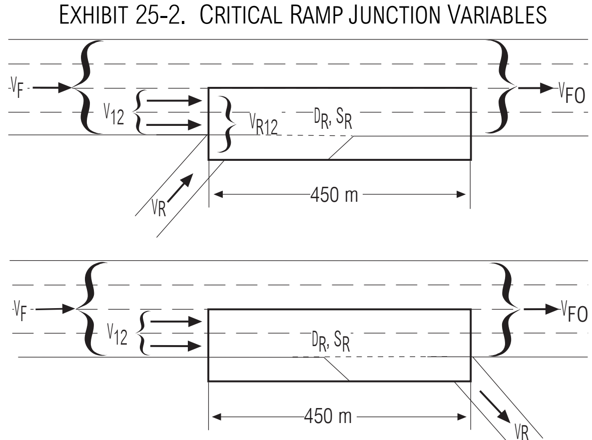
As shown in Exhibit 25-2, the basic approach to modeling merge and diverge areas focuses on an influence area of 450 m including the acceleration or deceleration lane and Lanes 1 and 2 of the freeway. Although other freeway lanes may be affected by merging or diverging operations and the impact of congestion in the vicinity of a ramp can extend beyond the 450-m influence area, this defined area experiences most of the operational impacts across all levels of service. Thus, the operation of vehicles within the ramp influence area, as defined in Exhibit 25-2, is the focus of the computational procedures.

EXHIBIT 25-1. RAMPS AND RAMP JUNCTIONS METHODOLOGY



Note:
a. Refer to Chapter 22.

EXHIBIT 25-2. CRITICAL RAMP JUNCTION VARIABLES



The methodology has three major steps. First, flow entering Lanes 1 and 2 immediately upstream of the merge influence area (v_{12}) or at the beginning of the deceleration lane at diverge is determined.

Second, capacity values are determined and compared with existing or forecast demand flows to determine the likelihood of congestion. Several capacity values are evaluated:

- Maximum total flow approaching a major diverge area on the freeway (v_F),
- Maximum total flow departing from a merge or diverge area on the freeway (v_{FO}),
- Maximum total flow entering the ramp influence area (v_{R12} for merge areas and v_{12} for diverge areas), and
- Maximum flow on a ramp (v_R).

The capacity of a merge or diverge area is always controlled by the capacity of its entering and exiting roadways, that is, the freeway segments upstream and downstream of the ramps, or by the capacity of the ramp itself. For diverge areas, failure most often occurs because of insufficient capacity on the off-ramp. Research has shown that the turbulence due to merging and diverging maneuvers does not affect the capacity of the roadways involved, although there may be local changes in lane distribution and use.

Finally, the density of flow within the ramp influence area (D_R) and the level of service based on this variable are determined. For some situations, the average speed of vehicles within the influence area (S_R) may also be estimated.

Exhibit 25-2 shows the ramp influence areas and key variables and their relationship to each other. A critical geometric parameter influencing operations at merge or diverge areas is the length of the acceleration lane (L_A) or deceleration lane (L_D). This length is measured from the point at which the left edge of the ramp lane or lanes and the right edge of the freeway lanes converge to the end of the taper segment connecting the ramp to the freeway. The point of convergence can be defined by painted markings or physical barriers or by some combination of the two. Note that both taper area and parallel ramps are measured in the same way.

All aspects of the model and LOS criteria are expressed in terms of equivalent maximum flow rates in passenger cars per hour (pc/h) under base conditions during the peak 15 min of the hour of interest. Therefore, before any of these procedures are applied, all relevant freeway and ramp flows must be converted to equivalent pc/h under base conditions during the peak 15 min of the hour, using Equation 25-1.

$$v_i = \frac{V_i}{PHF * f_{HV} * f_p} \tag{25-1}$$

where

v_i = flow rate for movement i under base conditions during peak 15 min of hour (pc/h),
V_i = hourly volume for movement i (veh/h),
PHF = peak-hour factor,
f_{HV} = adjustment factor for heavy vehicles, and
f_p = adjustment factor for driver population.

Adjustment factors are the same as those used for analysis of basic freeway segments and can be found in Chapter 23.

RAMP ROADWAYS

Because most operational problems occur at ramp terminals (either the ramp-freeway terminal or the ramp-street terminal), little information exists regarding the operational characteristics of ramp roadways themselves. Some basic design standards exist in AASHTO policies (*3*), but these are not related to specific operational characteristics. In the 1970s, this material was adapted (*2*) to provide a broader set of criteria, which were, again, unrelated to specific operational characteristics. Thus, information presented in this section is for general guidance only.

Ramp roadways differ from the freeway mainline in that

- They are roadways of limited length and width (often just one lane);
- Free-flow speed is frequently lower than that of the roadways connected, particularly the freeway;
- On single-lane ramps, where passing is not possible, the adverse impact of trucks and other slow-moving vehicles is more pronounced than on multilane roadways; and
- At ramp-street junctions, queuing may develop on the ramp, particularly if the ramp-street junction is signalized.

Exhibit 25-3 lists approximate criteria for the capacity of ramp roadways. These capacities are based on research studies (*1*) and previously noted work conducted in the 1970s (*2*).

The values in the exhibit are not capacities of freeway terminals, but rather of ramps themselves

EXHIBIT 25-3. APPROXIMATE CAPACITY OF RAMP ROADWAYS

Free-Flow Speed of Ramp, S_{FR} (km/h)	Capacity (pc/h) Single-Lane Ramps	Capacity (pc/h) Two-Lane Ramps
> 80	2200	4400
> 65–80	2100	4100
> 50–65	2000	3800
≥ 30–50	1900	3500
< 30	1800	3200

Note that Exhibit 25-3 gives the capacity of the ramp roadway itself, not that of the ramp-freeway terminal. There is no evidence, for example, that a two-lane on-ramp freeway terminal can accommodate more vehicles than a one-lane ramp terminal.

It is unlikely that two-lane on-ramps can accommodate more than 2,250 to 2,400 pc/h through the merge area itself. The two-lane configuration will achieve a merge with less turbulence and a higher LOS but will not increase the capacity of the merge, which is controlled by the capacity of the downstream freeway segment. For higher on-ramp flows, a two-lane on-ramp must be used in conjunction with a lane addition and a major merge configuration.

Two-lane off-ramps can accommodate higher ramp flows through the diverge area than can single-lane off-ramps. A major diverge configuration can also be considered, which may more effectively balance the per-lane flows on each departing leg.

Where an off-ramp terminates at a signalized or unsignalized intersection, the capacity of the ramp system may be controlled by the capacity of the ramp approach to the intersection. Signalized intersections are analyzed using the techniques of Chapter 16, and procedures to analyze unsignalized intersections are provided in Chapter 17.

LOS

LOS in merge (and diverge) influence areas is determined by density for all cases of stable operation, represented by LOS A through E. LOS F exists when the total flow departing from the merge area (v) exceeds the capacity of the downstream freeway segment. No density will be predicted for such cases. Refer to Chapter 22 for procedures to analyze LOS F conditions.

LOS criteria for merge and diverge areas are listed in Exhibit 25-4. The density values shown for LOS A through E assume stable operation, with no breakdowns within the merge influence area.

EXHIBIT 25-4. LOS CRITERIA FOR MERGE AND DIVERGE AREAS

LOS	Density (pc/km/ln)
A	≤ 6
B	> 6–12
C	> 12–17
D	> 17–22
E	> 22
F	Demand exceeds capacity

MERGE INFLUENCE AREAS

The subsections below describe the three primary steps in the model for analysis of merge areas. The model applies to single-lane, right-hand on-ramp merge areas. Additional sections discuss the application of procedures to other geometric configurations.

Predicting Flow Entering Lanes 1 and 2 (v_{12})

The principal influences on flow remaining in Lanes 1 and 2 immediately upstream of the merge influence area are

- Total freeway flow approaching merge area (v_F) (pc/h),
- Total ramp flow (v_R) (pc/h),
- Total length of acceleration lane (L_A) (m), and
- Free-flow speed of ramp at point of merge area (S_{FR}) (km/h).

Ramps on four-lane, eight-lane, and ten-lane freeways are always analyzed as isolated merge or diverge areas. The nature of the procedure for predicting v_{12} makes the four-lane case trivial, and data are insufficient to determine the effects of adjacent ramps on eight-lane and ten-lane freeways.

For six-lane freeways, however, sufficient data are available to take into account the effect of adjacent ramps on lane distribution at a subject ramp. When nearby ramps inject vehicles into or remove them from Lane 1, the lane distribution may be seriously altered. Important variables determining this impact include the total flow on the upstream (v_U) or downstream (v_D) ramp (or both), in pc/h and the distance from the subject ramp to the adjacent upstream (L_{up}) or downstream (L_{down}) ramp (or both), in meters. For ramps on six-lane freeways, therefore, an additional analysis step is necessary to determine whether adjacent ramps are close enough to affect lane distribution at the subject ramp.

With all of these variables, the total approaching freeway flow has the most dominant influence on flow in Lanes 1 and 2. Models are structured to account for this phenomenon without distorting other relationships. Longer acceleration lanes encourage less turbulence as ramp vehicles enter the freeway traffic stream and therefore lead to lower densities in the influence area and higher flows in Lanes 1 and 2. When the ramp has a higher free-flow speed, vehicles tend to enter the freeway at higher speeds, and approaching freeway vehicles tend to move further left to avoid the possibility of high-speed turbulence.

Exhibit 25-5 lists equations used for predicting v_{12} immediately upstream of the ramp influence area. These equations apply to six- and eight-lane freeways (with three and four lanes in each direction, respectively). For four-lane freeways (two lanes in each direction), only Lanes 1 and 2 exist, and $v_{12} = v_F$ by definition.

v_F, v_R, v_{12}, and v_D are in pc/h; L_A, L_{up}, and L_{down} are in meters; S_{FR} is in km/h

EXHIBIT 25-5. MODELS FOR PREDICTING v_{12} AT ON-RAMPS

$v_{12} = v_F * P_{FM}$		
For 4-lane freeways (2 lanes each direction)	$P_{FM} = 1.000$	
For 6-lane freeways (3 lanes each direction)	$P_{FM} = 0.5775 + 0.000092L_A$	(Equation 1)
	$P_{FM} = 0.7289 - 0.0000135\ (v_F + v_R) - 0.002048S_{FR} + 0.0002L_{up}$	(Equation 2)
	$P_{FM} = 0.5487 + 0.0801\ v_D/L_{down}$	(Equation 3)
For 8-lane freeways (4 lanes each direction)	$P_{FM} = 0.2178 - 0.000125v_R + 0.05887L_A/S_{FR}$	(Equation 4)

The variables used in Exhibit 25-5 are defined as follows:

v_{12} = flow rate in Lanes 1 and 2 of freeway immediately upstream of merge (pc/h),
v_F = freeway demand flow rate immediately upstream of merge (pc/h),
v_R = on-ramp demand flow rate (pc/h),
v_D = demand flow rate on adjacent downstream ramp (pc/h),
P_{FM} = proportion of approaching freeway flow remaining in Lanes 1 and 2 immediately upstream of merge,
L_A = length of acceleration lane (m),
S_{FR} = free-flow speed of ramp (km/h),
L_{up} = distance to adjacent upstream ramp (m), and
L_{down} = distance to adjacent downstream ramp (m).

The general model specifies that v_{12} is a proportion of the approaching freeway flow, v_F. For four-lane freeways, this is a trivial relationship since all approaching flow is in Lanes 1 and 2. For eight-lane freeways, a single equation is used to determine this proportion without regard to conditions on adjacent upstream or downstream ramps, or both.

For six-lane freeways, the analysis is complicated by the fact that the effect of some types of adjacent ramps can be predicted. Exhibit 25-6 lists the various sequences of ramps that may occur on six-lane freeways and the appropriate equation from Exhibit 25-5 that should be applied in each case.

EXHIBIT 25-6. SELECTING EQUATIONS FOR P_{FM} FOR SIX-LANE FREEWAYS

Adjacent Upstream Ramp	Subject Ramp	Adjacent Downstream Ramp	Equation(s) Used
None	On	None	Equation 1
None	On	On	Equation 1
None	On	Off	Equation 3 or 1
On	On	None	Equation 1
Off	On	None	Equation 2 or 1
On	On	On	Equation 1
On	On	Off	Equation 3 or 1
Off	On	On	Equation 2 or 1
Off	On	Off	Equation 3, 2, or 1

Equation 2 from Exhibit 25-5 addresses cases with an adjacent upstream off-ramp, whereas Equation 3 addresses cases with an adjacent downstream off-ramp. Adjacent on-ramps do not affect subject ramp behavior, and the analysis proceeds using Equation 1.

Where an adjacent upstream or downstream off-ramp (or both) exists, the decision to use Equation 2 or 3 versus 1 is made by determining the equilibrium separation distance

(L_{EQ}) between ramps. If the distance between ramps is greater than or equal to L_{EQ}, Equation 1 is always used. If the distance between ramps is less than L_{EQ}, Equation 2 or 3 is used as appropriate.

L_{EQ} is that distance for which Equation 1 and Equation 2 or 3, as appropriate, yield the same value of P_{FM}. Thus, where an adjacent upstream off-ramp exists, Equation 2 must be considered. If Equation 2 is set equal to Equation 1, L_{EQ}, is shown in Equation 25-2.

$$L_{EQ} = 0.0675\,(v_F + v_R) + 0.46L_A + 10.24S_{FR} - 757 \quad (25\text{-}2)$$

where

L_{EQ} = equilibrium distance when Equation 1 is set equal to Equation 2 from Exhibit 25-5 (m).

If $L_{up} \geq L_{EQ}$, Equation 1 is used. If $L_{up} < L_{EQ}$, Equation 2 is used. Similarly, when a choice between Equation 3 and Equation 1 must be made, Equation 25-3 is used to compute L_{EQ}:

$$L_{EQ} = \frac{v_D}{0.3596 + 0.001149\,L_A} \quad (25\text{-}3)$$

where

L_{EQ} = equilibrium distance when Equation 1 is set equal to Equation 3 from Exhibit 25-5 (m).

In this case, if the distance to the downstream off-ramp is greater than or equal to L_{EQ} ($L_{down} \geq L_{EQ}$), Equation 1 is used. If $L_{down} < L_{EQ}$, Equation 3 is used.

A special case exists when both a downstream and an upstream adjacent off-ramp exist. In such cases, two solutions for P_{FM} may arise, depending on whether the analysis considers the upstream or the downstream adjacent ramp, because they cannot be considered simultaneously. In such cases, the analysis resulting in the largest value of P_{FM} is used.

Determining Capacity

Two capacities are to be checked:

- Total flow from merge, and
- Total flow into merge influence area

The capacity of a merge area is determined primarily by the capacity of the downstream freeway segment. Thus, the total flow arriving on the upstream freeway and the on-ramp cannot exceed the basic freeway capacity of the departing downstream freeway segment. There is no evidence that the turbulence of the merge area causes the downstream freeway capacity to be less than that of a basic freeway segment.

Studies have also shown that there is a practical limit to the total flow rate that can enter the ramp influence area. For an on-ramp, the flow entering the ramp influence area includes v_{12} and v_R. Thus, the total flow entering the ramp influence area is given according to Equation 25-4.

$$v_{R12} = v_{12} + v_R \quad (25\text{-}4)$$

Exhibit 25-7 lists capacity flow rates for the total downstream freeway flow ($v = v_F + v_R$) and maximum desirable values for the total flow entering the ramp influence area (v_{R12}). Two conditions may occur for a given analysis. First, the total departing freeway flow (v) may exceed the capacity of the downstream freeway segment. Failure (LOS F) is expected, and queues will form upstream from the merge segment. When the downstream freeway capacity is exceeded, LOS F exists regardless of whether the flow rate entering the ramp influence area exceeds its capacity.

EXHIBIT 25-7. CAPACITY VALUES FOR MERGE AREAS

Freeway Free-Flow Speed (km/h)	Maximum Downstream Freeway Flow, v (pc/h)				Max Desirable Flow Entering Influence Area, v_{R12} (pc/h)
	Number of Lanes in One Direction				
	2	3	4	> 4	
120	4800	7200	9600	2400/ln	4600
110	4700	7050	9400	2350/ln	4600
100	4600	6900	9200	2300/ln	4600
90	4500	6750	9000	2250/ln	4600

The second condition occurs when the total flow entering the ramp influence area (v_{R12}) exceeds its maximum desirable level but the total freeway flow (v) does not exceed the capacity of the downstream freeway segment. In this case, locally high densities are expected, but no queuing is expected on the freeway. The actual lane distribution of entering vehicles is likely to consist of more vehicles in the outer lanes than is indicated by the models herein. Overall, operation will remain stable, and LOS F is not expected to occur.

When the total downstream flow exceeds the basic freeway capacity of the downstream segment, LOS F exists. In such cases, no further computations are needed, and LOS F is assigned. For all other cases, including cases in which v_{R12} exceeds its stated limit, LOS is determined by estimating the density in the ramp influence area.

Determining LOS

LOS criteria for merge areas are based on density in the merge influence area as shown in Exhibit 25-4. Studies (*2,4*) have shown that there is an overlap in density ranges in the area of capacity such that some breakdown operations may have lower densities than those achieved under stable operation. This situation is due to the wavelike motion of vehicles in a queue and the rather short length of the defined influence area, the result being that the determination of LOS F is based solely on the comparison of demand flows with capacity.

Equation 25-5 is used to estimate the density in the merge influence area. Note that the equation for density applies only to undersaturated flow conditions.

Equation applicable only to undersaturated flow conditions

$$D_R = 3.402 + 0.00456v_R + 0.0048v_{12} - 0.01278L_A \tag{25-5}$$

where

D_R = density of merge influence area (pc/km/ln),
v_R = on-ramp peak 15-min flow rate (pc/h),
v_{12} = flow rate entering ramp influence area (pc/h), and
L_A = length of acceleration lane (m).

Special Cases

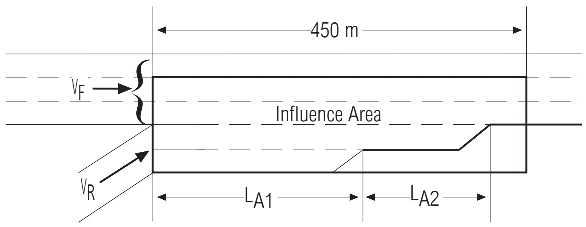
A number of merge configurations do not involve single-lane, right-side on-ramps. These are dealt with using modifications to the basic merge analysis procedure and adapting the results to the specific geometry being analyzed.

Two-Lane On-Ramps

Exhibit 25-8 illustrates a typical two-lane freeway on-ramp. It is characterized by two separate acceleration lanes, each successively forcing merging maneuvers to the left.

Two-lane on-ramps entail two modifications to the basic methodology: the flow remaining in Lanes 1 and 2 immediately upstream of the on-ramp is generally somewhat higher than that for one-lane on-ramps in similar situations, and densities in the merge area are lower than those for similar one-lane on-ramp situations. The lower density is primarily due to the existence of two acceleration lanes and the generally longer distance over which the two acceleration lanes extend. Thus, the effectiveness of two-lane on-ramps is that higher ramp flows are handled more smoothly and at better levels of service than if the same flows were carried on a one-lane ramp with conventional merge design.

EXHIBIT 25-8. TYPICAL TWO-LANE ON-RAMP



In computation of v_{12} for two-lane on-ramps, the standard expression in Exhibit 25-5 is used:

$$v_{12} = v_F * P_{FM}$$

For two-lane on-ramps, however, the following values of P_{FM} are used instead of the equations shown in Exhibit 25-5:

- Four-lane freeways, P_{FM} = 1.000;
- Six-lane freeways, P_{FM} = 0.555;
- Eight-lane freeways, P_{FM} = 0.209.

In computation of the expected density in the ramp influence area, Equation 25-5 is applied except that the length of the acceleration lane, L_A, is replaced by the effective length of the acceleration lane, L_{Aeff}, as computed by Equation 25-6.

$$L_{Aeff} = 2L_{A1} + L_{A2} \tag{25-6}$$

where L_{A1} and L_{A2} are as defined in Exhibit 25-8.

Capacities of two-lane ramps are the same as those for one-lane ramps

The values governing maximum flow rates for v and v_{R12} are not affected by the use of a two-lane on-ramp. The capacity of the downstream freeway segment continues to control the total output capacity of the merge, and the maximum desirable number of vehicles that may enter the influence area on Lanes 1 and 2 of the freeway is not enhanced by the existence of a two-lane on-ramp. The values of Exhibit 25-7 are applied without change.

Lane Additions

On-ramps are sometimes associated with the addition of a lane at the merge point. Where a single-lane on-ramp results in a lane addition, the capacity of the ramp is governed by the ramp geometry itself and not by the ramp-freeway junction. Where a two-lane on-ramp results in a lane addition, the junction should be classified as a major merge area.

Analysis of single-lane additions (and lane drops) is relatively straightforward. The downstream segment is simply considered to be a basic freeway segment with an additional lane. If, however, an added lane is dropped at a diverge point within 750 m of the point of addition, a weaving configuration will be formed, and the segment should be analyzed using the methodology of Chapter 24, "Freeway Weaving."

Major Merge Areas

Major merge defined

A major merge area is one in which two primary roadways, each having multiple lanes, merge to form a single freeway segment. The merging roadways may originate in a freeway interchange or from an urban street or rural highway. Major merges are different from one- and two-lane on-ramps in that each of the merging roadways is generally at or near freeway design standards and no clear ramp or acceleration lane is involved in the merge.

Such major merge areas come in a variety of geometries, all of which fall into two general categories, as illustrated in Exhibits 25-9 and 25-10. In Exhibit 25-9, the number of lanes departing from the merge area is one fewer than the total number of approaching lanes. This geometry is accomplished by having the right lane of the left merging leg and the left lane of the right merging leg combine to form a single lane. In geometries of the type illustrated in Exhibit 25-10, the number of lanes departing from the merge is the same as the total number of lanes approaching it.

EXHIBIT 25-9. MAJOR MERGE AREA WITH ONE FEWER LANE LEAVING INFLUENCE AREA

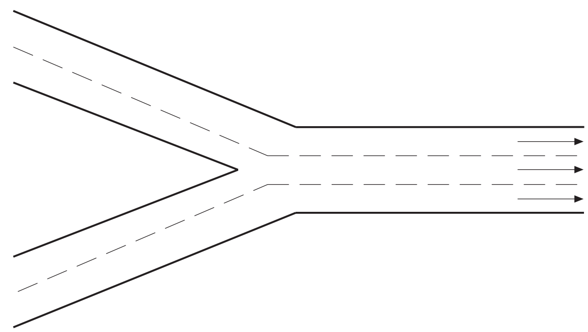
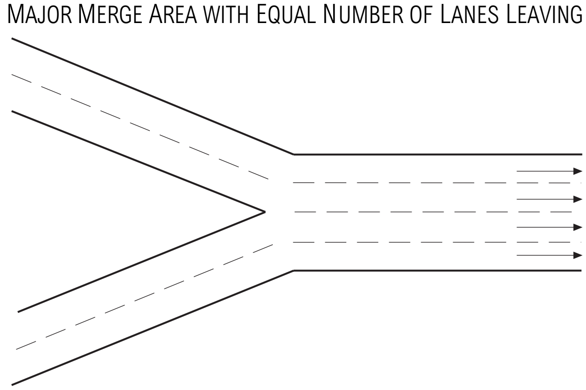


EXHIBIT 25-10. MAJOR MERGE AREA WITH EQUAL NUMBER OF LANES LEAVING INFLUENCE AREA



There are no effective models of performance for a major merge area. Therefore, the analysis is limited to checking capacities on approaching legs and the departing freeway. The capacity of each entering leg and the departing freeway is computed using the general values of Exhibit 25-7. The capacity of each entering leg is compared with the peak demand flow on each (converted to pc/h), whereas the capacity of the departing freeway is compared with the sum of the two peak entering demands (also converted to pc/h). Problems in major merge areas generally result from insufficient capacity of the downstream freeway segment.

On-Ramps on Ten-Lane Freeway (Five Lanes in Each Direction)

Although it is not common, there are freeway segments in North America where five lanes of traffic exist in each direction. A procedure is therefore needed to analyze a single-lane, right-hand on-ramp on such freeway segments. The flow rate in Lane 5 of the freeway is estimated and deducted from the approaching freeway flow. The remaining approaching freeway flow consists of flow that would be expected on a similar freeway of four lanes; thus standard procedures for analysis are used. The flow in Lane 5 of the freeway for on-ramps is estimated as shown in Exhibit 25-11.

EXHIBIT 25-11. FLOW IN LANE 5 OF FREEWAY APPROACHING SINGLE-LANE, RIGHT-SIDE ON-RAMP

Total Approaching Freeway Flow, v_F (pc/h)	Approaching Freeway Flow In Lane 5, v_5 (pc/h)
≥ 8500	2500
7500-8499	$0.285v_F$
6500-7499	$0.270v_F$
5500-6499	$0.240v_F$
< 5500	$0.220v_F$

Source: AASHTO (*3*).

Once the anticipated approaching flow in Lane 5 is determined, normal procedures are applied, assuming an eight-lane freeway (four lanes in one direction), with an effective approaching flow computed using Equation 25-7.

$$v_{F4eff} = v_F - v_5 \tag{25-7}$$

where

v_{F4eff} = effective approaching freeway flow four-lane (one-direction) freeway segment (pc/h),

v_F = total approaching freeway flow in five-lane (one-direction) freeway segment (pc/h), and

v_5 = anticipated approach flow in Lane 5 of freeway, computed as in Exhibit 25-11 (pc/h).

Left-Hand On-Ramps

Although not normally recommended, left-hand ramps do exist on some freeways and occur quite frequently on collector-distributor roadways. The left-hand ramp influence area covers the same length as that for right-hand ramps but now encompasses the two left lanes plus an acceleration lane. For right-hand on-ramps, a critical computation is the estimation of v_{12}. For left-hand ramps, the two left lanes are of interest. For a four-lane freeway, this flow rate remains v_{12} and there is no difficulty. For a six-lane freeway, the entering flow of interest is v_{23}, and for eight-lane freeways, it is v_{34}. Although there is no direct method for the analysis of left-hand on-ramps, some rational modifications can be applied to right-hand on-ramp methodologies to produce reasonable results (*2*).

It is suggested that the analyst first compute v_{12} using procedures for a right-hand on-ramp and then multiply the v_{12} value by 1.00, 1.12, or 1.20 to obtain v_{12}, v_{23}, or v_{34} for a left-hand on-ramp on four-, six-, or eight-lane freeways, respectively.

Remaining computations for density, speed, or both may continue, replacing v_{12} with v_{23} or v_{34} as appropriate. All capacity values remain unchanged.

Effects of Ramp Control at On-Ramps

For the purposes of this chapter, procedures are not modified in any way to account for the local effect of ramp control, except for the limitation the ramp meter may have on v_R. Research (*4*) has found that breakdown of a merge area may be a probabilistic event based on the platoon characteristics of the arriving ramp vehicles. Ramp meters provide for uniform gaps between entering ramp vehicles and may therefore reduce the probability of a breakdown on the freeway mainline.

DIVERGE INFLUENCE AREAS

Analysis procedures for diverge areas follow the same general approach as that for merge areas. Standard procedures have been calibrated from a research study (*2*) that apply to single-lane, right-hand off-ramps. The same three fundamental steps are followed: determine the approaching freeway flow in Lanes 1 and 2 of the freeway (v_{12}),

v_F, v_R, v_{12}, and v_D are in pc/h; L_D, L_{up}, and L_{down} are in meters

See Exhibit 25-2 for definition of terms

determine the capacity for the segment (v_F and v_{12}), and determine the density of flow within the ramp influence area (D_R). These procedures are then modified and applied to other diverge configurations and geometries.

Predicting Flow Entering Lanes 1 and 2 (v_{12})

Models for predicting freeway flow entering the diverge area in Lanes 1 and 2 of the freeway are shown in Exhibit 25-12. The approach is similar to that for merge areas and is affected by the same variables.

There are two major differences between merge-area analysis and diverge-area analysis. First, approaching flow in Lanes 1 and 2 (v_{12}) is predicted for a point immediately upstream of the deceleration lane even if this point is upstream or downstream of the beginning of the ramp influence area. Second, at a diverge area, v_{12} includes v_R. Thus, the general model treats v_{12} as the sum of the off-ramp flow plus a proportion of the through freeway flow.

EXHIBIT 25-12. MODELS FOR PREDICTING V_{12} AT OFF-RAMPS

$v_{12} = v_R + (v_F - v_R)P_{FD}$		
For 4-lane freeways (2 lanes each direction)	$P_{FD} = 1.00$	
For 6-lane freeways (3 lanes each direction)	$P_{FD} = 0.760 - 0.000025v_F - 0.000046v_R$	(Equation 5)
	$P_{FD} = 0.717 - 0.000039v_F + 0.184v_U/L_{up}$	(Equation 6)
	$P_{FD} = 0.616 - 0.000021v_F + 0.038v_D/L_{down}$	(Equation 7)
For 8-lane freeways (4 lanes each direction)	$P_{FD} = 0.436$	(Equation 8)

The variables used in Exhibit 25-12 are defined as follows:

v_{12} = flow rate in lanes 1 and 2 of freeway immediately upstream of diverge (pc/h),
v_F = freeway demand flow rate immediately upstream of diverge (pc/h),
v_R = off-ramp demand flow rate (pc/h),
v_U = demand flow rate on adjacent upstream ramp (pc/h),
v_D = demand flow rate on adjacent downstream ramp (pc/h),
P_{FD} = proportion of through freeway flow remaining in Lanes 1 and 2 immediately upstream of diverge,
L_{up} = distance to adjacent upstream ramp (m), and
L_{down} = distance to adjacent downstream ramp (m).

The general model specifies that v_{12} consists of the off-ramp flow (v_R) plus a proportion of the approaching freeway flow (v_F). For four-lane freeways, this is a trivial relationship since all approaching flow is in Lanes 1 and 2. For eight-lane freeways, a single value is used without regard to conditions on adjacent upstream or downstream ramps, or both.

For six-lane freeways, the analysis is complicated by the fact that the effect of some types of adjacent ramps can be accommodated. Exhibit 25-13 shows the various sequences of ramps that may occur on six-lane freeways and the appropriate equations from Exhibit 25-12 that should be applied in each case.

Equation 6 from Exhibit 25-13 addresses cases with an adjacent upstream on-ramp, and Equation 7 addresses cases with an adjacent downstream off-ramp. Adjacent upstream off-ramps and adjacent downstream on-ramps do not affect subject ramp behavior, and analysis proceeds using Equation 5.

EXHIBIT 25-13. SELECTING EQUATIONS FOR P_{FD} FOR SIX-LANE FREEWAYS

Adjacent Upstream Ramp	Subject Ramp	Adjacent Downstream Ramp	Equation(s) Used
None	Off	None	Equation 5
None	Off	On	Equation 5
None	Off	Off	Equation 7 or 5
On	Off	None	Equation 6 or 5
Off	Off	None	Equation 5
On	Off	On	Equation 6 or 5
On	Off	Off	Equation 7, 6, or 5
Off	Off	On	Equation 5
Off	Off	Off	Equation 7 or 5

Where an adjacent upstream on-ramp or downstream off-ramp exists, or where both exist, the decision to use Equation 6 or 7 versus 5 is made by determining the equilibrium separation distance (L_{EQ}) between ramps. If the distance between ramps is greater than or equal to L_{EQ}, Equation 5 is always used. If the distance between ramps is less than L_{EQ}, Equation 6 or 7 is used as appropriate.

L_{EQ} is that distance for which Equation 5 and Equation 6 or 7, as appropriate, yields the same value for P_{FD}. Thus, where an adjacent upstream on-ramp exists, Equation 6 must be considered. If Equation 6 is set equal to Equation 5, the following relationship is derived as Equation 25-8.

$$L_{EQ} = \frac{v_U}{0.2337 + 0.000076v_F - 0.00025v_R} \qquad (25\text{-}8)$$

where

L_{EQ} = equilibrium distance when Equation 5 is set equal to Equation 6, from Exhibit 25-12 (m)

and where all variables are as previously defined. If $L_{up} \geq L_{EQ}$, Equation 5 is used. If $L_{up} < L_{EQ}$, Equation 6 is employed.

A similar analysis is conducted where an adjacent downstream off-ramp exists. Equation 25-9 is used for the analysis.

$$L_{EQ} = \frac{v_D}{3.79 - 0.00011v_F - 0.00121v_R} \qquad (25\text{-}9)$$

where

L_{EQ} = equilibrium distance when Equation 5 is set equal to Equation 7, from Exhibit 25-12 (m).

In this case, if the distance to the downstream off-ramp is greater than or equal to L_{EQ} ($L_{down} \geq L_{EQ}$), Equation 5 is used. If $L_{down} < L_{EQ}$, Equation 7 is used.

A special case exists when both a downstream adjacent off-ramp and an upstream adjacent on-ramp exist. In such cases, two solutions for P_{FD} may arise, depending on whether the analysis considers the upstream or the downstream adjacent ramp since both cannot be considered simultaneously. In such cases, the analysis resulting in the largest value of P_{FD} is applied.

Three capacities are to be checked:

- Total flow that can depart,
- Maximum flow in Lanes 1 and 2 just prior to the deceleration lane, and
- Maximum flow on both downstream legs

Determining Capacity

The three limiting values that should be checked in a diverge area are the total flow that can depart from the diverge, the capacities of the departing freeway leg or legs or ramp, or both, and the maximum flow that can enter on Lanes 1 and 2 just prior to the deceleration lane.

In a diverge area, the total flow that can depart is generally limited by the capacity of freeway lanes approaching the diverge. In all appropriate diverge designs, the number of lanes leaving the diverge area is either equal to or one greater than the number entering. This flow (v_F) is as previously defined. Exhibit 25-14 lists capacity values for this flow.

EXHIBIT 25-14. CAPACITY VALUES FOR DIVERGE AREAS

Freeway Free-Flow Speed (km/h)	Maximum Upstream, v_{FI} or Downstream Freeway Flow, v (pc/h) Number of Lanes in One Direction				Max Flow Entering Influence Area, v_{12} (pc/h)
	2	3	4	> 4	
120	4800	7200	9600	2400/ln	4400
110	4700	7050	9400	2350/ln	4400
100	4600	6900	9200	2300/ln	4400
90	4500	6750	9000	2250/ln	4400

Note:
For capacity of off-ramp roadways, see Exhibit 25-3.

The second limit is most important, since it is the primary reason that diverge areas fail. Failure at a diverge is often related to the capacity of one of the exit legs, most often the ramp. The capacity of each exit leg must be checked against the expected flow. For a downstream freeway leg (at a major diverge area there may be two of these), capacity values may be drawn from Exhibit 25-14 for the appropriate number of freeway lanes. For off-ramp roadways, capacity values are provided in Exhibit 25-3.

The flow entering Lanes 1 and 2 just upstream of the deceleration lane is simply the flow in Lanes 1 and 2 (v_{12}), estimated as indicated in Exhibit 25-12. This flow includes the off-ramp flow. Exhibit 25-14 lists maximum desirable values for v_{12}.

Failure of the diverge segment (LOS F) is expected if any one of the following conditions is found:

- Capacity of the upstream freeway segment is exceeded by total arriving demand flow,
- Capacity of the downstream freeway segment is exceeded by the demand flow proceeding on the downstream freeway, or
- Capacity of the off-ramp is exceeded by the off-ramp demand flow.

When the total flow approaching the diverge influence area (v_{12}) exceeds its maximum desirable level but total demand flows are within all other capacity values, some locally high densities would be expected, but stable flow is still maintained. In such cases, it is likely that more vehicles will use outer lanes than is indicated by this methodology. LOS is determined by estimating the density in the ramp influence area, as indicated herein.

Determining LOS

LOS criteria for diverge areas are based on density in the diverge influence area. The numeric criteria are the same as those for merge areas, as shown previously in Exhibit 25-4.

Equation 25-10 is used to estimate density within the diverge influence area.

$$D_R = 2.642 + 0.0053v_{12} - 0.0183L_D \quad (25\text{-}10)$$

where

D_R = density of diverge influence area (pc/km/ln),

v_{12} = flow rate entering ramp influence area (pc/h), and
L_D = length of deceleration lane (m).

As was the case for merge areas, the equation predicting density in the segment (Equation 25-10) applies only to undersaturated flow conditions. Density is not computed when capacity is exceeded. Thus, when demand flows exceed the capacity of the approaching freeway segment or either the departing freeway segment or segments or the ramp, LOS F is automatically applied. For all other cases, including those in which the maximum flow is entering the ramp influence area (v_{12}), the density is computed using Equation 25-10, and LOS is determined using the criteria of Exhibit 25-4.

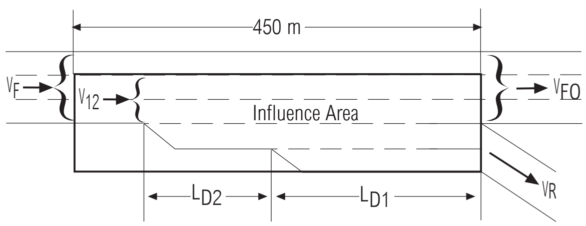
Special Cases

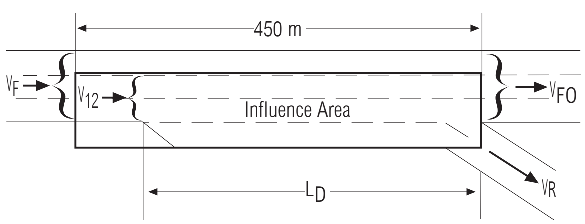
As was the case for merge areas, there are a number of other diverge configurations and geometries that do not conform to the single-lane, right-hand off-ramp case. These are handled as special cases, with modifications or additions to the basic analysis procedure to more accurately address these configurations.

Two-Lane Off-Ramps

Two common types of diverge designs are in use with two-lane, right-hand off-ramps. These are shown in Exhibit 25-15. In the first, two successive deceleration lanes are introduced. In the second, a single deceleration lane is used. The left-hand ramp lane splits from Lane 1 of the freeway at the gore area, without a deceleration lane. The existence of a two-lane off-ramp affects the lane distribution of approaching vehicles and thus the computation of v_{12}.

EXHIBIT 25-15. COMMON GEOMETRIES FOR TWO-LANE OFF-RAMPS





The general equation for computing v_{12} in a diverge area remains the same as that shown in Exhibit 25-12:

$$v_{12} = v_R + (v_F - v_R)\, P_{FD}$$

However, rather than using the standard equations of Exhibit 25-12, P_{FD} for two-lane off-ramps is found as follows:

- Four-lane freeways, P_{FD} = 1.000;
- Six-lane freeways, P_{FD} = 0.450; and
- Eight-lane freeways, P_{FD} = 0.260.

To estimate the density in the diverge influence area, Equation 25-10 is used. However, when the geometry of the two-lane off-ramp is similar to that shown in the top part of Exhibit 25-15, the length of the deceleration lane is replaced in the equation by the effective length, L_{Deff} (Equation 25-11).

$$L_{Deff} = 2L_{D1} + L_{D2} \qquad (25\text{-}11)$$

When the geometry is similar to that shown in the bottom part of Exhibit 25-15, the length of the deceleration lane is used without modification.

The capacity values associated with a two-lane off-ramp are the same as those associated with a one-lane off-ramp. That is, the capacity for total flow through the diverge is unchanged. However, its distribution is more flexible, since the two-lane off-ramp can accommodate more ramp traffic than a single-lane off-ramp.

Lane Drops

When a single-lane off-ramp results in a lane drop, the capacity of the ramp is governed by its geometry, and it is analyzed as a ramp roadway. When a two-lane off-ramp results in a lane drop, it should be treated as a major diverge segment.

When a lane drop occurs 750 m or less from a merge point at which a lane was added, a weaving configuration is created and should be analyzed using the procedures of Chapter 24. In all other cases, the entering and departing freeway segments are analyzed as basic freeway segments having different numbers of lanes.

Major Diverge Areas

The two common geometries for major diverge areas are illustrated in Exhibits 25-16 and 25-17. In Exhibit 25-16, the number of lanes entering the diverge area is the same as the number of lanes leaving the diverge area. In Exhibit 25-17, the number of lanes leaving the diverge area is one more than the number entering the segment.

EXHIBIT 25-16. MAJOR DIVERGE AREA WITH EQUAL NUMBER OF LANES ENTERING AND LEAVING INFLUENCE AREA

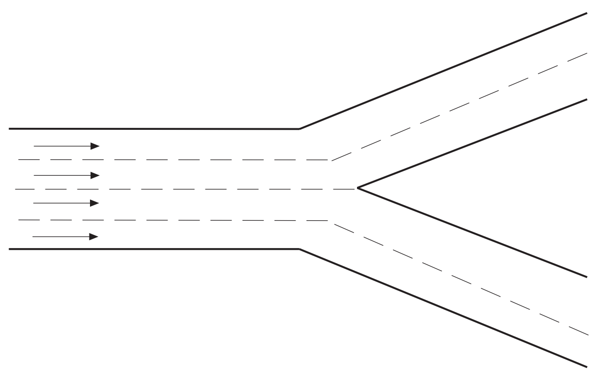
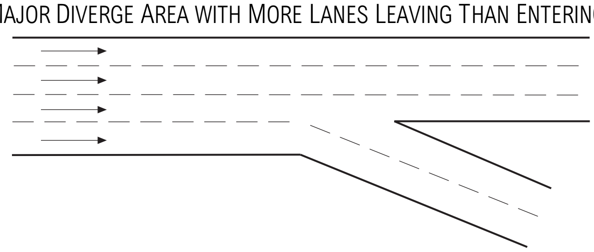


EXHIBIT 25-17. MAJOR DIVERGE AREA WITH MORE LANES LEAVING THAN ENTERING INFLUENCE AREA



The principal analysis of a major diverge area involves the capacity of entering and departing roadways, all of which are generally built to mainline standards. The entering demand and the departing demand on each exit leg must be checked against the capacity of the appropriate entry or departure leg. Equation 25-12 allows the density across all freeway lanes to be estimated for a distance of 450 m upstream of the gore area.

$$D = 0.0109 \frac{v_F}{N} \quad (25\text{-}12)$$

where

D = average density across all freeway lanes for a distance of 450 m upstream of diverge (pc/km/ln),
v_F = freeway flow rate approaching diverge area (pc/h/ln), and
N = number of lanes on freeway segment approaching diverge area.

This density can be compared with the LOS criteria in Exhibit 25-4 to determine the LOS in the diverge area.

Off-Ramps on Ten-Lane Freeways (Five Lanes in One Direction)

Segments of freeway exist in some urban areas in which there are five lanes in each direction. For off-ramps that must be analyzed on such sections, a special approach, similar to that for on-ramps, is employed. The flow in the fifth lane, v_5, is estimated using the criteria of Exhibit 25-18. The remaining four lanes then have a flow equal to

$$v_{F4eff} = v_F - v_5$$

as was the case for on-ramps (see Equation 25-7) on five-lane segments. The ramp is then analyzed as if it were on an eight-lane freeway (four lanes in one direction), using standard procedures and v_{F4eff} as v_F.

This special procedure applies only to single-lane, right-hand off-ramps on five-lane segments.

EXHIBIT 25-18. FLOW IN LANE 5 OF FREEWAY APPROACHING SINGLE-LANE, RIGHT-HAND OFF-RAMP

Total Approaching Freeway Flow, v_F (pc/h)	Flow in Lane 5, v_5 (pc/h)
≥ 7,000	$0.200v_F$
5,500–6,999	$0.150v_F$
4,000–5,499	$0.100v_F$
< 4,000	0

Left-Hand Off-Ramps

Left-hand off-ramps do exist along some freeway segments. In this case, the ramp influence area involves the two leftmost lanes of the freeway, not Lanes 1 and 2, except in the case of a four-lane freeway, where Lanes 1 and 2 make up the rightmost and leftmost lanes of the freeway.

To analyze such situations, v_{12} is estimated using the standard procedures of Exhibit 25-12. The flow in the two leftmost lanes entering the diverge influence area is then estimated by multiplying the v_{12} value by 1.00, 1.05, or 1.10 for left-hand ramps on four-, six-, or eight-lane freeways, respectively.

Remaining computations for density, speed, or both may continue, replacing v_{12} with v_{23} or v_{34} as appropriate. All capacity values remain unchanged.

OVERLAPPING RAMP INFLUENCE AREAS

Whenever a series of ramps on a freeway is analyzed, it is possible that the 450-m ramp influence areas overlap. In such cases, the operation in the overlapping region is determined by the ramp having the highest density.

DETERMINING SPEED AT RAMP INFLUENCE AREAS

To address freeway and multifacility LOS, it is necessary to predict average speeds on long segments of a facility. Thus, it is useful to provide models for estimating average speeds within ramp influence areas and on lanes outside the influence area (Lanes 3 and 4, where they exist) within the length of the 450-m ramp influence area. From such estimates, a space mean speed can be estimated for all vehicles traveling within the 450-m length of the ramp influence area on all lanes of the freeway.

Speeds of vehicles outside the ramp influence area are affected by merge and diverge operations

Note that this procedure reflects field observations that the average speeds of vehicles outside the ramp influence area are also affected by merge and diverge operations. Thus, it is not appropriate to assume that the speeds of vehicles in those outer lanes are the same as those on basic freeway segments for similar per-lane flow rates. In general, speeds in outer lanes in the vicinity of ramps will be somewhat reduced compared with speeds for similar flow levels on basic freeway segments, except when flow rates in those lanes are very low.

Exhibit 25-19 provides equations for estimating these speeds. Note that speeds can be estimated only for stable flow cases. Capacity analysis for freeway facilities operating with oversaturated flow conditions relies on deterministic queuing approaches, as presented in Chapter 22.

The equations for average speed in outer lanes reflect average per-lane flow rates of up to 2,988 veh/h/ln for merge areas and 2,350 veh/h/ln for diverge areas. In the case of merge lanes, this flow rate is well above the accepted average capacity of a freeway lane. Note, however, that freeway capacity per lane is always stated as an average across all lanes and that individual lanes will carry proportionally less or more flow. In merge and diverge areas, through vehicles tend to move left to avoid turbulence, resulting in cases where outer lanes are very heavily loaded compared with lanes within the ramp influence area (i.e., Lanes 1 and 2). Thus, even such high flow rates represent stable flow cases that have been observed in the field.

The equations apply to undersaturated conditions but with per-lane flows well above accepted levels at merge

EXHIBIT 25-19. AVERAGE SPEEDS IN VICINITY OF FREEWAY-RAMP TERMINALS

	Average Speed in Ramp Influence Area (km/h)	Average Speed in Outer Lanes of Ramp Influence Area (km/h)
Merge areas (on-ramps)	$S_R = S_{FF} - (S_{FF} - 67)M_s$ $M_s = 0.321 + 0.0039\, e^{(v_{R12}/1000)} - 0.004(L_A S_{FR}/1000)$	$S_O = S_{FF}$ where $v_{OA} < 500$ pc/h $S_O = S_{FF} - 0.0058(v_{OA} - 500)$ where $v_{OA} = 500$ to 2300 pc/h $S_O = S_{FF} - 10.52 - 0.01(v_{OA} - 2300)$ where $v_{OA} > 2300$ pc/h
Diverge areas (off-ramps)	$S_R = S_{FF} - (S_{FF} - 67)D_s$ $D_s = 0.883 + 0.00009v_R - 0.008S_{FR}$	$S_O = 1.06S_{FF}$ where $v_{OA} < 1000$ pc/h $S_O = 1.06S_{FF} - 0.0062(v_{OA} - 1000)$ where $v_{OA} \geq 1000$ pc/h

The variables used in Exhibit 25-19 are defined as follows:

S_R = space mean speed of vehicles within ramp influence area (km/h); for merge areas, this includes all vehicles in v_{R12}; for diverge areas, this includes all vehicles in v_{12};

S_O = space mean speed of vehicles traveling in outer lanes (Lanes 3 and 4, where they exist) within 450-m length range of ramp influence area (km/h);

S_{FF} = free-flow speed of freeway approaching merge or diverge area (km/h);

S_{FR} = free-flow speed of ramp (km/h);

L_A = length of acceleration lane (m);

v_R = flow rate on ramp (pc/h);
v_{R12} = sum of flow rates for ramp (v_R) and vehicles entering ramp influence area in Lanes 1 and 2 (v_{12}) at a merge area (pc/h);
v_{OA} = average per-lane flow rate in outer lanes (Lanes 3 and 4, where they exist) at beginning of ramp influence area (pc/h/ln);
M_s = intermediate speed determination variable for merge area; and
D_s = intermediate speed determination variable for diverge area.

The average per-lane flow rate in outer lanes (v_{OA}) is found according to Equation 25-13.

$$v_{OA} = \frac{v_F - v_{12}}{N_O} \tag{25-13}$$

where

v_{OA} = average per-lane demand flow in outer lanes (pc/h/ln),
N_O = number of outside lanes in one direction (not including acceleration or deceleration lanes or Lanes 1 and 2),
v_F = total approaching freeway flow rate (pc/h), and
v_{12} = demand flow rate approaching ramp influence area (pc/h).

Once S_R and S_O are determined, the space mean speed for all vehicles within the 450-m length range of the ramp influence area may be computed as the harmonic mean of the two according to Equation 25-14 for merge areas or Equation 25-15 for diverge areas.

$$S = \frac{v_{R12} + v_{OA}N_O}{\left(\frac{v_{R12}}{S_R}\right) + \left(\frac{v_{OA}N_O}{S_O}\right)} \tag{25-14}$$

$$S = \frac{v_{12} + v_{OA}N_O}{\left(\frac{v_{12}}{S_R}\right) + \left(\frac{v_{OA}N_O}{S_O}\right)} \tag{25-15}$$

Note that for merge areas, the average speed in outer lanes never exceeds the free-flow speed of the freeway. For diverge areas, at low flow rates in the outer lanes, average speeds may marginally exceed free-flow speed. Again, free-flow speed reflects the average speed of freeway vehicles under conditions of low flow, and average speeds in individual lanes may exceed the average or be less than the average. However, in all cases, the maximum prediction of the average speed, S, should be limited to the free-flow speed of the freeway. Thus, the average speed on the freeway in the vicinity of a ramp will never be predicted to be higher than the free-flow speed of the facility.

III. APPLICATIONS

The methodology of this chapter can be used to analyze the capacity and LOS of ramps and ramp junctions. First, the analyst identifies primary output. Primary outputs typically solved for in a variety of applications include LOS, length of acceleration and deceleration lanes (L_A, L_D), and number of ramp lanes (N). Performance measures related to density (D) and speed (S) are also achievable but are considered secondary outputs.

Guidelines for required inputs and estimated values are in Chapter 13

Second, the analyst must identify the default values or estimated values for use in the analysis. The analyst has three basic sources of input data: (a) default values found in this manual, (b) estimates and locally derived default values developed by the analyst, and (c) values derived from field measurements and observation. For each of the input variables, a value 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 facility or of a changed facility in the near term or distant future. This type of application is termed operational, and its primary output is LOS, with secondary outputs for density and speed. Another application is to check the adequacy or to recommend the required number of ramp lanes or acceleration and deceleration lane length given the volume or flow rate and LOS goal. This application is termed design since its primary output is a geometric attribute. Other outputs from this application include speed and density.

Another general type of analysis is termed planning. These analyses use estimates, HCM default values, and local default values as inputs in the calculation. As outputs, LOS, number of lanes, and length of acceleration or deceleration lane can be determined, 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 come from estimates or default values, whereas operational and design analyses tend to use field measurements or known values. Note that for each of the analyses, free-flow speed of the mainline and ramp, either measured or estimated, is required as an input for the computation.

COMPUTATIONAL STEPS

The worksheet for computations is shown in Exhibit 25-20. For all applications, the analyst provides general information and site information.

Operational (LOS)

For operational analysis (LOS), both the geometry and demand volumes must be fully specified. A sketch of the geometry of the ramp is entered into the upper portion of the worksheet. All demand volumes are specified in mixed vehicles per hour for the full hour under consideration and must be converted to flow rates (for the peak 15 min of the hour) in passenger cars per hour under equivalent base conditions. Then the flow rate of freeway vehicles remaining in Lanes 1 and 2 immediately upstream of the merge point or at the beginning of the deceleration lane is computed. Once v_{12} is estimated, this value can be combined with known values of v_F and v_R to find the checkpoint flow rates needed to compare with the capacity values. If the operations are undersaturated, the expected density in the ramp influence area is computed and LOS is determined by comparing the resultant density with LOS criteria of Exhibit 25-4. If speeds are desired as a secondary output or required for other analyses, they may be estimated.

Design (L_A, L_D, or N)

Design (L_A, L_D, or N) analysis is used to establish the required number of lanes or acceleration or deceleration lane length in a design application. The key to this application is the establishment of design hourly volumes and the desired LOS. All other input parameters are entered on the worksheet (see Exhibit 25-20) and assumed geometric features are noted. Then the analyst follows the same procedure described in the operational (LOS) application to determine LOS. The estimated LOS is compared with the desired LOS. This process is repeated by increasing or decreasing the attribute or attributes of a geometric feature until the estimated LOS matches or is better than the desired LOS.

PLANNING APPLICATIONS

Planning (LOS)
Planning (L_A, L_D, or N)

For the two planning applications, planning (LOS) and planning (L_A, L_D, or N), procedures correspond directly to procedures described for the operational (LOS) and design (L_A, L_D, or N) analyses in the previous section, respectively.

EXHIBIT 25-20. RAMPS AND RAMP JUNCTIONS WORKSHEET

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		Site Information	
Analyst	____________	Freeway/Direction of Travel	____________
Agency or company	____________	Junction	____________
Date Performed	____________	Jurisdiction	____________
Analysis Time Period	____________	Analysis Year	____________

❑ Operational (LOS) ❑ Design (L_A, L_D, or N) ❑ Planning (LOS) ❑ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp		Terrain ________	Downstream Adjacent Ramp	
❑ Yes	❑ On		❑ Yes	❑ On
❑ No	❑ Off		❑ No	❑ Off
L_{up} = ________ m			L_{down} = ________ m	
V_u = ________veh/h			V_D = ________veh/h	
		S_{FF} = ________ km/h S_{FR} = ________ km/h		
		Sketch (show lanes, L_A, L_D, v_R, v_F)		

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F									
v_R									
v_U									
v_D									

Merge Areas	Diverge Areas
Estimation of v_{12}	**Estimation of v_{12}**
$v_{12} = v_F * P_{FM}$	$v_{12} = v_R + (v_F - v_R)P_{FD}$
L_{EQ} = ________(Equation 25-2 or 25-3)	L_{EQ} = ________ (Equation 25-8 or 25-9)
P_{FM} = ________ using Equation ________ (Exhibit 25-5)	P_{FD} = ________ using Equation ________ (Exhibit 25-12)
v_{12} = ________ pc/h	v_{12} = ________ pc/h

Capacity Checks (Merge Areas)

	Actual	Maximum	LOS F?
v_{FO}		See Exhibit 25-7	
v_{R12}		4600: All	

Capacity Checks (Diverge Areas)

	Actual	Maximum	LOS F?
$v_{FI} = v_F$		See Exhibit 25-14	
v_{12}		4400: All	
$v_{FO} = v_F - v_R$		See Exhibit 25-14	
v_R		See Exhibit 25-3	

Level-of-Service Determination (if not F)	**Level-of-Service Determination (if not F)**
$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$	$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$
D_R = ____________ pc/km/ln	D_R = ____________ pc/km/ln
LOS = ____________(Exhibit 25-4)	LOS = ____________ (Exhibit 25-4)

Speed Estimation	**Speed Estimation**
M_s = ____________ (Exhibit 25-19)	D_s = ____________ (Exhibit 25-19)
S_R = ____________ km/h (Exhibit 25-19)	S_R = ____________ km/h (Exhibit 25-19)
S_0 = ____________ km/h (Exhibit 25-19)	S_0 = ____________ km/h (Exhibit 25-19)
S = ____________ km/h (Equation 25-14)	S = ____________ km/h (Equation 25-15)

The first criterion that categorizes these as planning applications is the use of estimates, HCM default values, or local default values on the input side of the calculation. Another factor that defines a given application as planning is the use of annual average daily traffic (AADT) to estimate directional design-hour volume (DDHV). DDHV is calculated using a known or forecast value of K (proportion of AADT occurring during the peak hour) and D. Further guidelines for computing DDHV are given in Chapter 8.

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

ANALYSIS TOOLS

The worksheet shown in Exhibit 25-20 and provided in Appendix A can be used to perform operational (LOS), planning (LOS), design (L_A, L_D, or N,) and planning (L_A, L_D, or N) analyses.

IV. EXAMPLE PROBLEMS

Problem No.	Description	Application
1	Determine LOS, density, and expected speed of an isolated on-ramp	Operational (LOS)
2	Determine LOS, density, and expected speed of two consecutive off-ramps	Operational (LOS)
3	Determine LOS, density, and expected speed of on-ramp, off-ramp pair	Operational (LOS)
4	Determine LOS, density, and expected speed of a two-lane on-ramp	Operational (LOS)
5	Determine LOS, density, and expected speed of an off-ramp	Operational (LOS)
6	Determine LOS, density, and expected speed of a left-side on-ramp	Operational (LOS)

EXAMPLE PROBLEM 1

The Ramp An isolated on-ramp (single lane) to a four-lane freeway.

The Question What is the LOS during the peak hour?

The Facts

- √ Isolated location,
- √ Two-lane (in one direction) freeway segment,
- √ 3.6-m lane width on freeway,
- √ 0 percent RVs,
- √ Ramp volume = 550 veh/h,
- √ 10 percent trucks on freeway,
- √ Acceleration lane length = 225 m,
- √ FFS = 70 km/h for ramp,
- √ One-lane ramp,
- √ Level terrain,
- √ Adequate lateral clearances,
- √ FFS = 100 km/h for freeway,
- √ 5 percent trucks on ramp,
- √ Freeway volume = 2,500 veh/h,
- √ PHF = 0.90, and
- √ Drivers are regular commuters.

Comments

- √ Use Chapter 23, “Basic Freeway Segments,” to identify f_{HV} and f_p.

Outline of Solution All input parameters are known; thus no default values are required. Demand volumes will be converted to flow rates. Capacity will then be checked. The density in the merge influence area will be calculated and LOS determined.

Steps

1. Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{2,500}{(0.90)(0.952)(1.000)} = = 2,918$ pc/h $v_R = \frac{550}{(0.90)(0.976)(1.000)} = 626$ pc/h
1a. Determine f_p (use Chapter 23).	For both ramp and freeway, $f_p = 1.000$
1b. Determine f_{HV} (use Chapter 23).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ f_{HV} (fwy) = $\frac{1}{1 + 0.10(1.5 - 1)} = 0.952$ f_{HV} (ramp) = $\frac{1}{1 + 0.05(1.5 - 1)} = 0.976$
2. Compute v_{12} (use Exhibit 25-5, $P_{FM} = 1.000$).	$v_{12} = v_F * P_{FM} = 2,918 * 1.000 = 2,918$ pc/h
3. Check capacity of downstream segment (Exhibit 25-7 shows 4,600 pc/h).	$v_{FO} = v_F + v_R$ $v_{FO} = 2,918 + 626 = 3,544$ pc/h
4. Check maximum flow entering influence area (Exhibit 25-7 shows 4,600 pc/h).	$v_{R12} = 3,544$ pc/h
5. Compute density (use Equation 25-5).	$D_R = 3.402 + 0.00456v_R + 0.0048v_{12} - 0.01278L_A$ $D_R = 3.402 + 0.00456(626) + 0.0048(2918) - 0.01278(225)$ = 17.4 pc/km/ln
6. Compute merge area speed as supplemental information (use Exhibit 25-19).	$S_R = S_{FF} - (S_{FF} - 67)M_s$ $M_s = 0.321 + 0.0039e^{(3544/1000)} - 0.004(225 * 70/1000) =$ 0.393 $S_R = 100 - (100 - 67)(0.393) = 87.0$ km/h $S = S_R = 87.0$ km/h
7. Determine LOS (use Exhibit 25-4).	LOS D

The Results This on-ramp merge influence area will provide LOS D during the peak hour. The merge area density will be 17.4 pc/km/ln, and the speed in the merge area is estimated as 87 km/h.

Example Problem 1

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		**Site Information**	
Analyst	RPR	Freeway/Direction of Travel	I-1
Agency or company	Poly	Junction	Ramp #1
Date Performed		Jurisdiction	
Analysis Time Period	PM Peak	Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp

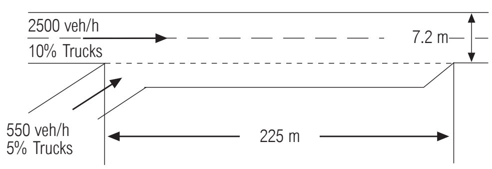
☐ Yes ☐ On

☒ No ☐ Off

L_{up} = ______ m

V_u = ______ veh/h

Terrain Level



S_{FF} = 100 km/h S_{FR} = 70 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp

☐ Yes ☐ On

☒ No ☐ Off

L_{down} = ______ m

V_D = ______ veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F				2500	0.90	10	0.952	1.000	2918
v_R				550	0.90	5	0.976	1.000	626
v_U									
v_D									

Merge Areas

Estimation of v_{12}

$v_{12} = v_F * P_{FM}$

L_{EQ} = ______ (Equation 25-2 or 25-3)

P_{FM} = 1.000 using Equation ______ (Exhibit 25-5)

v_{12} = 2918 pc/h

Capacity Checks

	Actual	Maximum	LOS F?
v_{FO}	3544	See Exhibit 25-7	No
v_{R12}	3544	4600: All	No

Level-of-Service Determination (if not F)

$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$

D_R = 17.4 pc/km/ln

LOS = D (Exhibit 25-4)

Speed Estimation

M_s = 0.393 (Exhibit 25-19)

S_R = 87.0 km/h (Exhibit 25-19)

S_0 = ______ km/h (Exhibit 25-19)

S = 87.0 km/h (Equation 25-14)

Diverge Areas

Estimation of v_{12}

$v_{12} = v_R + (v_F - v_R)P_{FD}$

L_{EQ} = ______ (Equation 25-8 or 25-9)

P_{FD} = ______ using Equation ______ (Exhibit 25-12)

v_{12} = ______ pc/h

Capacity Checks

	Actual	Maximum	LOS F?
$v_{FI} = v_F$		See Exhibit 25-14	
v_{12}		4400: All	
$v_{FO} = v_F - v_R$		See Exhibit 25-14	
v_R		See Exhibit 25-3	

Level-of-Service Determination (if not F)

$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$

D_R = ______ pc/km/ln

LOS = ______ (Exhibit 25-4)

Speed Estimation

D_s = ______ (Exhibit 25-19)

S_R = ______ km/h (Exhibit 25-19)

S_0 = ______ km/h (Exhibit 25-19)

S = ______ km/h (Equation 25-15)

EXAMPLE PROBLEM 2 (PART I)

The Ramp An off-ramp (single-lane) pair, 225 m apart, from a six-lane freeway. The length of the first deceleration lane is 150 m and that of the second deceleration lane is 90 m.

The Question What is the LOS during the peak hour for the first off-ramp?

The Facts

- √ One-lane off-ramps,
- √ FFS = 100 km/h for freeway,
- √ Rolling terrain,
- √ PHF = 0.95,
- √ 0 percent RVs,
- √ Drivers are regular commuters,
- √ FFS = 60 km/h for first off-ramp,
- √ Three-lane (in one direction) freeway segment,
- √ 5 percent trucks on freeway and off-ramps,
- √ Freeway volume = 4,500 veh/h, and
- √ First off-ramp volume = 300 veh/h.

Comments

- √ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.

Outline of Solution All input parameters are known; thus no default values are required. Demand volumes will be converted to flow rates. Capacity will then be checked. The density in the diverge influence area will be calculated and LOS determined. Computations for the first ramp are shown below.

Steps

1. Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{4{,}500}{(0.95)(0.930)(1.000)} = 5{,}093$ pc/h $v_{R1} = \frac{300}{(0.95)(0.930)(1.000)} = 340$ pc/h
1a. Determine f_p (use Chapter 23).	For ramps and freeway, $f_p = 1.000$
1b. Determine f_{HV} (use Chapter 23).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ f_{HV} (fwy and ramps) $= \frac{1}{1 + 0.05(2.5 - 1)} = 0.930$
2. Compute v_{12} (use Exhibit 25-12).	$v_{12} = v_R + (v_F - v_R)P_{FD}$ $v_{12} = 340 + (5{,}093 - 340)(0.617) = 3{,}273$ pc/h
2a. Decide on which equation to use, Equation 5 or 7 (use Equation 25-9).	$L_{EQ} = \frac{566}{3.79 - 0.00011(5093) - 0.00121(340)} = 201$m 225 m > 201 m ($L_{down} > L_{EQ}$); use Equation 5
2b. Compute P_{FD} (use Exhibit 25-12).	$P_{FD} = 0.760 - 0.000025v_F - 0.000046v_R$ $P_{FD} = 0.760 - 0.000025(5{,}093) - 0.000046(340) = 0.617$
3. Check capacity of upstream segment (Exhibit 25-14 shows 6,900 pc/h).	$v_F = 5{,}093$ pc/h
4. Check maximum flow entering diverge influence area (Exhibit 25-14 shows 4,400 pc/h).	$v_{12} = 3{,}273$ pc/h
5. Check capacity of downstream segment (Exhibit 25-14 shows 6,900 pc/h).	$v_{FO} = v_F - v_R$ $v_{FO} = 5{,}093 - 340 = 4{,}753$ pc/h
6. Check capacity of off-ramp (use Exhibit 25-3, 2,000 pc/h).	$v_R = 340$ pc/h
7. Compute density (use Equation 25-10).	$D_R = 2.642 + 0.0053v_{12} - 0.0183L_D$ $D_R = 2.642 + 0.0053(3273) - 0.0183(150) = 17.2$ pc/km/ln
8. Compute speeds as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-15).	$S_R = S_{FF} - (S_{FF} - 67)D_s$ $D_s = 0.883 + 0.00009(340) - 0.008(60) = 0.434$ $S_R = 100 - (100 - 67)(0.434) = 85.7$ km/h $v_{OA} = (v_F - v_{12})/N_O = (5{,}093 - 3{,}273)/1 = 1{,}820$ pc/h

8. (continued)	$S_O = 1.06S_{FF} - 0.0062(v_{OA} - 1000)$ $S_O = 1.06(100) - 0.0062(1820 - 1000) = 100.9$ km/h $S = \dfrac{3273 + (1820)(1)}{\left(\dfrac{3273}{85.7}\right) + \left(\dfrac{1820(1)}{100.9}\right)} = 90.6$ km/h
9. Determine LOS (use Exhibit 25-4).	LOS D

The Results The first off-ramp diverge influence area will provide LOS D with a diverge influence area speed of 86 km/h, system speed of 91 km/h, and density of 17.2 pc/km/ln.

Example Problem 2 (Part I)

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information

Analyst: *JMU*
Agency or company: *Poly*
Date Performed:
Analysis Time Period: *AM Peak*

Site Information

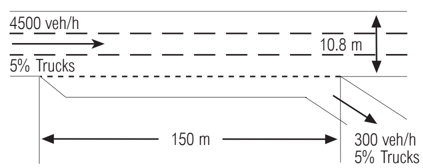
Freeway/Direction of Travel: *I-2*
Junction: *Ramp #1*
Jurisdiction:
Analysis Year: *1999*

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp: ☐ Yes ☐ On ☒ No ☐ Off
L_{up} = ____ m
V_u = ____ veh/h

Terrain: *Rolling*



S_{FF} = *100* km/h S_{FR} = *60* km/h
Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp: ☒ Yes ☐ On ☐ No ☒ Off
L_{down} = *225* m
V_D = *500* veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F				4500	0.95	5	0.930	1.000	5093
v_R				300	0.95	5	0.930	1.000	340
v_U				-	-	-	-	-	-
v_D				500	0.95	5	0.930	1.000	566

Merge Areas

Estimation of v_{12}

$v_{12} = v_F * P_{FM}$

L_{EQ} = ____ (Equation 25-2 or 25-3)
P_{FM} = ____ using Equation ____ (Exhibit 25-5)
v_{12} = ____ pc/h

Capacity Checks

	Actual	Maximum	LOS F?
v_{FO}		See Exhibit 25-7	
v_{R12}		4600: All	

Level-of-Service Determination (if not F)

$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$
D_R = ____ pc/km/ln
LOS = ____ (Exhibit 25-4)

Speed Estimation

M_s = ____ (Exhibit 25-19)
S_R = ____ km/h (Exhibit 25-19)
S_0 = ____ km/h (Exhibit 25-19)
S = ____ km/h (Equation 25-14)

Diverge Areas

Estimation of v_{12}

$v_{12} = v_R + (v_F - v_R)P_{FD}$

L_{EQ} = *201* (Equation 25-8 or 25-9)
P_{FD} = *0.617* using Equation *5* (Exhibit 25-12)
v_{12} = *3273* pc/h

Capacity Checks

	Actual	Maximum	LOS F?
$v_{FI} = v_F$	5093	See Exhibit 25-14	No
v_{12}	3273	4400: All	No
$v_{FO} = v_F - v_R$	4753	See Exhibit 25-14	No
v_R	340	See Exhibit 25-3	No

Level-of-Service Determination (if not F)

$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$
D_R = *17.2* pc/km/ln
LOS = *D* (Exhibit 25-4)

Speed Estimation

D_s = *0.434* (Exhibit 25-19)
S_R = *85.7* km/h (Exhibit 25-19)
S_0 = *100.9* km/h (Exhibit 25-19)
S = *90.6* km/h (Equation 25-15)

EXAMPLE PROBLEM 2 (PART II)

The Ramp An off-ramp (single-lane) pair, 225 m apart, from a six-lane freeway. The length of the first deceleration lane is 150 m and that of the second deceleration lane is 90 m.

The Question What is the LOS during the peak hour for the second off-ramp?

Additional Facts

- √ Second off-ramp volume = 500 veh/h, and
- √ FFS = 40 km/h for second off-ramp.

Comments

- √ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.

Outline of Solution All input parameters are known; thus no default values are required. Demand volumes will be converted to flow rates. Capacity will then be checked. The density in the diverge area will be calculated and LOS determined. Computations for the second ramp are summarized below.

Steps

1.	Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = 5{,}093 - 340 = 4{,}753$ pc/h $v_{R2} = \frac{500}{(0.95)(0.930)(1.000)} = 566$ pc/h
2.	Compute v_{12} (use Exhibit 25-12).	$v_{12} = v_R + (v_F - v_R)P_{FD}$ $v_{12} = 566 + (4{,}753 - 566)(0.615) = 3{,}141$ pc/h
2a.	Compute P_{FD} (use Exhibit 25-12).	$P_{FD} = 0.760 - 0.000025v_F - 0.000046v_R$ $P_{FD} = 0.760 - 0.000025(4{,}753) - 0.000046(566) = 0.615$
3.	Check capacity of upstream segment (Exhibit 25-14 shows 6,900 pc/h).	$v_F = 4{,}753$ pc/h
4.	Check maximum flow entering diverge influence area (Exhibit 25-14 shows 4,400 pc/h).	$v_{12} = 3{,}141$ pc/h
5.	Check capacity of downstream segment (Exhibit 25-14 shows 6,900 pc/h).	$v_{FO} = v_F - v_R$ $v_{FO} = 4{,}753 - 566 = 4{,}187$ pc/h
6.	Check capacity of off-ramp (use Exhibit 25-3, 1,900 pc/h).	$v_R = 566$ pc/h
7.	Compute density (use Equation 25-10).	$D_R = 2.642 + 0.0053v_{12} - 0.0183L_D$ $D_R = 2.642 + 0.0053(3141) - 0.0183(90) = 17.6$ pc/km/ln
8.	Compute speeds as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-15).	$S_R = S_{FF} - (S_{FF} - 67)D_s$ $D_s = 0.883 + 0.00009(566) - 0.008(40) = 0.614$ $S_R = 100 - (100 - 67)(0.614) = 79.7$ km/h $v_{OA} = (v_F - v_{12})/N_O = (4{,}753 - 3{,}141)/1 = 1{,}612$ pc/h $S_O = 1.06S_{FF} - 0.0062(v_{OA} - 1000)$ $S_O = 1.06(100) - 0.0062(1612 - 1000) = 102.2$ km/h $S = \frac{3141 + 1612(1)}{\left(\frac{3141}{79.7}\right) + \left(\frac{1612(1)}{102.2}\right)} = 86.1$ km/h
9.	Determine LOS (use Exhibit 25-4).	LOS D

The Results The second off-ramp diverge influence area will provide LOS D with a diverge influence area speed of 80 km/h, system speed of 86 km/h, and density of 17.6 pc/km/ln.

Example Problem 2 (Part II)

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		Site Information	
Analyst	JMU	Freeway/Direction of Travel	I-2
Agency or company	Poly	Junction	Ramp #2
Date Performed		Jurisdiction	
Analysis Time Period	AM Peak	Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp

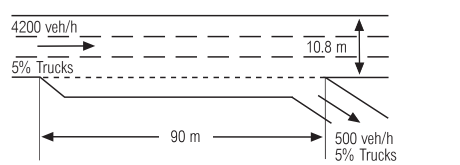
☒ Yes ☐ On

☐ No ☒ Off

L_{up} = 225 m

V_u = 300 veh/h

Terrain Rolling



S_{FF} = 100 km/h S_{FR} = 40 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp

☐ Yes ☐ On

☒ No ☐ Off

L_{down} = ______ m

V_D = ______ veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\, f_{HV}\, f_p}$
v_F									4753
v_R				500	0.95	5	0.930	1.000	566
v_U				300	0.95	5	0.930	1.000	340
v_D				-	-	-	-	-	-

Merge Areas	Diverge Areas
Estimation of v_{12}	**Estimation of v_{12}**
$v_{12} = v_F * P_{FM}$	$v_{12} = v_R + (v_F - v_R)P_{FD}$
L_{EQ} = ______ (Equation 25-2 or 25-3)	L_{EQ} = ______ (Equation 25-8 or 25-9)
P_{FM} = ______ using Equation ______ (Exhibit 25-5)	P_{FD} = 0.615 using Equation 5 (Exhibit 25-12)
v_{12} = ______ pc/h	v_{12} = 3141 pc/h

Capacity Checks (Merge Areas)

	Actual	Maximum	LOS F?
v_{FO}		See Exhibit 25-7	
v_{R12}		4600: All	

Capacity Checks (Diverge Areas)

	Actual	Maximum	LOS F?
$v_{FI} = v_F$	4753	See Exhibit 25-14	No
v_{12}	3141	4400: All	No
$v_{FO} = v_F - v_R$	4187	See Exhibit 25-14	No
v_R	566	See Exhibit 25-3	No

Level-of-Service Determination (if not F)	Level-of-Service Determination (if not F)
$D_R = 3.402 + 0.00456\, v_R + 0.0048\, v_{12} - 0.01278\, L_A$	$D_R = 2.642 + 0.0053\, v_{12} - 0.0183\, L_D$
D_R = ______ pc/km/ln	D_R = 17.6 pc/km/ln
LOS = ______ (Exhibit 25-4)	LOS = D (Exhibit 25-4)

Speed Estimation	Speed Estimation
M_s = ______ (Exhibit 25-19)	D_s = 0.614 (Exhibit 25-19)
S_R = ______ km/h (Exhibit 25-19)	S_R = 79.7 km/h (Exhibit 25-19)
S_0 = ______ km/h (Exhibit 25-19)	S_0 = 102.2 km/h (Exhibit 25-19)
S = ______ km/h (Equation 25-14)	S = 86.1 km/h (Equation 25-15)

EXAMPLE PROBLEM 3 (PART I)

The Ramp An on-ramp and off-ramp (single-lane) pair, 400 m apart, to an eight-lane freeway. The length of both the acceleration and deceleration lanes is 80 m.

The Question What is the LOS during the peak hour for the on-ramp merge influence area?

The Facts

√ One-lane on- and off-ramps,
√ Level terrain,
√ 3.6-m lane width on freeway,
√ PHF = 0.90,
√ Freeway volume = 5,500 veh/h,
√ FFS = 50 km/h for on-ramp,
√ FFS = 100 km/h for freeway,
√ Four-lane (in one direction) freeway segment,
√ 10 percent trucks on freeway,
√ 5 percent trucks on on-ramp,
√ 0 percent RVs,
√ On-ramp volume = 400 veh/h, and
√ Drivers are regular commuters.

Comments

√ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.

Outline of Solution All input parameters are known; thus no default values are required. Demand volumes will be converted to flow rates. Capacity will then be checked. The density in the merge influence area will be calculated and LOS determined.

Steps

1.	Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{5{,}500}{(0.90)(0.952)(1.000)} = 6{,}419$ pc/h $v_{R1} = \frac{400}{(0.90)(0.976)(1.000)} = 455$ pc/h
1a.	Determine f_{HV} (use Chapter 23).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV}\ (\text{fwy}) = \frac{1}{1 + 0.10(1.5 - 1)} = 0.952$ $f_{HV}\ (\text{on-ramp}) = \frac{1}{1 + 0.05(1.5 - 1)} = 0.976$
2.	Compute v_{12} (use Exhibit 25-5).	$v_{12} = v_F * P_{FM} = 6{,}419 * 0.255 = 1{,}637$ pc/h
2a.	Compute P_{FM} (use Exhibit 25-5).	$P_{FM} = 0.2178 - 0.000125v_R + 0.05887\ L_A/S_{FR}$ $P_{FM} = 0.2178 - 0.000125(455) + 0.05887(80/50) = 0.255$
3.	Check capacity of downstream segment (Exhibit 25-7 shows 9,200 pc/h).	$v_{FO} = 6{,}419 + 455 = 6{,}874$ pc/h
4.	Check maximum flow entering merge influence area (Exhibit 25-7 shows 4,600 pc/h).	$v_{R12} = 1{,}637 + 455 = 2{,}092$ pc/h
5.	Compute density (use Equation 25-5).	$D_R = 3.402 + 0.00456v_R + 0.0048v_{12} - 0.01278L_A$ $D_R = 3.402 + 0.00456(455) + 0.0048(1637) - 0.01278(80) =$ 12.3 pc/km/ln
6.	Compute speeds as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-14).	$S_R = S_{FF} - (S_{FF} - 67)M_s$ $M_s = 0.321 + 0.0039e^{(2092/1000)} - 0.004(80 * 50/1000) = 0.337$ $S_R = 100 - (100 - 67)(0.337) = 88.9$ km/h $v_{OA} = (v_F - v_{12})/N_O = (6{,}419 - 1{,}637)/2 = 2{,}391$ pc/h $S_O = S_{FF} - 10.52 - 0.01(v_{OA} - 2300)$ $S_O = 100 - 10.52 - 0.01(2391 - 2300) = 88.6$ km/h $S = \frac{2092 + 2391(2)}{\left(\frac{2092}{88.9}\right) + \left(\frac{2391 * 2}{88.6}\right)} = 88.7$ km/h
7.	Determine LOS (use Exhibit 25-4).	LOS C

The Results This on-ramp merge influence area will provide LOS C with a merge influence area speed of 89 km/h, system speed of 89 km/h, and density of 12.3 pc/km/ln.

Example Problem 3 (Part I)

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		Site Information	
Analyst	MMU	Freeway/Direction of Travel	I-3
Agency or company	UNC	Junction	Ramp #1
Date Performed		Jurisdiction	
Analysis Time Period	PM Peak	Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp

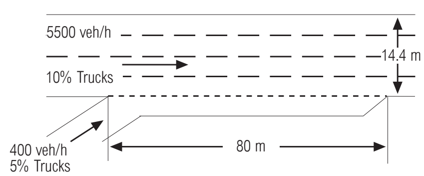
☐ Yes ☐ On

☒ No ☐ Off

L_{up} = ______ m

V_u = ______ veh/h

Terrain Level



S_{FF} = 100 km/h S_{FR} = 50 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp

☒ Yes ☐ On

☐ No ☒ Off

L_{down} = 400 m

V_D = 600 veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F				5500	0.90	10	0.952	1.000	6419
v_R				400	0.90	5	0.976	1.000	455
v_U				-	-	-	-	-	-
v_D				600	0.90	10	0.952	1.000	700

Merge Areas	Diverge Areas
Estimation of v_{12}	**Estimation of v_{12}**
$v_{12} = v_F * P_{FM}$	$v_{12} = v_R + (v_F - v_R)P_{FD}$
L_{EQ} = ______ (Equation 25-2 or 25-3)	L_{EQ} = ______ (Equation 25-8 or 25-9)
P_{FM} = 0.255 using Equation 4 (Exhibit 25-5)	P_{FD} = ______ using Equation ______ (Exhibit 25-12)
v_{12} = 1637 pc/h	v_{12} = ______ pc/h

Capacity Checks (Merge)

	Actual	Maximum	LOS F?
v_{FO}	6874	See Exhibit 25-7	No
v_{R12}	2092	4600: All	No

Capacity Checks (Diverge)

	Actual	Maximum	LOS F?
$v_{FI} = v_F$		See Exhibit 25-14	
v_{12}		4400: All	
$v_{FO} = v_F - v_R$		See Exhibit 25-14	
v_R		See Exhibit 25-3	

Level-of-Service Determination (if not F)	Level-of-Service Determination (if not F)
$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$	$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$
D_R = 12.3 pc/km/ln	D_R = ______ pc/km/ln
LOS = C (Exhibit 25-4)	LOS = ______ (Exhibit 25-4)

Speed Estimation	Speed Estimation
M_s = 0.337 (Exhibit 25-19)	D_s = ______ (Exhibit 25-19)
S_R = 88.9 km/h (Exhibit 25-19)	S_R = ______ km/h (Exhibit 25-19)
S_0 = 88.6 km/h (Exhibit 25-19)	S_0 = ______ km/h (Exhibit 25-19)
S = 88.7 km/h (Equation 25-14)	S = ______ km/h (Equation 25-15)

EXAMPLE PROBLEM 3 (PART II)

The Ramp An on-ramp and off-ramp (single-lane) pair, 400 m apart, to an eight-lane freeway. The length of acceleration and deceleration lanes is 80 m.

The Question What is the LOS of the off-ramp diverge influence area during the peak hour?

Additional Facts

√ 10 percent trucks on off-ramp,
√ FFS = 40 km/h for off-ramp, and
√ Off-ramp volume = 600 veh/h.

Comments

√ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.
√ Volume for freeway = 5,500 + 400 = 5,900 veh/h
√ % trucks on freeway = $\frac{5,500(10)+400(5)}{5,900}$ = 9.7%

Outline of Solution All input parameters are known; thus no default values are required. Demand volumes will be converted to flow rates. Capacity will then be checked. The density in the diverge influence area will be calculated and LOS determined.

Steps

1. Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{5,900}{(0.90)(0.954)(1.000)} = 6,872$ pc/h $v_{R2} = \frac{600}{(0.90)(0.952)(1.000)} = 700$ pc/h
1a. Determine f_{HV} (use Chapter 23).	f_{HV} (fwy) $= \frac{1}{1 + 0.097(1.5 - 1)} = 0.954$ f_{HV} (off-ramp) $= \frac{1}{1 + 0.10(1.5 - 1)} = 0.952$
2. Compute v_{12} (use Exhibit 25-12, P_{FD} = 0.436).	$v_{12} = v_R + (v_F - v_R)P_{FD}$ v_{12} = 700 + (6,872 – 700)(0.436) = 3,391 pc/h
3. Check capacity of upstream segment (Exhibit 25-14 shows 9,200 pc/h).	v_F = 6,872 pc/h
4. Check maximum flow entering diverge influence area (Exhibit 25-14 shows 4,400 pc/h).	v_{12} = 3,391 pc/h
5. Check capacity of downstream segment (Exhibit 25-14 shows 9,200 pc/h).	v_{FO} = 6,872 – 700 = 6,172 pc/h
6. Check capacity of off-ramp (use Exhibit 25-3, 1,900 pc/h).	v_{R2} = 700 pc/h
7. Compute density (use Equation 25-10).	$D_R = 2.642 + 0.0053v_{12} - 0.0183L_D$ D_R = 2.642 + 0.0053(3391) – 0.0183(80) D_R = 19.2 pc/km/ln
8. Compute speeds as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-15).	$S_R = S_{FF} - (S_{FF} - 67)D_s$ D_s = 0.883 + 0.00009(700) – 0.008(40) = 0.626 S_R = 100 – (100 – 67)(0.626) = 79.3 km/h $v_{OA} = (v_F - v_{12})/N_O$ = (6,872 – 3,391)/2 = 1,741 pc/h $S_O = 1.06S_{FF} - 0.0062(v_{OA} - 1000)$ S_O = 1.06(100) – 0.0062(1741 – 1000) = 101.4 km/h $S = \frac{3391+1741(2)}{\left(\frac{3391}{79.3}\right)+\left(\frac{1741*2}{101.4}\right)} = 89.1$ km/h
9. Determine LOS (use Exhibit 25-4).	LOS D

The Results The off-ramp diverge influence area will provide LOS D with a diverge influence area speed of 79 km/h, system speed of 89 km/h, and density of 19.2 pc/km/ln.

Example Problem 3 (Part II)

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information

Analyst	MMU
Agency or company	UNC
Date Performed	
Analysis Time Period	PM Peak

Site Information

Freeway/Direction of Travel	I-3
Junction	Ramp #2
Jurisdiction	
Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp

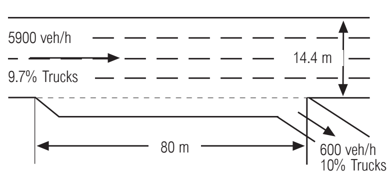
☒ Yes ☒ On

☐ No ☐ Off

L_{up} = 400 m

V_u = 400 veh/h

Terrain Level



S_{FF} = 100 km/h S_{FR} = 40 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp

☐ Yes ☐ On

☒ No ☐ Off

L_{down} = ______ m

V_D = ______ veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F				5900	0.90	9.7	0.954	1.000	6872
v_R				600	0.90	10	0.952	1.000	700
v_U				400	0.90	5	0.976	1.000	455
v_D				-	-	-	-	-	-

Merge Areas

Estimation of v_{12}

$v_{12} = v_F * P_{FM}$

L_{EQ} = ______ (Equation 25-2 or 25-3)

P_{FM} = ______ using Equation ______ (Exhibit 25-5)

v_{12} = ______ pc/h

Diverge Areas

Estimation of v_{12}

$v_{12} = v_R + (v_F - v_R)P_{FD}$

L_{EQ} = ______ (Equation 25-8 or 25-9)

P_{FD} = 0.436 using Equation 8 (Exhibit 25-12)

v_{12} = 3391 pc/h

Capacity Checks (Merge)

	Actual	Maximum	LOS F?
v_{FO}		See Exhibit 25-7	
v_{R12}		4600: All	

Capacity Checks (Diverge)

	Actual	Maximum	LOS F?
$v_{FI} = v_F$	6872	See Exhibit 25-14	No
v_{12}	3391	4400: All	No
$v_{FO} = v_F - v_R$	6172	See Exhibit 25-14	No
v_R	700	See Exhibit 25-3	No

Level-of-Service Determination (if not F) (Merge)

$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$

D_R = ______ pc/km/ln

LOS = ______ (Exhibit 25-4)

Level-of-Service Determination (if not F) (Diverge)

$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$

D_R = 19.2 pc/km/ln

LOS = D (Exhibit 25-4)

Speed Estimation (Merge)

M_s = ______ (Exhibit 25-19)

S_R = ______ km/h (Exhibit 25-19)

S_0 = ______ km/h (Exhibit 25-19)

S = ______ km/h (Equation 25-14)

Speed Estimation (Diverge)

D_s = 0.626 (Exhibit 25-19)

S_R = 79.3 km/h (Exhibit 25-19)

S_0 = 101.4 km/h (Exhibit 25-19)

S = 89.1 km/h (Equation 25-15)

EXAMPLE PROBLEM 4

The Ramp A two-lane on-ramp to a six-lane freeway. The length of the outer acceleration lane is 150 m and that of the inner acceleration lane is 270 m.

The Question What is the LOS of this ramp during the peak hour?

The Facts

- √ Two-lane on-ramp,
- √ Level terrain,
- √ 5 percent trucks on freeway and ramp,
- √ 0 percent RVs,
- √ FFS = 80 km/h for ramp,
- √ PHF = 0.95,
- √ Three-lane (in one direction) freeway segment,
- √ Freeway volume = 3,000 veh/h,
- √ On-ramp volume = 1,800 veh/h,
- √ Drivers are regular commuters, and
- √ FFS = 110 km/h for freeway.

Comments

- √ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.

Outline of Solution All input parameters are known; thus no default values are required. Demand volumes will be converted to flow rates. Capacity will then be checked. The density in the merge influence area will be calculated and LOS determined.

Steps

1. Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{3{,}000}{(0.95)(0.976)(1.000)} = 3{,}236$ pc/h $v_R = \frac{1{,}800}{(0.95)(0.976)(1.000)} = 1{,}941$ pc/h
1a. Determine f_{HV} (use Chapter 23).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ f_{HV} (fwy and ramps) $= \frac{1}{1 + 0.05(1.5 - 1)}$ f_{HV} (fwy and ramps) = 0.976
2. Compute v_{12} (P_{FM} = 0.555 for 2-lane ramp on 6-lane fwy).	$v_{12} = v_F * P_{FM}$ v_{12} = 3,236 * 0.555 = 1,796 pc/h
3. Check capacity of downstream segment (Exhibit 25-7 shows 7,050 pc/h).	v_{FO} = 3,236 + 1,941 = 5,177 pc/h
4. Check maximum flow entering merge influence area (Exhibit 25-7 shows 4,600 pc/h).	v_{R12} = 1,796 + 1,941 = 3,737 pc/h
5. Compute density (use Equation 25-5).	$D_R = 3.402 + 0.00456v_R + 0.0048v_{12} - 0.01278L_{Aeff}$ D_R = 3.402 + 0.00456 (1941) + 0.0048(1796) - 0.01278(420) = 15.5 pc/km/ln
5a. Compute L_{Aeff} (use Equation 25-6).	$L_{Aeff} = 2L_{A1} + L_{A2}$ L_{Aeff} = 2(150) + 120 = 420 m
6. Compute system speed as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-14).	$S_R = S_{FF} - (S_{FF} - 67)M_s$ $M_s = 0.321 + 0.0039e^{(3737/1000)} - 0.004(420 * 80/1000) = 0.350$ S_R = 110 – (110 – 67)(0.350) = 95.0 km/h $v_{OA} = (v_F - v_{12})/N_O$ = (3,236 – 1,796)/1 = 1,440 pc/h

6. (continued)	$S_O = S_{FF} - 0.0058(v_{OA} - 500)$ $S_O = 110 - 0.0058(1440 - 500) = 104.5$ km/h $S = \dfrac{3737 + 1440(1)}{\left(\dfrac{3737}{95.0}\right) + \left(\dfrac{1440 * 1}{104.5}\right)} = 97.5$ km/h
7. Determine LOS (use Exhibit 25-4).	LOS C

The Results The on-ramp merge influence area will provide LOS C with a merge influence area speed of 95 km/h, system speed of 98 km/h, and density of 15.5 pc/km/ln.

Example Problem 4

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		**Site Information**	
Analyst	CMU	Freeway/Direction of Travel	Route 4
Agency or company	Poly	Junction	Ramp #1
Date Performed		Jurisdiction	
Analysis Time Period	PM Peak	Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Terrain Level

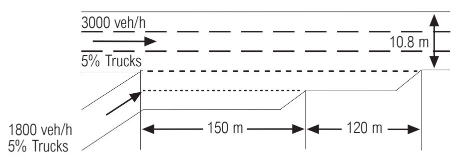
Upstream Adjacent Ramp

☐ Yes ☐ On

☒ No ☐ Off

L_{up} = ______ m

V_u = ______ veh/h



S_{FF} = 110 km/h S_{FR} = 80 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp

☐ Yes ☐ On

☒ No ☐ Off

L_{down} = ______ m

V_D = ______ veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \dfrac{V}{PHF\ f_{HV}\ f_p}$
v_F				3000	0.95	5	0.976	1.000	3236
v_R				1800	0.95	5	0.976	1.000	1941
v_U									
v_D									

Merge Areas	Diverge Areas
Estimation of v_{12}	**Estimation of v_{12}**
$v_{12} = v_F * P_{FM}$	$v_{12} = v_R + (v_F - v_R)P_{FD}$
L_{EQ} = ______ (Equation 25-2 or 25-3)	L_{EQ} = ______ (Equation 25-8 or 25-9)
P_{FM} = 0.555 using Equation special case (Exhibit 25-5)	P_{FD} = ______ using Equation ______ (Exhibit 25-12)
v_{12} = 1796 pc/h	v_{12} = ______ pc/h

Capacity Checks (Merge Areas)

	Actual	Maximum	LOS F?
v_{FO}	5177	See Exhibit 25-7	No
v_{R12}	3737	4600: All	No

Capacity Checks (Diverge Areas)

	Actual	Maximum	LOS F?
$v_{FI} = v_F$		See Exhibit 25-14	
v_{12}		4400: All	
$v_{FO} = v_F - v_R$		See Exhibit 25-14	
v_R		See Exhibit 25-3	

Level-of-Service Determination (if not F)	**Level-of-Service Determination (if not F)**
$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$	$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$
D_R = 15.5 pc/km/ln	D_R = ______ pc/km/ln
LOS = C (Exhibit 25-4)	LOS = ______ (Exhibit 25-4)

Speed Estimation	**Speed Estimation**
M_s = 0.350 (Exhibit 25-19)	D_s = ______ (Exhibit 25-19)
S_R = 95.0 km/h (Exhibit 25-19)	S_R = ______ km/h (Exhibit 25-19)
S_O = 104.5 km/h (Exhibit 25-19)	S_O = ______ km/h (Exhibit 25-19)
S = 97.5 km/h (Equation 25-14)	S = ______ km/h (Equation 25-15)

EXAMPLE PROBLEM 5

The Ramp An off-ramp (single-lane) from a 10-lane freeway. The length of the deceleration lane is 220 m.

The Question What is the LOS during the peak hour for current conditions?

The Facts

- √ One-lane off-ramp,
- √ Rolling terrain,
- √ 10 percent trucks on freeway and ramp,
- √ 0 percent RVs,
- √ Off-ramp volume = 400 veh/h,
- √ Commuter traffic,
- √ Five-lane (in one direction) freeway segment,
- √ PHF = 0.95,
- √ One-way peak-hour freeway volume = 7,200 veh/h,
- √ FFS = 70 km/h for off-ramp, and
- √ FFS = 100 km/h for freeway.

Comments

√ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.

√ Estimate eight-lane equivalent freeway segment flow rate assuming v_5 is 20 percent of v_F.

Outline of Solution Demand volumes will be converted to flow rates. An eight-lane equivalent freeway segment flow rate will be established. Capacity will then be checked. Density will be calculated and LOS determined.

Steps

1.	Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{7{,}200}{(0.95)(0.870)(1.000)} = 8{,}711$ pc/h $v_R = \frac{400}{(0.95)(0.870)(1.000)} = 484$ pc/h
1a.	Determine f_{HV} (use Chapter 23).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ f_{HV} (fwy and ramps) $= \frac{1}{1 + 0.10(2.5 - 1)} = 0.870$
2.	Estimate eight-lane equivalent freeway flow rate (Exhibit 25-18).	$v_{F4eff} = v_F - v_5$ $v_5 = 0.20v_F = 0.20(8{,}711) = 1{,}742$ pc/h $v_{F4eff} = 8{,}711 - 1{,}742 = 6{,}969$ pc/h
3.	Compute v_{12} (use Exhibit 25-12, P_{FD} = 0.436).	$v_{12} = v_R + (v_F - v_R)P_{FD}$ $v_{12} = 484 + (6{,}969 - 484)(0.436) = 3{,}311$ pc/h
4.	Check capacity of upstream segment (Exhibit 25-14 shows 9,200 pc/h).	$v_F = 6{,}969$ pc/h
5.	Check maximum flow entering diverge influence area (Exhibit 25-14 shows 4,400 pc/h).	$v_{12} = 3{,}311$ pc/h
6.	Check capacity of downstream segment (Exhibit 25-14 shows 9,200 pc/h).	$v_{FO} = 6{,}969 - 484 = 6{,}485$ pc/h
7.	Check capacity of off-ramp (use Exhibit 25-3, 2,100 pc/h).	$v_R = 484$ pc/h
8.	Compute density (use Equation 25-10).	$D_R = 2.642 + 0.0053v_{12} - 0.0183\ L_D$ $D_R = 2.642 + 0.0053(3311) - 0.0183(220) =$ 16.2 pc/km/ln
9.	Compute speeds as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-15).	$S_R = S_{FF} - (S_{FF} - 67)D_s$ $D_s = 0.883 + 0.00009(484) - 0.008(70) = 0.367$ $S_R = 100 - (100 - 67)(0.367) = 87.9$ km/h $v_{OA} = (v_F - v_{12})/N_O = (6969 - 3{,}311)/2 = 1{,}829$ pc/h

9. (continued)	$S_O = 1.06S_{FF} - 0.0062(v_{OA} - 1000)$ $S_O = 1.06(100) - 0.0062(1829 - 1000) = 100.9$ km/h $S = \dfrac{3311+1829(2)}{\left(\dfrac{3311}{87.9}\right)+\left(\dfrac{1829(2)}{100.9}\right)} = 94.3$ km/h
10. Determine LOS (use Exhibit 25-4).	LOS C

The Results The off-ramp diverge influence area will provide LOS C with a diverge influence area speed of 88 km/h, system speed of 94 km/h, and density of 16.2 pc/km/ln.

Example Problem 5

RAMPS AND RAMP JUNCTIONS WORKSHEET

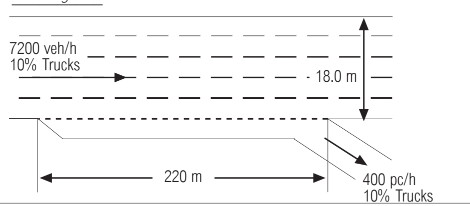
General Information		Site Information	
Analyst	RPR	Freeway/Direction of Travel	I-5
Agency or company	Poly	Junction	Ramp #1
Date Performed		Jurisdiction	
Analysis Time Period	AM Peak	Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp: ☐ Yes ☐ On ☒ No ☐ Off; L_{up} = ____ m; V_u = ____ veh/h

Terrain Rolling



S_{FF} = 100 km/h S_{FR} = 70 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp: ☐ Yes ☐ On ☒ No ☐ Off; L_{down} = ____ m; V_D = ____ veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F				7200	0.95	10	0.870	1.000	8711
v_R				400	0.95	10	0.870	1.000	484
v_U									
v_D									

Merge Areas

Estimation of v_{12}

$v_{12} = v_F * P_{FM}$

L_{EQ} = ____ (Equation 25-2 or 25-3)
P_{FM} = ____ using Equation ____ (Exhibit 25-5)
v_{12} = ____ pc/h

Capacity Checks

	Actual	Maximum	LOS F?
v_{FO}		See Exhibit 25-7	
v_{R12}		4600: All	

Level-of-Service Determination (if not F)

$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$

D_R = ____ pc/km/ln
LOS = ____ (Exhibit 25-4)

Speed Estimation

M_s = ____ (Exhibit 25-19)
S_R = ____ km/h (Exhibit 25-19)
S_0 = ____ km/h (Exhibit 25-19)
S = ____ km/h (Equation 25-14)

Diverge Areas

Estimation of v_{12}

$v_{12} = v_R + (v_F - v_R)P_{FD}$

L_{EQ} = ____ (Equation 25-8 or 25-9)
P_{FD} = 0.436 using Equation 8 (Exhibit 25-12)
v_{12} = 3311 pc/h

Capacity Checks

	Actual	Maximum	LOS F?
$v_{FI} = v_F$	6969	See Exhibit 25-14	No
v_{12}	3311	4400: All	No
$v_{FO} = v_F - v_R$	6485	See Exhibit 25-14	No
v_R	484	See Exhibit 25-3	No

Level-of-Service Determination (if not F)

$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$

D_R = 16.2 pc/km/ln
LOS = C (Exhibit 25-4)

Speed Estimation

D_s = 0.367 (Exhibit 25-19)
S_R = 87.9 km/h (Exhibit 25-19)
S_0 = 100.9 km/h (Exhibit 25-19)
S = 94.3 km/h (Equation 25-15)

EXAMPLE PROBLEM 6

The Ramp An on-ramp (single lane on the left-hand side of freeway) to a six-lane freeway. The length of the acceleration lane is 250 m.

The Question What is the LOS during the peak hour?

The Facts

- √ Left-side one-lane on-ramp,
- √ Level terrain,
- √ 5 percent trucks on ramp,
- √ Freeway volume = 4,000 veh/h,
- √ FFS = 50 km/h for on-ramp,
- √ FFS = 110 km/h for freeway,
- √ Three lanes in one direction,
- √ 15 percent trucks on freeway,
- √ PHF = 0.90,
- √ On-ramp volume = 500 veh/h,
- √ Commuter traffic, and
- √ 0 percent RVs.

Comments

- √ Use Chapter 23, "Basic Freeway Segments," to identify f_{HV} and f_p.
- √ On a six-lane freeway, the flow in the left two lanes is 1.12 times the flow in Lanes 1 and 2 if the ramp is on the left side.

Outline to Solution Demand volumes will be converted to flow rates. v_{12} is computed as if the ramp were on the right-hand side, then adjusted by a factor to account for the left-hand ramp. Two capacity values will then be checked (freeway departing and total flow entering the influence area). Density will be calculated and LOS determined.

Steps

1.	Convert volume (veh/h) to flow rate (pc/h) (use Equation 25-1).	$v = \frac{V}{(PHF)(f_{HV})(f_p)}$ $v_F = \frac{4{,}000}{(0.90)(0.930)(1.000)} = 4{,}779$ pc/h $v_R = \frac{500}{(0.90)(0.976)(1.000)} = 569$ pc/h
1a.	Determine f_{HV} (use Chapter 23).	$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$ $f_{HV}\ (fwy) = \frac{1}{1 + 0.15(1.5 - 1)} = 0.930$ $f_{HV}\ (ramp) = \frac{1}{1 + 0.05(1.5 - 1)} = 0.976$
2.	Compute v_{12} (use Exhibit 25-5).	$v_{12} = v_F * P_{FM} = 4{,}779 * 0.601 = 2{,}872$ pc/h
2a.	Compute P_{FM} (use Exhibit 25-5).	$P_{FM} = 0.5775 + 0.000092(250) = 0.601$
3.	Compute v_{23}.	$v_{23} = 2{,}872(1.12) = 3{,}217$ pc/h
4.	Check capacity of downstream segment (Exhibit 25-7 shows 7,050 pc/h).	$v_{FO} = v_F + v_R = 4{,}779 + 569 = 5{,}348$ pc/h
5.	Check v_{R23} (Exhibit 25-7 shows 4,600 pc/h).	$v_{R23} = v_{23} + v_R = 3{,}217 + 569 = 3{,}786$ pc/h
6.	Compute density (use Equation 25-5).	$D_R = 3.402 + 0.00456v_R + 0.0048v_{23} - 0.01278L_A$ $D_R = 3.402 + 0.00456(569) + 0.0048(3217) - 0.01278(250) = 18.2$ pc/km/ln
7.	Compute speeds as supplemental information (use Exhibit 25-19 and Equations 25-13 and 25-14).	$S_R = S_{FF} - (S_{FF} - 67)M_s$ $M_s = 0.321 + 0.0039e^{(3786/1000)} - 0.004(250 * 50/1{,}000) = 0.443$ $S_R = 110 - (110 - 67)(0.443) = 91.0$ km/h $v_{OA} = (v_F - v_{23})/N_O = (4{,}779 - 3{,}217)/1 = 1{,}562$ pc/h $S_O = S_{FF} - 0.0058(v_{OA} - 500) = 103.8$ km/h $S = \frac{3786 + 1562(1)}{\left(\frac{3786}{91.0}\right) + \left(\frac{1562(1)}{103.8}\right)} = 94.4$ km/h
8.	Determine LOS (use Exhibit 25-4).	LOS D

The Results This on-ramp merge influence area will provide LOS D with a merge influence area speed of 91 km/h, system speed of 94 km/h, and density of 18.2 pc/km/ln.

Example Problem 6

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		Site Information	
Analyst	XU	Freeway/Direction of Travel	Route 6
Agency or company	Poly	Junction	Ramp #1
Date Performed		Jurisdiction	
Analysis Time Period	PM Peak	Analysis Year	1999

☒ Operational (LOS) ☐ Design (L_A, L_D, or N) ☐ Planning (LOS) ☐ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp

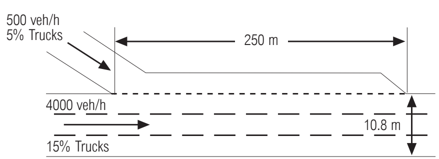
☐ Yes ☐ On

☒ No ☐ Off

L_{up} = ______ m

V_u = ______ veh/h

Terrain Level



S_{FF} = 110 km/h S_{FR} = 50 km/h

Sketch (show lanes, L_A, L_D, v_R, v_F)

Downstream Adjacent Ramp

☐ Yes ☐ On

☒ No ☐ Off

L_{down} = ______ m

V_D = ______ veh/h

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F				4000	0.90	15	0.930	1.000	4779
v_R				500	0.90	5	0.976	1.000	569
v_U									
v_D									

Merge Areas

Estimation of v_{12}

$v_{12} = v_F * P_{FM}$

L_{EQ} = ______ (Equation 25-2 or 25-3)

P_{FM} = 0.601 using Equation 1 (Exhibit 25-5)

v_{12} = 2872 pc/h $v_{23} = v_{12} \times 1.12 = 3217$

Capacity Checks

	Actual	Maximum	LOS F?
v_{FO}	5348	See Exhibit 25-7	No
v_{R12}	3786	4600: All	No

Level-of-Service Determination (if not F)

$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$

D_R = 18.2 pc/km/ln

LOS = D (Exhibit 25-4)

Speed Estimation

M_S = 0.443 (Exhibit 25-19)

S_R = 91.0 km/h (Exhibit 25-19)

S_0 = 103.8 km/h (Exhibit 25-19)

S = 94.4 km/h (Equation 25-14)

Diverge Areas

Estimation of v_{12}

$v_{12} = v_R + (v_F - v_R)P_{FD}$

L_{EQ} = ______ (Equation 25-8 or 25-9)

P_{FD} = ______ using Equation ______ (Exhibit 25-12)

v_{12} = ______ pc/h

Capacity Checks

	Actual	Maximum	LOS F?
$v_{FI} = v_F$		See Exhibit 25-14	
v_{12}		4400: All	
$v_{FO} = v_F - v_R$		See Exhibit 25-14	
v_R		See Exhibit 25-3	

Level-of-Service Determination (if not F)

$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$

D_R = ______ pc/km/ln

LOS = ______ (Exhibit 25-4)

Speed Estimation

D_s = ______ (Exhibit 25-19)

S_R = ______ km/h (Exhibit 25-19)

S_0 = ______ km/h (Exhibit 25-19)

S = ______ km/h (Equation 25-15)

V. REFERENCES

1. Roess, R., and J. Ulerio. *Capacity of Ramp-Freeway Junctions, Final Report.* NCHRP Project 3-37. Polytechnic University, Brooklyn, N.Y., Nov. 1993.
2. Leisch, J. *Capacity Analysis Techniques for Design and Operation of Freeway Facilities*. FHWA, U.S. Department of Transportation, 1974.
3. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington, D.C., 1990.
4. Elefteriadou, L. *A Probabilistic Model of Breakdown at Freeway-Merge Junctions*. Doctoral dissertation. Polytechnic University, Brooklyn, N.Y., June 1994.

APPENDIX A. WORKSHEET

RAMPS AND RAMP JUNCTIONS WORKSHEET

RAMPS AND RAMP JUNCTIONS WORKSHEET

General Information		Site Information	
Analyst	________	Freeway/Direction of Travel	________
Agency or company	________	Junction	________
Date Performed	________	Jurisdiction	________
Analysis Time Period	________	Analysis Year	________

❑ Operational (LOS) ❑ Design (L_A, L_D, or N) ❑ Planning (LOS) ❑ Planning (L_A, L_D, or N)

Inputs

Upstream Adjacent Ramp	Terrain ________	Downstream Adjacent Ramp
❑ Yes ❑ On		❑ Yes ❑ On
❑ No ❑ Off		❑ No ❑ Off
L_{up} = ________ m		L_{down} = ________ m
V_u = ________veh/h		V_D = ________veh/h
	S_{FF} = ________ km/h S_{FR} = ________ km/h	
	Sketch (show lanes, L_A, L_D, v_R, v_F)	

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	% HV	f_{HV}	f_p	$v = \frac{V}{PHF\ f_{HV}\ f_p}$
v_F									
v_R									
v_U									
v_D									

Merge Areas	Diverge Areas

Estimation of v_{12} (Merge Areas)

$v_{12} = v_F * P_{FM}$

L_{EQ} = ________(Equation 25-2 or 25-3)

P_{FM} = ________ using Equation ________ (Exhibit 25-5)

v_{12} = ________ pc/h

Estimation of v_{12} (Diverge Areas)

$v_{12} = v_R + (v_F - v_R)P_{FD}$

L_{EQ} = ________ (Equation 25-8 or 25-9)

P_{FD} = ________ using Equation ________ (Exhibit 25-12)

v_{12} = ________ pc/h

Capacity Checks (Merge Areas)

	Actual	Maximum	LOS F?
v_{FO}		See Exhibit 25-7	
v_{R12}		4600: All	

Capacity Checks (Diverge Areas)

	Actual	Maximum	LOS F?
$v_{FI} = v_F$		See Exhibit 25-14	
v_{12}		4400: All	
$v_{FO} = v_F - v_R$		See Exhibit 25-14	
v_R		See Exhibit 25-3	

Level-of-Service Determination (if not F) (Merge Areas)

$D_R = 3.402 + 0.00456\ v_R + 0.0048\ v_{12} - 0.01278\ L_A$

D_R = ________ pc/km/ln

LOS = ________(Exhibit 25-4)

Level-of-Service Determination (if not F) (Diverge Areas)

$D_R = 2.642 + 0.0053\ v_{12} - 0.0183\ L_D$

D_R = ________ pc/km/ln

LOS = ________ (Exhibit 25-4)

Speed Estimation (Merge Areas)

M_S = ________ (Exhibit 25-19)

S_R = ________ km/h (Exhibit 25-19)

S_0 = ________ km/h (Exhibit 25-19)

S = ________ km/h (Equation 25-14)

Speed Estimation (Diverge Areas)

D_s = ________ (Exhibit 25-19)

S_R = ________ km/h (Exhibit 25-19)

S_0 = ________ km/h (Exhibit 25-19)

S = ________ km/h (Equation 25-15)