

MUSTANSIRIYAH UNIVERSITY
 COLLEGE OF ENGINEERING
 HIGHWAY AND TRANSPORTATION ENGINEERING DEPARTMENT
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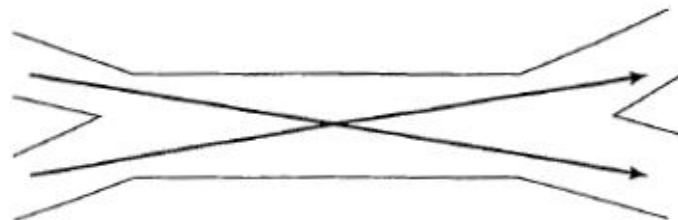
ADVANCED TRAFFIC ENGINEERING

Asst. Prof. Dr. Abeer K. Jameel

LECTURE 8:

WEAVING, MERGING, AND DIVERGING MOVEMENTS ON FREEWAYS AND MULTILANE HIGHWAYS

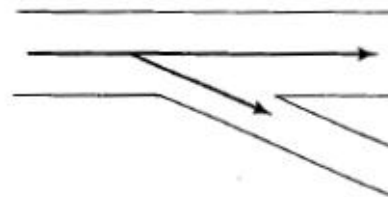
Segments of such facilities that accommodate weaving, merging, and/or diverging maneuvers, however, experience additional turbulence as a result of these movements. This additional turbulence in the traffic stream results in operations that cannot be simply analyzed using basic segment techniques.



(a) Weaving movements cross each others path.



(b) Merging movements join to form a single traffic stream.



(c) Diverging movements divide to form separate traffic streams.

Weaving, Merging, and Diverging Movements Illustrated

A. Weaving

Weaving is created when a merge area is closely followed by a diverge area. Drivers must cross the path of other drivers.

Example: A vehicle entering from an on-ramp and needing to exit via the next off-ramp within a short distance.

Key features:

- May require lane changes
- High conflict
- Most turbulence among the three
- Critical distance = between merge point and diverge point

A merge closely followed by a diverge, usually connected by a continuous auxiliary lane.

- Drivers entering need to exit
- Drivers exiting need to merge across
- Conflicting lane-changing patterns
- HCM uses a maximum practical length around **2,500 ft** (≈ 760 m), but recent research shows it varies

Non-weaving merge/diverge :If merge and diverge areas have:

- Separate acceleration/deceleration lanes
- No need for crossing paths
- No continuous auxiliary lane

B. Merging

Two separate streams join into one.

Example: Vehicles entering a freeway via an on-ramp.

Effects:

- Acceleration, gap-seeking
- Speed differentials
- Lane-changing concentrated at merge zone

C. Diverging

One stream split into two.

Example: Vehicles preparing to exit via an off-ramp.

Effects:

- Deceleration
- Lane selection
- Queue formation at ramps
- Lane-changes to position for correct exit

LEVEL-OF-SERVICE CRITERIA

1. Measure of Effectiveness → Density (pc/mi/ln)

For weaving, merging, and diverging segments, the Highway Capacity Manual uses density as the primary performance measure.

2. LOS Criteria

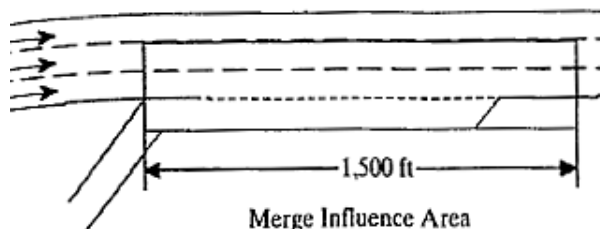
Level of Service	Weaving Areas		Merge or Diverge Areas
	Density Range (pc/mi/ln)		
	On Freeways	On Multilane Highways or C-D Roadways	On Freeways, Multilane Highways, or C-D Roadways
A	0–10	0–12	0–10
B	>10–20	>12–24	>10–20
C	>20–28	>24–32	>20–28
D	>28–35	>32–36	>28–35
E	>35	>36	>35
F	Demand Exceeds Capacity		

(Source: Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, 2000. Compiled from Exhibit 24-2, p. 24-3, and Exhibit 25-4, p. 25-5.)

3. Influence Areas for Merge, Diverge, Weaving Segments

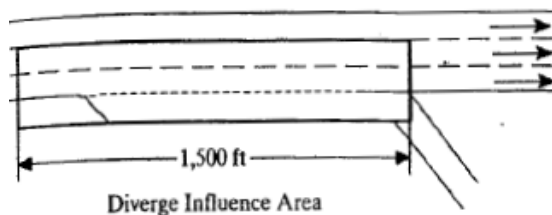
A. Merge influence area (1,500 ft upstream)

- Influence length: **1,500 ft upstream** of the merge point
- Includes: acceleration lane + adjacent through lanes
- Driver behavior: gap seeking, speed adjustment



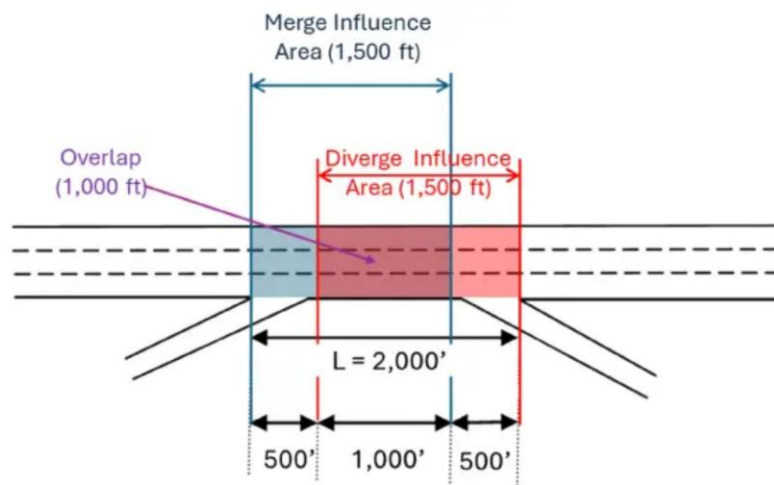
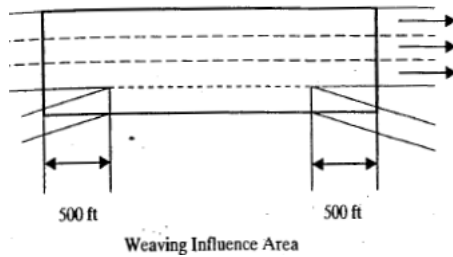
B. Diverge Influence Area (1,500 ft downstream)

- Influence length: **1,500 ft downstream** of diverge point
- Includes: deceleration lane + adjacent through lanes
- Driver behavior: lane selection, braking, hesitations



C. Weaving Influence Area (500 ft upstream + 500 ft downstream)

- Influence length: **500 ft upstream** of merge → **500 ft downstream** of diverge
- Total length: **1,000 ft**
- Captures bidirectional lane-changing (entering vs. exiting)



CONVERTING DEMAND VOLUMES

The HCM uses the following fundamental conversion:

$$v_i = \frac{V_i}{PHF \cdot f_{HV} \cdot f_p}$$

Symbol	Meaning
v_i	Demand flow rate , in <i>pc/h</i> (base conditions)
V_i	Demand volume , in <i>veh/h</i> (prevailing conditions)
PHF	Peak Hour Factor
f_{HV}	Heavy-vehicle adjustment factor
f_p	Driver-population adjustment factor

WEAVING SEGMENTS: BASIC CHARACTERISTICS AND VARIABLES

Flows in a Weaving Area

In a typical weaving area, four component flows may exist:

- Two weaving flows → cross each other's path
- Two nonweaving (outer) flows → do NOT cross

HCM uses the following notation:

Symbol	Meaning
v_{o1}	Larger nonweaving flow (outer flow)
v_{o2}	Smaller nonweaving flow
v_{w1}	Larger weaving flow
v_{w2}	Smaller weaving flow

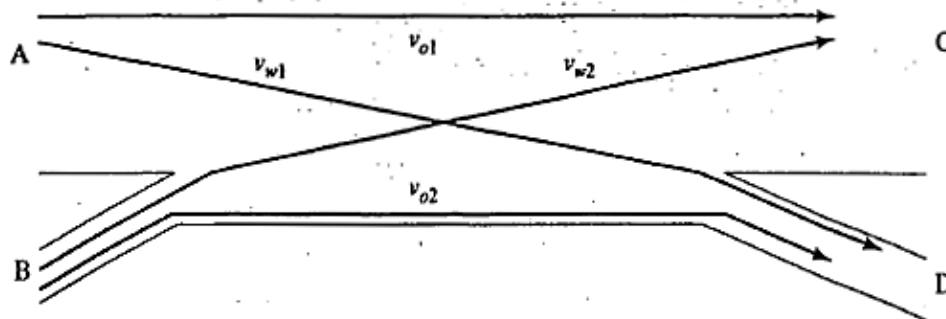
$$v_w = v_{w1} + v_{w2}$$

$$v_{nw} = v_{o1} + v_{o2}$$

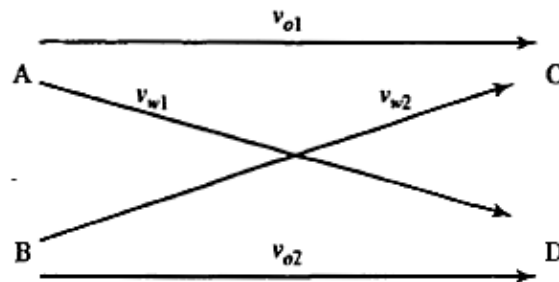
$$v = v_w + v_{nw} \quad (\text{total demand, pc/h})$$

$$VR = \text{volume ratio} = v_w/v$$

$$R = \text{weaving ratio} = v_{w2}/v_w$$



Weaving Segment Flows



Weaving Diagram

Critical Geometric Variables

Three geometric variables strongly influence weaving performance:

1. Lane Configuration
2. Length of the Weaving Area
3. Width (number of lanes)

Each affects the number and intensity of lane changes required.

1. LANE CONFIGURATION

Lane configuration defines how many lane changes must occur for weaving movements to be successfully completed.

There are two main categories:

A. One-Sided Weaving

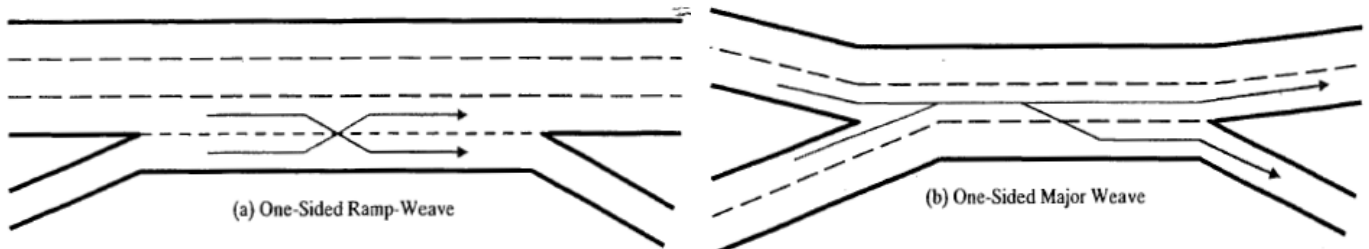
A one-sided weaving segment is one in which no weaving maneuver requires more than two lane changes. Both entry and exit are on the same side (usually the right).

Lane-changing is more localized and involves:

- Standard one-lane auxiliary section (ramp weave)
- Or major weave (with more lanes)

Types:

- One-Sided Ramp-Weave
- One-Sided Major Weave

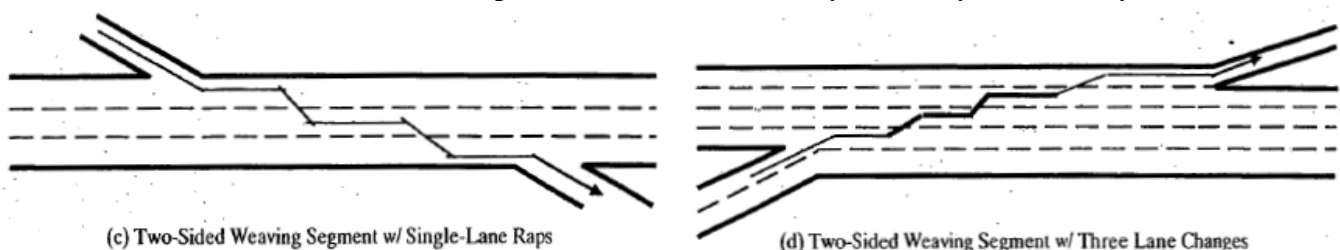


B. Two-Sided Weaving

Entry is on one side; exit is on the other.

This causes weaving to occur across all lanes and is more complex.

- A two-sided weaving segment is one in which one weaving maneuver requires three or more lane changes, or
- one in which a one-lane on-ramp on one side of the facility is closely followed by



Key numerical parameters

Two measures quantify lane-change requirements:

LC_{FR} = min lane changes for facility → ramp movement

LC_{RF} = min lane changes for ramp → facility movement

N_{WV} = number of lanes from which a weaving maneuver may be completed with one lane change, or no lane change.

- One-sided weaves → $LC_{FR}, LC_{RF} = 0$ or 1 ; $N_{WV} = 2$ or 3
- Two-sided weaves → generally $LC_{FR} = 3$; $N_{WV} = 0$

2. LENGTH OF THE WEAVING AREA

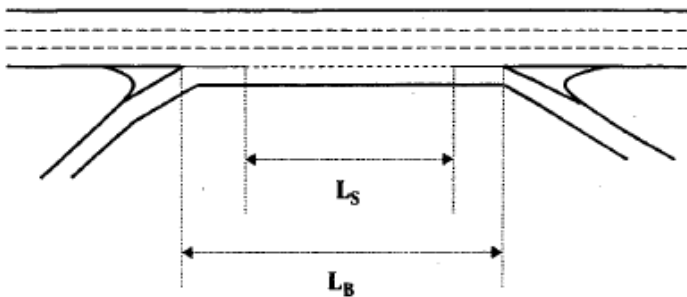
The length of the weaving segment directly affects weaving intensity.

Two lengths are defined:

- **Short length, L_S** : the distance between the end points of any barrier markings that prohibit or discourage lane changing.
- **Base length, L_B** : Base length (ft); the distance between points in the respective gore areas where the left edge of the ramp travel lanes and the right edge of the facility travel lanes meet. (From the left edge of the ramp taper to the right edge of the exit taper).

If local agency guidelines do not define these lengths:

$$L_S = 0.77 \cdot L_B$$



3. WIDTH (NUMBER OF LANES)

The weaving width is the total number of lanes available N .

- More lanes → more lane-change opportunities → lower turbulence
- Fewer lanes → stronger lane-changing competition → higher turbulence

Width is a crucial input in the HCM density and speed estimation models.

COMPUTATIONAL PROCEDURES FOR WEAVING AREA ANALYSIS

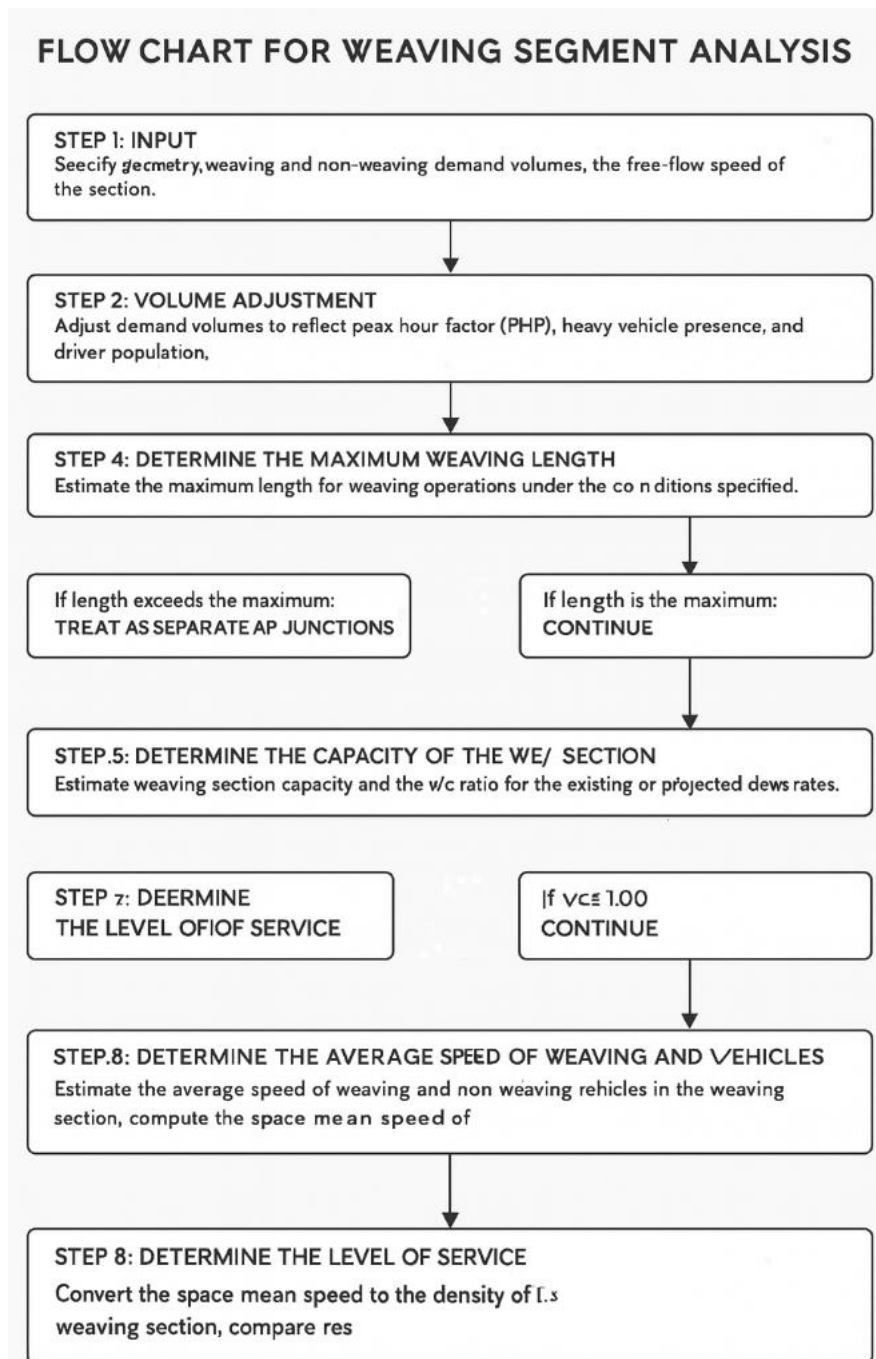
The HCM weaving methodology is most commonly used in operational analysis, where:

- Geometry is fixed
- All demand flows are known
- Speeds, densities, and LOS are required

The procedure results in:

- **Weaving segment LOS**
- **Weaving capacity**
- **Lane-changing rates**
- **Average speeds** for weaving & non-weaving flows

A complete flowchart is given in **Figure below**, and summarized below.

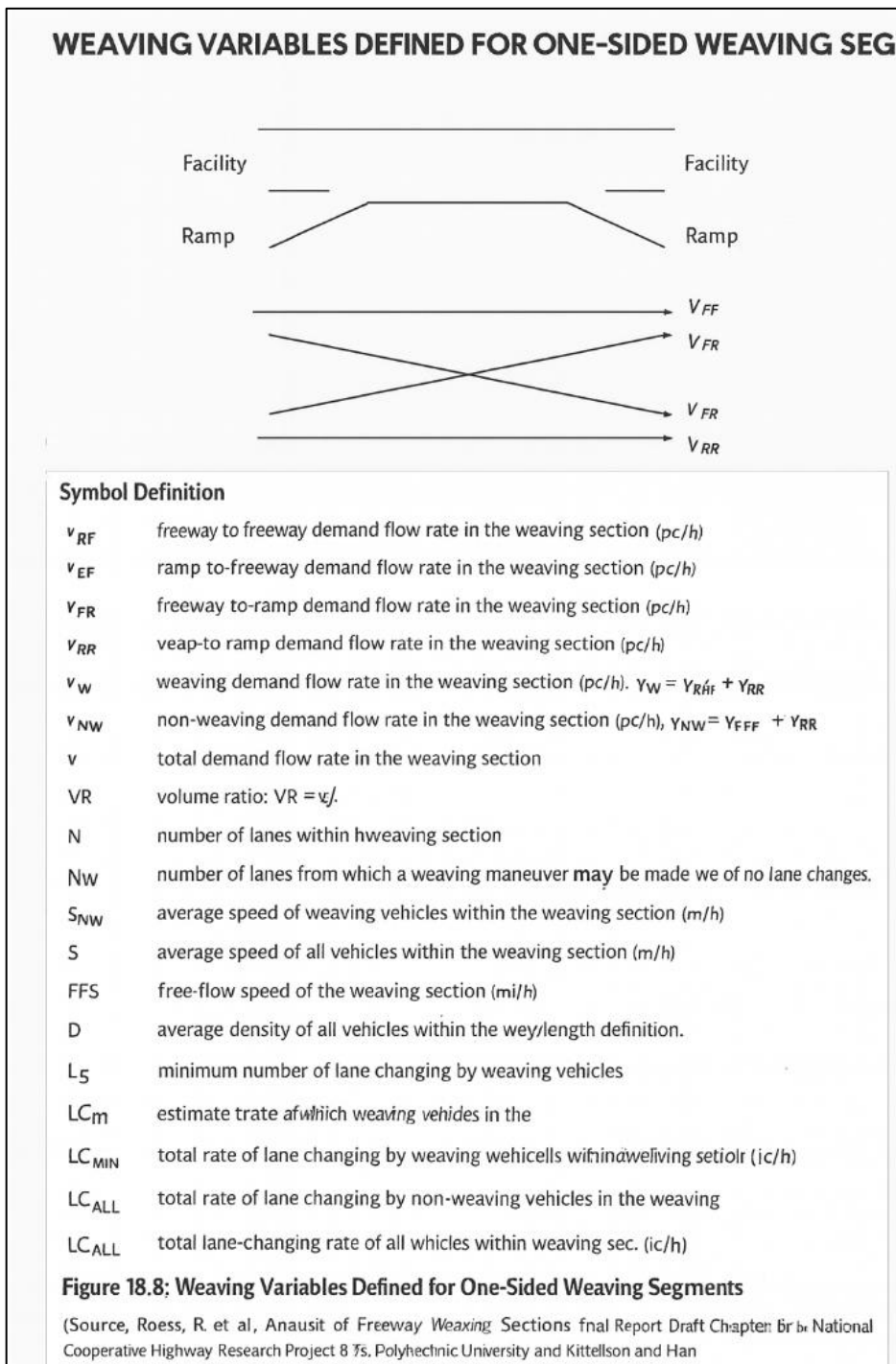


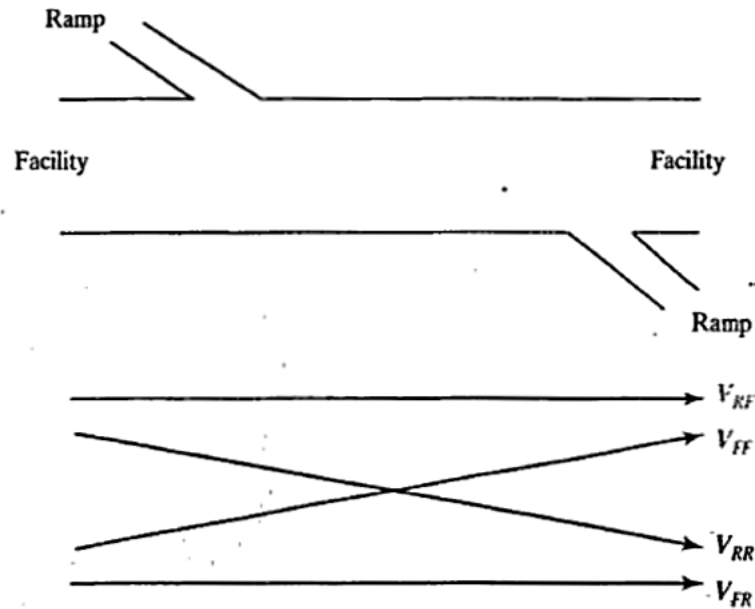
STEP 1 : DEFINE PARAMETERS USED IN WEAVING ANALYSIS

Weaving analysis uses many variables representing:

- Demand flows
- Weaving and non-weaving components
- Lane-changing parameters
- Weaving intensity
- Speeds, densities
- Geometric characteristics

Figures below define all variables for One-sided segments (Fig 15.8) and Two-sided segments (Fig 15.9)





All variables are defined as in Figure 15.8, except for the following variables related to flow designations and lane-changing variables.

Symbol Definition

- v_W total weaving demand flow rate within the weaving section (pc/h) $v_W = v_{RR}$
- v_{NW} total non-weaving demand flow rate within the weaving section (pc/h) $v_{NW} = v_{FR} + v_{RF} + v_{FF}$
- LC_{RR} minimum number of lane changes that must be made by *one* ramp-to-ramp vehicle to complete a weaving maneuver.
- LC_{MIN} minimum rate of lane changing that must exist for *all* weaving vehicles to successfully complete their weaving maneuvers (lc/h) $LC_{MIN} = (LC_{RR} \times v_{RR})$

Figure 15.9: Weaving Variables Defined for Two-Sided Weaving Segments

(Source: Roccs, R., et al., *Analysis of Freeway Weaving Sections*, Final Report, Draft Chapter for the HCM, National Cooperative Highway Research Program Project 3-75, Polytechnic University and Kittelson and Associates, Brooklyn, NY, September 2007, Exhibit 24-8, p. 13.)

STEP 2 : CONVERT VOLUMES TO FLOW RATES

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

All demand volumes must be expressed in pc/h under ideal conditions before entering the models.

STEP 3 — DETERMINE CONFIGURATION CHARACTERISTICS

Two parameters quantify configuration effects:

1. The number of “simple-weaving lanes” N_{wv} : the number of lanes from which weaving can be completed with **no more than one lane change**.

If weaving can be completed with 0 or 1 lane change → the lane counts as a simple weaving lane.

- One-sided segment: $N_{wv}=2$ or 3
- Two-sided segment: $N_{wv}=0$

2. Minimum lane-changing rate LC_{MIN} : the minimum number of lane changes required per hour for **all weaving vehicles** to complete their maneuvers.

This is **not** the total lane-changing rate in the segment.

It is the mandatory lane-changing rate (lc/h) that must happen within the weaving section for all weaving vehicles to reach their intended exit.

For one-sided weaving segments: Two weaving movements exist:

- Freeway → Ramp
- Ramp → Freeway

Each movement requires a certain number of mandatory lane changes:

LC_{FR} : required lane changes for Freeway → Ramp

LC_{RF} : required lane changes for Ramp → Freeway

Required minimum lane change rate LC_{MIN}

$$LC_{MIN} = (LC_{FR} \cdot v_{RF}) + (LC_{RF} \cdot v_{FR})$$

Where:

- v_{FR} = freeway-to-ramp flow (pc/h)
- v_{RF} = ramp-to-freeway flow (pc/h)

For two-sided weaving segments:

Only *ramp-to-ramp* vehicles are weaving (freeway-to-freeway and ramp-to-freeway become nonweaving).

Thus:

- LC_{RR} : the number of required lane changes for the ramp-to-ramp movement
- v_{RR} : ramp-to-ramp weaving flow (pc/h)

Required minimum lane change rate

$$LC_{MIN} = LC_{RR} \cdot v_{RR}$$

This is **not** the total lane-changing rate; it is the minimum required rate based strictly on geometry.

STEP 4 — DETERMINE THE MAXIMUM WEAVING LENGTH

“Weaving” only exists if the segment is short enough to force interaction between merge and diverge operations.

The HCM defines maximum weaving length based on capacity equivalence, not operational observation.

$$L_{MAX} = [5,728(1 + VR)^{1.6}] - [1,566N_{WV}]$$

- Longer weaving allowed when **VR** (V_w/V , volume ratio) is high
- Shorter weaving allowed when N_{WV} is high (more lanes available → less forced turbulence)
- If $L_{MAX} \geq L_S$ → Weaving Analysis Applies (Analyze as a weaving segment)
- If $L_{MAX} < L_S$ → Treat as Separate Merge and Diverge Segments

STEP 5 — DETERMINE THE CAPACITY OF THE WEAVING SECTION

Capacity is determined using two separate models, **and the smaller result controls**.

There are two mechanisms of breakdown:

A. Breakdown Based on Density (Main Control)

Total demand flow > Total segment capacity

Breakdown density of weaving segments = **43 pc/mi/ln.**

Capacity model:

$$c_{WL} = c_{IFL} - 438.2(1 + VR)^{1.6} + 0.0765L_S + 119.8N_{WV} \quad (15-5)$$

Where:

- c_{IFL} = basic freeway lane capacity from Table 15-2 with same FFS (pc/h/ln)
- c_{WL} = capacity per lane under ideal conditions
- VR = volume ratio = V_w/V
- L_S = short weaving length (ft)
- N_{WV} = number of simple-weaving lanes (2 or 3)

Table 15.2: Basic Facility Capacity Values (c_{IFL}) for Use in Equation 15-5

Freeways		Multilane Highways and C-D Roadways	
FFS (mi/h)	Capacity (pc/h/ln)	FFS (mi/h)	Capacity (pc/h/ln)
≥ 70	2,400	≥ 60	2,200
65	2,350	55	2,100
60	2,300	50	2,000
55	2,250	45	1,900 ^a

Convert to total capacity under prevailing conditions:

$$c_{W1} = c_{WL} N f_{HV} f_p$$

Symbol	Meaning
c_{W1}	total weaving capacity (veh/h) based on breakdown density
N	number of lanes in weaving segment
f_{HV}	heavy-vehicle adjustment factor
f_p	driver-population factor

B. Breakdown Based on Maximum Weaving Flow

$v_w >$ Maximum allowable weaving flow

Maximum weaving flow values:

(N_{wv})	Maximum Weaving Flow (pc/h)
2 lanes	2,400 pc/h
3 lanes	3,500 pc/h

If $N_{wv}=2$:

$$c_W = \frac{2,400}{VR}$$

If $N_{wv}=3$:

$$c_W = \frac{3,500}{VR}$$

Convert to prevailing:

$$c_{W2} = c_{W2} f_{HV} f_P$$

The weaving segment capacity is the **minimum** of the two capacity controls:

$$c_W = \min(c_{W1}, c_{W2})$$

Final Assessment: v/c Ratio

$$v/c = \frac{v f_{HV} f_p}{c_W}$$

- If $v/c > 1.00$ → LOS = F, analysis stops
- If $v/c \leq 1.00$ → Continue to speed & density estimation

STEP 6 — DETERMINE LANE-CHANGING RATES

There are **three types of lane changes** in an HCM weaving segment:

1. Required Lane Changes (Weaving Vehicles Only)

These are **mandatory** lane changes necessary for a weaving vehicle to complete its movement.

Examples:

- Ramp-to-freeway movement entering from the auxiliary lane must shift left
- Freeway-to-ramp movement must shift right

They represent the **minimum lane-changing rate**:

$$\text{Required LC rate} = LC_{\min}$$

Where:

- LC_{\min} was computed in Step 3
- It represents the absolute minimum number of lane changes needed to complete all weaving maneuvers

These lane changes **must** occur within the weaving segment.

2. Optional Lane Changes by Weaving Vehicles

Weaving vehicles may:

- Enter the segment in a lane *not closest* to their destination
- Leave the segment from a lane *not aligned* with their exit

These extra lane changes:

- Increase turbulence
- Increase density and reduce speed
- Must also be accounted for

3. Optional Lane Changes by Non-Weaving Vehicles

Non-weaving (“outer”) vehicles:

- Are **not required** to change lanes within the weaving segment
- But may **CHOOSE** to change lanes to avoid turbulence, trucks, merging, etc.

These must be estimated separately.

Total Lane-Changing Rate for Weaving Vehicles

The total lane-changing rate for weaving vehicles is:

$$LC_W = LC_{\min} + 0.39(L_S - 300)^{0.5} N^2 (1 + ID)^{0.8}$$

Variable	Meaning
LC_W	total lane-changing rate by weaving vehicles (lc/h)
LC_{\min}	minimum required weaving lane changes (lc/h)
L_S	short length of weaving segment (ft)
N	number of lanes in weaving segment
ID	interchange density (interchanges/mi)

- For any $L_S < 300$ ft, HCM forces **LS=300**, because weaving vehicles cannot physically make optional lane changes in such short segments.
- Longer segments allow more optional lane changes.
- Higher interchange density → more disturbance → more lane changes.
- More lanes → more opportunity for weaving movements.

Total Lane-Changing Rate for Non-Weaving Vehicles

Non-weaving vehicles (outer movements) make only optional lane changes.

HCM provides two separate regression equations:

Equation 1: General estimate

$$LC_{NW1} = (0.206 v_{NW}) + (0.542 L_S) - 192.6N$$

Equation 2: High-flow or unusual conditions

$$LC_{NW2} = 2135 + 0.223(v_{NW} - 2000)$$

Variable	Meaning
LC_{NW1}	first estimate of non-weaving LC rate
LC_{NW2}	second estimate (for heavy non-weaving demand)
v_{NW}	non-weaving flow rate (pc/h)
L_S	short length of segment
N	lanes in the segment

Switching Between the Two Equations

The two equations produce very different values—so HCM uses an interpolation index:

$$I_{NW} = \frac{L_S ID v_{NW}}{10,000}$$

Rules for determining final LC_{NW}

- If $I_{NW} \leq 1300$: $LC_{NW} = LC_{NW1}$

- If $I_{NW} \geq 1950$:> $LC_{NW} = LC_{NW2}$
- If $1300 < I_{NW} < 1950$: ...> Linear interpolation $LC_{NW} = LC_{NW1} + (LC_{NW2} - LC_{NW1}) \left(\frac{I_{NW} - 1300}{650} \right)$

Total Lane-Changing Rate in the Weaving Segment

$$LC_{ALL} = LC_W + LC_{NW}$$

Where:

- LC_W = lane-changing by weaving vehicles
- LC_{NW} = lane-changing by nonweaving vehicles
- LC_{ALL} = **total lane-changing rate** in the weaving segment (lc/h)

These values reflect turbulence intensity.

STEP 7 — DETERMINING THE AVERAGE SPEED OF VEHICLES WITHIN A WEAVING SEGMENT

The goal of Step 7 is to compute **average speeds** of:

1. **Sw: Weaving vehicles**
2. **SNw: Non-weaving vehicles**
3. **S: All vehicles (space-mean speed)**

Speed is not the primary performance measure (that is density), but is required to compute density in Step 8.

1. Average Speed of Weaving Vehicles

The HCM algorithm uses a “minimum–maximum speed” formula:

$$S_W = S_{MIN} + \frac{S_{MAX} - S_{MIN}}{1 + W}$$

Symbol Meaning

S_W average speed of weaving vehicles (mi/h)

$$S_W = 15 + \frac{FFS - 15}{1 + W}$$

Using **(1 + W)** ensures denominator is always > 1.0

S_{MIN} minimum expected weaving speed $S_{MIN} = \mathbf{15 \text{ mi/h}}$ (same as earlier HCM editions).

S_{MAX} maximum expected weaving speed S_{MAX} is taken as **FFS + 5**, to avoid low speed predictions

W weaving intensity factor

$$W = 0.226 \left(\frac{LC_{ALL}}{L_S} \right)^{0.789}$$

Symbol Meaning

LC_{ALL} total lane changes (Step 6)

L_S short weaving length (ft)

2. Average Speed of Non-Weaving Vehicles

Non-weaving vehicles experience speed reduction due to turbulence, even though they are not required to change lanes.

The HCM regression formula is:

$$S_{NW} = FFS - (0.0072LC_{MIN}) - (0.0048 v_{NW})$$

Symbol Meaning

S_{NW}	average speed of non-weaving vehicles
LC_{MIN}	minimum required lane-change rate (Step 3)
v_{NW}	non-weaving flow (pc/h)

Observations:

- More non-weaving flow → more turbulence → lower S_{NW} .
- Higher required weaving lane changes → more disturbance → lower S_{NW} .
- Regression showed LC_{MIN} is a stronger predictor than W .

3. Average Speed of All Vehicles (Space-Mean Speed)

With weaving and non-weaving speeds known:

$$S = \frac{v_W + v_{NW}}{\left(\frac{v_W}{S_W}\right) + \left(\frac{v_{NW}}{S_{NW}}\right)}$$

This gives space-mean speed, the correct measure for density conversion.

STEP 8 — DETERMINING DENSITY AND LEVEL OF SERVICE

The final step converts demand and speed into **density**, which determines LOS.

Weaving segment density:

$$D = \frac{v}{S} \quad (\text{pc/mi/ln})$$

Compare D to LOS thresholds in Table 15.1 for weaving segments:

Level of Service	Weaving Areas		Merge or Diverge Areas
	Density Range (pc/mi/ln)		
	On Freeways	On Multilane Highways or C-D Roadways	On Freeways, Multilane Highways, or C-D Roadways
A	0–10	0–12	0–10
B	>10–20	>12–24	>10–20
C	>20–28	>24–32	>20–28
D	>28–35	>32–36	>28–35
E	>35	>36	>35
F	Demand Exceeds Capacity		

(Source: Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, 2000. Compiled from Exhibit 24-2, p. 24-3, and Exhibit 25-4, p. 25-5.)

BASIC CHARACTERISTICS OF MERGE AND DIVERGE SEGMENT ANALYSIS

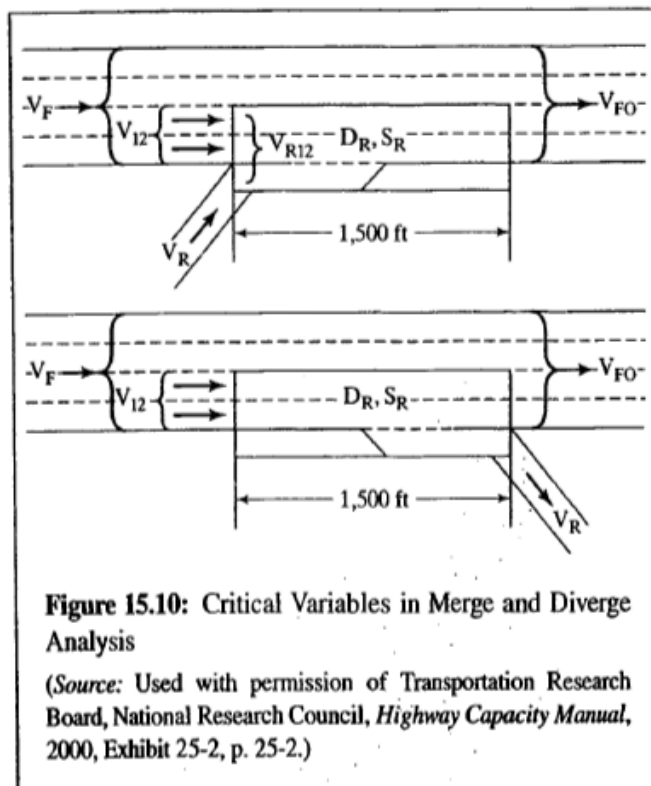
HCM analysis of merge and diverge segments focuses on the influence area, not the entire freeway cross-section. Unlike weaving segments—which span the full width of interacting lanes—merge/diverge analysis concentrates on only the right-most two freeway lanes plus the acceleration or deceleration lane.

As illustrated previously, analysis procedures for merge and diverge areas focus on the merge or diverge influence area that encompasses lanes 1 and 2 (shoulder and adjacent) freeway lanes and the acceleration or deceleration lane for a distance of 1,500 feet upstream of a diverge or 1,500 feet downstream of a merge area.

LOS in merge and diverge areas is based on Density (pc/mi/ln) in the influence area, compared with Table 15.1 (same density thresholds as weaving/merge/diverge segments):

The basic idea: Compute demand → convert to equivalent PCUs → assign lane distribution → estimate speed → compute density → apply LOS table.

CRITICAL VARIABLES



Demand Variables

- v_F : Flow in all freeway lanes immediately upstream of the merge or diverge
- v_{12} : Flow in lanes 1 and 2 upstream of the merge/diverge (important because only lanes 1–2 + ramp lane are analyzed)
- v_R : Ramp demand flow entering (at merge) or leaving (at diverge)
- v_{FO} : Outflow downstream on the freeway after ramp interaction

- v_{R12} :Total entering flow into the influence area:

$$v_{R12} = v_R + v_{12}$$

Performance Variables

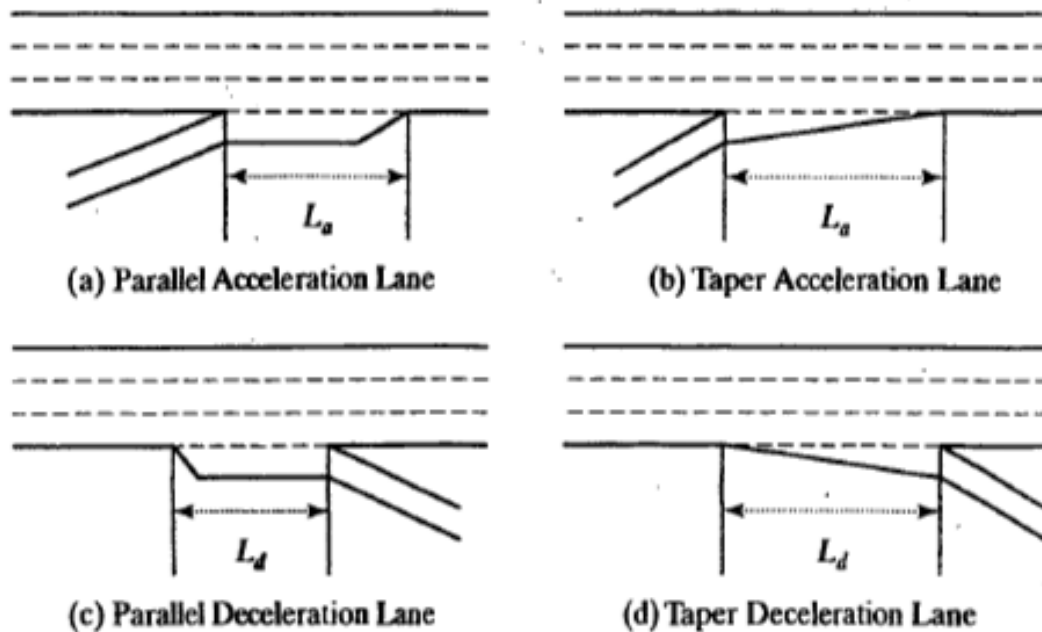
- D_R : Density in ramp influence area (pc/mi/ln)
- S_R : Space-mean speed in the ramp influence area (mi/h)

Geometric Inputs

A. Acceleration or Deceleration Lane Length (L_a or L_d)

Measured from:

- the point where the ramp lane and freeway lane first touch, to
- the point where the taper or parallel lane ends.



Measuring the Length of Acceleration and Deceleration Lanes

There are four configurations:

1. Parallel acceleration lane
2. Tapered acceleration lane
3. Parallel deceleration lane
4. Tapered deceleration lane

The measured length is the operational lane available for speed change, not the physical curve.

B. Ramp Free-Flow Speed (RFFS)

RFFS is:

- Best observed in the field, or
 - Estimated as the design speed of the most restrictive ramp element, typically: Tightest horizontal curve, Steepest vertical curve, and Narrowest section

Whichever element imposes the lowest operating speed governs RFFS.

LANE DISTRIBUTION

Merge and diverge analysis looks only at:

- Lane 1
- Lane 2
- Ramp lane

Therefore, a crucial step is to estimate **how much of the freeway** upstream flow remains in lanes 1 and 2 as traffic approaches the merge/diverge.

The model must determine:

Flow in Lanes 1–2 upstream = v_{12}

This reflects:

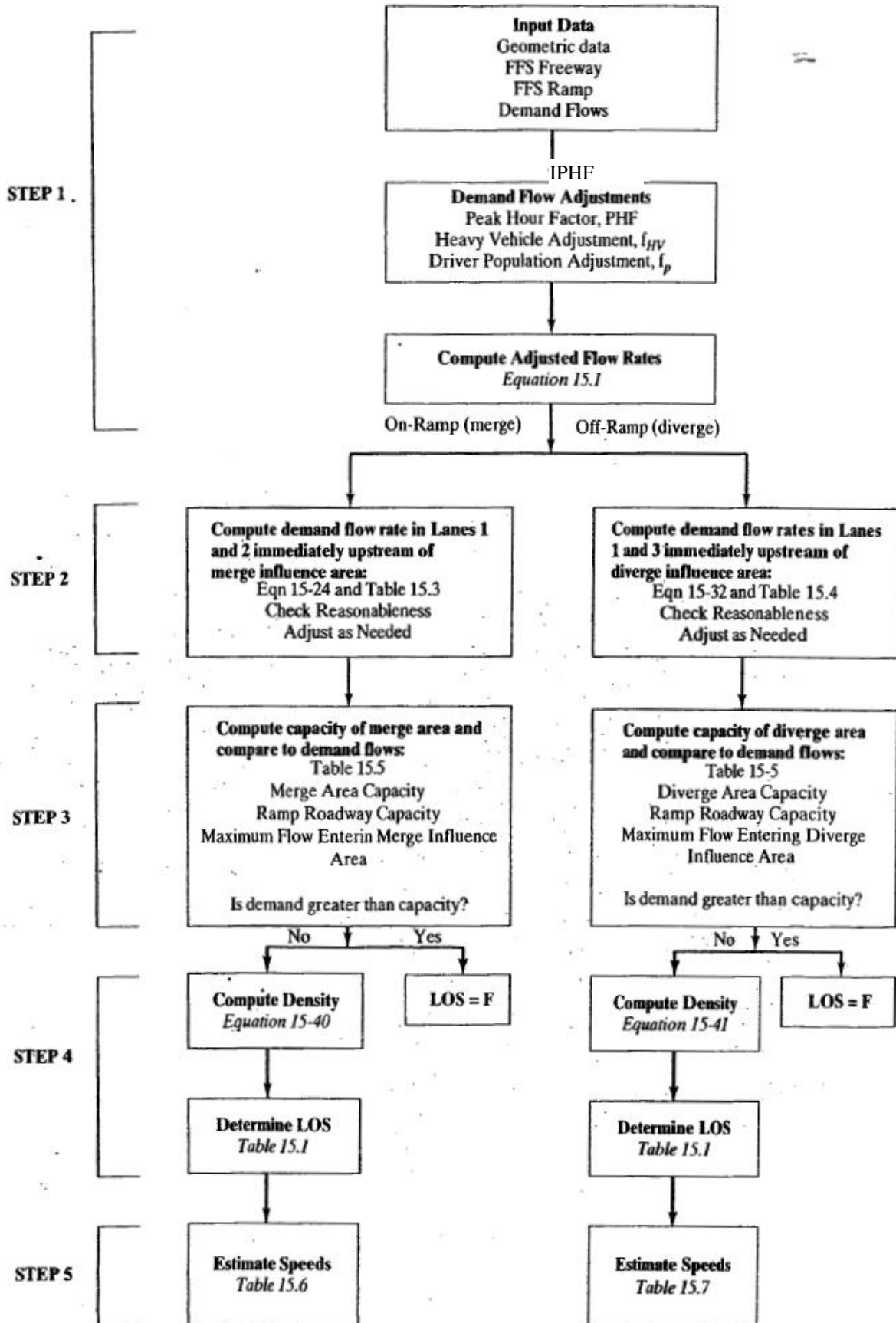
- Lane choice behavior
- Right-lane bias near ramps
- Lane changing upstream of the influence point

A correct lane distribution is essential because density in lanes 1–2 determines LOS.

COMPUTATIONAL PROCEDURES FOR MERGE & DIVERGE SEGMENTS

OVERVIEW — MAIN STEPS

Figure below describes **five main computational steps** for analyzing a merge or diverge segment:



STEP 1 — Input & Convert Demand

Collect all required data:

- Segment geometry
- Weaving & non-weaving demand flows
- Free-flow speed (FFS)

STEP 2 — Volume Adjustment

Adjust all volumes to **pc/h** under ideal conditions using:

- Peak-Hour Factor (PHF)
- Heavy-vehicle factor
- Driver population factor
- Eq. 15-1

FOR MERGE SEGMENTS (ON-RAMPS)

Flow remaining in lanes 1–2 upstream of the merge is:

$$v_{12} = v_F \cdot P_{FM}$$

where:

- v_F = total freeway flow upstream (pc/h)
- P_{FM} = proportion remaining in lanes 1–2 (from Table 15.3)

Table 15.3: Estimating P_{FM} at On-Ramps (Merge Segments)

No. of Freeway Lanes ^a	Model for Determining P_{FM}	
4	$P_{FM} = 1.000$	
6	$P_{FM} = 0.5775 + 0.000028L_A$	Equation 15-25
	$P_F = 0.7289 - 0.0000135(v_F + v_R) - 0.003296S_{FR} + 0.000063L_{UP}$	Equation 15-26
	$P_{FM} = 0.5487 + 0.2628(v_D/L_{DOWN})$	Equation 15-27
8	For $v_F/RFFS \leq 72$: $P_{FM} = 0.2178 - 0.000125v_R + 0.0115(L_A/S_{FR})$	Equation 15-28
	For $v_F/RFFS > 72$: $P_{FM} = 0.2178 - 0.000125 v_R$	Equation 15-29

Selecting Equations for P_{FM} for 6-Lane Freeways

Adjacent Up stream Ramp	Subject Ramp	Adjacent Downstream Ramp	Equation(s) Used
None	On	None	Equation 15-25
None	On	On	Equation 15-25
None	On	Off	Equation 15-27 or 15-25
On	On	None	Equation 15-25
Off	On	None	Equation 15-26 or 15-25
On	On	On	Equation 15-25
On	On	Off	Equation 15-27 or 15-25
Off	On	On	Equation 15-27 or 15-25
Off	On	Off	Equation 15-25, 15-26, or 15-27.

Note: ^a4 lanes = 2 lanes in each direction.

(Source: Modified from Draft Chapter 13, HCM2010, National Cooperative Highway Research Program Project 3-92, Kittelson and Associates. Portland OR. Exhibit 13-6. p. 13-12, 2008.)

Inputs to choose the correct equation for PFM :

- Freeway lane count (4, 6, or 8)
- Presence/absence of **adjacent upstream ramp**
- Presence/absence of **adjacent downstream ramp**
- Distances to adjacent ramps
- Ramp free-flow speed
- Ramp flow

Where:

- L_a = acceleration lane length
- S_{FR} = ramp free-flow speed
- L_{UP}, L_{DOWN} = distances to adjacent upstream/downstream ramps
- v_D = downstream ramp demand

Equivalence Distance for Upstream Off-Ramps

Used to determine whether a merge area is effectively isolated.

$$L_{EQ} = 0.214(v_F + v_R) + 0.444L_a + 53.32RFFS - 2403$$

- $L_{UP} \geq L_{EQ}$ → Upstream ramp effect negligible → Use Eq. 15-25
- $L_{UP} < L_{EQ}$ → Upstream ramp influential → Use Eq. 15-26

Equivalence Distance for Downstream Off-Ramps

$$L_{EQ} = \frac{v_d}{0.1096 + 0.0000107L_a}$$

- $L_{DOWN} \geq L_{EQ}$ → Downstream ramp not influential → Use Eq. 15-25
- $L_{DOWN} < L_{EQ}$ → Downstream ramp influential → Use Eq. 15-27

Special Note – 8-Lane Freeways

Two equations (15-28 and 15-29) must be used carefully because increasing L_a can paradoxically increase density.

HCM advises selecting the **more conservative (worse LOS)** result.

FOR DIVERGEGSEGMENTS (ON-RAMPS)

Diverge areas are analyzed differently from merge areas because **all exiting traffic must be in lanes 1 and 2** immediately upstream of the diverge. Therefore, the flow in these two lanes is:

- The **full off-ramp flow** (because all exiting vehicles must be in lanes 1–2), **plus**
- A **proportion of the through traffic** that remains in lanes 1–2.

Base Equation for Lanes 1 and 2 Upstream of Diverge

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

Where:

- v_{12} = flow rate in lanes 1 and 2 (pc/h)
- v_R = off-ramp flow (pc/h)
- v_F = facility flow upstream of diverge (pc/h)
- P_{FD} = proportion of through vehicles staying in lanes 1 and 2 upstream of the diverge

$(v_F - v_R)$ is the remaining through flow, and P_{FD} determines how much of it stays in lanes 1–2.

Selecting P_{FD} for Diverge Areas

The value of P_{FD} depends on:

- Number of freeway lanes (6 or 8)
- Distance to adjacent upstream on-ramps
- Distance to adjacent downstream off-ramps

A selection matrix (Table 15.4) is used, similar to merge analysis.

For 8-lane freeways, HCM assumes:

$$P_{FD} = 0.436$$

Table 15.4: Estimating P_{FD} at Off-Ramps (Diverge Segments)

No. of Freeway Lanes ^a	Model for Determining P_{FD}	
4	$P_{FD} = 1.000$	
6	$P_{FD} = 0.760 - 0.000025 v_F - 0.000046 v_R$	Equation 15-33
	$P_{FD} = 0.717 - 0.000039 v_F + 0.604 (v_U / L_{UP})$	Equation 15-34
	$P_{FD} = 0.616 - 0.000021 v_F + 0.124 (v_D / L_{DOWN})$	Equation 15-35
8	$P_{FD} = 0.436$	

Selecting Equations for P_{FD} for 6-Lane Freeways

Adjacent Upstream Ramp	Subject Ramp	Adjacent Downstream Ramp	Equation(s) Used
None	Off	None	Equation 15-33
None	Off	On	Equation 15-33
None	Off	Off	Equation 15-35 or 15-33
On	Off	None	Equation 15-34 or 15-33
Off	Off	None	Equation 15-33
On	Off	On	Equation 15-34 or 15-33
On	Off	Off	Equation 15-33, 15-34, or 15-35

Note: ^a4 lanes = 2 lanes in each direction.

(Source: Modified from Draft Chapter 13, HCM2010, National Cooperative Highway Research Program Project 3-92, Kittelson and Associates, Portland OR, Exhibit 13-6, p. 13-12, 2008.)

Equivalence Distance (LEQ)

To determine if adjacent ramps influence the diverge, HCM defines an **equivalence distance** L_{EQ} , beyond which a ramp is considered "isolated."

A. Adjacent Upstream On-Ramp

$$L_{EQ} = \frac{v_u}{0.071 + 0.000023v_F - 0.000076v_R}$$

Where:

- v_u = upstream on-ramp demand flow (pc/h)

Rule:

- If $L_{up} \geq L_{EQ} \rightarrow$ ramp is **isolated**
- If $L_{up} < L_{EQ} \rightarrow$ effect **must be included** (use Eq. 15-34)

B. Adjacent Downstream Off-Ramp

$$L_{EQ} = \frac{v_d}{1.15 - 0.000032v_F - 0.000369v_R}$$

Where:

- v_d = flow on downstream off-ramp (pc/h)

Rule:

- If $L_{dn} \geq L_{EQ} \rightarrow$ downstream ramp **isolated**
- If $L_{dn} < L_{EQ} \rightarrow$ downstream ramp influences (use Eq. 15-35)

Special Case – Both Adjacent Ramps Exist

If there is:

- An upstream on-ramp and
- A downstream off-ramp

→ **Both must be tested separately.**

If equations produce two valid values:

Choose the one yielding the worst (most conservative) traffic condition.

CHECKING THE REASONABLENESS OF LANE DISTRIBUTION PREDICTIONS

After estimating the demand flow rate in lanes **1 and 2**, the HCM requires applying a **reasonableness check**.

Because the lane-distribution equations are **regression-based**, using them outside their calibrated range can produce **illogical lane distributions**.

Therefore, the predicted lane distribution must satisfy **two mandatory conditions**:

Reasonableness Conditions

1. Maximum allowable flow in outer lanes

$$\text{Average flow rate in outer lanes} \leq 2,700 \text{ pc/h/ln}$$

2. Outer-to-inner flow ratio limit

$$\text{Average flow in outer lanes} \leq 1.5 \times \text{average flow in lanes 1 and 2}$$

Relationship to Number of Lanes

Depending on freeway width:

- **4-lane freeway (2×2):**
No outer lanes → all traffic already in lanes 1 and 2.
- **6-lane freeway (3×3):**
One outer lane → lane 3.
- **8-lane freeway (4×4):**
Two outer lanes → lanes 3 and 4.

If either limit is violated, the flow rate in lanes 1 and 2 must be **adjusted downward**.

Adjustment 1 — Based on the 2,700 pc/h/ln limit

$$v_{\text{outer}} > 2,700 \text{ pc/h/ln,}$$

then lane-1-2 flow becomes:

$$V_{12} = V_F - 2700N_O$$

Where:

- V_F = total freeway flow (pc/h)
- N_O = number of outer lanes

Adjustment 2 — Based on the 1.5 × rule

$$v_{\text{outer}} > 1.5 \times v_{12},$$

then recompute V_{12} depending on outer-lane count:

For $N_O=1$:

$$V_{12} = \frac{V_F}{1.75}$$

For $N_O=2$:

$$V_{12} = \frac{V_F}{2.50}$$

For $N_O>2$:

$$V_{12} = \frac{2V_F}{1.5N_O + 2}$$

This formula evenly distributes the remaining flow so both criteria are satisfied.

STEP 3- Capacity Considerations

The HCM requires checking three main types of capacity:

1. Freeway Segment Capacity

This is checked upstream and/or downstream of the merge or diverge location.

- **Merge areas:** Check downstream capacity → flow = $V_{FO} = V_F + V_R$
- **Diverge areas:** Check upstream capacity → flow = V_F

If facility flow exceeds the basic freeway capacity, LOS = F immediately.

2. Ramp Roadway Capacity

Every ramp flow (V_R) must be checked:

Use capacities from Table 15.5

Important for diverge areas, because: Off-ramps can fail first if demand > ramp capacity and A congested off-ramp forces vehicles to queue into lanes 1–2 → failing the diverge segment

Table 15.5 ramp capacities refer to the ramp roadway, not the junction.

Example: A “two-lane ramp” listed in the table does **not** mean the merge junction can accept two full lanes merging—practically it cannot.

Table 15.5: Capacity Values for Ramp Checkpoints

Freeway FFS (mi/h)	Maximum Freeway Flow Upstream/Downstream of Merge or Diverge (pc/h)				Maximum Desirable Flow Entering Merge Influence Area (pc/h)	Maximum Desirable Flow Entering Diverge Influence Area (pc/h)
	Number of Lanes in One Direction					
	2	3	4	≥5		
≥70	4,800	7,200	9,600	2,400/ln	4,600	4,400
65	4,700	7,050	9,400	2,350/ln	4,600	4,400
60	4,600	6,900	9,200	2,300/ln	4,600	4,400
55	4,500	6,750	9,000	2,250/ln	4,600	4,400

Ramp Free-Flow Speed RFFS (mi/h)	Capacity of Ramp Roadway (pc/h)	
	Single-Lane Ramps	Two-Lane Ramps
>50	2,200	4,400
>40–50	2,100	4,100
>30–40	2,000	3,800
≥20–30	1,900	3,500
<20	1,800	3,200

(Source: Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, 2000, compiled from Exhibits 25-3, p. 25-4, 25-7, p. 25-9, and 25-14, p. 25-14.)

3. Total Flow Entering the Influence Area

This flow includes:

- **For merge zones:**

$$V_{R12} = V_{12} + V_R$$

- **For diverge zones:**
 v_{12} (all off-ramp traffic assumed in lanes 1–2)

Compare this flow against “maximum desirable flow” from Table 15.5.

Exceeding this value does NOT automatically mean LOS = F **unless** another capacity is exceeded. But it indicates operating conditions will likely degrade.

STEP 4: Determining Density and Level of Service in the Ramp Influence Area

For merges:

$$D_R = 5.475 + 0.00734v_R + 0.0078v_{12} - 0.00627L_a$$

For diverges:

$$D_R = 4.252 + 0.0086v_{12} - 0.009L_d$$

Density is compared to **Table 15.1** → LOS A–E.

STEP 5: Determining Expected Speed Measures

HCM requires three separate speed measures for ramp influence areas (≈1500 ft):

1. Speed within the Ramp Influence Area (SR)

- Space mean speed of all vehicles inside the ramp influence zone.
- Based on v_{R12} for merge areas or v_{12} for diverge areas.

2. Speed in Outer Lanes (S_o)

- Average speed in lanes 3 and 4, where they exist.
- Calculated separately because outer-lane drivers feel less ramp turbulence.

3. Combined Average Space-Mean Speed (S)

- Weighted speed across all lanes within the 1500-ft zone.
- Used for system-level analysis.

Table 15.6: Estimating Average Speeds in Merge Areas

Avg Spd In _____	Estimation Algorithm
Ramp Influence Area	$S_R = FFS - (FFS - 42)M_S$ $M_S = 0.321 + 0.0039e^{(v_{R12}/1000)} - 0.002(La * RFFS/1,000)$
Outer Lanes	$S_o = FFS \quad v_{oa} < 500 \text{ pc/h}$ $S_o = FFS - 0.0036(v_{oa} - 500) \quad v_{oa} = 500 - 2,300 \text{ pc/h}$ $S_o = FFS - 6.53 - 0.006(v_{oa} - 2300) \quad v_{oa} > 2,300 \text{ pc/h}$
All Lanes	$S = \frac{V_{R12} + V_{OA}N_o}{\left(\frac{V_{R12}}{S_R}\right) + \left(\frac{V_{OA}N_o}{S_o}\right)}$

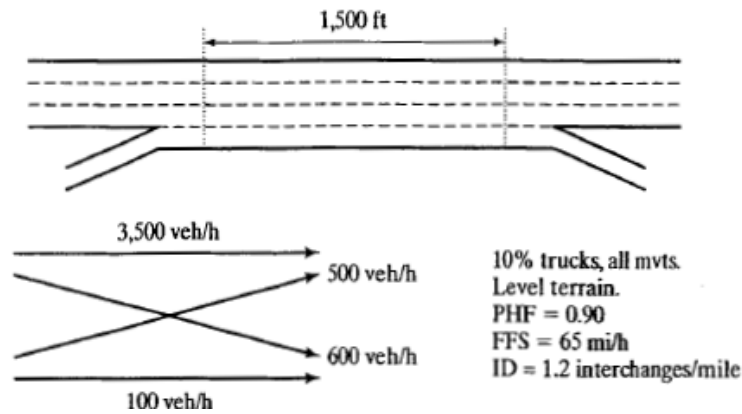
Table 15.7: Estimating Average Speeds in Diverging Areas

Avg Spd In _____	Estimation Algorithm
Ramp Influence Area	$S_R = FFS - (FFS - 42)D_S$ $D_S = 0.883 + 0.00009v_{12} - 0.013RFFS$
Outer Lanes	$S_o = 1.097FFS \quad v_{oa} < 1,000 \text{ pc/h}$ $S_o = 1.097FFS - 0.0039(v_{oa} - 1,000) \quad v_{oa} \geq 1000 \text{ pc/h}$
All Lanes	$S = \frac{V_{12} + V_{OA}N_o}{\left(\frac{V_{12}}{S_R}\right) + \left(\frac{V_{OA}N_o}{S_o}\right)}$

Symbol	Meaning	Where Used
S_R	Speed within ramp influence zone	Merge & Diverge
S_o	Speed in outer lanes (3 & 4)	Merge & Diverge
S	Combined space-mean speed	Merge & Diverge
M_S	Speed proportioning factor (merge cases)	Merge
D_S	Speed proportioning factor (diverge cases)	Diverge
v_{∞}	Average outer-lane demand flow rate	For S_o
N_o	Number of outer lanes (1 for 3-lane, 2 for 4-lane)	For S_o

EXAMPLE 1 : ANALYSIS OF A RAMP-WEAVE AREA

Figure below illustrates a typical ramp-weave section on a six-lane freeway (three lanes in each direction). The analysis is to determine the expected LOS and capacity for the prevailing conditions shown.



SOLUTION

Step 1 & Step 2 — Convert All Demand Volumes to Base Flow Rates

Convert each demand volume v into **pc/h** using:

$$v_p = \frac{v}{PHF f_{HV} f_p}$$

Given:

- $PHF = 0.90$
- $f_{HV} = 0.952$
- $f_p = 1.00$

Convert all component flows (freeway → ramp, ramp → freeway, ramp → ramp, etc.).

Useful conversions for the example:

- $v_{01} = 4085$ pc/h
- $v_{02} = 117$ pc/h
- $v_{w1} = 700$ pc/h
- $v_{w2} = 584$ pc/h

Then compute:

- $v_w = v_{w1} + v_{w2} = 1284$ pc/h
- $v_{nw} = v_{01} + v_{02} = 4202$ pc/h
- Total flow: $v = 1284 + 4202 = 5486$ pc/h
- Density base: $wN = \frac{v}{4} = 1372$ pc/mi/ln
- Volume ratio: $VR = \frac{v_w}{v} = 0.23$

Step 3 — Determine Configuration Characteristics

Two configuration parameters are needed:

1. Number of weaving lanes N_{WV}

From the geometry → **2 lanes**.

2. Minimum Lane changes LC_{MIN}

Formula for **two-sided weaving**:

$$LC_{MIN} = LC_{FR} \cdot v_{FR} + LC_{RF} \cdot v_{RF}$$

Given:

- $LC_{FR} = 1, v_{FR} = 700$
- $LC_{RF} = 1, v_{RF} = 584$

$$LC_{MIN} = (1)(700) + (1)(584) = 1284 \text{ lc/h}$$

Step 4 — Determine Maximum Weaving Length L_{MAX}

$$L_{MAX} = 5728(1 + VR)^{1.6} - 1566N_{WV}$$

$$L_{MAX} = 5728(1 + 0.23)^{1.6} - 1566(2)$$

$$L_{MAX} = 7977 - 3132 = 4845 \text{ ft}$$

Given actual length $L=1500 \text{ ft} \ll L_{MAX}$, **the segment is a weaving segment** → continue analysis.

Step 5 — Determine Weaving Segment Capacity

(1) Capacity based on breakdown density (43 pc/mi/ln):

Use:

$$c_{WL} = c_{IFL} - [438.2(1 + VR)^{1.6}] + [0.0765L_s] + (119.9N_{WV})$$

Substitute the values:

$$c_{WL} \approx 2094 \text{ pc/h/ln}$$

Convert to total capacity:

$$c_{WI} = c_{WL} N f_{HV} f_p = 7,974 \text{ veh/h}$$

(2) Capacity based on weaving flow:

$$c_W = \frac{2400}{VR} = \frac{2400}{0.23} = 10,235 \text{ pc/h}$$

Convert to prevailing conditions:

$$c_{W2} = 9744 \text{ veh/h}$$

→ Governing capacity = 7,974 veh/h

(Whichever is smaller.)

Demand check:

$v = 5,222 \text{ veh/h} < 7,974 \text{ veh/h} \Rightarrow$ Flow is stable; continue analysis

Step 6 — Determine Total Lane-Changing Rates

Lane-changing for weaving vehicles:

$$LC_W = LC_{MIN} + 0.39(L_s - 300)^{0.5} N^2 (1 + ID)^{0.8}$$

Given data:

$$LC_W = 1284 + 406.4 = 1690.4 \text{ lc/h}$$

Lane-changing for non-weaving vehicles

First compute index:

$$I_{NW} = \frac{L_s I_D v_{NW}}{10,000}$$

$$I_{NW} = 756.4$$

Since $I_{NW} \leq 1300$:

$$LC_{NW} = 0.206 v_{NW} + 0.542 L_s - 192.6 N$$

$$LC_{NW} = 899.2 \text{ lc/h}$$

T

Total lane changing:

$$LC_{ALL} = LC_W + LC_{NW}$$

$$LC_{ALL} = 1690.4 + 899.2 = 2589.6 \text{ lc/h}$$

Step 7 — Compute Average Speeds

Weaving speed:

Intensity:

$$W = 0.226 \left(\frac{LC_{ALL}}{L_s} \right)^{0.789}$$

$$W = 0.348$$

Speed:

$$S_W = 15 + \frac{FFS - 15}{1 + W}$$

$$S_W = 52.1 \text{ mi/h}$$

Non-weaving speed:

$$S_{NW} = FFS - (0.0072LC_{MIN}) - (0.0048 \frac{v}{N})$$

$$S_{NW} = 49.2 \text{ mi/h}$$

Overall speed:

$$S = \frac{v_W + v_{NW}}{\frac{v_W}{S_W} + \frac{v_{NW}}{S_{NW}}}$$

$$S = 49.9 \text{ mi/h}$$

Step 8 — Determine Density and LOS

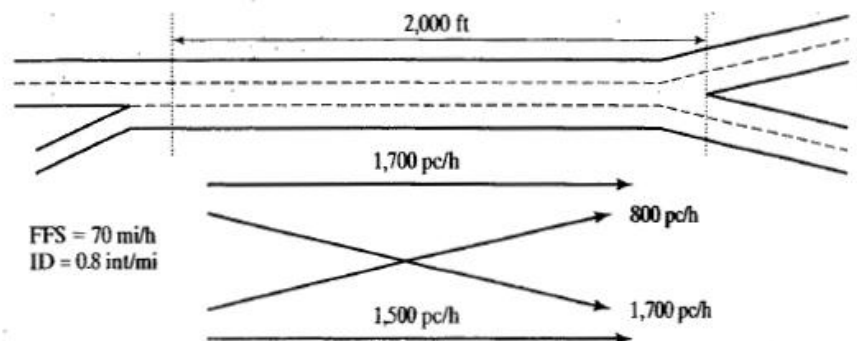
$$D = \frac{(v/N)}{S}$$

$$D = \frac{5486/4}{49.9} = 27.5 \text{ pc/mi/ln}$$

From Table 15.1 → LOS = C (very close to LOS D boundary of 28).

EXAMPLE 2 (MAJOR WEAVING AREA)

The freeway weaving area shown in Figure is to be analyzed to determine the expected LOS for the conditions shown and the capacity of the weaving area. For convenience, all demand volumes have already been converted to flow rates in pc/h under equivalent base conditions. For information purposes, the following values were used to make these conversions: PHF = 0.95, $f_{HV}=0.93$, $f_p = 1$.



SOLUTION

Step 1 & 2 — Convert Demands and Summarize Key Variables

All flows are already given in pc/h. Compute:

- Weaving demand:
 $v_W = 800 + 1700 = 2500 \text{ pc/h}$
- Non-weaving demand:
 $v_{NW} = 1700 + 1500 = 3200 \text{ pc/h}$
- Total flow:
 $v = 5700 \text{ pc/h}$
- Density flow ratio:
 $v/N = 1900 \text{ pc/h/ln}$
- Volume ratio:
 $VR = v_W/v = 2500/5700 = 0.439$
- Segment length:
 $L = 2000 \text{ ft}$

Step 3 — Determine Configuration Characteristics

- Number of lanes used for weaving with ≤ 1 lane change: $N_{WW}=3$
- Minimum required lane changes: One direction requires none, other requires one:

$$LC_{\min} = (0 \cdot v_{FR}) + (1 \cdot 800) = 800 \text{ lc/h}$$

Step 4 — Determine Maximum Weaving Length

$$L_{\max} = [5728(1 + VR)^{1.6}] - [1566N_{WW}]$$

$$L_{\max} = [5728(1 + 0.439)^{1.6}] - 1566(3)$$

$$L_{\max} = 5556 \text{ ft}$$

Since the actual length **2000 ft** < **5556 ft**, this is a valid weaving segment.

Step 5 — Determine Weaving Capacity

Two limits:

(a) Capacity based on density = 43 pc/mi/ln

$$c_{WL} = c_{IFL} - [438.2(1 + VR)^{1.6}] + [0.0765L_S] + [119.9N_{WW}]$$

$$c_{WL} = 2128 \text{ pc/h/ln}$$

Total (3 lanes):

$$c_W = 2128 \times 3 = 6384 \text{ pc/h}$$

(b) Capacity based on max weaving flow

$$c_{W_2} = \frac{3500}{VR} = 7973 \text{ pc/h}$$

Governing Capacity = Minimum

$$c_W = 6384 \text{ pc/h}$$

Demand = 5700 pc/h → **stable flow (not LOS F)**.

Step 6 — Determine Lane-Changing Rates

Weaving vehicles

$$LC_W = LC_{\min} + 0.39(L_S - 300)^{0.5} N^2 (1 + ID)^{0.8}$$

$$LC_W = 800 + 0.39(1700)^{0.5} (3)^2 (1.8)^{0.8}$$

$$LC_W = 1032 \text{ lc/h}$$

Non-weaving vehicles

Lane-changing index:

$$I_{NW} = \frac{L_S \cdot I_D \cdot v_{NW}}{10000} = \frac{2000 \cdot 0.8 \cdot 3200}{10000} = 512 < 1300$$

$$LC_{NW} = 0.206v_{NW} + 0.542L_S - 192N$$

$$LC_{NW} = 659.2 + 1084 - 576 = 1167 \text{ lc/h}$$

Total lane changes

$$LC_{ALL} = LC_W + LC_{NW} = 1032 + 1167 = 1679 \text{ lc/h}$$

Step 7 — Determine Speeds

$$W = 0.226 \left(\frac{LC_{ALL}}{L_S} \right)^{0.789}$$

$$W = 0.226 \left(\frac{1679}{2000} \right)^{0.789} = 0.197$$

Weaving speed

$$S_W = 15 + \frac{FFS - 15}{1 + W}$$

$$S_W = 15 + \frac{70 - 15}{1.197} = 60.9 \text{ mi/h}$$

Non-weaving speed

$$S_{NW} = FFS - (0.0072LC_{\min}) - (0.0048v/N)$$

$$S_{NW} = 70 - (0.0072 \cdot 800) - (0.0048 \cdot 1900) = 55.1 \text{ mi/h}$$

Average speed in the segment

$$S = \frac{v_W + v_{NW}}{\frac{v_W}{S_W} + \frac{v_{NW}}{S_{NW}}}$$

$$S = \frac{5700}{\frac{2500}{60.9} + \frac{3200}{55.1}}$$

$$S = 58.2 \text{ mi/h}$$

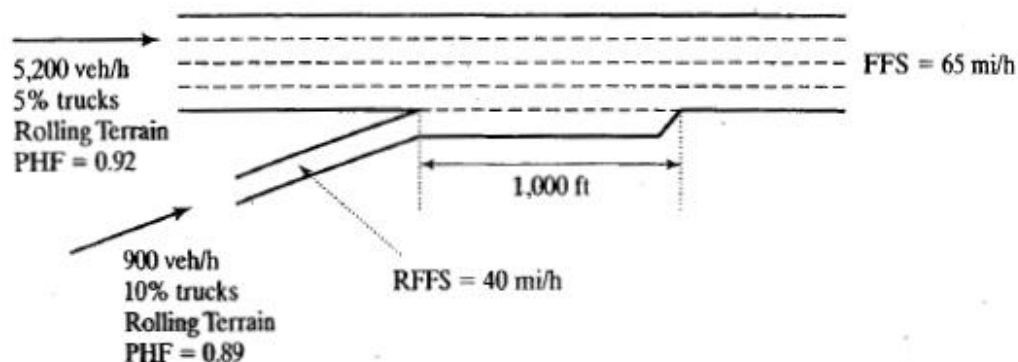
Step 8 — Determine Density & LOS

$$D = \frac{v/N}{S} = \frac{1900}{58.2} = 32.6 \text{ pc/mi/ln}$$

From HCM Table → **LOS = D**

EXAMPLE 3 (ISOLATED ON-RAMP)

An on-ramp to a busy eight-lane urban freeway is illustrated in Figure 15.15. An analysis of this merge area is to determine the likely LOS under the prevailing conditions shown.



SOLUTION

Step 1: Convert All Demand Volumes to Base-Condition Flow Rates (pc/h)

Convert freeway and ramp flows from veh/h → pc/h using:

$$v_p = \frac{v}{PHF \cdot f_{HV} \cdot f_p}$$

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

Results:

- Ramp flow: $v_R=1,162$ pc/h
- Freeway flow: $v_F=6,078$ pc/h

Step 2: Estimate Demand Flow in Lanes 1 and 2 Upstream of Merge

Use P_{FM} (proportion of flow staying in lanes 1–2).

$$\frac{v_F}{RFFS} = \frac{6078}{40} = 151.9 > 72$$

$$P_{FM} = 0.2178 - 0.000125 v_R$$

$$v_{12} = v_F \cdot P_{FM} = 441 \text{ pc/h}$$

Reasonableness Check

Two conditions:

1. Outer-lane flow $\leq 2,700$ pc/h/ln
2. Outer-lane flow $\leq 1.5 \times$ lanes 1–2 flow

$$v_{12} = \frac{v_F}{2.50} = 2,431 \text{ pc/h}$$

This revised value satisfies both criteria.

Step 3: Check Merge Area Capacity

Critical capacity is the downstream freeway section:

$$v_{FO} = v_F + v_R = 6,078 + 1,162 = 7,240 \text{ pc/h}$$

Capacity at 65 mi/h FFS (Table 15-5): **9,400 pc/h**

$$7,240 < 9,400$$

No failure due to freeway flow.

Ramp capacity (Table 15-5, RFFS = 40 mi/h) = **2,000 pc/h**

Ramp demand = **1,162 pc/h** → also acceptable.

Step 4: Compute Density in Ramp Influence Area

$$D_R = 5.475 + 0.00734 v_R + 0.0078 v_{12} - 0.00627 L_a$$

$$D_R = 26.7 \text{ pc/mi/ln}$$

Compare with Table 15-1:

Density 26.7 → **LOS C**, but close to LOS D boundary (28).

Step 5: Estimate Speed Parameters

Use Table 15-6 formulas.

Speed in ramp influence area:

$$S_R = FFS - (FFS - 42)M_S$$

$$M_S = 0.321 + 0.0039e^{(v_{R12}/1000)} - 0.002 \left(\frac{L_a \times RFFS}{1000} \right)$$

Results:

- $M_S = 0.383$
- $S_R = 56.2 \text{ mi/h}$

Speed in outer lanes:

$$S_O = FFS - 0.0036(v_{o4} - 500)$$

Result:

- $S_O = 60.2 \text{ mi/h}$

Overall average speed:

$$S = \frac{v_{R12} + v_{o4}}{\frac{v_{R12}}{S_R} + \frac{v_{o4}}{S_O}}$$

$$S = 57.2 \text{ mi/h}$$

Final LOS Determination

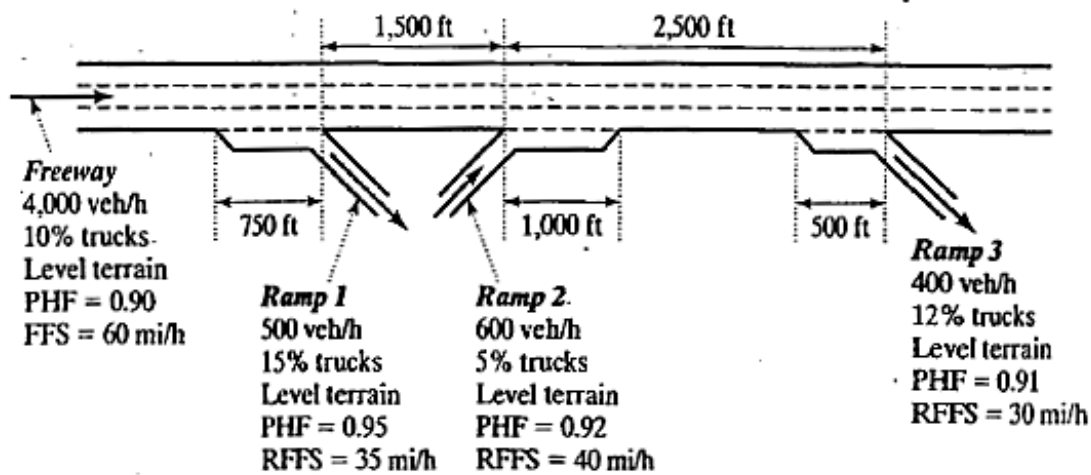
LOS in ramp influence area → **LOS C**

But outer-lane density → **LOS D**

Because the freeway flow is dominant → overall operation = **LOS D**

EXAMPLE 4 (SEQUENCE OF FREEWAY RAMPS)

Figure shows a series of three ramps on a six-lane freeway (three lanes in each direction). All three ramps are to be analyzed to determine the LOS expected under the prevailing conditions shown.



SOLUTION

Step 1 — Convert All Demand Volumes to Equivalent Flow Rates (pc/h)

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

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

Convert:

Freeway demand $\rightarrow v_F$

Ramp 1 $\rightarrow v_{R1}$

Ramp 2 $\rightarrow v_{R2}$

Ramp 3 $\rightarrow v_{R3}$

Step 2 — Determine v_{12} Upstream of Each Ramp

For each ramp, determine:

- Is there an adjacent upstream ramp?
- Is there an adjacent downstream ramp?
- What is the distance to each?
- What is the correct algorithm (15-25, 15-26, 15-27, 15-28, 15-29, or 15-34)?

Then apply:

General form:

$$v_{12} = v_R + (v_F - v_R)P_{FD} \quad \text{or} \quad v_{12} = v_F P_{FM}$$

Where:

- P_{FM} : merge proportion
- P_{FD} : diverge proportion
- Determined from **Table 15.4**
- Using correct equations depending on "isolated" vs "non-isolated"

For this example:

- **Ramp 1:** None-OFF-ON → use Eq. 15-33
- **Ramp 2:** OFF-ON-OFF → use Eq. 15-30 (check equivalence distances)
- **Ramp 3:** ON-OFF-None → use Eq. 15-34 (because upstream ramp is close)

At each ramp, verify **reasonableness**:

- Outer lane $\leq 2,700$ pc/h/ln
- Outer lane $\leq 1.5 \times$ average of lanes 1+2

Step 3 — Check Capacities

Compare each demand:

$$v_{12}, v_{R1}, v_{R2}, v_{R3}$$

with capacity values from **Table 15.5**:

- Freeway: 6,900 pc/h
- Ramps: 2,000 – 1,900 pc/h depending on RFFS

If **demand > capacity**, LOS = F.

If not, continue.

Step 4 — Compute Densities in Each Ramp Influence Area

On-ramp density equation

$$D_R = 5.475 + 0.00734v_R + 0.0078v_{12} - 0.00627L_a$$

Off-ramp density equation

$$D_R = 4.252 + 0.0086v_{12} - 0.009L_d$$

Compute density for:

- Ramp 1
- Ramp 2
- Ramp 3

Use Table 15.1 to determine LOS (A–F).

Step 5 — Determine Speeds

Use Tables 15.6 and 15.7 algorithms:

1. Compute speed-proportioning factor M_s .
2. Compute:
 - Speed in ramp influence area S_R
 - Speed in outer lanes S_O
3. Combine to find average speed of all vehicles:

$$S = \frac{v_{R12} + v_O}{\left(\frac{v_{R12}}{S_R}\right) + \left(\frac{v_O}{S_O}\right)}$$

Step 6 — Report Final LOS

From Step 4 density results:

- Ramp 1 → LOS C
- Ramp 2 → LOS C
- Ramp 3 → LOS D (worst and controlling)

Note: Ramp 3 influence area overlaps with Ramp 2, so Ramp 3 LOS dominates.

Overall segment LOS = D, controlled by Ramp 3.

References

1. Knoop, V. L. (2017). Introduction to traffic flow theory: An introduction with exercises. *Delft University of Technology: Delft, The Netherlands*.
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3. Traffic engineering / Roger P. Roess, Elena S. Prassas, William R. McShane. -4th ed.