Uninterrupted Flow

1. Merge and Diverge Segments

Merge and diverge segments are found where an on-ramp or off-ramp results in vehicles entering or exiting the freeway. The lane-change maneuvers needed for vehicles to enter or exit the freeway often cause turbulence that reduce the capacity of these segments, relative to a uniform basic freeway segment. Further, it is important to note that merge and diverge segments impact the demand on the freeway, as either more traffic enters or some traffic leaves the facility.

2.1 Methodology

In the HCM, the merge and diverge segment methodology contains five computational steps as shown in Figure below. Each step is discussed in more details in the following.

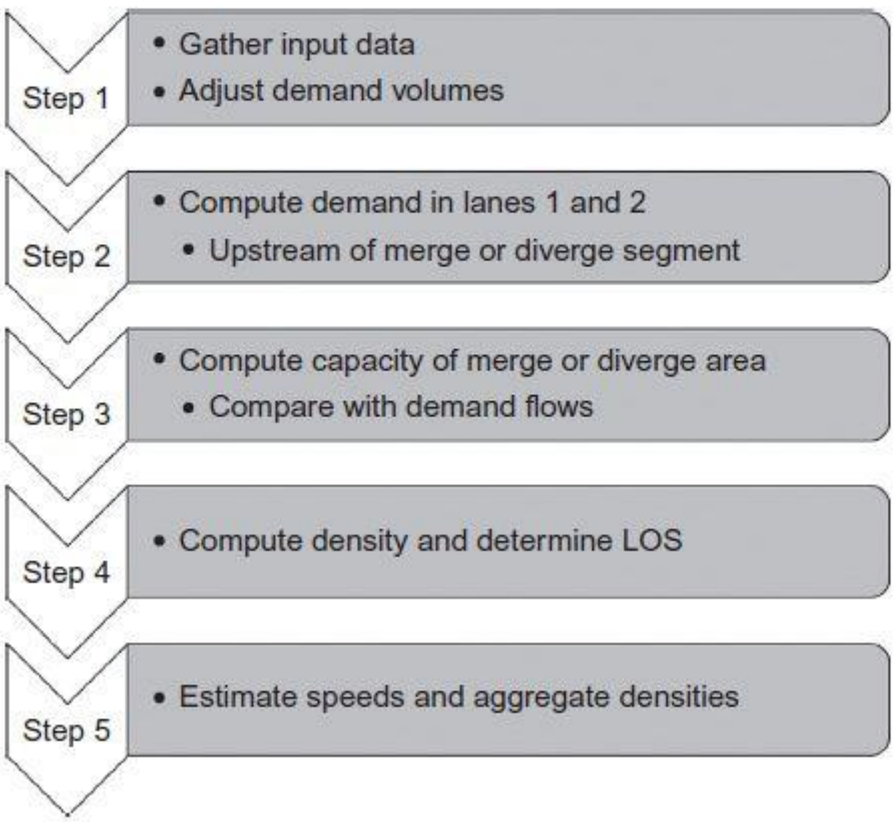

Figure: Methodology steps for merge/diverge analysis.

Step 1: Gather Input Data and Adjust Demand Volumes

In the HCM, merge and diverge segments are defined by a maximum ramp influence area (RIA) length of 1500 ft, measured downstream of the gore point at merges, or upstream of the gorge point for diverges. Outside of this 1500-ft RIA, research suggests that traffic has stabilized to where most of the merge/diverge turbulence has subsided, and the operations of the freeway again are categorized as a basic segment. The analysis focus in the HCM is further on the two rightmost lanes of the segment, plus the acceleration or deceleration lanes. Research has shown that typically any additional freeway lanes (i.e., the third or third and fourth lanes on six-lane or eight-lane freeways, etc.) show more stable flow conditions without the influence of on-ramp and off-ramp turbulence. Figure below illustrates the geometry of both merge and diverge segments, as well as the key traffic volume parameters in the form of the volume in the two rightmost lanes in the ramp influence area, V_{12}, and the volume on the on-ramp or off-ramp, V_R.

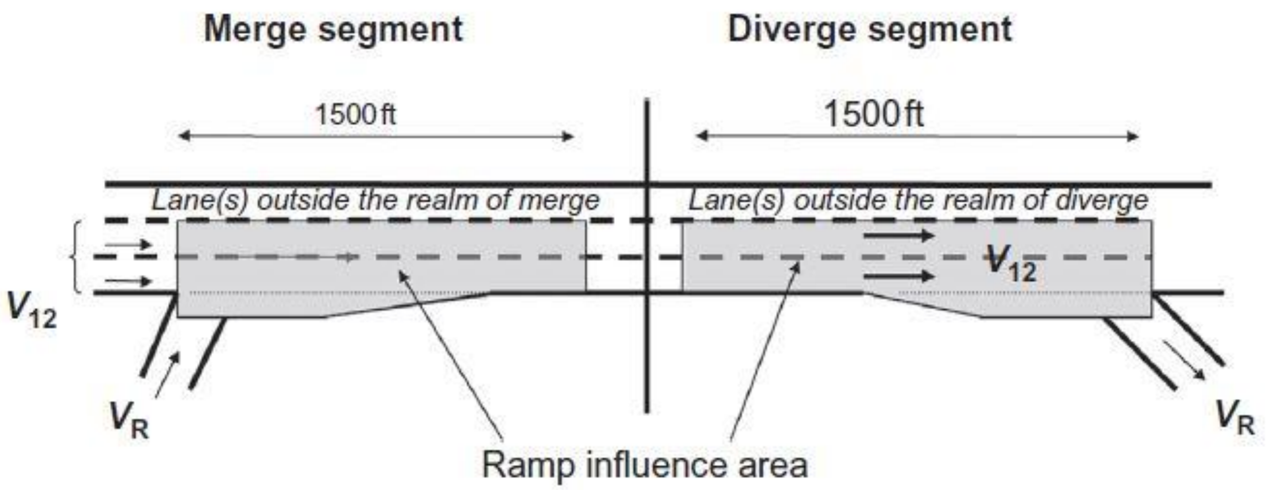

Figure: Schematic of merge and diverge segments.

In the first step, the entering hourly demand volume in vehicles per hour is converted to the peak 15-min low rate expressed in passenger cars per hour, as shown in Equation below.

$$v_f = \frac{V}{(PHF \times f_{HV})}$$

Where

V_f =peak 15-min flow rate on the freeway, in passenger cars/h.
V=directional analysis volume, in vph.
PHF=peak hour factor.
f_{HV} =heavy vehicle adjustment factor.
The heavy vehicle effects for merge and diverge segments mirror those described previously for basic segments.

Step 2: Compute Demand in Lanes 1 and 2

The second step in the procedure is to estimate the amount of traffic volume in lanes 1 and 2 of the merge and diverge segment. For a four lane freeway (two lanes per direction) the total demand by definition has to be the same as the demand in lanes 1 and 2. But for six-lane and eight-lane freeways, some portion of traffic is expected to be in the third and/or fourth lane, both presumed in the methodology to be unaffected by the merge/diverge turbulence.

The demand in lanes 1 and 2 is a function of the total freeway demand and the total flow on the ramp. It is also affected by the geometry of the ramp itself, namely by the length of the acceleration or deceleration lane, and the ramp's free-flow speed. Finally, the distribution of traffic across the lanes is impacted by the presence of upstream and downstream ramp. For example, a downstream on-ramp is expected to result in more traffic in lanes 1 and 2 (especially if closely spaced), as the prior on-ramp vehicles have not yet have had a chance to switch lanes into the outside lanes.
Similarly, downstream (closely spaced) off-ramps are expected to increase the flow in lanes 1 and 2 of the subject segment, as vehicles are likely to preposition in preparation for the downstream off-ramp. Mathematically, the flow rate in lanes 1 and 2 is calculated by multiplying the total entering flow rate (from step 1) by a factor describing the proportion of vehicles expected to be in lanes 1 and 2.

$$v_{12,merge} = v_F \times P_{FM}$$

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

Where:

v_{12}=estimated flow rate in lanes 1 and 2 of ramp influence area (passenger cars/h).
v_F =flow rate in all lanes of freeway just upstream of the merge or diverge (passenger cars/h).
PFM=proportion of freeway vehicles expected in lanes 1 and 2 of merge area (passenger cars/h).
PFD=proportion of freeway vehicles expected in lanes 1 and 2 of diverge area (passenger cars/h).

The equations used for estimating PFM for merge areas are given in Table below. In the case of six-lane freeways, multiple equations exist depending on the separation of the subject ramp and adjacent ramps. Guidance for which equations should be used is summarized in Table below.
Equation (1) refers to the base condition, or a merge area that is isolated from other ramps. Equations (2) and (3) then describe the cases where the subject ramp is impacted by an upstream off-ramp and a downstream off-ramp, respectively. The condition for whether the base equation or the adjusted equation is applied depends on the spacing between the two ramps. Specifically, if the distance between the two ramps is larger than or equal to a calculated equilibrium distance, L_{EQ}, then the isolated equation is used. For distances less

than L_{EQ}, the adjusted equations are used. No impacts for adjacent on-ramps have been found for adjacent on-ramps, and thus the base equation is always used in those cases.
In the special case where both an adjacent upstream off-ramp and downstream off-ramp are present and are located within the equilibrium distance, the P_{FM} is calculated twice, and the larger of the two values used in subsequent computations.

Table: Estimating proportion of traffic in lanes 1 and 2 for merge area.

Number of freeway lanes^a	Equations for determining PFM	Equation
4	$P_{FM} = 1.000$	
6	$P_{FM} = 0.5775 + 0.000028 L_A$	Equ. 1
	$P_{FM} = 0.7289 - 0.0000135(v_F + v_R) - 0.003296 S_{FR} + 0.000063 L_{UP}$	Equ. 2
	$P_{FM} = 0.5487 + 0.2628\left(v_D / L_{DOWN}\right)$	Equ. 3
	For $v_F / S_{FR} \leq 72$: $P_{FM} = 0.2178 - 0.000125 v_R + 0.01115(L_A / S_{FR})$	Equ. 4
8	For $v_F / S_{FR} \leq 72$: $P_{FM} = 0.2178 - 0.000125 v_R + 0.01115(L_A / S_{FR})$ For $v_F / S_{FR} > 72$: $P_{FM} = 0.2178 - 0.000125 v_R$	Equ. 5

Table Selecting equations for PFM for six-lane freeways.

Adjacent upstream ramp	Subject ramp	Adjacent downstream ramp	Equation(s) used as a function of separation distance between ramps, D
None	On	None	Equ. 1
None	On	On	Equ. 1
None	On	Off	Equ. 1 for $D \geq L_{EQ}$ Equ. 2 for $D < L_{EQ}$
On	On	None	Equ. 1
On	On	None	Equ. 1
Off	On	None	Equ. 1 for $D \geq L_{EQ}$ Equ. 2 for $D < L_{EQ}$
On	On	On	Equ. 1
On	On	Off	Equ. 1 for $D \geq L_{EQ}$ Equ. 3 for $D < L_{EQ}$
Off	On	On	Equ. 1 for $D \geq L_{EQ}$ Equ. 2 for $D < L_{EQ}$
Off	On	Off	Equ. 1 or Equ. 2 or Equ. 3

The equilibrium distances for merge areas are calculated from Eq. (6) for adjacent upstream off-ramps and Eq. (7) for adjacent downstream off-ramps. In general, if the distance between the subject ramp and the adjacent off-ramps is greater than or equal to the equilibrium distance, the subject ramp will be treated as isolated, and the base
Eq. (1) is used to estimate the flow in lanes 1 and 2. If the distance is less than LEQ, the respective adjusted equation is used.

$$L_{EQ,Merge,\ Upstream\ OFR} = 0.214(v_F + v_R) + 0.444L_A + 52.32S_{FR} - 2,403$$

Equ. 6

$$L_{EQ,\ Merge,\ Downstream\ OFR} = \frac{v_D}{0.1096 + 0.000107L_A}$$

Equ. 7

Where:
v_F =flow rate in all lanes of freeway just upstream of the merge (passenger cars/h).
v_R =flow rate on subject ramp (passenger cars/h).
v_D =flow rate on downstream ramp (passenger cars/h).
L_A=length of acceleration lanes (ft).
L_{UP}=distance to the adjacent upstream ramp (ft).
L_{DOWN}=distance to the adjacent downstream ramp (ft).
S_{FR}=ramp free-flow speed (mph).

The equations used for estimating P_{FD} for diverge areas are given in Table below. Similar as the case for merge areas, six-lane freeways have different equations describing the proportion of flow in lanes 1 and 2. Guidance for which equations should be used is summarized in below:

Table: Estimating proportion of traffic in lanes 1 and 2 for diverge area

Number of freeway lanes^a	Equations for determining PFM	Equation
4	$P_{FM} = 1.000$	n/a
6	$P_{FD} = 0.760 - 0.000025v_F - 0.000046v_R$ $P_{FD} = 0.760 - 0.000025v_F - 0.000046v_R$ $P_{FD} = 0.717 - 0.000039v_F + 0.604(v_U/L_{UP})$	Equ. 8 Equ. 9 Equ. 10
8	$P_{FD} = 0.436$	n/a

n/a= not applicable

Table: Selecting equations for PFD for six-lane freeways.

Adjacent upstream ramp	Subject ramp	Adjacent downstream ramp	Equation(s) used as a function of separation distance between ramps, D
None None None	Off Off off	None On Off	Equ. 8 Equ. 8, Equ. 1 Equ. 8 for $D \geq L_{EQ}$ Equ. 10 for $D < L_{EQ}$
On On	Off On	None None	Equ. 8 for $D \geq L_{EQ}$ Equ. 9 for $D < L_{EQ}$ Note: when v_u/L_{up} <=0.2, always Equ. 8
Off On	Off Off	None On	Equ. 8 Equ. 8 for $D \geq L_{EQ}$ Equ. 9 $D < L_{EQ}$ Note: when v_u/L_{up} <=0.2, always Equ. 8
On	Off	Off	Equ. 8 or Equ. 9 or Equ. 10
Off Off	Off Off	On Off	Equ. 8 for $D \geq L_{EQ}$ Equ. 9 for $D < L_{EQ}$

Equation (8) refers to the base condition, or a diverge area that is isolated from other ramps. Equation (8) is used when there is an adjacent on-ramp upstream of the subject diverge segment, while Eq. (9) is used when a downstream off-ramp is present. Similar to merge areas, the condition for whether the base equation or the adjusted equation is applied, depends on the spacing between the two ramps. Specifically, if the distance between the two ramps is larger than or equal to a calculated equilibrium distance, L_{EQ}, then the isolated equation is used. For distances less than L_{EQ}, the adjusted equations are used.
In the special case where both an adjacent upstream on-ramp and downstream off-ramp are present and are located within the equilibrium distance, the P_{FD} is calculated twice, and the larger of the two values used in subsequent computations.

The equilibrium distances for diverge areas are calculated from Eq. (10) for adjacent upstream on-ramps and Eq. (11) for adjacent downstream off-ramps. In general, if the distance between the subject ramp and the adjacent ramp is greater than or equal to the equilibrium distance, the subject ramp will be treated as isolated, and the base Eq. (8) is used to estimate the flow in lanes 1 and 2. If the distance is less than LEQ, the respective adjusted equation is used.

$$L_{EQ,\ Diverge,\ Upstream\ ONR} = \frac{v_U}{0.071 + 0.000023 v_F - 0.000076 v_R}$$ Equ. 11

$$L_{EQ,\ Diverge,\ Downstream\ OFR} = \frac{v_D}{1.15 - 0.000032 v_F - 0.000369 v_R}$$ Equ. 12

Where
v_F =flow rate in all lanes of freeway just upstream of the merge (passenger cars/h).
v_R =flow rate on subject ramp (passenger cars/h).
v_U =flow rate on adjacent upstream ramp (passenger cars/h).
v_D =flow rate on adjacent downstream ramp (passenger cars/h).
L_{UP}=distance to the adjacent upstream ramp (ft).
L_{DOWN}=distance to the adjacent downstream ramp (ft).

As a final check in step 2, the analyst should verify the reasonableness in the lane distribution arrived at from above Tables, as the underlying regression equations may sometimes predict values outside the calibrated and reasonable range. Specifically, the following two limitations are applied to all predictions of flow rates in lanes 1 and 2:

1. The average flow in the outer lanes (lanes 3 and 4) has to be less than or equal to 2700 passenger cars/h per lane.
2. The average flow per lane in the outer lanes has to be less than or equal to 1.5 times the average flow per lane in lanes 1 and 2.

If these conditions do not hold, special adjustments are needed. For six-lane and eight-lane freeways, if condition 1 is violated, an adjusted v_{12}, adjusted is calculated as shown in the following:

$$v_{12,adj,six-lane} = v_F - 2700$$

$$v_{12,adj,eight-lane} = v_F - 5400$$

Similarly, if condition 2 is violated, the adjusted flow in lanes 1 and 2 is calculated as:

$$v_{12,adj,six-lane} = \left(\frac{v_F}{1.75}\right)$$

$$v_{12,adj,eight-lane} = \left(\frac{v_F}{2.50}\right)$$

Step 3: Compute Capacity of Merge or Diverge Area

With the flow in lanes 1 and 2 determined, the capacity of the merge or diverge area is estimated, and that capacity is compared to the predicted demand flows. In particular, capacity is estimated (and checked against demands) for three different components:

1. The capacity of the ramp roadway itself2. The capacity of the freeway entering or exiting the merge or diverge area.
2. The maximum flow rate of the freeway entering the merge or diverge area, which in the case of a merge area constitutes the sum of mainline and on-ramp demands.

The capacities of ramp roadways as a function of the ramp free-flow speed are shown in Table below.

Table: Capacity of ramp roadways.

Ramp FFS S_{FR} (mph)	Single-lane ramps
>50	2200
>40–50	2100
>30–40	2000
≥ 20–30	1900
<20	1800

The capacity of the freeway segment upstream or downstream of the merge/diverge area, as well as the maximum desirable entering flow rates, are shown in Table below for freeways,

Table: Capacity and maximum flow rates for freeway merges and diverges.

FFS (mph)	Capacity of upstream or downstream freeway segment (per lane)	Maximum desirable flow rate (v_{R12}) entering merge influence area	Maximum desirable flow rate (v_{12}) entering diverge influence area
≥ 70	2400/ln	4600	4400
65	2350/ln	4600	4400
60	2300/ln	4600	4400
55	2250/ln	4600	4400

And in Table below used for multilane highways and ramps on collector-distributor (C-D) roadways. In these two tables, it is emphasized that demands exceeding the shown capacities result in LOS5F, while demands exceeding the shown maximum desirable flow rates merely indicate that the conditions in the merge or diverge area are likely to be undesirable and worse than predicted by the HCM method.

Table: Capacity and maximum flow rate for multilane highways and C-D roads.

FFS (mph)	Capacity of upstream or downstream highway or C-D segment (per lane)	Maximum desirable flow rate (v_{R12}) entering merge influence area	Maximum desirable flow rate (v_{12}) entering diverge influence area
≥ 60	2200/ln	4600	4400
55	2100/ln	4600	4400
50	2000/ln	4600	4400
45	1900/ln	4600	4400

Similar to basic freeway segments, the capacity of merge or diverge areas can be adjusted for the impacts of weather, incidents, and work zones, as well as to calibrate the segment capacity to local conditions. The capacity adjustment factor (CAF) approach and adjustment factors for this are the same as described previous for basic segments.

The capacity values determined in step 3 of the merge/diverge procedure are used to check the demand volumes against. If any demands (ramp, upstream segment, or downstream segment) exceed the capacity, the LOS for the merge or diverge segment is F and no further speed and density estimation is possible. Instead, a freeway facility analysis should be conducted to estimate queuing upstream of the merge/diverge bottleneck.

If the demand exceeds the maximum desirable flow rate entering the ramp influence area, the LOS is not necessarily F, but performance may be worse than predicted by the methodology. In that case, a freeway facility analysis is again recommended to check for queuing impacts.

Step 4: Compute Density and Determine LOS

Assuming the various segment demands pass all capacity checks, the density of the merge or diverge influence area can be calculated using Equations below for merge and diverge segments, respectively.

From these densities, the LOS of the merge or diverge segment can be determined from Table below. LOS F is defined as demand exceeding capacity for either the ramp itself, the segment upstream of the merge/ diverge, or the downstream segment.

Table: LOS for merge or diverge segment.

LOS	Density (passenger cars/mi per lane)
A	≤ 10
B	$>10-20$
C	$>20-28$
D	$>28-35$
E	>35
F	Demand exceeds capacity

Step 5: Estimate Speeds and Aggregate Densities

The final step in the methodology is to estimate the speeds. Speeds can be estimated in lanes 1 and 2 of the ramp influence area, as well as in the outer lanes, separately. While the primary analysis focus in this methodology is on the ramp influence area, speeds in the outer lanes may be of interest, especially if evaluating a merge/diverge segment in the context of a freeway facility. The two speeds are estimated separately, and can further be aggregated to a total average segment speed. The latter can be used to obtain an aggregated density across the entire segment (note that the step 4 density applies only for lanes 1 and 2 and the acceleration or deceleration lanes). The equations for the various speeds in merge and diverge segments are given in Table below. In the table, SAF refers to a speed adjustment factor to account for impacts of weather, incidents, work zones, or local calibration.

Table: Speed estimation for merge and diverge areas.

Segment type	Average speed in	Equation	Condition
Merge	Ramp influence area	$S_R = FFS \times SAF - (FFS \times SAF - 42)M_S$, where $M_S = 0.321 + 0.0039e^{(v_{R12}/1,000)} - 0.002(L_A \times S_{FR} \times SAF/1000)$	
	Outer lanes of freeway	$S_O = FFS \times SAF$	$v_{OA} < 500$passenger care/h
		$S_O = FFS \times SAF - 0.0036(v_{OA} - 500)$	$500 \leq v_{OA} \leq 2300$passenger car/h
		$S_O = FFS \times SAF - 6.53 - 0.006(v_{OA} - 2300)$	$v_{OA} > 2300$passenger car/h
Diverge	Ramp influence area	$S_R = FFS \times SAF - (FFS \times SAF - 42)D_S$, where $D_S = 0.883 + 0.00009v_R - 0.013S_{FR} \times SAF$	
	Outer lanes of freeway	$S_O = 1.097 \times FFS \times SAF$	$v_{OA} < 1000$ passenger car/h
		$S_O = 1.097 \times FFS \times SAF - 0.0039(v_{OA} - 1000)$	$v_{OA} \geq 1000$ passenger car/h

The default values for SAF are the same as were shown for basic segments With the speeds in the ramp influence area and the outside lanes estimated, the combined average segment speed can be estimated as the weighted average speed across all lanes. To do this, we need to first calculate the volume in the outside two lanes, which is estimated from Eq. below:

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

Where:

v_{12}=demand flow rate in lanes 1 and 2 of the freeway immediately upstream of the ramp influence area (passenger cars/h).

v_{OA} =average demand flow per lane in outer lanes adjacent to the ramp influence area (not including flow in lanes 1 and 2) (passenger cars/h per lane).

v_F =demand flow rate on freeway immediately upstream of the ramp influence area (passenger cars/h).

N_O=number of outer lanes on the freeway (1 for a six-lane freeway; 2 for an eight-lane freeway) from this, the aggregated speed in a merge or diverge area is estimated from Eqs. Below, respectively.

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

$$S = \frac{v_{12} + v_{OA}N_O}{\left(\frac{v_{12}}{S_R}\right) + \left(\frac{V_{OA}N_O}{S_O}\right)}$$

Where:

S_R =average speed of vehicles within the ramp influence area (mph); for merge areas, this includes all ramp and freeway vehicles in lanes 1 and 2; for diverge areas, this includes all vehicles in lanes 1 and 2.

S_O=average speed of vehicles in outer lanes of the freeway, adjacent to the 1500-ft ramp influence area (mph).

S=average speed of all vehicles in all lanes within the 1500-ft length covered by the ramp influence area (mph).

v_{12}=demand flow rate in lanes 1 and 2 of the freeway immediately upstream of the ramp influence area (passenger cars/h).

v_{R12}=total demand flow rate entering the on-ramp influence area, including v12 and vR (passenger cars/h).

v_{OA} =average demand flow per lane in outer lanes adjacent to the ramp influence area (not including flow in lanes 1 and 2) (passenger cars/h per lane).

NO=number of outer lanes on the freeway (1 for a six-lane freeway; 2 for an eight-lane freeway).

If the merge or diverge segment is to be used in the context of a freeway facility analysis, one last step is the aggregation of densities across all lanes on the freeway. With the total volume and average speed known, the best way to estimate density is to use the fundamental relationship of traffic flow as shown in Eq. below:

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

Where:

D=density including all lanes of the ramp influence area (passenger cars/mi per lane).

V=total flow rate through the merge or diverge area, all lanes (passenger cars/h per lane).

S=average speed of all vehicles through the merge/diverge area, all lanes (mph).

The level of service for a merge or diverge segment is then obtained from table below:

Table: LOS for merge and diverge segments.

Level of service	Density range (passenger cars/mi per lane)
A	≤10
B	>10–20
C	>20–28
D	>28–35
E	>35
F	Demand exceeds capacity

2. Weaving Segments

A typical freeway weaving segment is formed when an on-ramp is followed by a downstream off-ramp, and the two ramps are connected by an auxiliary lane. In this configuration, turbulence is created from onramp traffic merging into the freeway mainline, while off-ramp traffic diverges from the mainline to the off-ramp. The two ramp flows (cross-) weave, which can result in significant reductions in speed. Additionally, some on-ramp traffic may be destined for the downstream off-ramp, and thus may not change lanes at all.
Many other variations of weaving segments exists, including those with multilane on-ramps and/or multilane off-ramps. There are also two-sided weaving segments, where the on-ramp and off-ramp are located on opposite sides of the freeway mainline. But in all cases, the operations of the weaving segment are impacted by a few key variables:

- The number of lane changes taking place, which is primarily a function of the varying movement demands and the lane geometry.
- The number of lanes available for those lane changes.
- The length of the weaving segment, or the distance over which these lane changes have to occur.

The HCM methodology for weaving segments estimates the parameters just mentioned and translates the various inputs into a number of lane changes per mile. This measure is then translated to varying performance measures, including speed, density, and LOS.

2.1 Methodology

The HCM weaving methodology consists of eight basic steps that are illustrated in Figure below. Each step is discussed in more details in the following.

Step 1: Gather Input Data and Adjust Demand Volumes

The first step in every methodology is gathering input data. For the weaving method, the input data are fundamentally divided between geometric data describing the weaving segment, and demand data. The following geometric data are needed:

- Number of lanes in the weaving segment, counting the auxiliary lane.
- Short length of the weaving segment (in feet), defined as the distance from ramp gore point at the on-ramp to the gore point at the off-ramp.
- Location of ramps on the segment, which could be either on the left or right side of the segment.
- Number of required lane changes from ramp to freeway, from freeway to ramp, and from ramp to ramp, which are used to eventually determine total lane change rates. With an increasing number of required lane changes, the turbulence in the weave segment is expected to increase and operations to deteriorate.

- Number of weaving lanes defined as the number of lanes from which a weaving movement can be completed with zero or one lane change. The number of weaving lanes, NWL, essentially describes how many lanes are available for the weaving maneuver, with a higher NWL resulting in improved performance.
- Interchange density in units of interchanges per mile.
- Terrain type, classified as either level, rolling, or a specific grade to account for truck effects.
- Equivalent capacity of a basic segment, which is used as an anchor point in the methodology to estimate the weave segment capacity.

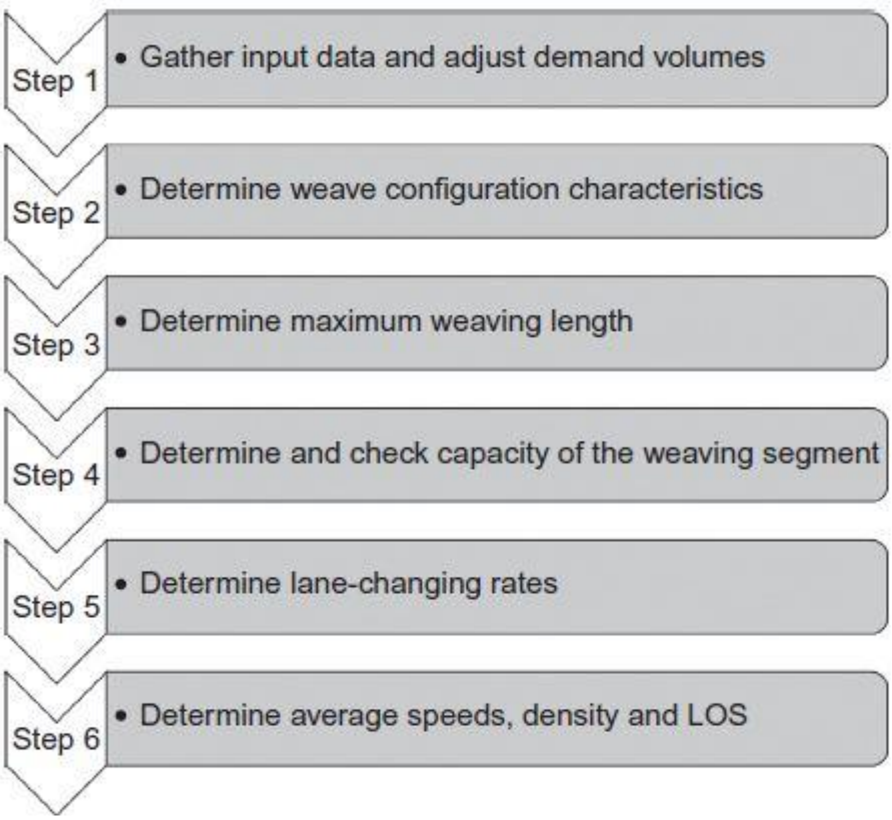

Figure: Methodology steps for weaving methodology.

In addition to these geometric inputs, several demand inputs are needed, including hourly demands on the mainline, on-ramp, off-ramp, and the specific demand from on-ramp to off-ramp. As with other operational methods, peak hour factor and heavy vehicle adjustments are needed to convert volumes in vehicles per hour to hourly flow rates in passenger car units. The volume conversion is identical to the process used for merge/diverge segments shown before.
Finally calibration factors in the form of speed and capacity adjustment factors (SAF and CAF) can be used as calibration tools to match the methodology to locally observed conditions.

Step 2: Determine Weave Configuration Characteristics

The weave methodology is fundamentally tied to the configuration of the weaving segments. The two key parameters are the minimum number of lane changes needed in the weaving segment, L_{C} min, and the number of weaving lanes, N_{WL}, which describe in essence how many lanes are available to complete the weaving maneuvers. The number of weaving lanes is defined as the number of lanes from which a weaving segment can be completed with zero or one lane change, resting on the assumption that this is where most weaving vehicles are likely to be positioned to complete their weaving maneuvers.
The minimum number of lane changes is a simple summation of the lane changes needed for each of the weaving movements multiplied by its corresponding flow rate, as given in:

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

Where

L_{CRF}=the minimum number of lane changes for a vehicle to move from the on-ramp to the freeway mainline.
L_{CFR}=the minimum number of lane changes for a vehicle to move from the freeway mainline to the off-ramp.
v_{RF} =the flow rate from ramp to freeway (passenger cars/h).
v_{FR} =the flow rate from freeway to ramp (passenger cars/h).

The estimation of L_{CRF} and L_{CFR} emerges from the geometric configuration of the weaving segment as illustrated in Figure below. Part (a) of the figure shows a very common ramp weave with four lanes in the weaving segment. The number of lane changes from ramp to freeway and from freeway to ramp are each one. The number of weaving lanes is two, as for both of the two outside lanes a weaving movement can be completed with zero or one lane change as indicated by the dashed and dotted arrows.
Figure below (b) illustrates a more complicated weaving segment. Here the ramp-to-freeway movement needs to complete two lane changes, while the freeway-to-ramp movement actually does not need to make any lane changes. Further, the number of weaving lanes is three, as all three outside lanes meet the definition. For this particular weaving segment, it becomes very evident how the configuration alone does not fully predict the operations. In fact, the example shown in Figure below (b) may function very well if the freeway-to-ramp volume is heavy and the ramp to freeway volume is low. But if the two flows are reversed, the expected operations are worse worse, as equation above predicts more lane changes and therefore more turbulence in the segment.

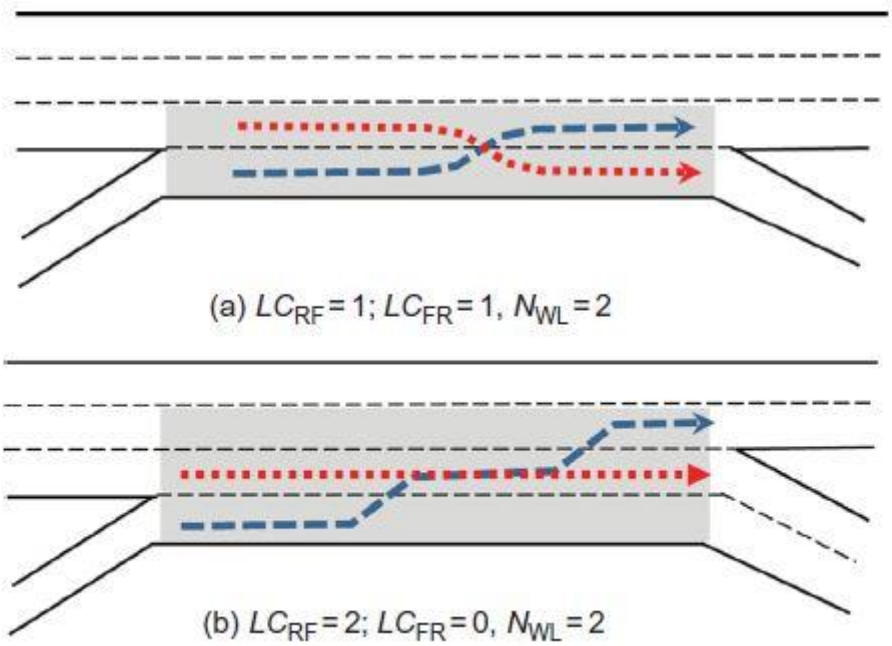

Figure: Illustrative example of weave configuration.

Step 2 is similar for two-sided weaving segments, with two exceptions. First, only the (left-to-right or right-to-left) ramp-to-ramp flow is considered to be a weaving maneuver, simplifying the computation of the minimum lane changes as shown in Eq. below. Second, the number of weaving lanes is always defined to be zero for a two-sided weave, regardless of the number of lanes on the mainline. Presumably, this is because the weaving maneuver always needs to make more than one change when weaving from an on-ramp on one side to an off-ramp on the opposite site, given that freeways typically have two or more mainline lanes.

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

Where

LC_{RR}=the minimum number of lane changes for a vehicle to move from the on-ramp to the off-ramp on the opposite side of the freeway.

v_{RF} =the flow rate from on-ramp to off-ramp (passenger cars/h).

Step 3: Determine Maximum Weaving Length

The next step in the methodology is to determine the maximum length of the weaving segment, which conceptually is the length at which the resulting weaving maneuvers no longer result in any reduction in performance of the segment, as compared to a basic segment. In other words, the weaving turbulence is negligible relative to the overall segment operations. Essentially then, this step checks if the segment in fact operates as a weave, or if it is so long that it should simply be analyzed as a basic segment. The maximum weaving length is calculated from equation below:

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

Where
L_{MAX} = maximum weaving segment length (feet).
VR = volume ratio, which is calculated from Eq. below.
N_{WL} = number of weaving lanes as defined previously.

The volume ratio is calculated as the volume of weaving vehicles to the total number of vehicles on the segment as shown in Equation below:

$$VR = \frac{v_W}{v_{total}} = \frac{v_W}{v_W + v_{NW}} = \frac{v_{RF} + v_{FR}}{v_{RF} + v_{FR} + v_{FF} + v_{RR}}$$

Where
v_W= weaving demand flow rate in the weaving segment (passenger cars/h), vW5vRF1vFR
v_{NW}= nonweaving demand flow rate in the weaving segment (passenger cars/h),
$v_{NW} = v_{FF} + v_{RR}$

The maximum weaving length increases with an increase in the volume ratio, which is intuitive as a higher volume ratio means more turbulence and therefore a higher maximum length limit. The maximum weaving length decreases with a greater number of weaving lanes, as more space is available for a given number of lane changes. This effect is illustrated in Figure below. In the procedure, if the short length of the weaving segment, Ls, is greater than the maximum weaving length, the analysis should stop and the segment instead be analyzed as a basic segment.

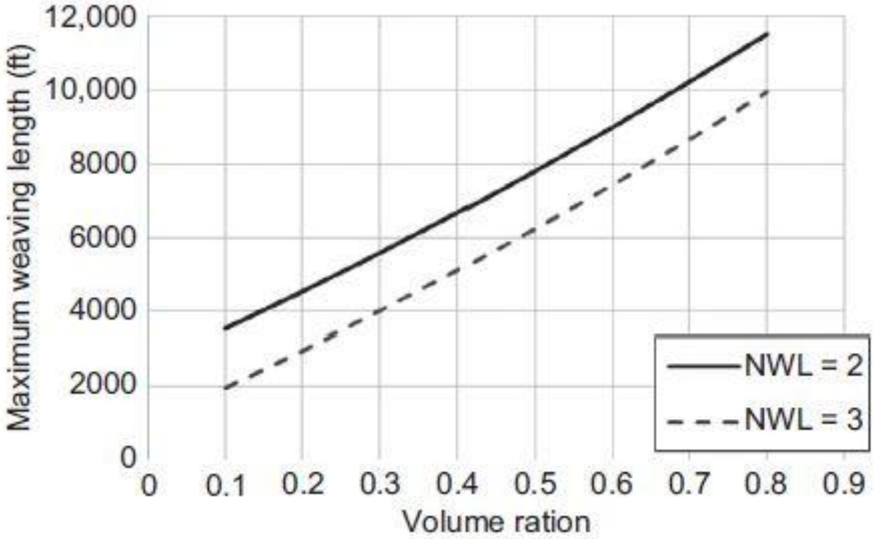

Figure: Illustration of maximum weaving length.

Step 4: Determine and Check the Capacity of the Weave Segment

Next, the capacity of the weaving segment is checked using two different definitions. The first definition is based on density, and defines capacity as the segment reaching a density of 43 passenger cars/mi per lane, which is also the LOS E-F boundary for weaving segments. The second definition is based on weaving demand flows, which recognizes that at some point there are simply too many lane changes to be accommodated in the available number of weaving lanes.

For the first definition, the capacity is estimated from Figure:

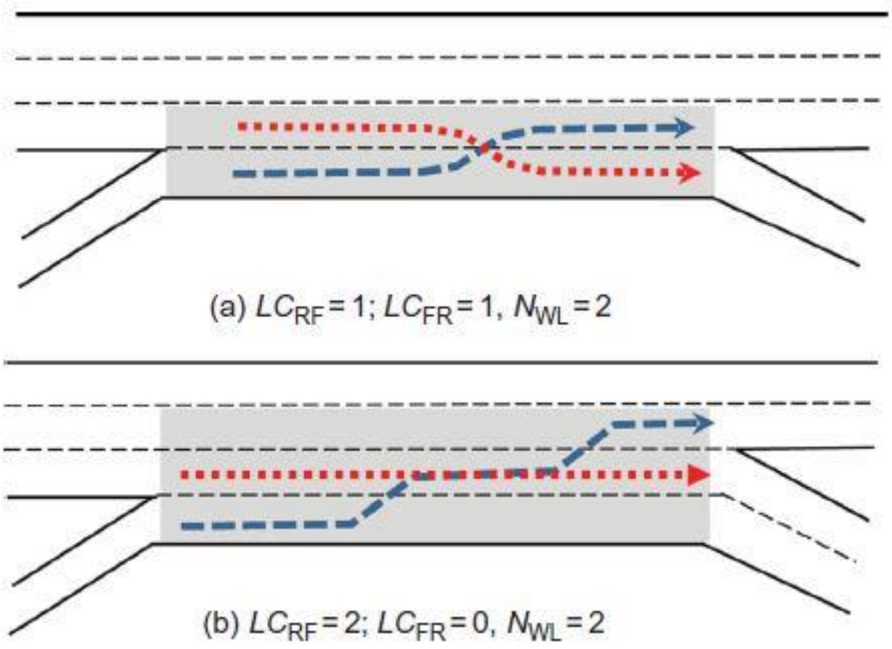

Figure: Illustrative example of weave configuration.

$$c_{IWL} = c_{IFL} - [438.2(1+VR)^{1.6}] + [0.0765L_S] + [119.8N_{WL}]$$

Where:

c_{IWL} =capacity of the weaving segment under ideal conditions, per lane (passenger cars/h per lane)

c_{IFL}=equivalent capacity of a basic freeway segment with the same FFS as the weaving segment under ideal conditions, per lane (passenger cars/h per lane)

L_s=the short length of the weaving segment measured from gore to gore (ft).

(All other variables are as previously defined)

The capacity of the weaving segment mentioned decreases with an increasing volume ratio (larger negative number subtracted from base), and increases with more available space for weaving, either in terms of segment length, or in terms of the number of weaving lanes. When comparing this capacity under prevailing conditions (in units of passenger cars/h per lane), back to total volume inputs (in veh/h), it needs to be converted back using Eq.:

$$c_W = c_{IWL} \times N \times f_{HV}$$

Where:

c_w=capacity of the weaving segment under prevailing conditions, (veh/h)
N=number of lanes in the weaving segment
f_{HV}=heavy vehicle flow rate adjustment factor, which is the inverse of equation:

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

where

v_p = flow rate, in passenger cars/h per lane
V = directional analysis volume, in vph
PHF = peak hour factor
N = number of lanes in the direction of travel
f_{HV} = heavy vehicle adjustment factor

Also another definition of capacity is used in this methodology, which essentially limits capacity by the maximum weaving demand flows that can realistically be accommodated in the segment. This limiting condition is shown in Eq. below:

$$c_{IW} = \begin{cases} \dfrac{2400}{VR} \text{for } N_{WL} = 2 \text{ lanes} \\ \dfrac{3500}{VR} \text{for } N_{WL} = 3 \text{ lanes} \end{cases}$$

Where:

c_{IW} =the capacity across all lanes in units of passenger cars/h.
(All other terms are as defined previously)

Similar to the first condition, this capacity under prevailing conditions (across all lanes, but in units of passenger cars/h) needs to be converted to a capacity under ideal conditions (in veh/h) by multiplying by the heavy vehicle adjustment factor as shown in Eq. below:

$$c_W = c_{IW} \times f_{HV}$$

With these two capacities, the analyst compares the total volume to the total capacity in the segment. Both terms should be in the same units (passenger cars/h) to assure a valid comparison. In addition, the capacity could be calibrated for local conditions, or to reflect the impact of rain or incidents, by first multiplying the capacity with a capacity adjustment factor (CAF) as was described in previous Section for basic segments.
If the volume exceeds capacity, the analysis stops, and the analyst should instead refer to the freeway facilities methodology to evaluate the (congested) weaving segment and any queue spillback issues resulting from the overcapacity segment.

Step 5: Determine Lane Changing Rates

This step is the key computational step in the methodology, in which lane-changing rates (in units of lane changes per mile) are estimated, with the underlying premise that more lane changes result in more turbulence, and thus generally degraded performance.

Lane changes in a weaving segment fall into three categories:

- Lane changes required by weaving vehicles to continue on their desired path.
- Optional lane changes by weaving vehicles, which considers the fact that not every vehicle is correctly prepositioned when entering the segment.
- Optional lane changes by nonweaving vehicles to, for example, merge to the left to avoid the weave turbulence area to the right.

The number of required plus optional lane changes by weaving vehicles (1 and 2 in the list) is estimated from Eq. below:

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

Where

L_{CW}=hourly rate at which weaving vehicles make required lane changes within the weaving segment (lane change/h)
LC_{MIN}=minimum hourly lane change rate within the weaving segment for required lane changes from step 2 (lane change /h)
LS=short length of the weaving segment, which is constrained to be greater than or equal to 300 ft in this equation (ft)
N=number of lanes in the segment
ID=interchange density, the number of interchanges within 3 mi upstream and downstream of the center of the subject weaving segment divided by 6, in interchanges per mile (interchanges/mi).

Conceptually, the first term of previous Eq. represents the required lane changes, while the second represents the optional lane changes. Optional lane changes increase with increasing segment length, more lanes, and increasing interchange density. The last term accounts for the fact that lane changes are generally more frequent with more upstream and downstream interchanges, as is often the case in urban areas.

In addition, the lane-changing rate for nonweaving vehicles has to be estimated. A total of three equations exist for this, describing different flow regimes distinguished by an index term shown in Eq. below:

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

This index is calculated first as a function of segment length, interchange density, and the nonweaving vehicle volume as summarized in Table below.

As a final boundary condition, if LC_{NW2} is greater than or equal to LC_{NW1}, then LC_{NW2} is used as the final lane change rate for nonweaving vehicles. The total lane change rate in the weaving segment is the sum of weaving vehicles (from previous and nonweaving vehicles (from Table below), as shown in Eq. below:

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

<u>Table:</u> Estimating lane change rates for nonweaving vehicles.

Equations for determining LCNW	Equation
$LC_{NW1} = (0.206 v_{NW}) + (0.542 L_S) - (192.6N)$	Equ. 1
$LC_{NW2} = 2135 + 0.223(v_{NW} - 2000)$	Equ. 2
$LC_{NW3} = LC_{NW1} + (LC_{NW2} - LC_{NW1})\left(\frac{I_{NW} - 1300}{650}\right)$	Equ. 3

Step 6: Determine Average Speeds, Density, and LOS

The average speeds in the weaving segment are determined under consideration of the speed of weaving and the speed of nonweaving vehicles. First, the speed of weaving vehicles is estimated from Eqs below:

$$S_W = 15 + \left(\frac{FFS \times SAF - 15}{1 + W}\right)$$

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

Where

S_W=average speed of weaving vehicles within the weaving segment (mph).
W=weaving intensity factor.
(All other terms are as defined previously).

Note that the weaving intensity factor takes the total number of required and optional lane changes, and scales them by the segment length to essentially get an entity in units of lane changes per foot of length in the segment. Intuitively, a higher weaving intensity factor corresponds to more lane changes per distance, which can be thought of as a measure of lane change density across the segment.

The speed of nonweaving vehicles is estimated from Eq. below as a function of free-flow speed, number of lane changes, and the total volume per lane.

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

The total average space mean speed on the segment is obtained from Eq. below, mirroring the procedure for merge/diverge segments:

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

The density of the segment is then estimated from equ. below:

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

That density is in conjunction with Table below to determine the LOS for the weaving segment.

Table: LOS for weaving segments.

Level of service	Density range (passenger cars/mi per lane)
A	0–10
B	>10–20
C	>20–28
D	>28–35
E	>35–43
F	>43, or demand exceeds capacity