Uninterrupted Flow

1. Definition

Uninterrupted flow represents travel on facilities without at-grade intersections and traffic control devices that stop traffic to control movement priority. The interstate system consists of uninterrupted flow facilities and segments, with freeways being generally access controlled and entering or exiting traffic processed through grade-separated interchanges. Uninterrupted flow conditions also apply to two-lane or multilane highway segments, if they are outside of the influence of traffic signals or other traffic control devices, typically at distances greater than 2 mi or 3.2 km.

2. Concepts

The operations and performance of uninterrupted flow is generally governed by the interaction of vehicles or, more specifically, their drivers. Uninterrupted flow facilities typically do not have traffic control devices to control traffic flow at junctions, but rather process entering and exiting traffic at grade-separated ramps at interchanges. These interchanges can represent bottlenecks or choke points on the freeway system, as turbulence due to lane-changing, merging, and weaving maneuvers reduces the capacity relative to a "basic" freeway segment.

3. Access Control and Interchange Operations

Uninterrupted flow facilities are access controlled, meaning that any traffic entering or exiting the freeway does so through grade-separated ramps at interchanges. The operational maneuver performed at these on-ramp or off-ramp locations are described as either merging or diverging, respectively.

Often, these merge and diverge maneuvers occur at high speeds, and therefore function very differently from signalized intersections. There are a variety of types of interchanges that all differ in their operational patterns, and can range widely in their capacities and ability to handle specific traffic maneuvers. Interchanges represent junctions between interrupted and uninterrupted flow, but are generally treated as interrupted flow, except for the merge and diverge points. In other words, the bottom ends of the on-ramps and off-ramps where traffic merges with or diverges from freeway traffic are treated as uninterrupted flow, while the top of the ramps (where traffic may, for example, turn left at a signalized intersection or roundabout to get to the on-ramp) are treated as interrupted flow.

4. Flow Regimes on Uninterrupted Flow Facilities

At low traffic volumes, the flow on uninterrupted facilities is governed by the prevailing speed limit, but has also been shown to be influenced by geometric conditions on the facility, including lane widths and shoulder clearances. The desired speed by drivers at these low flow conditions, also referred to as the free-flow speed, is a function of these geometric attributes and the level of comfort of drivers to travel at such speed. Traffic flow under low-volume conditions is thus less impacted by vehicle-to-vehicle interaction (as there aren't many cars), and more by the geometric attributes and "feel" of the roadway.

As traffic flow increases, the interaction of vehicles begins to govern the operations on the facility. Eventually, the density on the facility increases to a point where speeds begin to drop, as drivers are no longer comfortable maintaining high speeds with the now limited maneuver space (recall the discussion of spacing and. Eventually, traffic flow conditions reach the maximum sustainable flow rate before reaching breakdown conditions, which is referred to as the capacity. The flow regime between free flow and capacity is also referred to as undersaturated or uncongested flow.

If traffic demand continues to increase and exceeds the available capacity, breakdown occurs, where the flow becomes unstable and congested. The results are continually increasing densities and decreasing speeds, which are associated with a decrease in throughput as vehicles are queuing upstream of the bottleneck point. Theoretically, traffic densities can increase up to a point where vehicles are literally spaced "bumper to bumper" and traffic flow and speeds approach zero. The flow regime between capacity and this jam density is also referred to as the oversaturated or congested flow.

The various flow regimes on an uninterrupted flow facility are illustrated in Figure below. The figure shows free-flow conditions at low flow rates, and prebreakdown (but still stable) conditions as traffic volumes increase. The free-flow regime shows a fixed speed as volumes increase, while the prebreakdown regime exhibits a steady decrease in speed as the flow approaches capacity.

The queue discharge flow regime typically occurs downstream of a bottleneck, where traffic begins to discharge from a queue. It is noted that the queue discharge flow rates are lower than the capacity value. This is commonly observed, and research has shown that the average

queue discharge flow rate is approximately 7% lower than the prebreakdown capacity (Hu et al., 2012), but with some facilities showing drops in throughput on the order of 20% when transitioning from prebreakdown flow to queue discharge.

The final flow regime in Figure below, congested flow, represents flow in a queue upstream of a bottleneck. As is evident in the figure, the speeds and flow rates in this regime are much deteriorated relative to the other regimes.

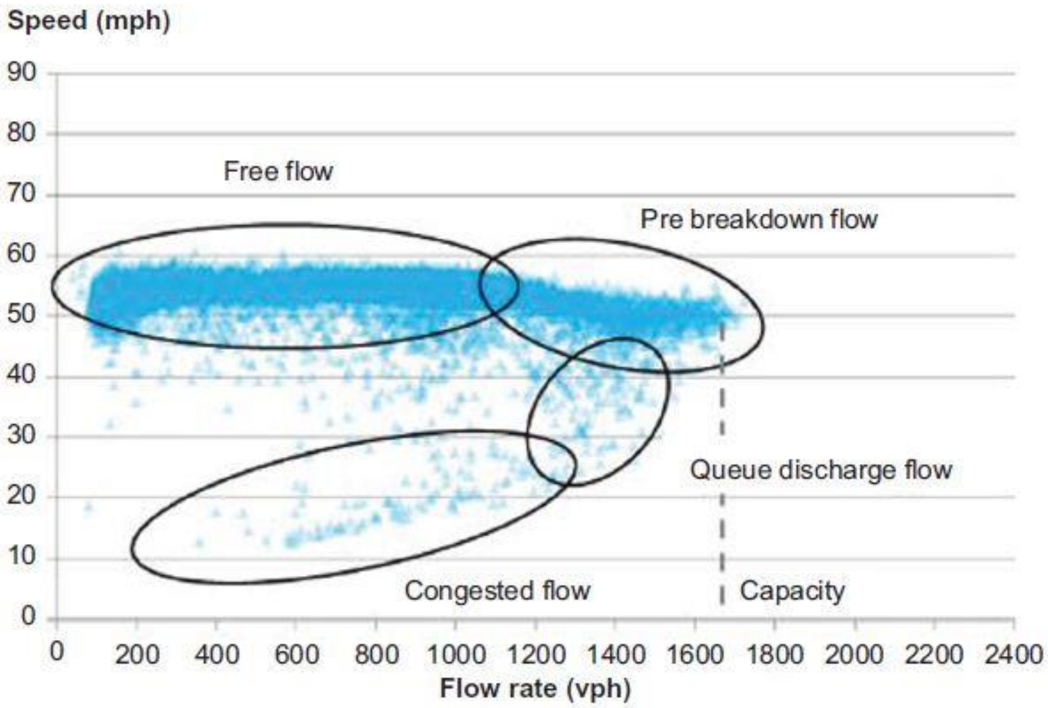

Figure: Freeway speed-flow data example.

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The final flow regime in Figure above, congested flow, represents flow in a queue upstream of a bottleneck. As is evident in the figure above, the speeds and flow rates in this regime are much deteriorated relative to the other regimes.

5. Terminology

The following list introduces several key terms that will be used throughout the section on uninterrupted flow.

- Prebreakdown capacity (veh/h): The maximum sustainable flow rate on a freeway that can be achieved without the facility breaking down and transitioning to congested flow.
- Queue discharge rate (veh/h): The flow rate immediately following breakdown as traffic discharges from a queued freeway segment. The queue discharge rate is typically less than the prebreakdown capacity, by an average of approximately 7%.
- Jam density (veh/mi): The maximum achievable density on a freeway, corresponding to essentially stand, still conditions. The jam density is the inverse of the minimum spacing between vehicles.
- Free-flow speed (mph): The speed of vehicles at low-volume conditions, impacted only by the geometry of the facility (and the speed limit), but without any speed-reducing effects due to traffic interaction.
- Speed-flow curve: A mathematical formula (or series of formulas) describing how speed changes as a function of increasing flow rates.

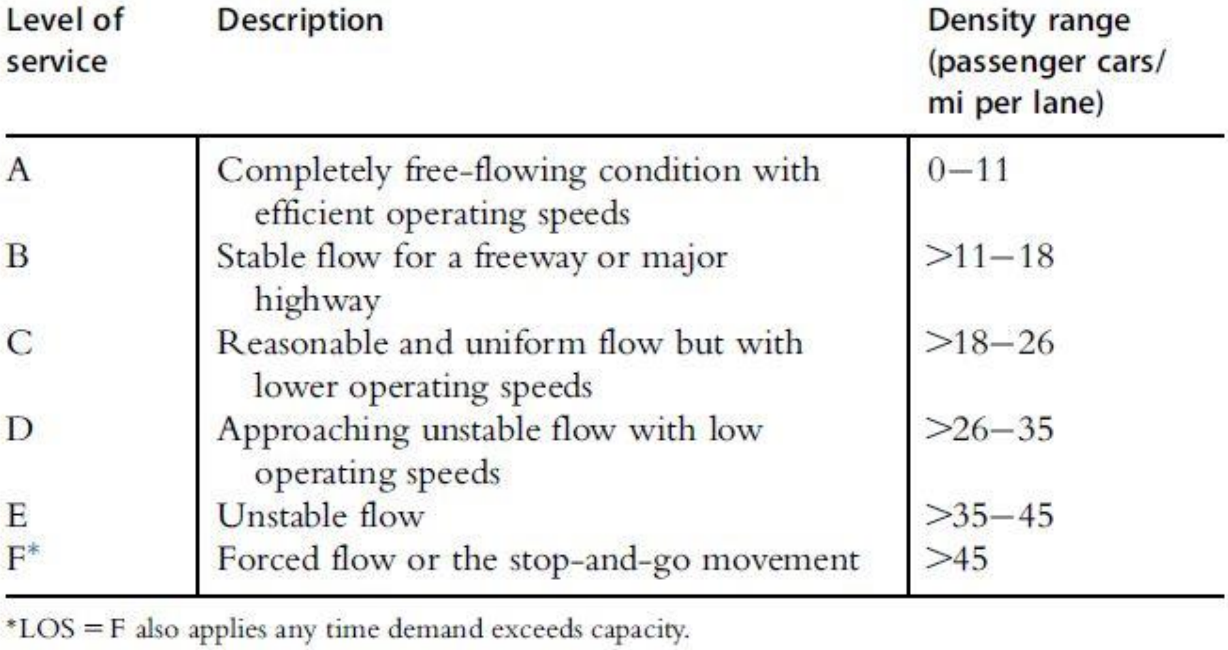
6. Basic Freeway and Multilane Highway Segments

The methodologies to analyze basic freeway segments and multilane highways are conceptually very similar, and so are presented together here (as well as in the HCM). A basic freeway segment is defined as a divided highway with full control of access and two or more lanes for the exclusive use of traffic in each direction that is outside of the influence of onramps or off-ramps (defined in the HCM as greater than 1500 ft). A multilane highway segment similarly provides uninterrupted flow on an access-controlled facility with no signalized or stop-controlled at-grade intersections intersecting the mainline. However, multilane highways sometimes allow for isolated driveway access and are generally not held to the same high design standards as freeways. Accordingly, their capacities are expected to be lower than a basic freeway segment. In the HCM, a multilane highway segment is considered as an uninterrupted flow segment if it is more than 2 miles from a signalized intersection or other at-grade junction point.

6.1 Capacity and Level of Service

Freeway capacity is defined as the maximum sustained 15-min flow rate, expressed in passenger cars per hour per lane, that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow. The calculation of this 15-min flow rate, as well as the conversion from vehicles to passenger cars, was discussed previously. The service measure for freeway LOS is the average segment density in passenger cars per mile per lane. Table below lists the thresholds for each LOS range for basic freeway and multilane highway segments in the HCM.

Table: LOS thresholds for basic freeway and multilane highway segments.



Level of service	Description	Density range (passenger cars/mi per lane)
A	Completely free-flowing condition with efficient operating speeds	0–11
B	Stable flow for a freeway or major highway	>11–18
C	Reasonable and uniform flow but with lower operating speeds	>18–26
D	Approaching unstable flow with low operating speeds	>26–35
E	Unstable flow	>35–45
F*	Forced flow or the stop-and-go movement	>45

*LOS = F also applies any time demand exceeds capacity.

Therefore, a freeway with a density of 22 passenger cars/mi per lane, for example, would be experiencing an LOS of C. The upper limit of 45 passenger cars/mi per lane for LOS E is the maximum density at which sustained flows at capacity are expected to occur. Figure below shows example images for LOS for a basic freeway segment, adopted from the HCM.

Common questions for a freeway operations analysis include:

- How good or bad is the facility performing now?
- How will the facility perform in future?
- Under what conditions will the facility break down?
- How do we design a new facility?
- What is the capacity?
- What is the average travel speed?

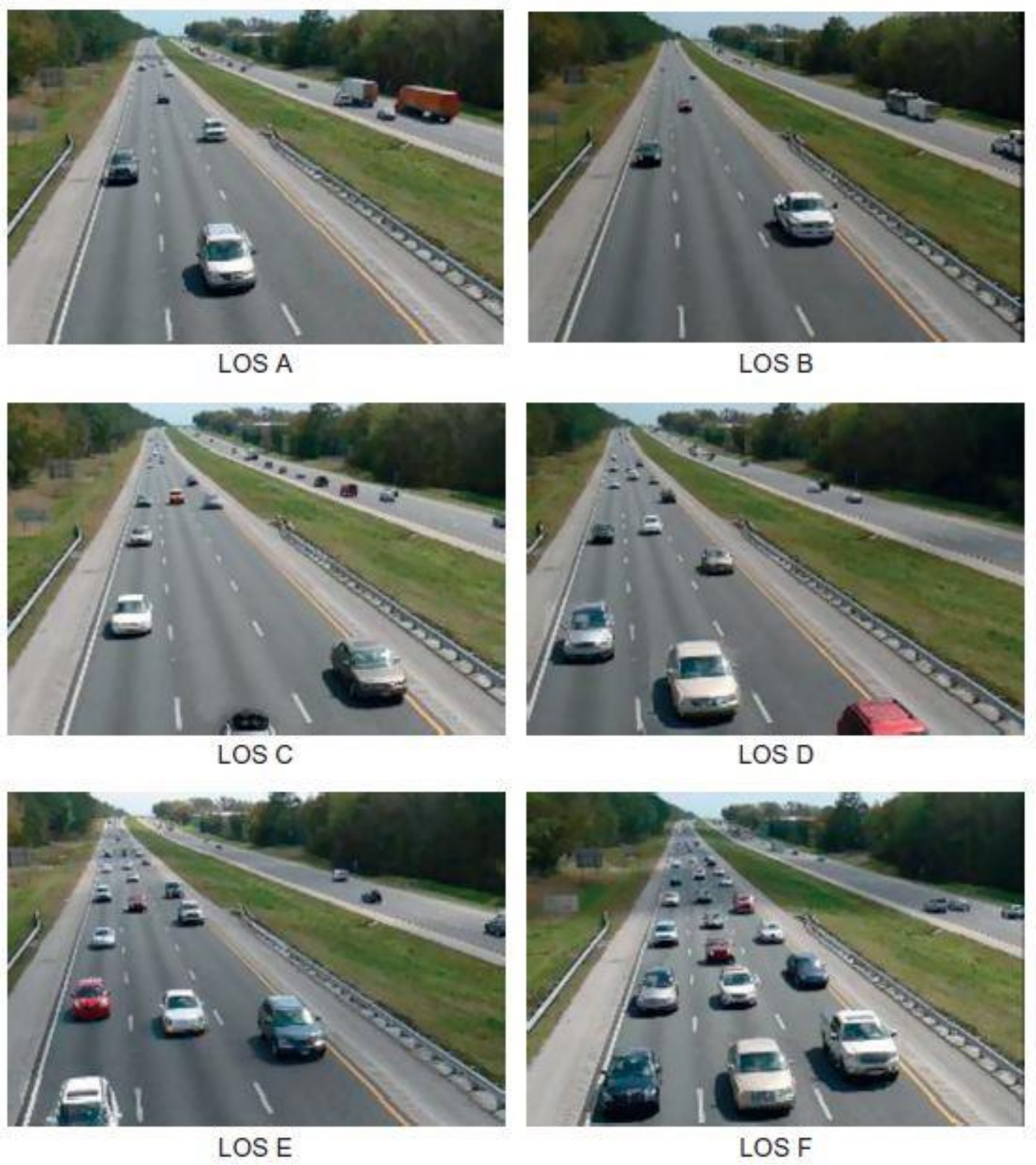

LOS A
LOS B
LOS C
LOS D
LOS E
LOS F

Figure: LOS examples for freeways.

6.2 Methodology

The basic freeway segment methodology in the HCM follows a series of six computational steps as shown in Figure below. Multilane highway segments generally follow the same procedure, and any differences between the two are discussed in more detail in the respective steps.

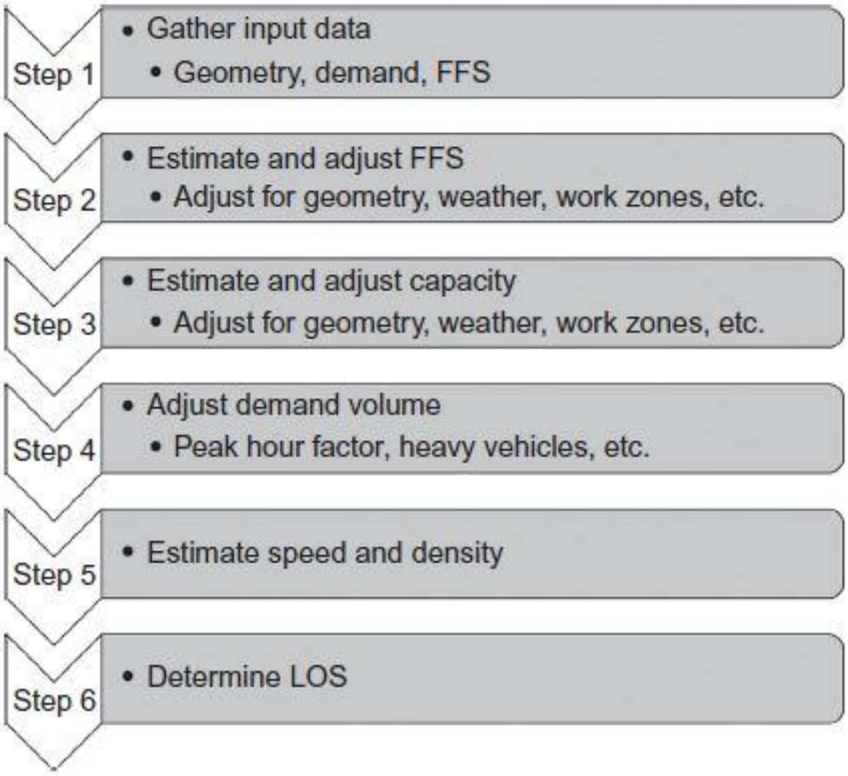


Figure: Basic freeway segment methodological steps.

Step 1: Gather Input Data

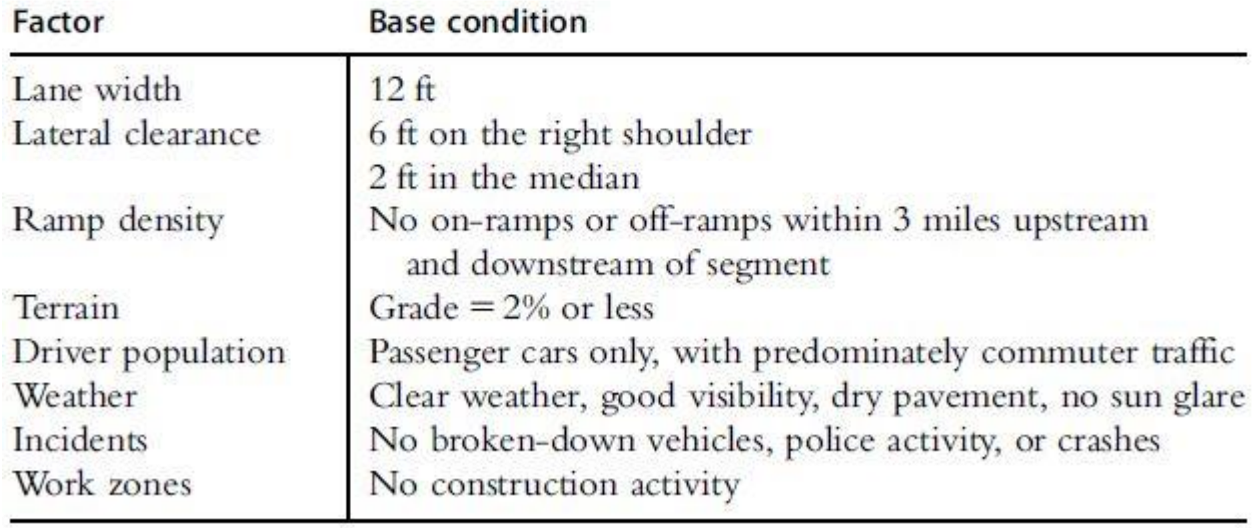
To use the method described in the HCM to determine the LOS of a basic freeway or multilane highway segment, three main categories of data are needed:

- Geometric data (e.g., lane width, shoulder width, number of lanes, etc.)
- Field-measured free-flow speed (FFS) or a base free-flow speed (BFFS)
- Volume/flow rate data.

These input data are typically collected in traffic studies or, in some cases, are estimated from a transportation planning model. Geometric data are typically obtained from maps, aerial photography, or design drawings for a new facility. Free-flow speed can be field measured for an existing facility or can be estimated using the equation described in Step 2. Traffic volumes are typically field measured and include the percentage of heavy vehicles to convert the traffic stream to passenger car equivalents for the purpose of analysis in Step 3.

For a roadway to perform at its optimal efficiency, it must be designed using ideal conditions. In principle, an ideal condition is one for which further improvement will not achieve any increase in capacity. These conditions are also referred to as base conditions. Table below lists many factors that can affect traffic flow and the base condition for each.

Table: Base conditions for basic freeway segments.



Factor	Base condition
Lane width	12 ft
Lateral clearance	6 ft on the right shoulder 2 ft in the median
Ramp density	No on-ramps or off-ramps within 3 miles upstream and downstream of segment
Terrain	Grade = 2% or less
Driver population	Passenger cars only, with predominately commuter traffic
Weather	Clear weather, good visibility, dry pavement, no sun glare
Incidents	No broken-down vehicles, police activity, or crashes
Work zones	No construction activity

Often, due to costs, terrain, development around the roadway, and many other factors, it is difficult to design a roadway using these ideal conditions. Because of this, it is important in LOS analysis to gather geometric data for the roadway to determine how close or far it is from these ideal conditions.

Step 2: Estimate and Adjust Free-Flow Speed

The free-flow speed (FFS) is considered to be the average passenger car travel speed that most drivers will choose under low flow conditions. For existing roadways, FFS can be measured directly in the field when flows are less than 1000 passenger cars/h per lane. Otherwise, FFS can be estimated by adjusting a base free-flow speed (BFFS) downward to reflect the influence of four geometric factors. In the HCM, these factors are lateral clearance, number of lanes, and total ramp density.

The base condition for each of these factors was given in Table above. Deviating from these base conditions causes drivers to slow down and thus affects capacity. Reducing lane width or lateral clearance forces drivers closer together than they would prefer. To accommodate for the lack of space, they decrease speed. Likewise, increasing interchange density causes increased weaving and merging, which disrupts flow and causes drivers to decrease speed.

The equation for estimating FFS using BFFS and adjustment factors for basic freeway segments is given:

$$FFS = BFFS - f_{LW} - f_{RLC} - 3.22 \times TRD^{0.84}$$

Where:

FFS = free-flow speed of basic freeway segment (mph).
BFFS= base FFS for basic freeway segment (mph).
f_{LW} = adjustment for lane width (mph) Table.
f_{RLC} = adjustment for right-side lateral clearance (mph) Table.
TRD = total ramp density (ramps/mi).

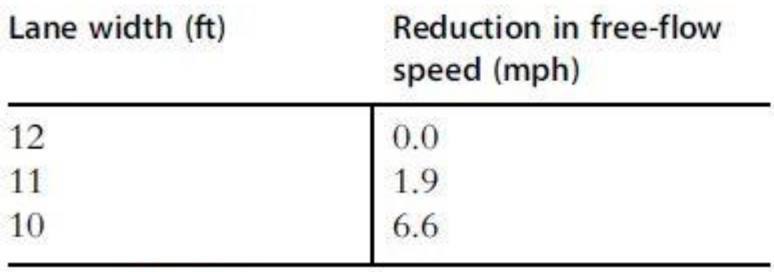
The equation for estimating FFS for multilane highway segments is given below:

$$FFS = BFFS - f_{LW} - f_{TLC} - f_M - f_A$$

Where:

FFS=free-flow speed of multilane highway segment (mph).
BFFS=base FFS for multilane highway segment (mph).
f_{LW}=adjustment for lane width (mph) Table.
f_{TLC}=adjustment for total lateral clearance (mph) Table.
f_M=adjustment for median type (mph) Table.
f_A=adjustment for access-point density (mph) Table.

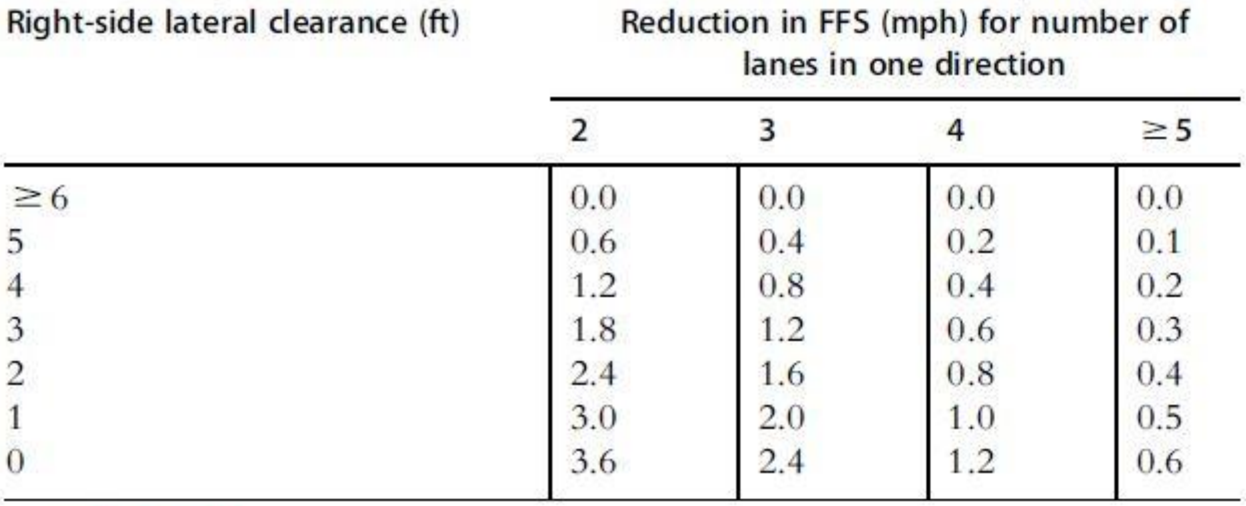
Table: Adjustments for lane width (f_{LW}) for freeways and multilane highways.



Lane width (ft)	Reduction in free-flow speed (mph)
12	0.0
11	1.9
10	6.6

Source: TRB, 2015.

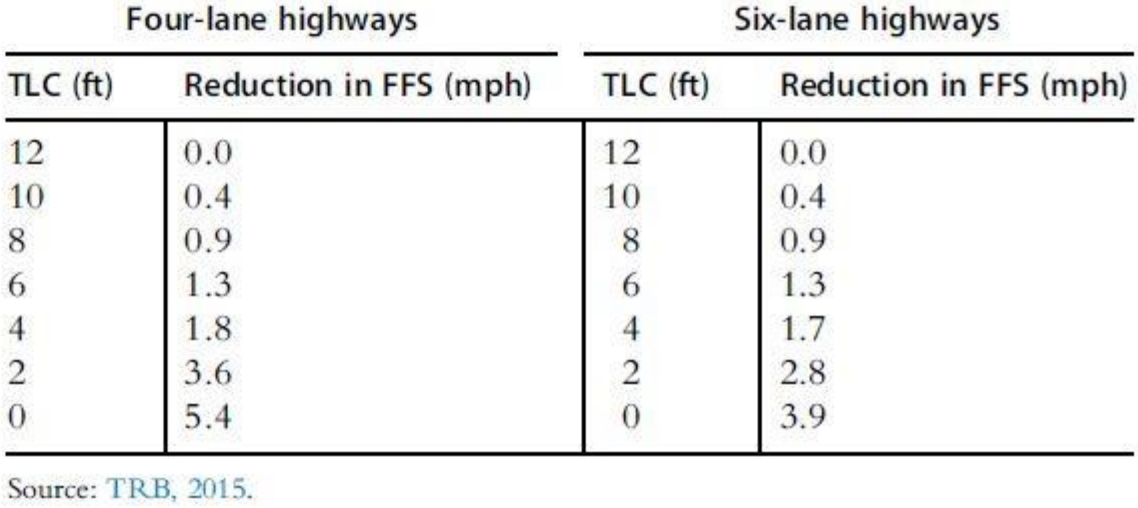
Table: Adjustments for right-shoulder lateral clearance on freeways (f_{LC}).



Right-side lateral clearance (ft)	Reduction in FFS (mph) for number of lanes in one direction			
	2	3	4	≥5
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Source: TRB, 2015.

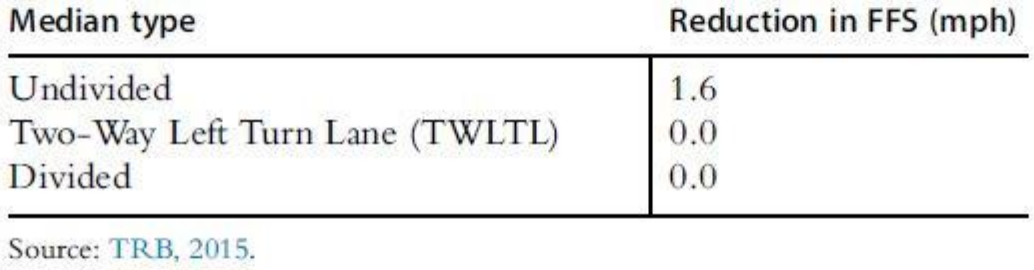
Table: Adjustment for total lateral clearance (f_{TLC}, left plus right side) for multilane highways.



Four-lane highways		Six-lane highways	
TLC (ft)	Reduction in FFS (mph)	TLC (ft)	Reduction in FFS (mph)
12	0.0	12	0.0
10	0.4	10	0.4
8	0.9	8	0.9
6	1.3	6	1.3
4	1.8	4	1.7
2	3.6	2	2.8
0	5.4	0	3.9

Source: TRB, 2015.

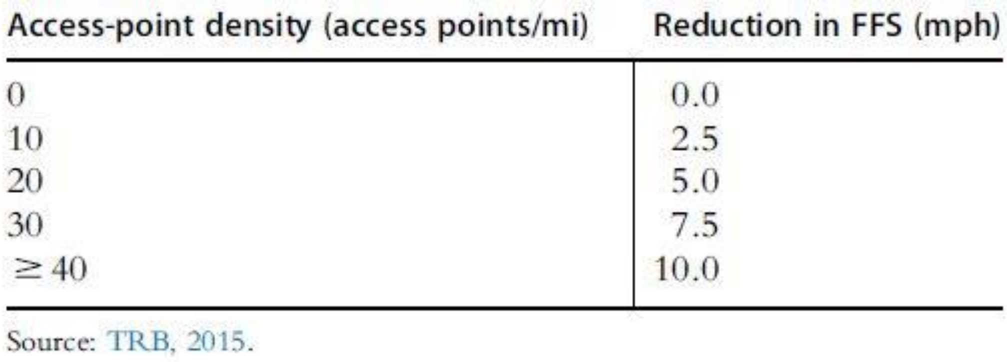
Table: Adjustment for median type (f_M) for multilane highways.



Median type	Reduction in FFS (mph)
Undivided	1.6
Two-Way Left Turn Lane (TWLTL)	0.0
Divided	0.0

Source: TRB, 2015.

Table: Adjustment for access point density (f_{AP}) for multilane highways.



Access-point density (access points/mi)	Reduction in FFS (mph)
0	0.0
10	2.5
20	5.0
30	7.5
≥ 40	10.0

Source: TRB, 2015.

The base free-flow speed (BFFS) in previous equation is 75.4 mph, which allows for estimation of FFS up to facilities signed at 70 mph, which often have FFS around 75 mph under ideal conditions. For multilane highways, limited research exists on estimating the BFFS. It is recommended that the roadway design speed (not necessarily the speed limit) is used for those facilities as an initial estimate of BFFS, and that local data be considered whenever possible.

The effect for total ramp density used in Equation for basic freeway segments is estimated by directly plugging the total ramp density for the segment under study into the equation. The total ramp density is measured over a distance of 6 miles (3) miles upstream and 3 miles downstream of the segment), and calculated by the number of ramps divided by distance (in units of ramps per mile). This adjustment term implies that a full cloverleaf interchange (four ramps per direction) has a proportionally higher impact on the FFS than a diamond interchange with only two ramps per direction. The various adjustments for geometric conditions of the roadway in the HCM are limited to reductions in FFS, rather than having a direct on capacity. Research on the effects of roadway geometry on freeway capacity is limited (other than in specialized applications, such as work zones), but it is intuitive that reduced geometric standards would also impact the capacity, as discussed further in the following.

Step 3: Estimate and Adjust Capacity

With all geometric and volume data obtained, an estimate of the roadway capacity is needed to calculate volume-to-capacity (v/c) ratio, performance measures, and ultimately LOS for a basic freeway or multilane highway segment. The ideal or base capacity of the segment can be calculated from Equation below as a function of the free-flow speed (FFS) as follows:

$$c\,(\textit{basic freeway segment}) = 2200 + 10 \times (FFS - 50)$$

$$c\,(\textit{multilane highway segment}) = 1900 + 20 \times (FFS - 45)$$

The capacities obtained from these equations are for segments under ideal conditions, and do not consider a variety of potential capacity reducing effects. Some of these effects are implicitly accounted for in the FFS estimation, including lane widths, lateral clearance, and total ramp density. Because these attributes (if not in ideal or base condition) lead to a reduction in FFS, they also implicitly impact the resulting capacity. But various other factors can lead to a reduction in capacity, including:

- Lane width and lateral clearance effects in addition to those included in the FFS estimation.
- Lane drops that create turbulence as drivers have to merge into the lanes that continue past the lane-drop point.
- Poor visibility due to horizontal and vertical curvature, or due to weather conditions (fog, sun glare, etc.).
- Poor pavement conditions, especially if rutting or potholes are frequent on the facility.
- Travel across bridges, through tunnels, or adjacent to landmarks and other points of interest that divert driver attention.
- Presence of a significant portion of unfamiliar drivers in the traffic stream.
- Lane changes and turbulence resulting from downstream on- or off-ramps.

- Presence of incidents or work zones that either reduce lanes or result in onlooker effects.
- Poor weather conditions in the form of rain, snow, or ice precipitation.

Given the variety of potential capacity-reducing factors, it is critical to properly calibrate the capacity for prevailing conditions for the segment under study. This calibration can occur through local observations and sensor data on freeways, which is the preferred approach. Alternatively, the analyst may refer to various sources in the literature to estimate the magnitude of the capacity-reducing effects. Some of these sources are referenced in the next section. These factors are then incorporated in the estimation of freeway performance through a capacity-reduction factor (CAF) that is multiplied with the ideal capacity to obtain the locally calibrated prevailing capacity, as shown below:

$$c_{adj} = c \times CAF$$

Where

c_{adj} =adjusted capacity of segment (passenger cars/h).

c =base capacity of segment (passenger cars/h).

CAF=capacity adjustment factor.

The importance of calibrating the capacity, especially for a known freeway bottleneck, cannot be underestimated. In fact, the ideal capacities (e.g., 2400 passenger cars/h per lane for a facility with FFS of 70 mph) may be rarely observed in reality.

Step 4: Adjust Demand Volume

Once the geometric and FFS data are gathered, the only data remaining to be collected are the volume and flow rate data. The flow rate (v_p) is based on the volume and several other factors and can be calculated using Equation below:

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

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

Heavy vehicles, including trucks, buses, and recreational vehicles create less-than-ideal flows. Longer and more frequent gaps of excessive length form in front of and behind heavy vehicles, vehicles in adjacent lanes are often disrupted, and heavy vehicles tend to be about two to three times the length of a passenger car. Accordingly, the heavy vehicle factor, f_{HV}, is introduced into the flow rate equation to convert the vehicle mix using the facility into equivalent passenger cars.

The heavy vehicle factor is estimated from an equivalency factor that equates each heavy vehicle to a number of passenger car equivalents, or PCEs. PCEs are defined for general terrain (level or rolling). Level terrain is defined as a segment that allows trucks to generally obtain and maintain the same speeds as passenger cars, which is expected for grades less than 2%. Rolling terrain is defined as a segment that causes trucks to slightly reduce their speed over passenger cars, but without steep grades (above 4%) that may cause some trucks to operate at crawl speeds. The PCE equivalency for trucks factors (ET) for level and rolling terrain are shown in Table below.

Table: General terrain PCE equivalents for heavy vehicles.

Passenger car equivalent (PCE) factor	Type of terrain	
	Level	Rolling
E_T	2.0	3.0

From these equivalency factors and from the percentage of trucks in the traffic stream, the heavy vehicle adjustment factor for volume is calculated from Eq. below:

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

Where

f_{HV} = heavy-vehicle adjustment factor.

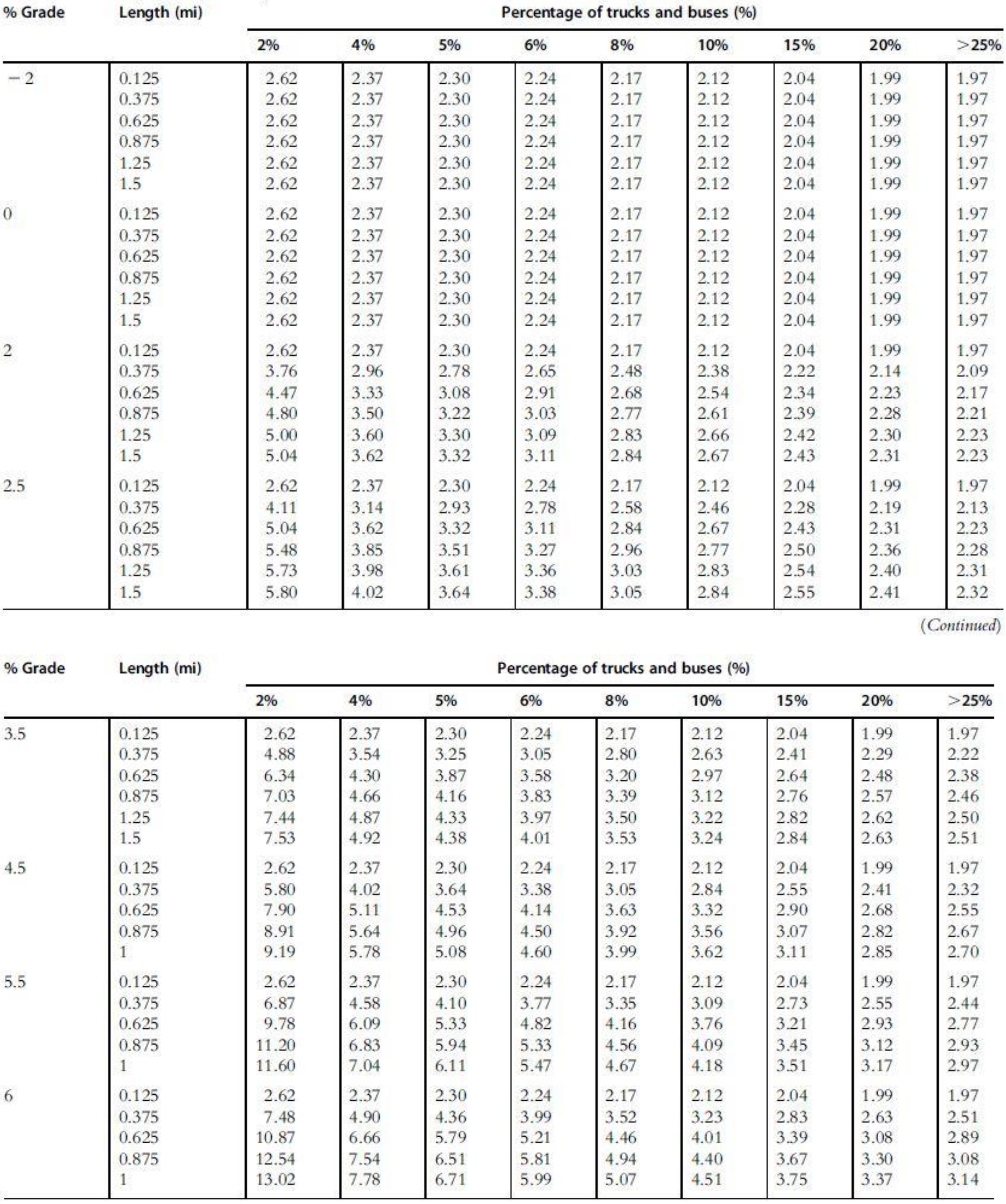
P_T = proportion of heavy vehicles in traffic stream.

E_T = passenger-car equivalent (PCE) of one heavy vehicle.

For mountainous terrain and generally steeper grades, no general terrain factors for PCEs exist, and so the analyst has to refer to the specific grade adjustments found in the HCM and repeated here as Tables below refer to a mix of single unit trucks (SUT) and tractor trailer trucks (TT) of 30%/70%, 50%/50%, and 70%/ 30%, respectively. The SUT category encompasses heavy vehicles classes 4 and 5 as defined by FHWA, as well as large recreational vehicles (RVs). The TT category includes any vehicles of FHWA class 6 and higher. The resulting E_T values from these tables can then be plugged into previous equation to estimate the heavy vehicle adjustment factor. Values not contained in the tables directly can be obtained through linear interpolation.

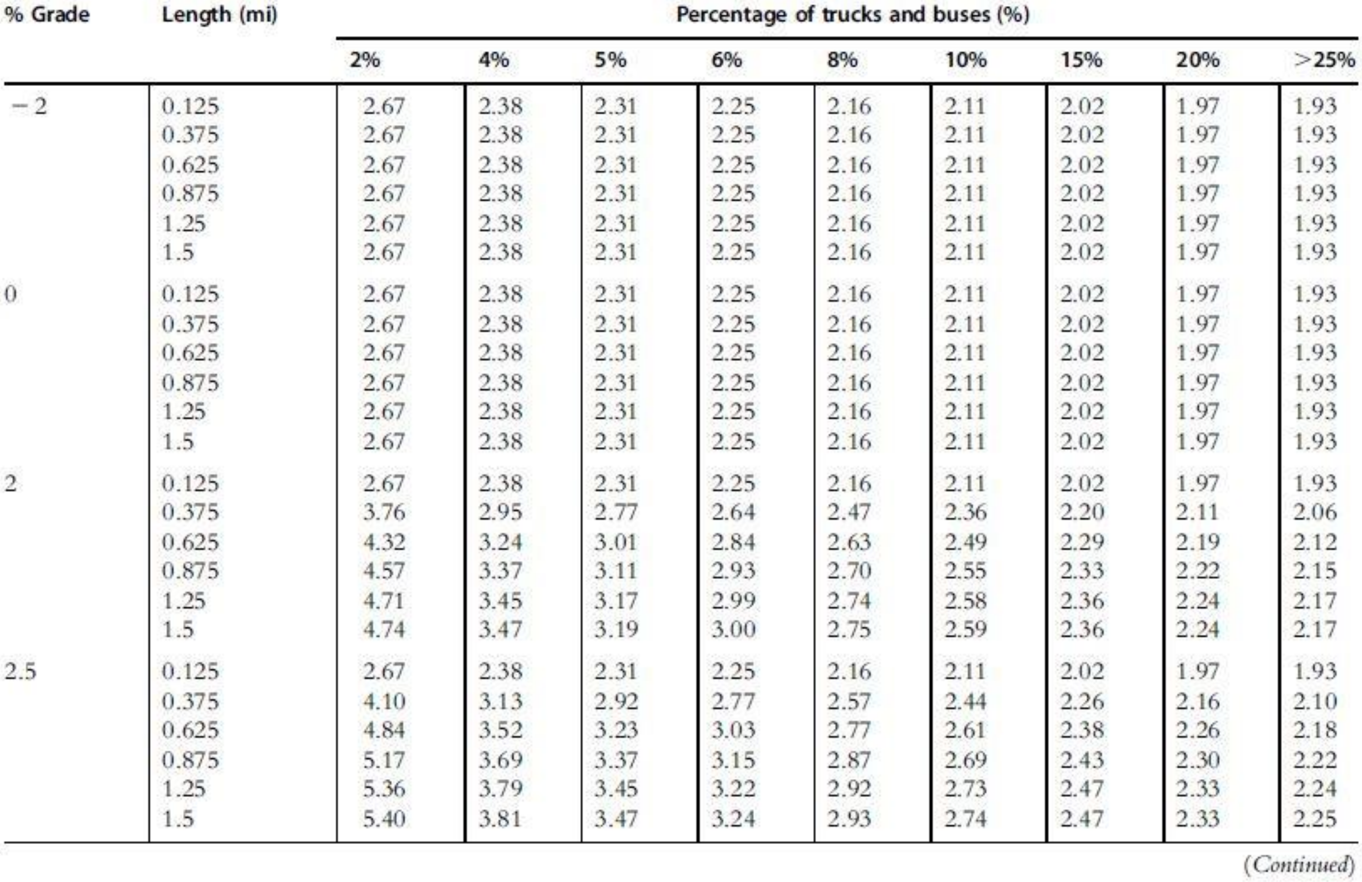
The HCM also offers a specific mixed-flow model methodology for estimating the speed of trucks on long steep grades that is beyond the scope of this text.

Table: Passenger car equivalency factors for 30% SUT and 70% TT fleet mix.



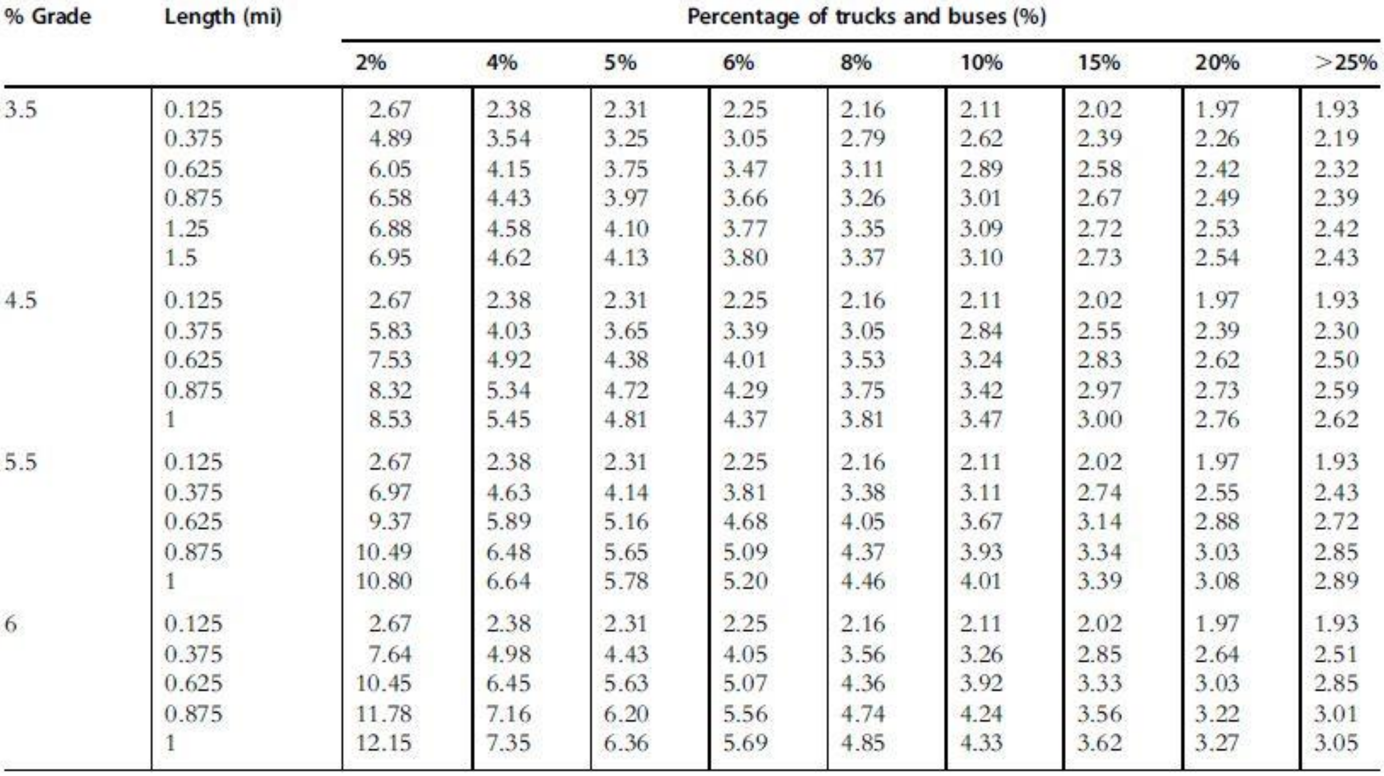
% Grade	Length (mi)	Percentage of trucks and buses (%)								
		2%	4%	5%	6%	8%	10%	15%	20%	>25%
−2	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.625	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.875	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	1.25	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	1.5	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
0	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.625	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.875	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	1.25	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	1.5	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
2	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	3.76	2.96	2.78	2.65	2.48	2.38	2.22	2.14	2.09
	0.625	4.47	3.33	3.08	2.91	2.68	2.54	2.34	2.23	2.17
	0.875	4.80	3.50	3.22	3.03	2.77	2.61	2.39	2.28	2.21
	1.25	5.00	3.60	3.30	3.09	2.83	2.66	2.42	2.30	2.23
	1.5	5.04	3.62	3.32	3.11	2.84	2.67	2.43	2.31	2.23
2.5	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	4.11	3.14	2.93	2.78	2.58	2.46	2.28	2.19	2.13
	0.625	5.04	3.62	3.32	3.11	2.84	2.67	2.43	2.31	2.23
	0.875	5.48	3.85	3.51	3.27	2.96	2.77	2.50	2.36	2.28
	1.25	5.73	3.98	3.61	3.36	3.03	2.83	2.54	2.40	2.31
	1.5	5.80	4.02	3.64	3.38	3.05	2.84	2.55	2.41	2.32
3.5	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	4.88	3.54	3.25	3.05	2.80	2.63	2.41	2.29	2.22
	0.625	6.34	4.30	3.87	3.58	3.20	2.97	2.64	2.48	2.38
	0.875	7.03	4.66	4.16	3.83	3.39	3.12	2.76	2.57	2.46
	1.25	7.44	4.87	4.33	3.97	3.50	3.22	2.82	2.62	2.50
	1.5	7.53	4.92	4.38	4.01	3.53	3.24	2.84	2.63	2.51
4.5	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	5.80	4.02	3.64	3.38	3.05	2.84	2.55	2.41	2.32
	0.625	7.90	5.11	4.53	4.14	3.63	3.32	2.90	2.68	2.55
	0.875	8.91	5.64	4.96	4.50	3.92	3.56	3.07	2.82	2.67
	1	9.19	5.78	5.08	4.60	3.99	3.62	3.11	2.85	2.70
5.5	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	6.87	4.58	4.10	3.77	3.35	3.09	2.73	2.55	2.44
	0.625	9.78	6.09	5.33	4.82	4.16	3.76	3.21	2.93	2.77
	0.875	11.20	6.83	5.94	5.33	4.56	4.09	3.45	3.12	2.93
	1	11.60	7.04	6.11	5.47	4.67	4.18	3.51	3.17	2.97
6	0.125	2.62	2.37	2.30	2.24	2.17	2.12	2.04	1.99	1.97
	0.375	7.48	4.90	4.36	3.99	3.52	3.23	2.83	2.63	2.51
	0.625	10.87	6.66	5.79	5.21	4.46	4.01	3.39	3.08	2.89
	0.875	12.54	7.54	6.51	5.81	4.94	4.40	3.67	3.30	3.08
	1	13.02	7.78	6.71	5.99	5.07	4.51	3.75	3.37	3.14

Table: Passenger car equivalency factors for 50% SUT and 50% TT fleet mix.



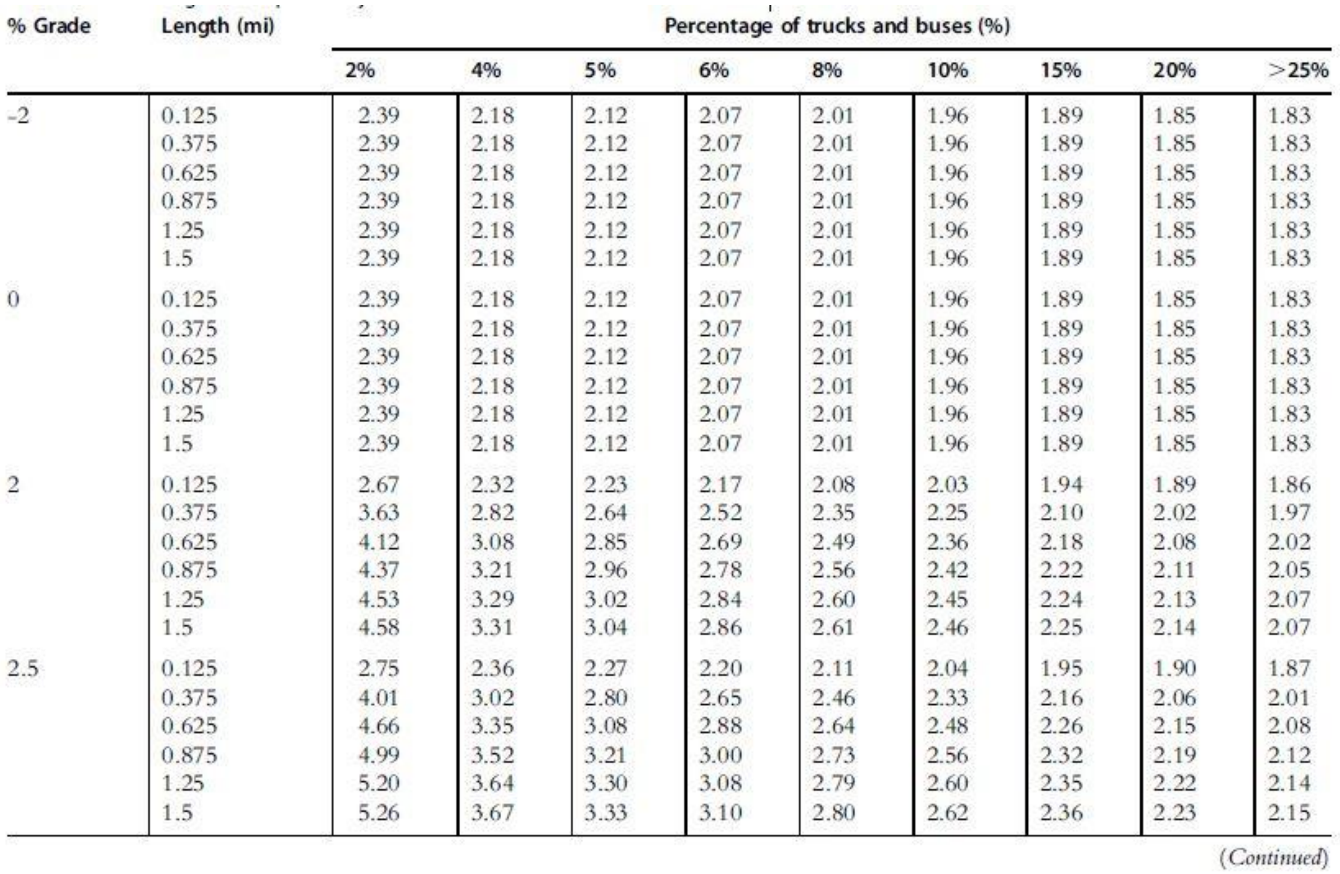
% Grade	Length (mi)	Percentage of trucks and buses (%)								
		2%	4%	5%	6%	8%	10%	15%	20%	>25%
−2	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.625	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.875	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	1.25	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	1.5	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
0	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.625	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.875	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	1.25	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	1.5	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
2	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	3.76	2.95	2.77	2.64	2.47	2.36	2.20	2.11	2.06
	0.625	4.32	3.24	3.01	2.84	2.63	2.49	2.29	2.19	2.12
	0.875	4.57	3.37	3.11	2.93	2.70	2.55	2.33	2.22	2.15
	1.25	4.71	3.45	3.17	2.99	2.74	2.58	2.36	2.24	2.17
	1.5	4.74	3.47	3.19	3.00	2.75	2.59	2.36	2.24	2.17
2.5	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	4.10	3.13	2.92	2.77	2.57	2.44	2.26	2.16	2.10
	0.625	4.84	3.52	3.23	3.03	2.77	2.61	2.38	2.26	2.18
	0.875	5.17	3.69	3.37	3.15	2.87	2.69	2.43	2.30	2.22
	1.25	5.36	3.79	3.45	3.22	2.92	2.73	2.47	2.33	2.24
	1.5	5.40	3.81	3.47	3.24	2.93	2.74	2.47	2.33	2.25

(*Continued*)



% Grade	Length (mi)	Percentage of trucks and buses (%)								
		2%	4%	5%	6%	8%	10%	15%	20%	>25%
3.5	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	4.89	3.54	3.25	3.05	2.79	2.62	2.39	2.26	2.19
	0.625	6.05	4.15	3.75	3.47	3.11	2.89	2.58	2.42	2.32
	0.875	6.58	4.43	3.97	3.66	3.26	3.01	2.67	2.49	2.39
	1.25	6.88	4.58	4.10	3.77	3.35	3.09	2.72	2.53	2.42
	1.5	6.95	4.62	4.13	3.80	3.37	3.10	2.73	2.54	2.43
4.5	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	5.83	4.03	3.65	3.39	3.05	2.84	2.55	2.39	2.30
	0.625	7.53	4.92	4.38	4.01	3.53	3.24	2.83	2.62	2.50
	0.875	8.32	5.34	4.72	4.29	3.75	3.42	2.97	2.73	2.59
	1	8.53	5.45	4.81	4.37	3.81	3.47	3.00	2.76	2.62
5.5	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	6.97	4.63	4.14	3.81	3.38	3.11	2.74	2.55	2.43
	0.625	9.37	5.89	5.16	4.68	4.05	3.67	3.14	2.88	2.72
	0.875	10.49	6.48	5.65	5.09	4.37	3.93	3.34	3.03	2.85
	1	10.80	6.64	5.78	5.20	4.46	4.01	3.39	3.08	2.89
6	0.125	2.67	2.38	2.31	2.25	2.16	2.11	2.02	1.97	1.93
	0.375	7.64	4.98	4.43	4.05	3.56	3.26	2.85	2.64	2.51
	0.625	10.45	6.45	5.63	5.07	4.36	3.92	3.33	3.03	2.85
	0.875	11.78	7.16	6.20	5.56	4.74	4.24	3.56	3.22	3.01
	1	12.15	7.35	6.36	5.69	4.85	4.33	3.62	3.27	3.05

Table: Passenger car equivalency factors for 70% SUT and 30% TT fleet mix.



% Grade	Length (mi)	Percentage of trucks and buses (%)								
		2%	4%	5%	6%	8%	10%	15%	20%	>25%
-2	0.125	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	0.375	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	0.625	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	0.875	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	1.25	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	1.5	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
0	0.125	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	0.375	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	0.625	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	0.875	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	1.25	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
	1.5	2.39	2.18	2.12	2.07	2.01	1.96	1.89	1.85	1.83
2	0.125	2.67	2.32	2.23	2.17	2.08	2.03	1.94	1.89	1.86
	0.375	3.63	2.82	2.64	2.52	2.35	2.25	2.10	2.02	1.97
	0.625	4.12	3.08	2.85	2.69	2.49	2.36	2.18	2.08	2.02
	0.875	4.37	3.21	2.96	2.78	2.56	2.42	2.22	2.11	2.05
	1.25	4.53	3.29	3.02	2.84	2.60	2.45	2.24	2.13	2.07
	1.5	4.58	3.31	3.04	2.86	2.61	2.46	2.25	2.14	2.07
2.5	0.125	2.75	2.36	2.27	2.20	2.11	2.04	1.95	1.90	1.87
	0.375	4.01	3.02	2.80	2.65	2.46	2.33	2.16	2.06	2.01
	0.625	4.66	3.35	3.08	2.88	2.64	2.48	2.26	2.15	2.08
	0.875	4.99	3.52	3.21	3.00	2.73	2.56	2.32	2.19	2.12
	1.25	5.20	3.64	3.30	3.08	2.79	2.60	2.35	2.22	2.14
	1.5	5.26	3.67	3.33	3.10	2.80	2.62	2.36	2.23	2.15

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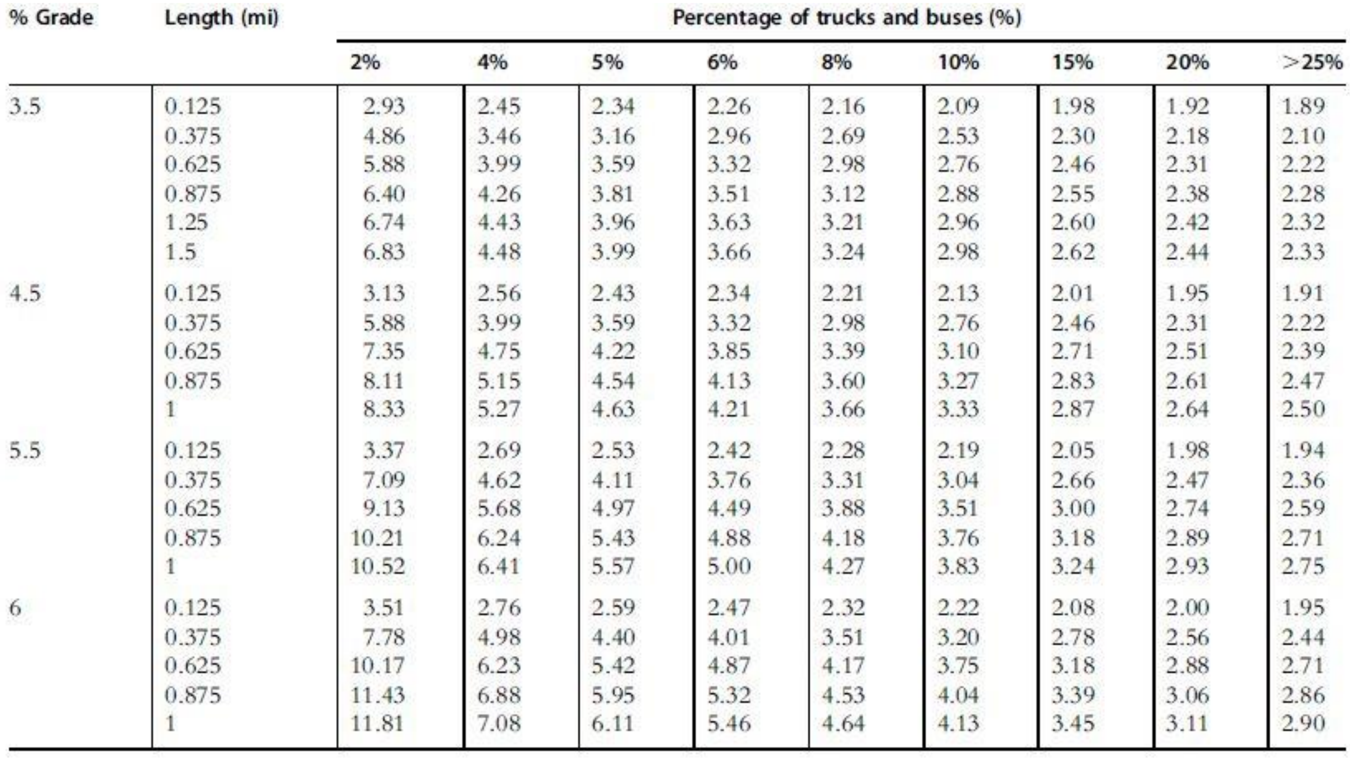


% Grade	Length (mi)	Percentage of trucks and buses (%)								
		2%	4%	5%	6%	8%	10%	15%	20%	>25%
3.5	0.125	2.93	2.45	2.34	2.26	2.16	2.09	1.98	1.92	1.89
	0.375	4.86	3.46	3.16	2.96	2.69	2.53	2.30	2.18	2.10
	0.625	5.88	3.99	3.59	3.32	2.98	2.76	2.46	2.31	2.22
	0.875	6.40	4.26	3.81	3.51	3.12	2.88	2.55	2.38	2.28
	1.25	6.74	4.43	3.96	3.63	3.21	2.96	2.60	2.42	2.32
	1.5	6.83	4.48	3.99	3.66	3.24	2.98	2.62	2.44	2.33
4.5	0.125	3.13	2.56	2.43	2.34	2.21	2.13	2.01	1.95	1.91
	0.375	5.88	3.99	3.59	3.32	2.98	2.76	2.46	2.31	2.22
	0.625	7.35	4.75	4.22	3.85	3.39	3.10	2.71	2.51	2.39
	0.875	8.11	5.15	4.54	4.13	3.60	3.27	2.83	2.61	2.47
	1	8.33	5.27	4.63	4.21	3.66	3.33	2.87	2.64	2.50
5.5	0.125	3.37	2.69	2.53	2.42	2.28	2.19	2.05	1.98	1.94
	0.375	7.09	4.62	4.11	3.76	3.31	3.04	2.66	2.47	2.36
	0.625	9.13	5.68	4.97	4.49	3.88	3.51	3.00	2.74	2.59
	0.875	10.21	6.24	5.43	4.88	4.18	3.76	3.18	2.89	2.71
	1	10.52	6.41	5.57	5.00	4.27	3.83	3.24	2.93	2.75
6	0.125	3.51	2.76	2.59	2.47	2.32	2.22	2.08	2.00	1.95
	0.375	7.78	4.98	4.40	4.01	3.51	3.20	2.78	2.56	2.44
	0.625	10.17	6.23	5.42	4.87	4.17	3.75	3.18	2.88	2.71
	0.875	11.43	6.88	5.95	5.32	4.53	4.04	3.39	3.06	2.86
	1	11.81	7.08	6.11	5.46	4.64	4.13	3.45	3.11	2.90

Steps 5 and 6: Estimate Speed, Density, and LOS

With all necessary input parameters and adjustments obtained, the prevailing speed on the basic freeway segment can be estimated for undersaturated flow using a two-regime model shown in Equation below. The model predicts an initial portion of the speed-flow regime where the speed is fixed at the adjusted FFS. After a breakpoint the speed then begins to deteriorate as volumes approach capacity. The two equations are fundamentally a function of FFS, capacity, and input volume, as well as SAF and CAF adjustments.

$$S = \begin{cases} FFS \times SAF & V_p \le BP_{adj} \\ FFS \times SAF - \dfrac{\left(FFS \times SAF - \dfrac{c \times CAF}{45}\right)}{(c \times CAF - BP_{adj})^2} \times (V_p - BP_{adj})^2 & V_p > BP_{adj} \end{cases} \qquad (5.19)$$

$$BP_{adj}(FFS \times SAF, CAF) = [1000 + 40 \times (75 - FFS \times SAF)] \times CAF^2$$

Where

S=segment space mean speed, mph.
Vp=segment flow rate, passenger cars/h per lane.
SAF=free-flow speed adjustment factor.
CAF=capacity adjustment factor.
BPadj=adjusted breakpoint flow rate, passenger cars/h per lane.

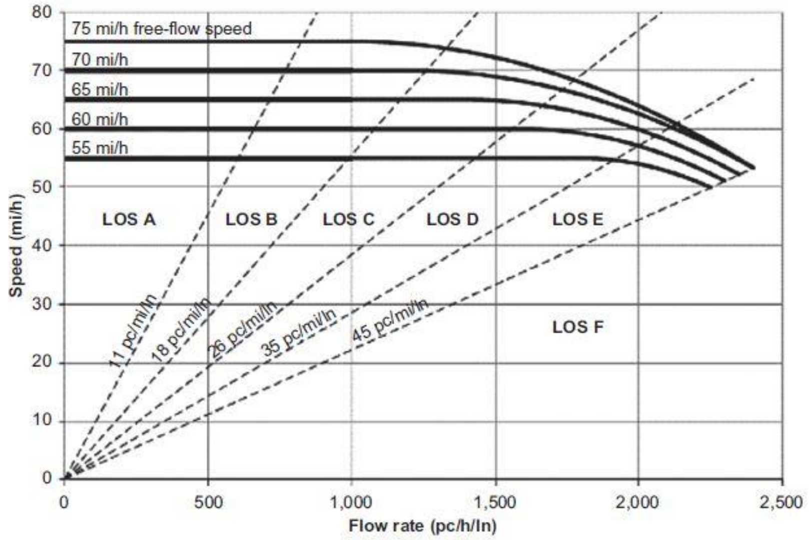


Figure: Speed-flow curves for basic freeway segments.

From this speed, density on the segment can be estimated from equation below:

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

Where:
D=density (passenger cars/mi per lane).
vp=demand flow rate (passenger cars/h per lane).
S=mean speed of traffic stream under base conditions (mph).

Figure above depicts the speed-flow curves for a basic segment obtained from previous Equation these curves are used to find the LOS for a freeway. Curves are drawn in for 75 mph, 70 mph, 65 mph, 60 mph, and 55 mph average passenger-car travel speed.
The LOS can also be obtained directly by comparing the results of Eq. above with the LOS thresholds.

Figure above graphically shows level of service ranges A through E as defined by the diagonal dashed lines. These lines are not arbitrary. The slope of the line is the density in passenger cars per mile per lane. The density values for the LOS thresholds between each LOS are shown on the figure. The capacity points for the FFS curves drawn on the figure are described in Table below.
Note the shape of the FFS curves in previous figure. They are straight for a significant portion and then begin to curve down from the breakpoint to their ultimate capacity point at the end of the curve. The straight portion of each curve is the free-flow speed portion. That is, drivers will travel at the free-flow speed when the flow rate is within the range shown. For example, at an FFS of 75 mph, drivers will travel at this speed until the flow rate exceeds 1000 passenger cars/h per lane. Beyond this flow, speed will drop off with an increase in flow rate until capacity is reached, at 2400 passenger cars/h per lane and a speed of 53 mph. Thus, the curved portion of the FFS curve shows the average passenger car travel speed at those flow rates beyond the breakpoint, and this speed will be lower than the FFS.

<u>Table</u>: Free flow speeds and corresponding capacities.

Free flow speed (mph)	Capacity (passenger cars/h per lane)	Average passenger-car speed (mph) at capacity
70	2400	53
65	2350	52
60	2300	51
55	2250	50

Adjustments for Weather and Incidents, and Work Zones

Both the free-flow speed and the capacity on freeways have been shown to be impacted by nonrecurring sources of congestion, including weather, incidents, and work zones. Especially in the context of a freeway reliability analysis as discussed in the following, it is important that these factors be considered in the operational analysis methodology. Specifically, these effects can be incorporated using speed adjustment factors and capacity adjustment factors that are multiplied by the prevailing FFS and capacity values to obtain the adjusted, calibrated FFS and capacity estimates.

Tables below presents SAF and CAF factors for inclement weather conditions for a free-flow speed of 70 mph. And CAF factors for incidents on a freeway with varying levels of severity (SAF for all incidents is 1.0).

For work zones, the CAF and SAF are estimated through equations developed in national research (NCHRP, 2015). The research explored a variety of factors believed to impact work zone performance, including barrier type, area type, lane closure patterns, shoulder widths, work intensity, police presence, speed limit, and lighting conditions. The resulting model to estimate the queue discharge capacity of a freeway work zone is shown in Equation below:

$$QDR_{wz} = 2093 - 154 \times f_{LCSI} - 194 \times f_{Br} - 179 \times f_{A} + 9 \times f_{LAT} - 59 \times f_{DN}$$

where

QDR_{wz} = average 5-min queue discharge rate

$f_{\mathrm{LCSI}} = \frac{1}{OR \times N_o}$

OR = open ratio (number of open lanes divided by original lanes)

N_o = number of open lanes

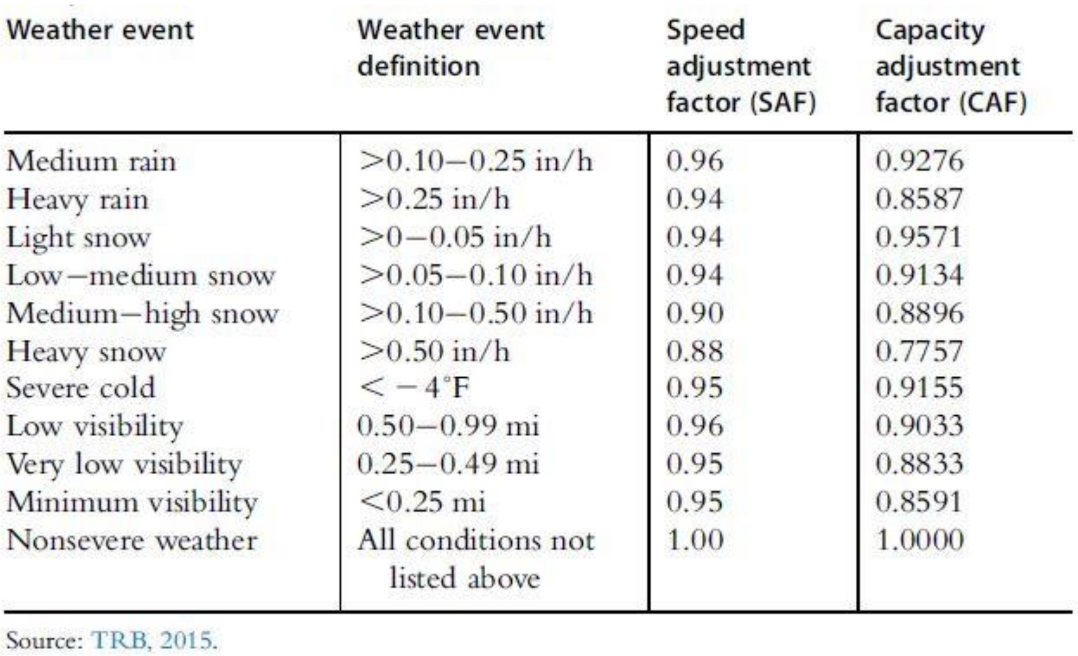
f_{Br} = 0: concrete, 1: soft barrier

f_{A} = 0: urban, 1: rural

f_{LAT} = lateral distance of 12 ft

f_{DN} = 0: day, 1: night

Table: Capacity and speed adjustment factors for inclement weather for 70 mph FFS.



Weather event	Weather event definition	Speed adjustment factor (SAF)	Capacity adjustment factor (CAF)
Medium rain	>0.10–0.25 in/h	0.96	0.9276
Heavy rain	>0.25 in/h	0.94	0.8587
Light snow	>0–0.05 in/h	0.94	0.9571
Low–medium snow	>0.05–0.10 in/h	0.94	0.9134
Medium–high snow	>0.10–0.50 in/h	0.90	0.8896
Heavy snow	>0.50 in/h	0.88	0.7757
Severe cold	< -4°F	0.95	0.9155
Low visibility	0.50–0.99 mi	0.96	0.9033
Very low visibility	0.25–0.49 mi	0.95	0.8833
Minimum visibility	<0.25 mi	0.95	0.8591
Nonsevere weather	All conditions not listed above	1.00	1.0000

Source: TRB, 2015.

Table: Capacity adjustment factors for remaining open lanes during incidents.

Number of lanes (one direction)	Shoulder closure	One-lane closure	Two-lane closure	Three-lane closure	Four-lane closure
2	0.81	0.70	NA	NA	NA
3	0.83	0.74	0.51	NA	NA
4	0.85	0.77	0.50	0.52	NA
5	0.87	0.81	0.67	0.50	0.50
6	0.89	0.85	0.75	0.52	0.52
7	0.91	0.88	0.80	0.63	0.63
8	0.93	0.89	0.84	0.66	0.66

NA = not applicable.
Source: TRB, 2015.

One of the most critical parameters in this equation was found to be the lane closure severity index (LCSI), which takes into account both the number of closed lanes and the number of original lanes. As such, a work zone with a lane closure from 5 original lanes to 2 final lanes (5-to-2) is estimated to have a lower per-lane capacity than a 3-to-2 work zone.
These two configurations are illustrated in Figure below. The LCSI values for the 5-to-2 and 3-to-2 scenarios are 1.25 and 0.75, respectively.

PHASE I

CONSTRUCT LANE 4, LANE 5, AND PROPOSED OUTSIDE SHOULDER

PHASE I

CONSTRUCT 12' PROPOSED OUTSIDE SHOULDER

Figure: Work zone lane closure scenarios. Source: Schroeder et al., 2014.

Previous Equation estimates the queue discharge flow rate of a freeway work zone. The corresponding prebreakdown capacity of a freeway work was found to be on average 13.4% higher than the queue discharge flow rate. In other words, a work zone loses 13.4% of throughput from its prebreakdown flow rate after breakdown. As such, the capacity adjustment factor (CAF) for a work zone (WZ) is calculated by Eq. (5.23) below:

$$\mathrm{CAF_{WZ}} = QDR_{WZ}/(0.864 \times c_{base})$$

where

CAF_{wz} = capacity adjustment factor for a freeway work zone
c_{Base} = base capacity of freeway segment
QDR_{wz} = average 5-min queue discharge rate

Similarly, the work zone FFS can be calculated directly from:

$$FFS_{wz} = 9.95 + 33.49 \times f_{Sr} + 0.53 \times f_S - 5.60 \times f_{LCSI} - 3.84 \times f_{Br} - 1.71 \times f_{DN} - 1.45 \times f_{Nr}$$

Where

f_{sr}=work zone to non-work zone speed ratio.
f_s=work zone posted speed limit (mph).
f_{Nr}=number of ramps (other parameters are as defined previously).

Designing with LOS in Mind

In design problems, the number of lanes is determined to provide a certain target LOS and a given design volume of traffic. The LOS chosen is generally LOS C in rural areas and LOS D in urban areas. LOS E is not used for design purposes. The same figures are used for the design process. The solution is trial and error, where you select a number of lanes and see if that provides the desired LOS. Start with N52, as this is the minimum number of lanes per direction for a freeway.