Transportation System Engineering 2 , 10601461

Chapter 6
Capacity and LOS of Multi-Lane Highways Sections

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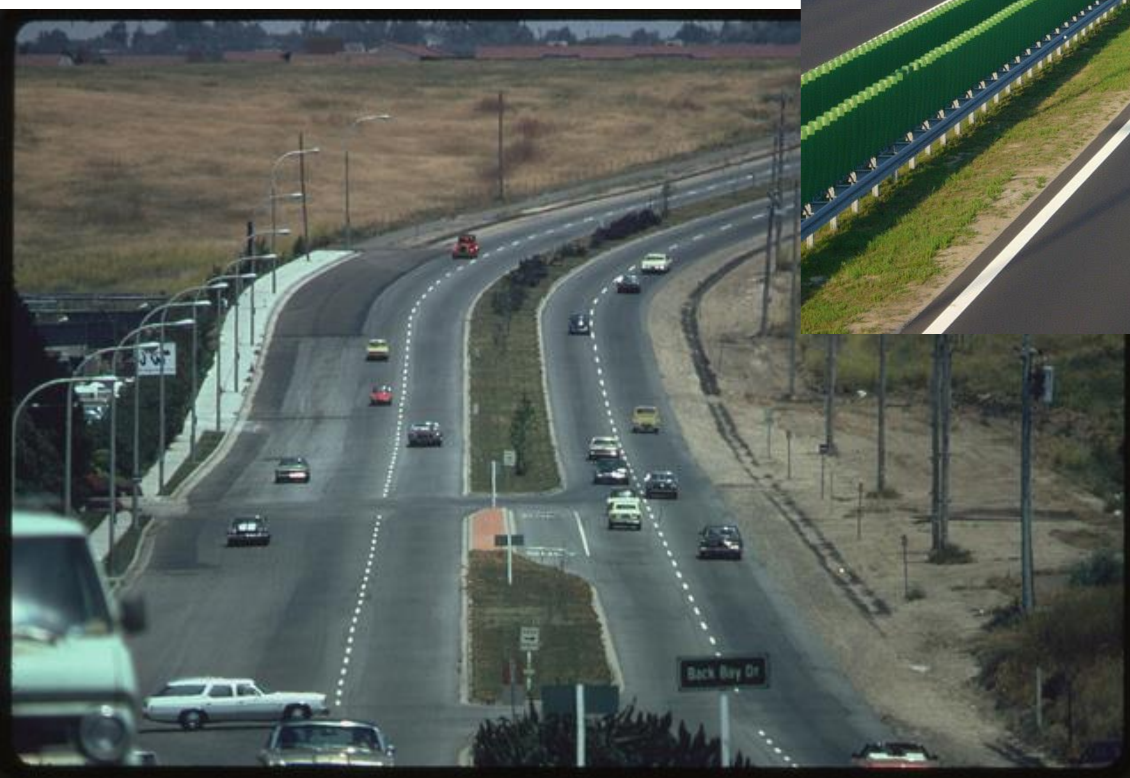
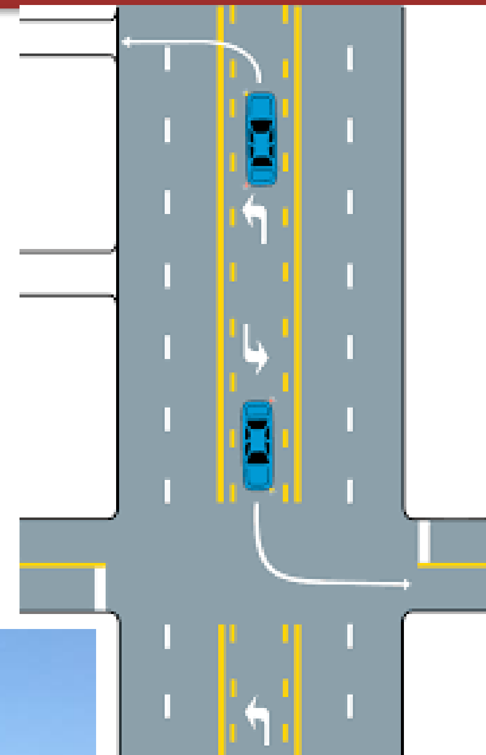
Multilane Highways

- Multilane highways may exhibit some of the following characteristics:
  - Posted speed limits are usually between 60 and 100 km/h
  - They may be undivided or include medians
  - They are located in suburban areas or in high-volume rural corridors
  - They may include a two-way, left-turn median lane (TWLTL)
  - Traffic volumes range from 15,000 to 40,000/day
  - Volumes are up to 100,000/day with grade separations and no cross-median access
  - Traffic signals at major crossing points are possible
  - There is partial control of access

Multilane Highways



Road Diet project in Honolulu, Hawaii.



Typical Capacity Values

Table 13.1: Capacity Under Ideal Conditions for Uninterrupted Flow Facilities

Type of Facility	Free-Flow Speed (mi/h)	Capacity
Freeways	≥70	2,400 pc/h/ln
	65	2,350 pc/h/ln
	60	2,300 pc/h/ln
	55	2,250 pc/h/ln
Multilane Highways	≥60	2,200 pc/h/ln
	55	2,100 pc/h/ln
	50	2,000 pc/h/ln
	50	1,900 pc/h/ln
Two-Lane Highways	All	3,200 pc/h (total, both dir) 1,700 pc/h (max. one dir)

Multilane Highways

- Any two of the following three performance characteristics can describe the level of service (LOS) for a multilane highway:

V_p : Flow rate (pc/h/ln)
S: Average passenger car speed (mi/h)
D: Density defined as number of cars per mi (pc/mi/ln)

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

Although density is the primary parameter in defining the LOS for Multilane highways

Multilane Highways

- Following figure illustrates the level-of-service regimes

Constant up to 1400pc/hr/ln

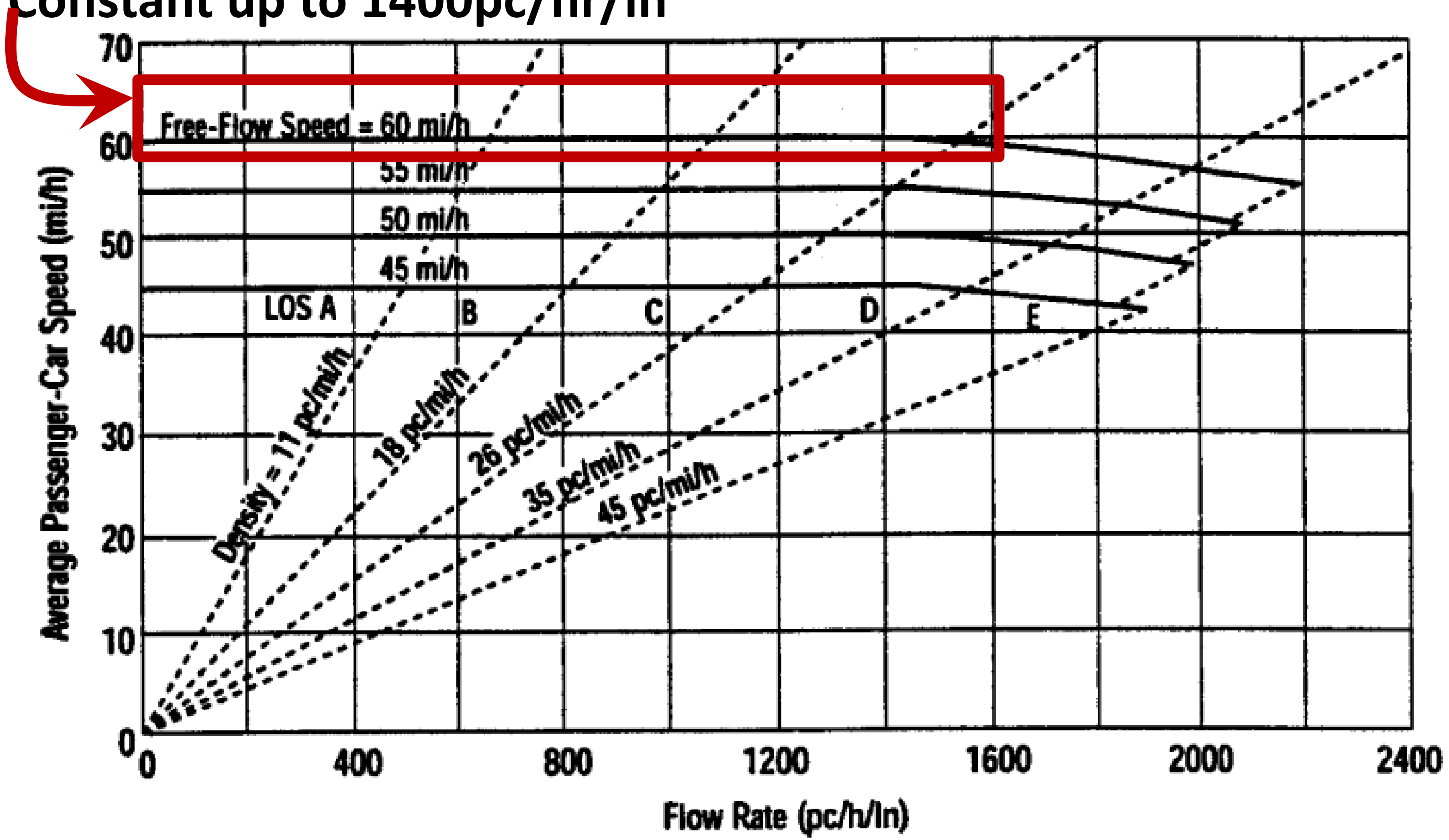


Figure 9.15 Speed-Flow Curves with Level-of-Service Criteria for Multilane Highways

Table 9.33

LOS Criteria of Multilane Highways

Table 9.33 Level-of-Service Criteria for Multilane Highways

Free-Flow Speed	Criteria	LOS A	LOS B	LOS C	LOS D	LOS E
60 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	40
	Average speed (mi/h)	60.0	60.0	59.4	56.7	55.0
	Maximum volume-to-capacity ratio (v/c)	0.30	0.49	0.70	0.90	1.00
	Maximum service flow rate (pc/h/ln)	660	1080	1550	1980	2200
55 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	41
	Average speed (mi/h	55.0	55.0	54.9	52.9	51.2
	Maximum v/c	0.29	0.47	0.68	0.88	1.00
	Maximum service flow rate (pc/h/ln)	600	990	1430	1850	2100
50 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	43
	Average speed (mi/h)	50.0	50.0	50.0	48.9	47.5
	Maximum v/c	0.28	0.45	0.65	0.86	1.00
	Maximum service flow rate (pc/h/ln)	550	900	1300	1710	2000
45 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	45
	Average speed (mi/h)	45.0	45.0	45.0	44.4	42.2
	Maximum v/c	0.26	0.43	0.62	0.82	1.00
	Maximum service flow rate (pc/h/ln)	480	810	1170	1550	1900

Service Flow Rates and Service Volumes

- **A Service Flow (SF) Rate** is defined as the maximum rate of flow that can be reasonably expected on a lane or roadway under prevailing roadway, traffic, and control conditions **while maintaining a particular level of service (LOS)**.
- Each LOS covers a range of values

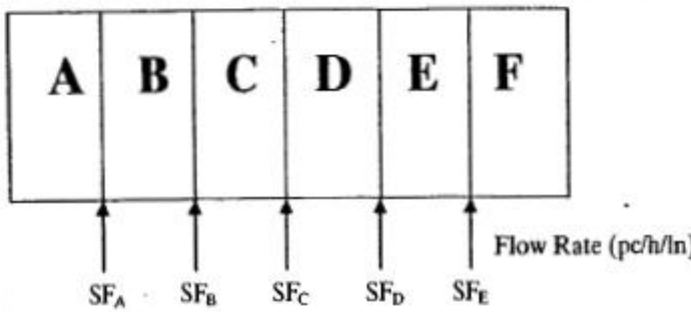


Figure 13.1: Illustration of Levels of Service and Service Flow Rates

- The **SF rate** is defined as the max. flow rate that can be sustained without exceeding the max. density defined for the LOS. There are only 5 SF rates, not 6.
- **LOS F** represents unstable flow; exceeds capacity (mostly LOS E).


LOS A


LOS B


LOS C


LOS D


LOS E


LOS F

Multilane Highways

Calculating the Flow Rate for a Multilane Highway

- The flow rate in pc/h/ln for a multilane highway is computed as:

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

v_p = 15-minute passenger-car equivalent flow rate (pc/h/ln)
V = hourly peak vehicle volume (veh/h) in one direction
N = number of travel lanes in one direction (2 or 3)
f_p = driver population factor with a range of 0.85 to 1.00. Use 1.00 for commuter traffic.

If there is significant recreational or weekend traffic, the value is reduced

Calculating the Flow Rate for a Multilane Highway

f_{HV} = heavy-vehicle adjustment factor (Eq. 9.4)

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

P_T and P_R = decimal portion of trucks/buses and recreational vehicles in the traffic stream

E_T and E_R = passenger car equivalents. Number of cars using the same space as a truck/bus or a recreational vehicle

Calculating the Flow Rate for a Multilane Highway

- To estimate $\mathbf{E_T}$ and $\mathbf{E_R}$ There are two situations that must be considered:

1. Extended general segments

Use **Table 9.25**

2. Specific grades

- *Upgrades: **Tables 9.26 and 9.27***
- *Downgrades:* $\mathbf{E_T}$ *from **Table 9.28** while* $\mathbf{E_R}$ *are treated as if* they were on level terrain

PCEs for trucks & buses can be determined for three grade conditions:

- 1) extended general segments
  - These occur when a single grade is not too long or steep to have significant impact on capacity.
  - When grades ≥ 3% and < ¼ mi, or grades < 3% and < ½ mi
- 2) specific upgrades
  - Any segment's grade ≥ 3% and > ¼ mi, or a grade < 3% and > ½ mi, should be considered as a separate segment.
- 3) specific downgrades.

- **Composite grades:** When a segment of multi-lane highway consists of two or more consecutive upgrades with different slopes, the PCE of heavy vehicles is determined by using :
   1. **The average grade**: by dividing the total rise in elevation by the total horizontal distance. The average grade technique is valid for conditions where grades are < 3% or the total length of the composite grade is < 4000 ft.

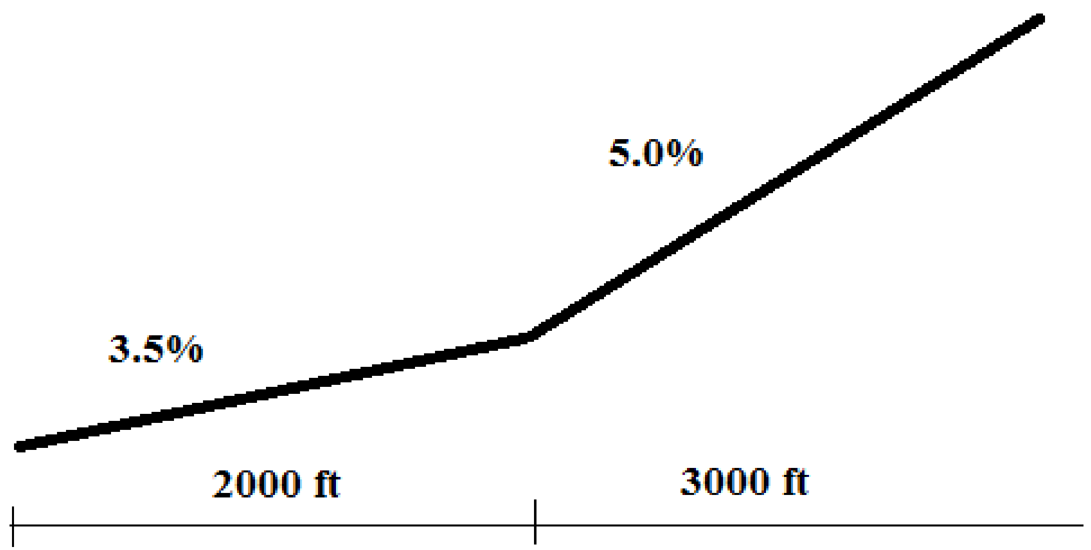
Sample for Average Grade

- The average grade is:

$$(3.5 \times 2000 + 5 \times 3000) / 5000 = 4.4\%$$

Or, Total Rise = 0.035 x 2000 + 0.05 x 3000 = 320 ft

Average Grade = 320 / 5000 = 4.4%



Multilane Highways

Table 9.25 Passenger-Car Equivalents for Trucks and Buses (E_T) and RVs (E_R) on General Highway Segments: Multilane Highways and Basic Freeway Sections

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

Multilane Highways

Table 9.26 Passenger-Car Equivalents for Trucks and Buses (E_T) on Upgrades, Multilane Highways, and Basic Freeway Sections

Upgrade (%)	Length (mi)	E_T: Percentage of Trucks and Buses 2	4	5	6	8	10	15	20	25
< 2	All	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
≥ 2–3	> 0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.50–0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.75–1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	> 1.00–1.50	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 1.50	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
> 3–4	> 0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	> 0.50–0.75	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	> 0.75–1.00	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	> 1.00–1.50	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	> 1.50	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
> 4–5	> 0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 0.50–0.75	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	> 0.75–1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	> 1.00	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
> 5–6	> 0.00–0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.30	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 0.30–0.50	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	> 0.50–0.75	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0
	> 0.75–1.00	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	> 1.00	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
> 6	> 0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	> 0.25–0.30	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	> 0.30–0.50	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	> 0.50–0.75	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	> 0.75–1.00	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	> 1.00	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

Multilane Highways

Table 9.27 Passenger-Car Equivalents for RVs (E_R) on Uniform Upgrades, Multilane Highways, and Basic Freeway Segments

		E_R								
		Percentage of RVs								
Grade (%)	*Length (mi)*	*2*	*4*	*5*	*6*	*8*	*10*	*15*	*20*	*25*
≤ 2	All	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
> 2–3	> 0.00–0.50	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	> 0.50	3.0	1.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2
> 3–4	> 0.00–0.25	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	> 0.25–0.50	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	> 0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
> 4–5	> 0.00–0.25	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0
	> 0.50	4.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0
> 5	> 0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5
	> 0.25–0.50	6.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0
	> 0.50	6.0	4.5	4.0	4.5	3.5	3.0	3.0	2.5	2.0

Multilane Highways

Table 9.28 Passenger-Car Equivalents for Trucks (E_T) on Downgrades, Multilane Highways, and Basic Freeway Segments

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

Downgrades: $\mathbf{E_T}$ *from* ***Table 9.28*** *while* $\mathbf{E_R}$ *are treated as if* they were on level terrain

Calculating the Average Passenger Car Speed (S), Density (D), and Level of Service (LOS) for a Multilane Highway

- FFS could be **field measured (no adjustment)**, or computed.

Step 1. Compute the Value of Free-Flow Speed. Use Eq. 9.25 to estimate FFS:

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A \tag{9.25}$$

where

FFS = estimated free-flow speed (mi/h)
$BFFS$ = base free-flow speed (mi/h). In the absence of field data, a default value of 60 mi/h is used for rural/suburban miltilane highways
f_{LW} = adjustment for lane width (Table 9.29)
f_{LC} = adjustment for lateral clearance (Table 9.34)
f_M = adjustment for median type (Table 9.35)
f_A = adjustment for access-point density (Table 9.36)

Table 9.29 Adjustment (f_{LW}) for Lane Width

Lane Width (ft)	*Reduction in FFS, f_{LW} (mi/h)*
12	0.0
11	1.9
10	6.6

Table 9.34 Adjustment (f_{LC}) for Lateral Clearance

Four-Lane Highways		*Six-Lane Highways*	
Total Lateral Clearance (ft)	*Reduction in FFS (mi/h)*	*Total Lateral Clearance (ft)*	*Reduction in FFS (mi/h)*
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

Table 9.35 Adjustment (f_M) for Median Type

Median Type	*Reduction in FFS (mi/h)*
Undivided highways	1.6
Divided highways (including TWLTLs)	0.0

Table 9.36 Adjustment (f_A) for Access-Point Density

Access Points/Mile	*Reduction in FFS (mi/h)*
0	0.0
10	2.5
20	5.0
30	7.5
$40	10.0

- Lateral Clearance: a total from both sides.
- Ideal = 12 ft (6 from each side)
- Maximum accounted for each side is 6 ft
- For example, right side has a LC = 10 ft, left side = 4 ft, then total clearance = 6 (maximum from the right) + 4 = 10 ft

Example - Multi-Lane Highway

- A four-lane undivided multilane highway in a suburban area has the following characteristics: **posted speed limit = 50 mi/h**; 11-foot lanes; Lateral clearance = 10 ft; 30 access points/mi on the right side of the facility. What is the free-flow speed for the direction described?
- **Solution:**
  - Since posted speed limit is 50 mi/hr, the BFFS may be assumed to be 5 or 10 mi/hr greater
  - Assume BFFS = 55 mi/hr
  - f_{LW} = 1.9 mi/h (Table 9.29, 11-ft lanes)
  - f_{LC} = 0.4 mi/h (Table 9.34)
  - f_M = 1.6 mi/h (Table 9.35)
  - f_A = 7.5 mi/h (Table 9.36 access points/mi)
  - FFS = 55 – 1.9 – 0.4 – 1.6 – 7.5 = 43.6 mi/hr

Example 9.16

Determining the LOS of a Multilane Highway Segment of Uniform Grade

- A 3200 ft segment of 3.25-mi four-lane undivided multilane highway in a suburban area is at a 1.5% grade.
- The highway is in level terrain, and lane widths are 11 ft.
- **The measured free-flow** speed is 46.0 mi/h.
- The peak-hour volume is 1900 veh/h, PHF is 0.90, and there are 13% trucks and 2% RVs.
- Determine the LOS, speed, and density for upgrade and downgrade.

Solution:

- Compute v_p using Eqs. 9.4 and 9.22.
  Input data:

$$V = 1900 \text{ veh/h}$$
$$PHF = 0.90$$
$$N = 2$$
$$f_p = 1.00$$
$$f_{HV} = 0.935 \text{ computed from Eq. 9.4}$$
$$E_T = 1.5,\ E_R = 1.2 \text{ (Table 9.25) since 1.5 percent grade is considered level terrain}$$
$$P_T = 0.13,\ P_R = 0.02$$

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

$$= \frac{1}{1 + 0.13(1.5 - 1) + 0.02(1.2 - 1)} = 0.935$$

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

$$= \frac{1900}{(0.90)(2)(1.00)(0.935)} = 1129 \text{ pc/h/ln}$$

Thus,

$$S = FFS = 46 \text{ mi/h (since } v_p < 1400)$$

- Compute density from Eq. 9.21.

$$D = \frac{v_p}{S} = \frac{1129}{46} = 24.5 \text{ pc/mi/ln}$$

LOS C (Table 9.33).

- Compute v_p using Eq. 9.21 for the upgrade direction.

Input data:

$$V = 1900$$

$$PHF = 0.9$$

$N = 2$
$f_p = 1.00$
$f_{HV} = 0.905$ computed from Eq. 9.4
$E_T = 1.5$, (Table 9.26) ~~$E_R = 3.0$~~ (Table 9.27)
$P_T = 0.13$, $P_R = 0.02$

$E_R = 1.2$

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

$$= \frac{1}{1 + 0.13(1.5 - 1) + 0.02(3.0 - 1)} = 0.905$$

$f_{HV} = 0.935$

$$v_p = \frac{V}{(PHF)(N)(f_p)(f_{HV})} = \frac{1900}{(0.90)(2)(1.00)(0.905)} = 1166 \text{ pc/h/ln}$$

Thus,

$$\text{FFS} = 46 \text{ mi/h (since } v < 1400)$$

- Compute density from Eq. 9. 21

$$D = \frac{v_p}{S} = \frac{1166}{46} = 25.3 \text{ pc/mi/ln}$$

LOS C (Table 9.33).

Multi-Lane Highway - Design

- Determine the number of lanes required for a divided multi-lane highway of 0.35-mi long and a 4.5% grade, if the section is to operate at LOS C. The following design features apply to this section:
  - V 3000 veh/h (weekly commuter traffic)
  - PHF 0.95
  - Trucks and Buses 10%
  - RVs 2%
  - Base Free Flow Speed (BFFS) = 50 mi/h
  - Lane width 11 ft
  - Lateral obstruction: None
  - Access spacing 1 mi (no access within the section)
  - Driver population – familiar drivers

Compute free-flow speed.

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

- **BFFS = 50**
- **f_{LW} = 1.9**
- **f_{LC} = 0.0**
- **f_M = 0.0**
- **f_A = 0.0**
- **FFS = 50 – 1.9 = 48.1 mph**

- **Then, use FFS = 50 mph**
- **Maximum SF @ LOS C for S = 50 mph = 1300 pc/hr/ln (Table 9.33)**

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Table 9.33

LOS Criteria of Multilane Highways

Table 9.33 Level-of-Service Criteria for Multilane Highways

Free-Flow Speed	Criteria	LOS A	LOS B	LOS C	LOS D	LOS E
60 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	40
	Average speed (mi/h)	60.0	60.0	59.4	56.7	55.0
	Maximum volume-to-capacity ratio (v/c)	0.30	0.49	0.70	0.90	1.00
	Maximum service flow rate (pc/h/ln)	660	1080	1550	1980	2200
55 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	41
	Average speed (mi/h	55.0	55.0	54.9	52.9	51.2
	Maximum v/c	0.29	0.47	0.68	0.88	1.00
	Maximum service flow rate (pc/h/ln)	600	990	1430	1850	2100
50 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	43
	Average speed (mi/h)	50.0	50.0	50.0	48.9	47.5
	Maximum v/c	0.28	0.45	0.65	0.86	1.00
	Maximum service flow rate (pc/h/ln)	550	900	1300	1710	2000
45 mi/h	Maximum density (pc/mi/ln)	11	18	26	35	45
	Average speed (mi/h)	45.0	45.0	45.0	44.4	42.2
	Maximum v/c	0.26	0.43	0.62	0.82	1.00
	Maximum service flow rate (pc/h/ln)	480	810	1170	1550	1900

Solution:

Determine PCE equivalents.

$$E_T = 2.0 \text{ (Table 9.26)}$$
$$E_R = 4.0 \text{ (Table 9.27)}$$

Compute heavy-vehicle adjustment factor

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

$$f_{HV} = \frac{1}{1 + 0.1(2 - 1) + 0.02(4 - 1)} = 0.86$$

Convert vehicle/hour to peak 15-minute passenger-car equivalent flow rate for two, three, and four lanes.

$$v_P = \frac{V}{PHF \times N \times f_p \times f_{HV}}$$
$$= \frac{3000}{0.95 \times 2 \times 1.00 \times 0.86}$$
$$= 1834 \text{ pc/h/ln}$$

For $N = 3$ $\quad v_p = 1223$ pc/h/ln
For $N = 4$ $\quad v_p = 917$ pc/h/ln

Then, 3 lanes are required

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Or an alternate way (not highly accurate)

– **FFS 48.1 mph (calculated before)**

- **Density (D = v_p / S). Maximum D at LOS C = 26 pc/mi/ln**
- **26 = v_p / 48.1; v_p = 1251 pc/hr/ln**
- **N = 3000 / (1251 x 0.95 x 1.0 x 0.86)**
- **N = 2.94 lanes; 3 lanes are required in each direction**

- Another type of question is **<u>how much (additional) traffic</u>** the highway can accommodate to maintain specific LOS.
- **<u>(Example)</u>** A 6-lane multi-lane highway with a measured FFS of 47 mph and a directional flow rate of 2000 veh/hr on rolling terrain and PHF of 0.90. f_{HV} = 0.89. Determine how much additional traffic the highway can accommodate to maintain LOS C?
- Maximum service volume for LOS C = 1170 pc/hr/ln
- 1170 = V / {(0.90)(3)(1.0)(0.89)}
- V = 2812 veh/hr
- Therefore, additional traffic = 2812 – 2000 = 812 veh/hr

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

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Chapter 6
Capacity and LOS of Multi-Lane Highways and Freeway Sections