MUSTANSIRIYAH UNIVERSITY

COLLEGE OF ENGINEERING

HIGHWAY AND TRANSPORTATION ENGINEERING DEPARTMENT

POSTGRADUATE/MSC

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ADVANCED TRAFFIC ENGINEERING

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LECTURE 7:

UNINTERRUPTED FLOW FACILITIES: CAPACITY AND LEVEL OF SERVICE

1. CORE DEFINITIONS

- **Volume (v)**
  The **actual number of vehicles counted** passing a specific point during a given time (usually 1 hour). → What is observed.

- **Demand (d)**
  The **number of vehicles wishing to pass** a point during the period, including:

- Those that successfully pass (volume), and
- Those prevented from doing so due to congestion or delays (queued or diverted vehicles).
  → What motorists want to do.

- **Capacity (c)**
  The **maximum sustainable rate of flow** that a roadway can handle under stable conditions (vehicles/hour).
  → What is physically possible.

Capacity is the maximum hourly rate at which persons or vehicles can be reasonably expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions.

2. KEY CONCEPTS IN CAPACITY ANALYSIS

(a) **Maximum Hourly Rate**

- Capacity is defined as a maximum hourly rate (veh/h or person/h).
- Typically measured for the peak 15 minutes of the peak hour.
- It is critical that volume, demand, and capacity are expressed in the same time units and terms.

(b) Persons vs. Vehicles

- Capacity may be expressed as
  - **Vehicle capacity** (veh/h/lane) → for general traffic.
  - **Person capacity** (persons/h/lane) → for multimodal systems, HOV lanes, and transit.
- With increasing multimodal focus, **person-based capacity** is often more meaningful for urban design.

(c) Prevailing Roadway, Traffic, and Control Conditions

- Capacity is not fixed — it depends on:
  - Roadway geometry: **number of lanes, lane width, shoulders, alignment.**
  - Traffic composition: **cars, trucks, buses, RVs (affect Passenger Car Equivalents, PCEs).**
  - Control conditions: **mainly relevant for interrupted facilities (signals, stop signs).**
- A change in any of these conditions → a change in capacity.

(d) Point or Uniform Segment

- Capacity applies to a point (e.g., a ramp, merge, or intersection) or a uniform segment of a facility.
- "Uniform" means consistent prevailing conditions throughout the segment.

(e) Reasonable Expectancy

- Capacity is based on expected achievable flow, not the single highest rate ever observed.
- It incorporates stochastic variability (random fluctuations in driver behavior, demand, or weather).
- Implies that capacity values represent flows achievable most of the time under similar conditions.

. DEFINITION OF UNINTERRUPTED FLOW

Uninterrupted flow exists when vehicles move without external control devices that interrupt traffic. Instead, all vehicles enter and exit using high-speed ramps or controlled access points.

All interruptions are internal, meaning they arise from interactions among vehicles within the traffic stream — such as lane changing, merging, or driver behavior — not from external control.

- No fixed interruptions (no signals or stop-controlled intersections).
- No direct access to adjacent properties.
- Flow is continuous but can still experience congestion, particularly during peak hours — congestion here is a result of demand exceeding capacity, not external stops.

Capacity and LOS analyses quantify maximum flow rates and quality of traffic operation. They guide design optimization and performance evaluation.

While freeways represent the most classic case, other roads may also exhibit uninterrupted flow if they are sufficiently distant from fixed interruptions.

Type	Definition / Conditions	Key Characteristics
Freeways	Fully controlled-access highways with no at-grade intersections.	Pure uninterrupted flow; typical of high-speed, high-volume facilities.
Multilane Highways	Four or six-lane roads (>2 miles from any fixed control).	Operate similarly to freeways but often have adjacent land access and more environmental influences.
Rural Two-Lane Highways	One lane per direction, >2 miles from any fixed control.	Uninterrupted, but with one critical feature — passing occurs in the opposing lane, so flows in each direction interact.

Facility Type	External Controls?	Access Points	Flow Interaction	Example Analysis Metric
Freeway	None	Ramps only	Independent per direction	LOS (A–F) based on flow rate per lane
Multilane Highway	None (>2 mi apart signals)	Some driveways	Independent	Speed–flow–density relationship
Rural Two-Lane	None (>2 mi apart signals)	Few accesses	Interacting directions	Percent time following / passing opportunities

CURRENT VALUES OF CAPACITY (HCM 2010)

Freeways & Multilane Highways:

- Capacity is directly related to free-flow speed:
  - Higher free-flow speed → higher capacity.
  - Lower free-flow speed → lower capacity.

- Free-flow speed is affected by:
  - Narrow lanes or shoulders,
  - Median type (for multilane highways),
  - Ramp density (for freeways),
  - Roadside access points (for multilane highways).

Two-Lane Highways:

- Capacity does not depend on free-flow speed, since speed is constrained by passing opportunities and opposing flow interactions.
- Expressed as total capacity in both directions, recognizing that passing occurs in the opposing lane.

Capacity Under Ideal Conditions

Type of Facility	Free-Flow Speed (mi/h)	Capacity (pc/h/ln)
Freeways	≥70	2,400
	65	2,350
	60	2,300
	55	2,250
Multilane Highways	≥60	2,200
	55	2,100
	50	2,000
	45	1,900
Two-Lane Highways	All	3,200 (both directions) or 1,700 (one direction)

THE LEVEL OF SERVICE (LOS) CONCEPT

Definition:

Level of Service (LOS) describes the overall quality of traffic operations experienced by motorists or passengers on a given facility under prevailing roadway, traffic, and control conditions.

LOS provides a **qualitative** measure of performance (comfort, convenience, freedom to maneuver, stability of flow) using a letter scale (A–F).

LOS	Description	General Condition
A	Free flow	Minimal delay, high speed, low density
B	Reasonably free flow	Slight restrictions, stable flow
C	Stable flow	Noticeable interaction among vehicles
D	Approaching unstable	Speeds decline, reduced comfort
E	At capacity	Unstable flow, minimal gaps, risk of breakdown
F	Breakdown	Demand > capacity, stop-and-go conditions

Relationship Between LOS and Capacity

- Capacity represents the maximum flow achievable under prevailing conditions.
- LOS grades the quality of flow below or up to capacity.
- At LOS E, the facility is operating at or near capacity; LOS F indicates failure (demand exceeds capacity).

SERVICE FLOW RATE (SF) AND SERVICE VOLUME (SV)

Service Flow Rate (SF): The maximum flow rate (veh/h/ln) that can be expected while maintaining a specified LOS.

In other words, it is a "capacity at a given LOS."

$$SF_i = \text{maximum flow rate for LOS } i$$

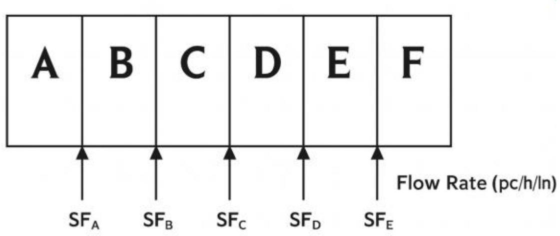
- For LOS **E**, $SF_E = \text{capacity}$
- For LOS **A–D**, $SF_i < \text{capacity}$
- No SF_F because LOS F is **unstable flow** (breakdown condition).

Service Volume (SV): Represents the actual hourly volume (veh/h) that can be served at a given LOS, calculated using the Peak Hour Factor (PHF):

$$SV_i = SF_i \times PHF$$

Where:

- SV_i = service volume for LOS i (veh/h)
- SF_i = service flow rate for LOS i (veh/h)
- PHF = peak hour factor (typically 0.85–0.95)



This figure shows that:

- **Each LOS (A–E)** corresponds to a range of flow rates.
- **LOS F** has no fixed SF because it represents unstable, oversaturated **flow**.
- The boundary between LOS E and F represents c**apacity**.

Interpretation:

Two segments operating at the same LOS (e.g., D) may still differ slightly in density or delay, depending on where within the LOS range they lie.

THE VOLUME-TO-CAPACITY (V/C) RATIO

The **v/c ratio** measures how efficiently a facility is operating relative to its capacity.

$$\frac{v}{c} = \frac{\text{current or projected volume (demand)}}{\text{capacity of the facility}}$$

v/c Ratio	Interpretation
< 0.85	Under capacity (good LOS A–C)
0.85–1.00	Near capacity (LOS D–E, unstable)
> 1.00	Oversaturated (LOS F, queues form)

- A v/c > 1.00 indicates that demand exceeds capacity, causing queue formation and upstream congestion.
- Queues dissipate only when demand drops below capacity.
- Long-term v/c > 1.0 triggers design or policy interventions.

BASIC FREEWAY SEGMENTS AND MULTILANE HIGHWAYS

MULTILANE UNINTERRUPTED FLOW FACILITIES

- Road segments that allow continuous (uninterrupted) vehicle flow between fixed interruptions (mainly traffic signals).
- **Freeways:** Pure uninterrupted flow.
  - Full access control (only via ramps).
  - No at-grade intersections, no driveway access, no parking.
  - Classified by total lanes per direction: 4-, 6-, 8-, or even 10-lane freeways in large urban areas.
- **Multilane Highways:**
  - Partial access control; may have at-grade intersections.
  - Uninterrupted if signal spacing > 2 miles.
  - If spacing < 1 mile → arterial (interrupted).
  - Between 1–2 miles: conditional; depends on coordination of signals.
- **Median Treatment and Alignment:**
  - **Divided:** Physical median separates opposing flows; midblock left turns only at breaks in the median.
  - **Undivided:** Two-way traffic separated only by painted markings.
  - **Two-Way Left-Turn Lane (TWLTL):** Center Lane used for left turns from both directions (typically 3, 5, or 7 lanes total).

BASIC FREEWAY AND MULTILANE HIGHWAY CHARACTERISTICS

Speed–Flow Characteristics

- **Analysis Basis:**
  Both freeway and multilane highway analyses are based on **calibrated speed–flow curves** under **Base Conditions**:
  - No heavy vehicles in the stream
  - Regular, experienced drivers
  - Good weather, dry pavement, and ideal geometry

- **Key Concept:**

  - Free-Flow Speed (FFS): Speed when flow ≈ 0 on the curve.
  - Capacity**:** Maximum flow rate before unstable conditions begin.
  - Freeways: FFS maintained until 1000–1800 pc/h/ln.
  - Multilane highways: FFS maintained up to 1400 pc/h/ln.

Figures 14.2 and 14.3 show the standard curves calibrated for use in the capacity analysis of basic freeway sections and multilane highways. These exhibits also show the density lines that define levels of service for uninterrupted flow facilities.

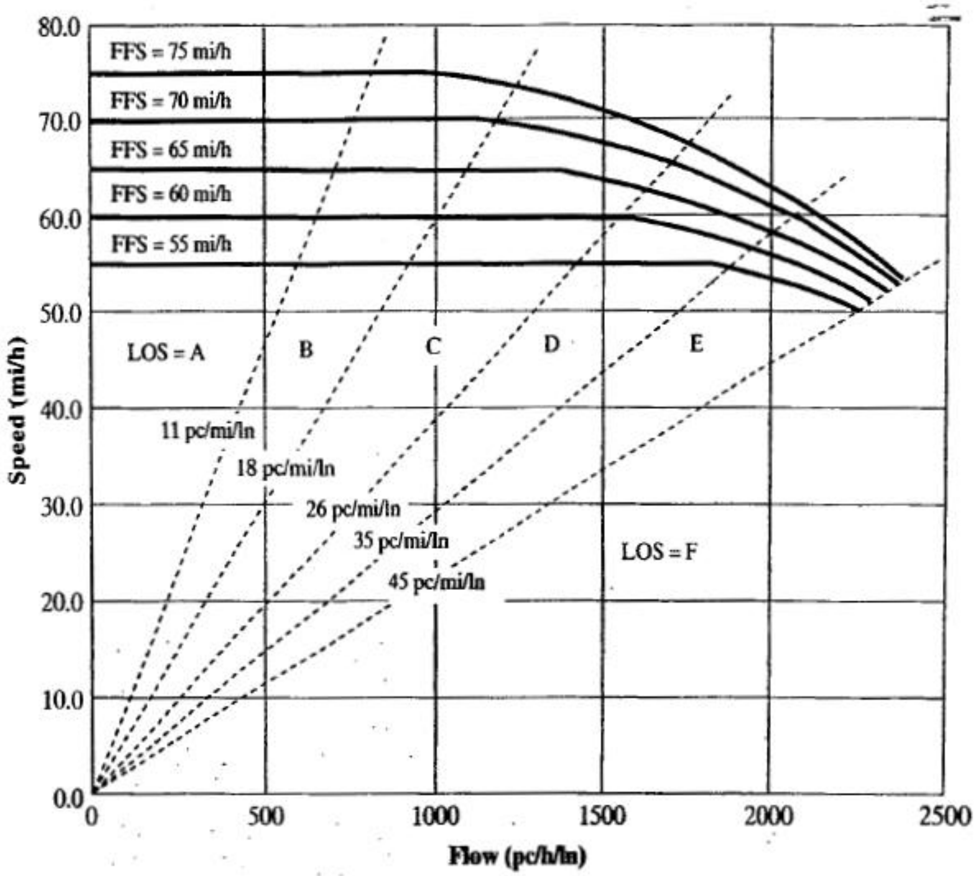


Figure 14.2: Base Speed-Flow Curves for Freeways

(*Source: Basic Freeway Segments*, Draft Chapter 11, NCHRP Project 3-92, Production of the 2010 *Highway Capacity Manual*, Kittelson and Associates, Portland OR, 2009, Exhibit 11-6, p. 11-8.)

Table 14.1 provides equations for the freeway curves of Figure 14.2, which -are comprised of three linear segments.

Table 14.1: Equations for Curves in Figure 14.1

FFS (mi/h)	Break-Point (pc/h/ln)	Flow Rate Range ≥ 0 ≤ Break-Point	> Break-Point ≤ Capacity
75	1,000	75	$75 - 0.00001107\,(v_p - 1{,}000)^2$
70	1,200	70	$70 - 0.00001160\,(v_p - 1{,}200)^2$
65	1,400	65	$65 - 0.00001418\,(v_p - 1{,}400)^2$
60	1,600	60	$60 - 0.00001816\,(v_p - 1{,}600)^2$
55	1,800	55	$55 - 0.00002469\,(v_p - 1{,}800)^2$

Notes:
1. FFS = free-flow speed.
2. Maximum flow rate for the equations is capacity: 2,400 pc/h/ln for 70- and 75-mph FFS; 2,350 pc/h/ln for 65-mph FFS; 2,300 pc/h/ln for 60-mph FFS; and 2,250 pc/h/ln for 55-mph FFS.

(*Source: Basic Freeway Segments*, Draft Chapter 11, NCHRP Project 3-92, Production of the 2010 *Highway Capacity Manual*, Kittelson and Associates, Portland OR, 2009, Exhibit 11-3, p. 11-4.)

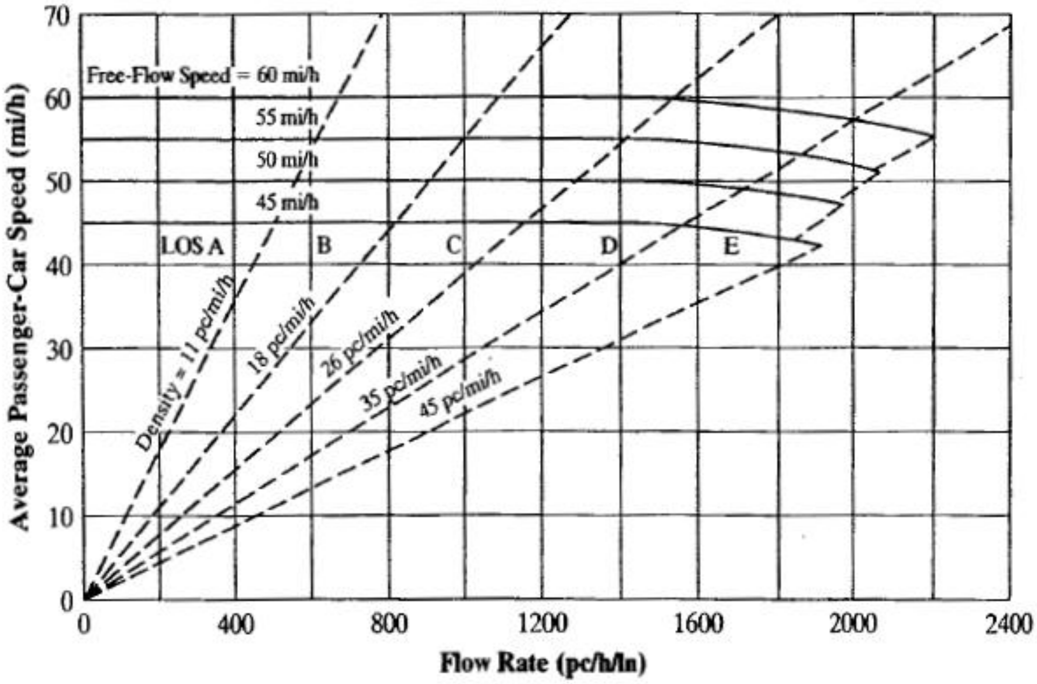
Complex equations for multilane highways are shown in Figure 14.3, but the curves were originally graphic fits, and direct graphic use of the curves is recommended.

- The break-point identifies the flow rate (in passenger cars per hour per lane) where the speed–flow curve transitions from a constant free-flow region to a declining-speed region.
- Before the break-point, speed remains nearly constant at FFS.
- After the break-point, speeds start to decrease as flow increases due to interactions among vehicles.
- When flow rate is below or equal to the break-point**,**→ Speed = FFS (constant) When flow exceeds the break-point but remains below capacity, **speed decreases quadratically** with flow, as shown by:

$$S = \text{FFS} - a(v_p - \text{Break-Point})^2$$

Where:

- v_p: flow rate (pc/h/ln)
- a: empirical constant (varies with FFS)
- The value of a is given for each FFS (see table).



Equations for Curves

FFS (mi/h)	For v ≤ 1,400 pc/h/ln S (mi/h)	For v > 1,400 pc/h/ln S (mi/h)
60	S=60	$S = 60 - \left[5.00\left(\frac{v_p - 1{,}400}{800}\right)^{1.31}\right]$
55	S=55	$S = 55 - \left[3.78\left(\frac{v_p - 1{,}400}{700}\right)^{1.31}\right]$
50	S=50	$S = 50 - \left[3.49\left(\frac{v_p - 1{,}400}{600}\right)^{1.31}\right]$
45	S=45	$S = 45 - \left[2.78\left(\frac{v_p - 1{,}400}{500}\right)^{1.31}\right]$

Figure 14.3: Base Speed-Flow Curves for Multilane Highways

(*Source:* Used with permission of Transportation Research Board, National Research Council, from *Highway Capacity Manual*, December 2000, Exhibit 21-3, p. 21–4.)

Example Calculation

For a freeway with:

- $FFS = 70 \text{ mi/h}$
- Flow $v_p = 1800 \text{ pc/h/ln}$

Since $v_p > 1200$:

$$S = 70 - 0.00001160(1800 - 1200)^2$$

= 65.8 mi/h

LEVELS OF SERVICE (LOS)

- **Primary Measure:** Density (pc/mi/ln)
  Density is preferred to speed because it reflects vehicle proximity and maneuverability freedom.
  $v = S \times D$

- **Critical Density at Capacity:**
  - Freeways: ≈ 45 pc/mi/ln
  - Multilane: 40–45 pc/mi/ln depending on FFS

- For uninterrupted flow facilities, the density boundary between levels of service E and F is defined as the density which capacity occurs. The speed-flow curves determine this critical boundary.
- For freeways, the curves indicate a constant density of 45 pc/mi/ln.
- For multilane highways, capacity occurs at densities ranging from 40 to 45 pc/mi/ln, depending on the free-flow speed of the segment.
- Other level-of-service boundaries are set judgmentally by the Highway Capacity and Quality of Service Committee (HCQSC) to provide reasonable ranges of both density and service flow rates.

Table 14.2 shows the defined level of-service criteria for basic freeway sections and multilane Highways

Table 14.2: Level of Service Criteria for Basic Freeway Segments and Multilane Highways

Level of Service	Density Range for Basic Freeway Sections (pc/mi/ln)	Density Range for Multilane Highways (pc/mi/ln)
A	≥0≤11	≥0≤11
B	>11≤18	>11≤18
C	>18≤26	>18≤26
D	>26≤35	>26≤35
E	>35≤45	>35≤(40–45) depending on FFS
F	Demand Exceeds Capacity >45	Demand Exceeds Capacity >(40–45) depending on FFS

Level of Service A – Free-Flow

- Describes unconstrained operations at very low densities.
- Drivers can select desired speeds freely; vehicle interactions are minimal.
- Speed ≈ FFS (Free-Flow Speed).
- Lane changing, merging, and diverging maneuvers are easily performed.
- Typical spacing: ~480 ft (≈ 24 car lengths).
- Minor lane blockages cause no significant disruption.

Level of Service B – Stable Flow

- Drivers begin to respond to other vehicles in the traffic stream.
- Operations remain near free-flow but require more driver attention.
- Still sufficient gaps for maneuvers; slight speed fluctuations may occur.
- Typical spacing: ~293 ft (≈ 15 car lengths).
- Minor disturbances may slightly affect flow.

Level of Service C – Stable Flow (Noticeable Interaction)

- Influence of other vehicles is clearly felt.
- Maneuverability becomes restricted; drivers must adjust paths to pass or merge.
- Vigilance is higher; spacing between vehicles decreases.
- Typical spacing: ~203 ft (≈ 10 car lengths).
- Flow remains stable, but small disturbances may propagate through the stream.

Level of Service D – Approaching Unstable Flow

- Average speeds decline noticeably with increasing flow.
- Maneuvering is difficult; gaps must often be searched for over time.
- Traffic stream cannot absorb minor disruptions — queues form quickly.
- Typical spacing: ~151 ft (≈ 7 car lengths).
- Reflects the onset of congestion; drivers operate under constrained conditions.

Level of Service E – At Capacity

- Maximum density and flow rate that can be maintained without breakdown.
- No usable gaps exist for lane changes; speeds fluctuate sharply.
- Even small disturbances cause shock waves and queuing.
- Typical spacing: ~117 ft (≈ 6 car lengths).
- Operation is unstable, representing capacity conditions.

Level of Service F – Breakdown / Forced Flow

- Demand exceeds capacity ($v/c > 1.0$).
- Vehicles form queues and experience stop-and-go flow.
- Breakdown point occurs due to insufficient capacity.
- Actual discharge speed may still be high within the queue, but flow is constrained.
- Density > 45 pc/mi/ln (for freeways).
- Describes forced or breakdown flow; long-term queues may persist.

SERVICE FLOW RATES AND CAPACITY

- **Maximum Service Flow Rate (MSF):** The maximum hourly flow rate per lane (pc/h/ln) that can be sustained under base (ideal) conditions at a specific Level of Service (LOS).
- These values are derived from speed–flow curves (Figures 14.2 and 14.3).
- All values are rounded to the nearest 10 pc/h/ln.

Table 14.3 Maximum Service Flow Rates for Basic freeway Sections

FFS (mi/h)	LOS A	LOS B	LOS C	LOS D	LOS E (Capacity)
75	820	1,310	1,750	2,110	2,400
70	770	1,250	1,690	2,080	2,400
65	710	1,170	1,630	2,030	2,350
60	660	1,080	1,560	2,010	2,300
55	600	990	1,430	1,900	2,250

- Freeway capacity (LOS E) varies 2,250–2,400 pc/h/ln, depending on FFS.
- Higher FFS → slightly higher capacity and service flow at all LOS levels.
- Example: A 70-mi/h freeway can sustain 1,690 pc/h/ln at LOS C, and 2,400 pc/h/ln at LOS E.

Table 14.4 Maximum Service Flow Rates for Multilane highway

FFS (mi/h)	LOS A	LOS B	LOS C	LOS D	LOS E (Capacity)
60	660	1,080	1,550	1,980	2,200
55	600	990	1,430	1,850	2,100
50	540	910	1,300	1,710	2,000
45	490	810	1,170	1,550	1,900

- Multilane highway capacity (LOS E) ≈ 1,900–2,200 pc/h/ln.
- Capacity and flow rates are lower than freeways due to access points and lower design quality.
- Example: A 55-mi/h multilane highway can sustain 1,430 pc/h/ln at LOS C and 2,100 pc/h/ln at LOS E.
- Freeways have higher MSF values due to full access control (no intersections).
- Multilane highways have slightly reduced performance due to side friction (access, driveways, etc.).
- LOS E = Capacity, where $v/c = 1.0$ and density ≈ 45 pc/mi/ln.
- As FFS decreases, the capacity and LOS flow rates decline proportionally.

Analysis Methodologies for Basic Freeway Sections and Multilane Highways

This section explains how to analyze **operational conditions**, **service flow rates**, and **design lane requirements** for uninterrupted-flow facilities under both **base** and **prevailing** conditions.

Because "base conditions" rarely exist in reality, adjustment factors are applied to account for prevailing features such as geometry, traffic composition, and driver behavior.

PREVAILING CONDITIONS AFFECTING ANALYSIS

Key factors that modify performance include:

- **Lane widths** (narrow lanes reduce capacity and speed)
- **Lateral clearances** (restricted shoulders or barriers reduce driver comfort)
- **Type of median** (for multilane highways)
- **Frequency of ramps or access points** (introduces turbulence in flow)
- **Presence of heavy vehicles** (trucks, buses affect equivalent flow rate)
- **Driver population** (occasional/unfamiliar users reduce performance)

Some of these affect the **Free-Flow Speed (FFS)**, others influence the **equivalent flow rate (v_p)**.

TYPES OF ANALYSIS

Three types of analysis are used in the HCM framework:

Type	Purpose	Main Output
Operational Analysis	Evaluates current or projected conditions	Level of Service (LOS), speed, and density
Service Flow Rate & Service Volume Analysis	Determines service flow or volume for specific LOS	Flow rate (pc/h/ln) and total hourly volume (veh/h)
Design Analysis	Determines number of lanes required for a target LOS	Required lanes (N_i) for given DDHV

An additional type, **Planning Analysis**, uses AADT (Average Annual Daily Traffic) converted to DDHV (Directional Design Hour Volume) to estimate capacity needs.

1. Operational Analysis

Used for existing or forecast conditions to determine **speed**, **density**, and **LOS**.

Step 1 – Compute Equivalent Flow Rate

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

where:

- v_p = demand flow rate per lane under ideal conditions (pc/h/ln)
- V = observed or projected volume (veh/h)
- PHF = peak-hour factor
- N = number of lanes (one direction)
- f_{HV} = heavy-vehicle adjustment factor
- f_p = driver population adjustment factor

Step 2 – Determine Speed and LOS

Using vp enter Figure 14.2 **(for freeways**) or **Figure 14.3** (for multilane highways).
Find intersection with the curve corresponding to the **Free-Flow Speed (FFS)** to determine:

- **Average speed (S)**
- **Density (D = v_p / S)**
- **Level of Service (LOS)**

Example (Freeway):

- $v_p = 1800\,\mathrm{pc/h/ln}$, $FFS = 65\,\mathrm{mi/h}$
  → From the curve, $S = 62\,\mathrm{mi/h}$
  → $D = 1800/62 = 29.0\,\mathrm{pc/mi/ln}$
  → Corresponds to **LOS D**.

If more accuracy is needed, use the equation (from Table 14.1):

$$S = 65 - 0.00001418(v_p - 1400)^2$$

→ $S = 62.7\,\mathrm{mi/h}$

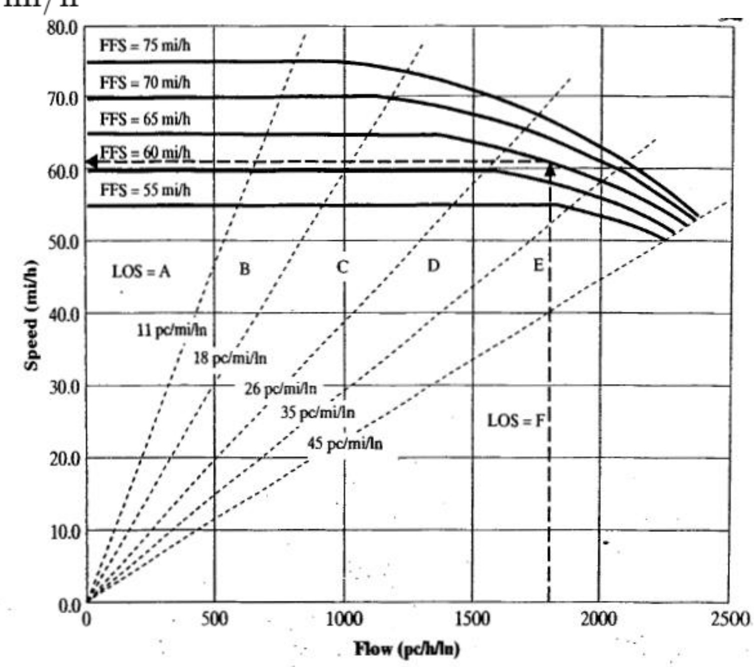


Figure 14.4: Graphic Solution for Speed on a Basic Freeway Segment

2. Service Flow Rate and Service Volume Analysis

Used to determine the **flow rate or volume corresponding to a desired LOS**.

Step 1- Service Flow Rate

$$SF_i = MSF_i \times f_{HV} \times f_p$$

where:

- SF_i = service flow rate (pc/h/ln) for LOS i
- MSF_i = maximum service flow rate (from Tables 14.3 or 14.4)
- f_{HV}, f_p = adjustment factors

(b) Service Volume

$$SV_i = SF_i \times PHF$$

This gives the veh/h per lane or per direction volume during the peak hour.

2. Design Analysis

Determines the number of lanes (N_i) needed to achieve a target LOS for a given DDHV (Directional Design Hour Volume).

$$N_i = \frac{DDHV}{PHF \times MSF_i \times f_{HV} \times f_p}$$

where:

- N_i = required lanes (rounded up to nearest integer)
- $DDHV$ = directional design hour volume (veh/h)
- MSF_i, f_{HV}, f_p as defined previously

Example:

If $N_i = 3.1$ → **Provide 4 lanes**.

- Same speed–flow curves as Figure 14.2
- The vertical intersection of v_p with the FFS curve gives S.
- Dashed LOS lines (A–F) indicate the LOS classification.

Analysis Type	Input	Output	Example Equation
Operational	V, PHF, N, fHV, fp	LOS, Speed, Density	$v_p = \frac{V}{PHFNfHVfp}$
Service Flow	LOS, MSF, fHV, fp	Flow or Volume	$SF_i = MSF_i fHV fp$
Design	DDHV, PHF, MSF, fHV, fp	Required Lanes	$N_i = \frac{DDHV}{PHFMSF_i fHV fp}$

DETERMINING THE FREE-FLOW SPEED (FFS)

Determination Methods

(a) Field Measurement :Best approach when data collection is possible. Measure the average passenger-car speed at volumes ≤ 1,000 veh/h/ln. This observed average is taken as the FFS.

(b) Analytical Estimation :Used when field data are unavailable or impractical (e.g., new design, budget limitations). Empirical equations allow estimation based on roadway and traffic characteristics.

Freeway FFS Estimation

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\,(TRD)^{0.84}$$

where:

- FFS = estimated freeway free-flow speed (mi/h)
- f_{LW} = lane width adjustment (mi/h)
- f_{LC} = right-shoulder lateral clearance adjustment (mi/h)
- TRD = total ramp density (ramps/mi, both directions)

a. Lane Width Adjustment (Table 14.5)

Narrower lanes reduce FFS due to driver caution and lateral confinement

Table 14.5: Adjustment to Free-Flow Speed for Lane Width on a Freeway

Lane Width (ft)	Reduction in Free-Flow Speed, f_{LW} (mi/h)
≥12	0.0
11	1.9
10	6.6

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 23-4, p. 23-6.)

b. Lateral Clearance Adjustment (Table 14.6)

(For right shoulder lateral clearance less than 6 ft)

Table 14.6: Adjustment to Free-Flow Speed for Lateral Clearance on a Freeway

Right Shoulder Lateral Clearance (ft)	Reduction in Free-Flow Speed, f_{LC} (mi/h)			
	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	2.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 23-5, p. 23-6.)

Small shoulder clearances (e.g., 2–4 ft) reduce driver comfort → lower FFS.

Wider freeways (≥5 lanes) have smaller effects because inner lanes shield drivers.

c. Total Ramp Density (TRD)

$$TRD = \frac{\text{Number of on-ramps + off-ramps within } \pm 3 \text{ mi of midpoint}}{6}$$

- Represents ramp activity level (ramps/mi).
- Higher ramp density → greater speed reduction due to turbulence.
- Typical range: 0 to 6 ramps/mi.

<u>3. Multilane Highway FFS Estimation</u>

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

where:

- $BFFS$ = Base Free-Flow Speed
  - 60 mi/h for rural/suburban highways
  - ≈ posted speed + 7 mi/h for rural sites
- f_{LW} = lane width adjustment
- f_{LC} = total lateral clearance adjustment
- f_M = median-type adjustment
- f_A = access-point density adjustment

a. Lane Width Adjustment (Multilane Highways)

Same as freeways (Table 14.5).

b. Total Lateral Clearance (Table 14.7)
(Sum of right + left side clearances, in ft)

Table 14.7: Adjustment to Free-Flow Speed for Total Lateral Clearance on a Multilane Highway

4-Lane Multilane Highways		6-Lane Multilane Highways	
Total Lateral Clearance (ft)	**Reduction in Free-Flow Speed, f_{LC} (mi/h)**	**Total Lateral Clearance (ft)**	**Reduction in Free-Flow Speed, f_{LC} (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

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 21-5, p. 21-6.)

c. Median Type Adjustment (Table 14.8)

Median Type	Reduction (f_M) (mi/h)
Undivided	1.6
TWLTL (Two-Way Left Turn Lane)	0.0
Divided	0.0

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 21-6, p. 21-6.)

Divided roads maintain higher FFS due to separation of opposing flows.

d. Access-Point Density Adjustment (Table 14.9)

Access Points per Mile	Reduction (f_A) (mi/h)
0	0.0
10	2.5
20	5.0
30	7.5
≥40	10.0

Frequent access points (driveways, unsignalized intersections) create turbulence, lowering FFS.

Example (Multilane Highway)

Given:

- $BFFS = 60$ mi/h
- Lane width = 11 ft → $f_{LW} = 1.9$
- Total lateral clearance = 6 ft → $f_{LC} = 1.3$
- Median type = undivided → $f_M = 1.6$
- Access density = 20 pts/mi → $f_A = 5.0$

$$FFS = 60 - (1.9 + 1.3 + 1.6 + 5.0) = \boxed{50.2\,\text{mi/h}}$$

- The calculated FFS reflects **realistic performance** under local geometric and operational conditions.
- FFS is then used as input to **speed–flow curves (Figures 14.2, 14.3, or 14.4)** to determine LOS and density

EXAMPLE: URBAN FREEWAY

GIVEN DATA

- Facility type: **6-lane urban freeway**
- Lane width = **11 ft**
- Right-side obstructions = **2 ft** from edge
- Ramp density = **3 ramps/mi**

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22(TRD)^{0.84}$$

Parameter	Description	Source	Value (mi/h)
(f_{LW})	Lane width adjustment (11 ft)	Table 14.5	1.9
(f_{LC})	Right lateral clearance (2 ft, 3 lanes)	Table 14.6	1.6
(TRD)	Total ramp density	Given	3 ramps/mi

Solution

$$FFS = 75.4 - 1.9 - 1.6 - 3.22(3^{0.84})$$

$$= \boxed{63.8 \text{ mi/h}}$$

- The freeway's free-flow speed is **~63.8 mi/h**, which is **~11 mi/h below ideal conditions** (75 mi/h base).
- The reductions reflect **narrow lanes**, **obstructions**, and **moderate ramp activity** typical of urban settings

EXAMPLE: UNDIVIDED MULTILANE HIGHWAY

Given Data

- Facility: **4-lane undivided multilane highway**
- Area: suburban
- Posted speed limit = **50 mi/h**
- Lane width = **11 ft**
- Right-side obstructions = **4 ft** clearance
- Access points = **30 per mile**

Parameter	Description	Source	Value (mi/h)
(BFFS)	Base free-flow speed (≈ posted + 5 mi/h)		55
(f_{LW})	Lane width = 11 ft	Table 14.5	1.9
(f_{LC})	Total lateral clearance = 10 ft (4 right + 6 median)	Table 14.7	0.4
(f_M)	Median type = Undivided	Table 14.8	1.6
(f_A)	Access density = 30 points/mi	Table 14.9	7.5

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

$$FFS = 55.0 - 1.9 - 0.4 - 1.6 - 7.5$$

$$= \boxed{43.6 \text{ mi/h}}$$

- The FFS drops from 55 → 43.6 mi/h (a reduction of **≈21%**) due to:
- High access density (most significant contributor)
- Narrow lanes and limited clearance
- Undivided configuration (reduced comfort and safety).

Feature	Urban Freeway	Suburban Multilane Highway
Base Model		
Base FFS	75.4 mi/h	55 mi/h
Major Adjustments	Lane width, lateral clearance, ramp density	Lane width, clearance, median, access density
Calculated FFS	**63.8 mi/h**	**43.6 mi/h**
Main Reason for Drop	Ramp density and geometry	High access point density

Choosing a Free-Flow Speed Curve

- After the Free-Flow Speed (FFS) has been determined — either measured in the field or estimated analytically — the next step in the HCM procedure is to select the correct speed–flow **curve** (Figure 14.2 for freeways, Figure 14.3 for multilane highways).

  These curves define the relationship between:

  Speed (S)↔Flow (v_p)↔Density (D)

- The FFS value should be **measured or predicted to the nearest 0.1 mi/h**.
- Small changes in FFS can noticeably affect the predicted **LOS boundaries** (A–F) because the curves are relatively close together at high speeds.
- Use the calibrated FFS curves directly from the HCM (no interpolation).
- The HCM speed–flow curves are non-linear and were developed from empirical calibration.
- Interpolating between two curves (e.g., between 60 mi/h and 65 mi/h) is not recommended, since intermediate curves may not follow the same shape or inflection behavior.

Table 14.10 provides **guidelines** for choosing the most suitable curve:

Table 14.10: Selecting a Speed-Flow Curve in Figures 14.2 and 14.3

Free-Flow Speed is: (mi/h)	Use Speed-Flow Curve for a *FFS* of: (mi/h)
≥72.5 < 77.5	75
≥67.5 < 72.5	70
≥62.5 < 67.5	65
≥57.5 < 62.5	60
≥52.5 < 57.5	55
≥47.5 < 52.5	50
≥42.5 < 47.5	45

DETERMINING THE HEAVY-VEHICLE FACTOR (FHV)

- The **heavy-vehicle adjustment factor** accounts for the effect of trucks, buses, and recreational vehicles (RVs) on traffic stream performance.
- Heavy vehicles reduce overall flow efficiency due to lower acceleration, reduced speeds on grades, and larger spacing needs.
- Heavy-Vehicle Categories: **Trucks and Buses:** grouped together for analysis (commercial vehicles, avg. 150 lb/hp). **Recreational Vehicles (RVs):** privately owned, lower weight-to-power ratio (~75–100 lb/hp), typically driven by non-professional drivers.

Each heavy vehicle is converted into an equivalent number of passenger cars.

PCEs depend on **grade, length, and % of heavy vehicles** in the stream.

Table 14.11 shows passenger-car equivalents for freeways and multilane highways on extended sections of general terrain.

Table 14.11: Passenger-Car Equivalents for Trucks, Buses, and RVs on Extended General Terrain Sections of Freeways or Multilane Highways

Factor	Type of Terrain		
	Level	Rolling	Mountainous
E_T	1.5	2.5	4.5
E_R	1.2	2.0	4.0

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 23-8, p. 23-9.)

Basic Equations

Step 1 – Convert veh/h to passenger-car equivalents:

$$V_{pce} = V_{ph} \times (P_T\, E_T + P_R\, E_R + (1 - P_T - P_R)\, 1.0)$$

where

V_{ph} = hourly volume (veh/h),

P_T = proportion of trucks and buses,

P_R = proportion of RVs.

Step 2 – Define the heavy-vehicle factor:

$$f_{HV} = \frac{V_{ph}}{V_{pce}}$$

Simplified form (HCM Eq. 14-9):

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

This converts actual volume (veh/h) to equivalent passenger-car flow (pc/h).

Example

Given:

- $V_{ph} = 1000$ veh/h
- $P_T = 10\%$, $P_R = 2\%$
- $E_T = 2.5$, $E_R = 2.0$

$$f_{HV} = \frac{1}{1 + 0.10(2.5 - 1) + 0.02(2.0 - 1)} = 0.8547$$

$$V_{pce} = \frac{1000}{0.8547} = 1170\, pc/h$$

So, the 1000 veh/h flow operates as if it were **1170 passenger cars per hour**.

<u>Passenger-Car Equivalents from HCM Tables</u>

a. Table 14.12 – Trucks / Buses on Upgrades

Values of ET increase with **grade (%)**, **length (mi)**, and **% trucks**.

Table 14.12: Passenger-Car Equivalents for Trucks and Buses on Upgrades

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
	>050–0.75	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	2.5	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

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 29-8, p. 23-10.)

b. Table 14.13 – RVs on Upgrades

Similar structure for E_R, typically **1.2–6.0**.

Table 14.13: Passenger-Car Equivalents for RVs on Upgrades

Grade (%)	Length (mi)	E_R								
		Percentage of RVs (%)								
		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	2.5	2.0	2.0	1.5
	>0.25–50	6.0	4.0	4.0	4.0	3.5	3.0	2.5	2.5	2.0
	>0.50	6.0	4.5	4.0	4.0	4.0	3.5	3.0	2.5	2.0

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 23-10, p. 23-10.)

c. Table 14.14 – Trucks / Buses on Downgrades

For steep downgrades (> 6 %), E_T can reach **7.5** due to braking control.

Table 14.14: Passenger-Car Equivalents for Trucks and Buses on Downgrades

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

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit 23-11, p. 23-11.)

Composite Grades

When a roadway has **multiple consecutive grades**:

- Compute an average grade (simplified approach), or
- Use composite-grade technique (Figures 14.5–14.6) for more accuracy.

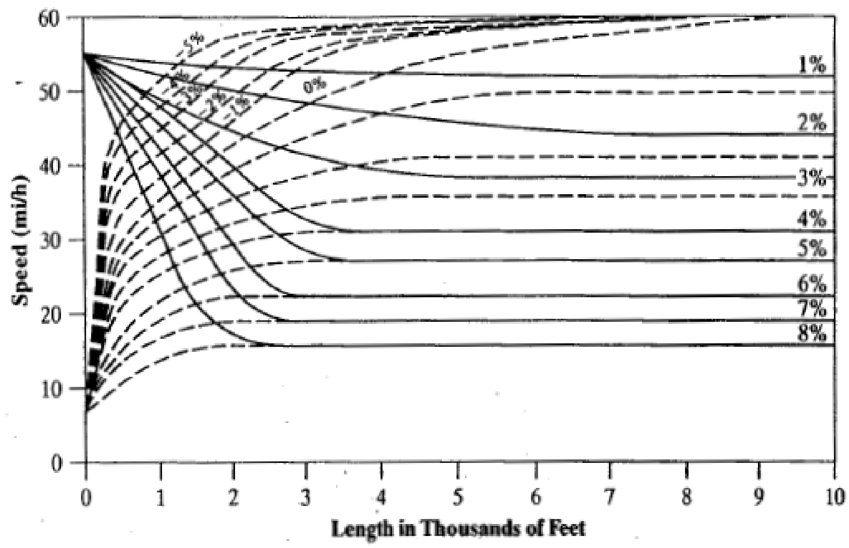


Figure 14.5: Performance of a Typical Truck on Grades

(*Source:* Used with permission of Transportation Research Board, National Research Council, *Highway Capacity Manual*, December 2000, Exhibit A23-2, p. 23-30.)

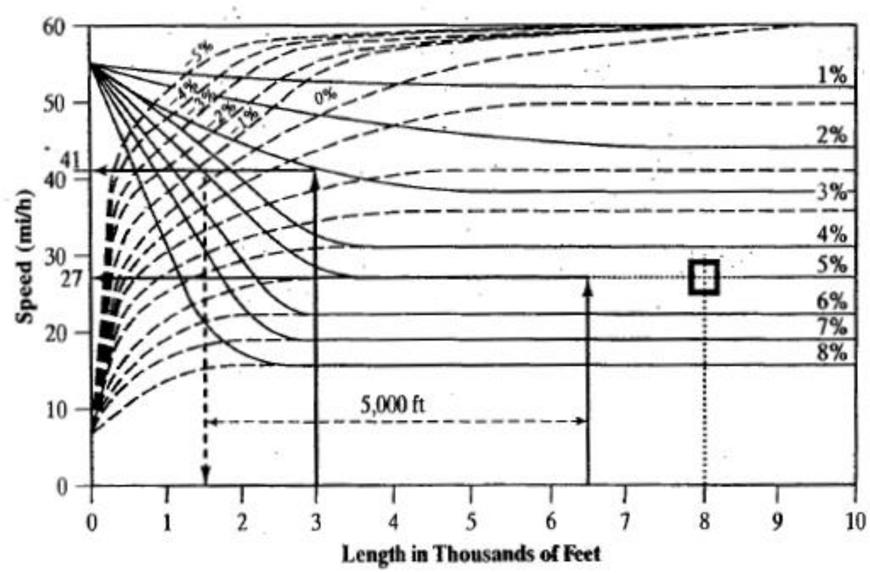


Figure 14.6: Composite Grade Solution for Example

EXAMPLE – APPLICATION

Consider the following situation: A volume of 2,500 veh/h traverses a section of freeway and contains 15% trucks and 5% RVs. The section in question is on a 5% upgrade, 0.75 miles in length. What is the equivalent volume in passenger-car equivalents?

Given:

- $V_{ph} = 2500$ veh/h
- 15 % trucks, 5 % RVs
- 5 % upgrade, 0.75 mi

From Tables 14.12 & 14.13: $E_T = 2.5$, $E_R = 3.0$

$$f_{HV} = \frac{1}{1 + 0.15(2.5 - 1) + 0.05(3.0 - 1)} = 0.7547$$

$$V_{pce} = \frac{2500}{0.7547} = 3313\,pc/h$$

Determining the Driver-Population Factor (fP)

Accounts for differences in driver familiarity with roadway conditions.

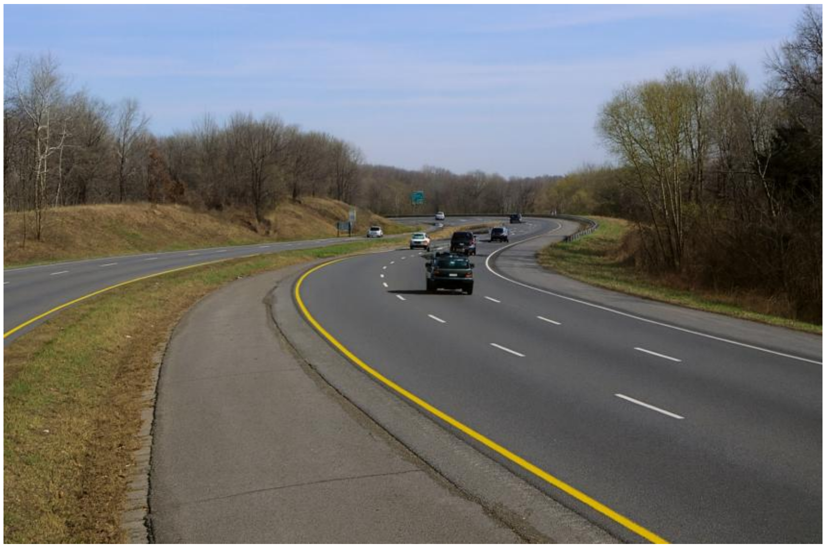
Base HCM procedures assume **commuter traffic** (familiar users).
Unfamiliar or occasional drivers tend to:

- Drive slower,
- Maintain longer headways,
- React more cautiously.

Driver Population Type	*(f_P)*
Predominantly familiar (commuters)	1.00
Mixed or occasional users	0.90 – 0.95
Predominantly unfamiliar (recreational routes)	0.85 *("worst case")*

Example— Analysis of an Older Urban Freeway

Figure shows a section of an old freeway in New York City. It is a four-lane freeway (additional service roads are shown in the picture) with the following characteristics:
-Ten-foot travel lanes
-Obstructions at 0 feet at the roadside
-Total ramp density is 4.5 ramps/mile
-Rolling terrain
The roadway has a current peak demand volume of 3,500 veh/h. The peak-hour factor is 0.95, and there are no trucks, buses, or RVs in the traffic stream because the roadway is classified as a parkway and such vehicles are prohibited. At what level of service will the freeway operate during its peak period of demand?



Given Data

Parameter	Description	Value
Lane width	10 ft	—
Lateral obstruction	0 ft (at roadside)	—
Total ramp density (TRD)	4.5 ramps/mi	—
Terrain	Rolling	—
Number of lanes (one direction)	2	—
Peak-hour factor (PHF)	0.95	—
Traffic composition	100 % passenger cars (no trucks, buses, or RVs)	—
Driver population factor (f_p)	1.00 (commuter population)	—
Peak-hour demand volume (V)	3,500 veh/h	—

Solution

Step 1 – Determine the Free-Flow Speed (FFS)

Use Equation 14-5 for **freeways**:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22(TRD)^{0.84}$$

Adjustment	Source	Value (mi/h)
(f_W)	Table 14.5, 10 ft lanes	6.6
(f_C)	Table 14.6, 0 ft clearance (2 lanes)	3.6
(TRD)	Given	4.5 ramps/mi

$$FFS = 75.4 - 6.6 - 3.6 - 3.22(4.5)^{0.84}$$
$$FFS = 75.4 - 6.6 - 3.6 - 11.4$$

$$\boxed{FFS = 53.8 \text{ mi/h}}$$

According to Table 14.10, this FFS (between 52.5 and 57.5 mi/h) corresponds to the **55 mi/h curve** in Figure 14.2.

Step 2 – Determine the Demand Flow Rate under Base Conditions
Use Equation 14-1:

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

Since there are **no heavy vehicles** and **commuter drivers**:

$$f_{HV} = 1.00, \quad f_P = 1.00$$

$$v_p = \frac{3500}{0.95 \times 2 \times 1.00 \times 1.00}$$

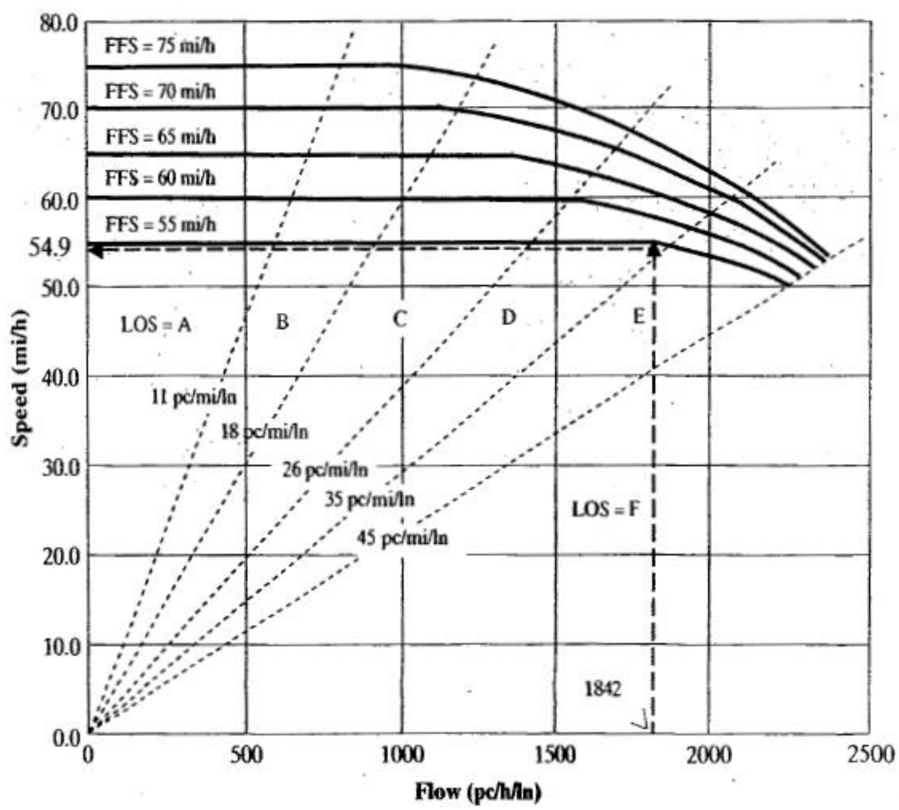
$$\boxed{v_p = 1842 \text{ pc/h/ln}}$$

Step 3 – Find the Speed and Level of Service (LOS)

From **Figure 14.2**, using:

- $v_p = 1842 \text{ pc/h/ln}$
- **FFS = 55 mi/h**

→ The corresponding **operating speed ≈ 54.9 mi/h**.



Compute Density

$$D = \frac{v_p}{S} = \frac{1842}{54.9} = 33.6 \text{ pc/mi/ln}$$

Compare with **LOS criteria**:

LOS	Density Range (pc/mi/ln)
A	≤ 11
B	12 – 18
C	19 – 26
D	27 – 35
E	36 – 45

$$\boxed{D = 33.6 \text{ pc/mi/ln} \rightarrow \text{LOS D}}$$

Step 4 – Interpretation

- The freeway operates **just below capacity**, near the upper limit of LOS D (≈ 35 pc/mi/ln).
- Flow is stable, but maneuverability is **significantly constrained**.
- Drivers experience reduced freedom to change lanes or maintain desired speeds.

This example demonstrates how **older or constrained freeway geometries** (narrow lanes, minimal shoulders, high ramp density) significantly reduce **FFS**, leading to degraded **LOS** even at moderate volumes.

EXAMPLE — ANALYSIS OF A MULTILANE HIGHWAY SECTION

A four-lane multilane highway section with a Ml median carries a peak-hour volume of 2,600 veh/h in the heaviest direction. There are 12% trucks and 2% RVs in the traffic stream. Motorists are primarily regular users of the facility. The section under study is on a 3% sustained grade, 1 mile in length. The PHF is 0.88. Field studies have been conducted to determine that free-flow speed of the facility is 55.0 mi/h. At what level of service will this facility operate during the peak hour?

Parameter	Description	Value
(V)	Peak-hour volume	2,600 veh/h
(PHF)	Peak-hour factor	0.88
(N)	Lanes per direction	2
(PT)	Proportion of trucks/buses	12%
(PR)	Proportion of RVs	2%
Grade	3% sustained (1 mi)	—
Terrain	Rolling	—
(FFS)	Free-flow speed (measured)	55 mi/h
(fp)	Driver population factor	1.00 (regular commuters)

Solution

Step 1: Compute the Heavy-Vehicle Factor for the Upgrade

Use Equation (14-9):

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

From HCM Tables 14.12 and 14.13:

- For **trucks** on a 3 % grade, > 0.75 mi, 12 % trucks → $E_T = 1.5$
- For **RVs** on a 3 % grade, > 0.50 mi, 2 % RVs → $E_R = 3.0$

$$f_{HV} = \frac{1}{1 + 0.12(1.5 - 1) + 0.02(3.0 - 1)} = \frac{1}{1.10} = 0.909$$

Step 2: Determine Upgrade Demand Flow Rate (in pc/h/ln)

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

$$v_p = \frac{2600}{0.88 \times 2 \times 0.909 \times 1.00} = 1625 \text{ pc/h/ln}$$

Step 3: Compute the Heavy-Vehicle Factor for the Downgrade

From HCM Tables 14.14 and 14.13:

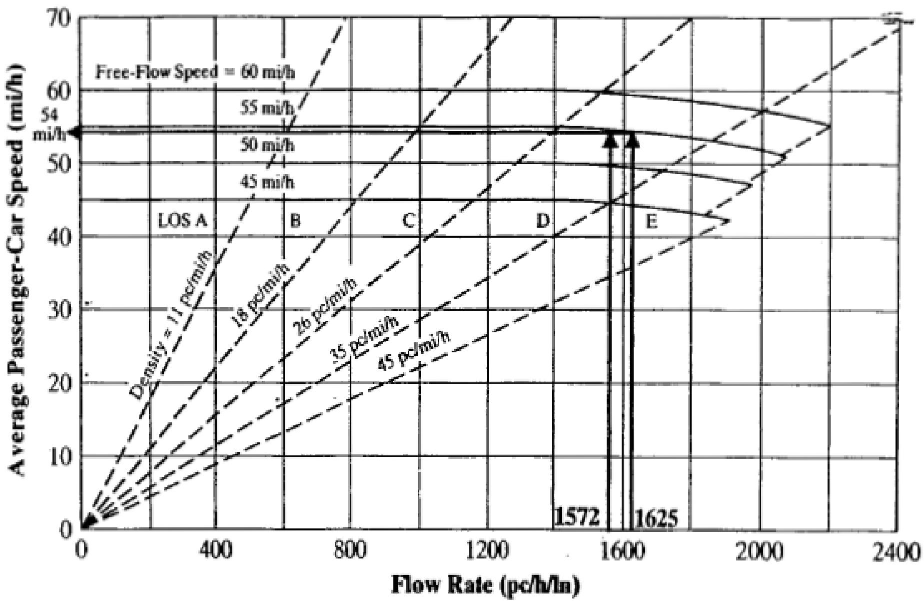
- For **trucks** on a < 4 % downgrade → $E_T = 1.5$
- For **RVs** (level terrain assumption) → $E_R = 1.2$

$$f_{HV} = \frac{1}{1 + 0.12(1.5 - 1) + 0.02(1.2 - 1)} = \frac{1}{1.064} = 0.940$$

$$v_p = \frac{2600}{0.88 \times 2 \times 0.940 \times 1.00} = 1572 \text{ pc/h/ln}$$

Step 4: Determine the Speed and LOS (from Figure 14.9)

Using the **55 mi/h free-flow curve** in Figure 14.3:



Direction	Flow (pc/h/ln)	Speed (mi/h)	Density (pc/mi/ln)	LOS
Upgrade	1625	≈ 54	(1625 / 54 = 30.1)	D
Downgrade	1572	≈ 54	(1572 / 54 = 29.1)	D

Step 5: Interpretation

- Both **upgrade** and **downgrade** operate at **LOS D**.
- Flow remains **stable**, though lane-changing and passing freedom are **limited**.
- Average speeds remain close to **FFS (≈ 55 mi/h)**.
- Density lies within LOS D limits (26–35 pc/mi/ln).

Parameter	Upgrade	Downgrade
Heavy-vehicle factor	0.909	0.940
Flow rate	1625	1572
Average speed	54	54
Density	30.1	29.1
LOS	**D**	**D**

EXAMPLE– FINDING SERVICE FLOW RATES AND SERVICE VOLUMES FOR A FREEWAY SEGMENT:

A six-lane urban freeway has the following characteristics: 12-foot lanes, 6-feet clearances on the right side of the roadway, rolling terrain, a ramp density of 2.8 ramps per mile, and a PHF of 0.92. The traffic consists of 8% trucks and no RVs, and all drivers are regular users of the facility.
The peak-hour volume on the facility is currently 3,600 veh/h, which ifexpected to grow at a rate of 6% a year for the next 20 years. What is the current level of service on the facility, and what levels of service can be expected in 5 years? In 10 years? In 15 years? In 20 years?

Given (one direction)

- 6-lane **urban freeway** → **N = 3** lanes
- **Lane width** 12 ft; **right shoulder clearance** 6 ft → no geometric reductions
- **Rolling terrain**, **ramp density** = **2.8 ramps/mi**
- **PHF = 0.92**
- Traffic mix: **8% trucks**, **0% RVs** (regular commuters → f_p **= 1.00**)
- **Current peak-hour demand** V_0 = **3,600 veh/h**, growing **6%/yr** for 20 years

<u>Solution</u>

1) Free-Flow Speed (FFS)

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\,TRD^{0.84}$$

Here $f_{LW} = 0,\ f_{LC} = 0,\ TRD = 2.8 \rightarrow$

$$FFS = 75.4 - 3.22(2.8)^{0.84} = 67.8\ \text{mi/h} \ \Rightarrow\ \text{use the **70 mi/h** curve}$$

2) Heavy-vehicle factor fHV

Use HCM (rolling terrain) PCE for trucks: ET=2.5

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.08(1.5)} = \boxed{0.893}$$

3) Maximum Service Flow (MSF) per lane for FFS = 70 mi/h **(HCM Table)**

A: 770 | B: 1,250 | C: 1,690 | D: 2,080 | **E (capacity): 2,400** pc/h/ln

Convert to **Service Flow (SF)** and **Service Volume (SV)** for the section:

$$SF_i = MSF_i \times N \times f_{HV} \times f_p, \quad SV_i = SF_i \times PHF$$

Using the table’s fHV=0.863 (to replicate their numbers):

LOS	SF (veh/h)	SV = SF×0.92 (veh/h)
A	1,994	1,834
B	3,236	2,977
C	4,375	4,301
D	5,385	4,954
E	**6,214**	**5,617** (= **capacity** for the hour)

4) Forecast peak-hour demand

$$V_j = V_0(1.06)^n$$

- $V_5 = 3,600(1.06)^5 = 4,818$ veh/h
- $V_{10} = 6,447$ veh/h
- $V_{15} = 8,628$ veh/h
- $V_{20} = 11,546$ veh/h

5) LOS by year (compare Vj to SV thresholds)

Year	Demand (V_j) (veh/h)	LOS
0	3,600	**C** (between 2,977 and 4,301)
5	4,818	**D** (between 4,301 and 4,954)
10	6,447	**F** (exceeds capacity 5,617)
15	8,628	**F**
20	11,546	**F**

Capacity is reached between years 5 and 10.
Solve exactly for the “capacity year” n

$$5,617 = 3,600(1.06)^n \Rightarrow n = \frac{\ln(5,617/3,600)}{\ln(1.06)} = \boxed{7.63 \text{ years}}$$

- Today the segment operates at **LOS C**; by **year 5** it degrades to **LOS D**.
- Around **year 7.6**, **demand = capacity** → recurrent breakdowns expected in peaks.
- Options: add a lane (recompute with N=4N=4N=4), manage demand (TDM, ramp metering), or shift

EXAMPLE: A DESIGN APPLICATION

A new freeway is being designed through a rural area. The directional design hour volume (DDHV) has been forecast to be 2,700 veh/h during the peak hour, with a PHF of 0.85 and 15% trucks in the traffic stream. The total ramp density is 0.50 ramps/mi. A long section of the facility will have level terrain characteristics, but one 2-mile section involves a sustained grade of 4%. If the objective is to provide level of service C, with a minimum acceptable level of D, how many lanes must be provided?

Parameter	Symbol	Value
Design hour volume	DDHV	2,700 veh/h
Peak-hour factor	PHF	0.85
% Trucks	(P_T)	15%
% RVs	(P_R)	0%
Ramp density	TRD	0.5 ramps/mi
Sustained grade	4% (2-mi section)	
Terrain	Level, rolling with one sustained grade	
Target LOS	C (minimum D)	
Driver population	(f_p)	1.00

Solution

Step 1 – Determine Free-Flow Speed (FFS)

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\,TRD^{0.84}$$

Given that lane and shoulder widths meet standards:

$$FFS = 75.4 - 0 - 0 - 3.22(0.5)^{0.84} = 74.8 \text{ mi/h}$$

→ **Use 75 mi/h** free-flow curve.

Step 2 – Select Maximum Service Flow Rate (MSF)

From HCM Table 14.3 for **FFS = 75 mi/h:**

LOS	(MSF) (pc/h/ln)
C	1,750
D	2,110

Step 3 – Compute Heavy-Vehicle Factors

For **trucks only**:

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

(a) level terrain:

From Table 14.11, ET=1.5

$$f_{HV,\text{level}} = \frac{1}{1 + 0.15(1.5 - 1)} = \frac{1}{1.075} = 0.930$$

(b) Upgrade (4 %, 2 mi, 15 % trucks):

From Table 14.12, ET=2.5

$$f_{HV,\text{up}} = \frac{1}{1 + 0.15(2.5 - 1)} = \frac{1}{1.225} = 0.816$$

(c) Downgrade (4 %, 2 mi, 15 % trucks):

From Table 14.14, ET=1.5

$$f_{HV,\text{down}} = 0.930$$

Step 4 – Determine Required Number of Lanes

$$N_i = \frac{DDHV}{PHF \times MSF_i \times f_{HV} \times f_p}$$

(a) **Level & Downgrade (use f_{HV}=0.93)**

$$N = \frac{2700}{0.85 \times 1750 \times 0.93 \times 1.00} = 1.9 \text{ lanes}$$

→ Round up → 2 lanes

(**B) Upgrade (Use f_{HV}=0.816)**

$$N = \frac{2700}{0.85 \times 1750 \times 0.816 \times 1.00} = 2.2 \text{ lanes}$$

→ Round up → 3 lanes

Step 5 – Check LOS D on the Upgrade

If only 2 lanes were built:

$$v_p = \frac{V}{PHF \times N \times f_{HV} \times f_p} = \frac{2700}{0.85 \times 2 \times 0.816 \times 1.00} = 1{,}949 \text{ pc/h/ln}$$

Compare to MSFD=2,110 pc/h/ln
Since 1,949 < 2,110 → LOS D.
Hence, **2 lanes = LOS D**, **3 lanes = LOS C**.

Section	**(f_{HV})**	**Required (Ni)**	**Design LOS**
Level	0.93	2 lanes	C
Downgrade	0.93	2 lanes	C
Upgrade (4 %)	**0.816**	**3 lanes**	**C (target)** / D (min)

- Construct as a **four-lane freeway** (2 + 2 lanes each direction) **with a truck-climbing lane** on the sustained upgrade.
- Alternatively, design for 2 lanes but acquire ROW and grade structures for an **add-later climbing lane**.

This design example illustrates how **grade, truck percentage, and desired LOS** govern the lane requirement—not just total volume.
The engineer must balance LOS goals with cost, environmental, and social constraints before finalizing the cross-section