

Highway Capacity (I)

Learning Objectives

- To define basic concepts relating to highway capacity analysis
- To apply capacity and LOS analysis for freeways

(Chapter 7.1 ~ 7.3; HCM Ch23)

Transportation Facilities

- Uninterrupted-flow facilities
 - no fixed elements external to the traffic stream to interrupt flow
 - Freeways, multilane hwy, two-lane hwy
- Interrupted-flow facilities
 - have controlled and uncontrolled access points that can interrupt flow
 - (un)signalized intersections, urban streets
- Performance?

Capacity Analysis

- Procedures for estimating the traffic-carrying ability of segments or points of a facility over a range of defined operational conditions
- Purposes
 - Assessing facility performance
 - Planning and designing improved facilities

Capacity

maximum hourly rate at which persons or vehicles reasonably can be 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

(HCM 2000)

Capacity

- “maximum hourly rate at which persons or vehicles reasonably can be 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” (HCM 2000)
- Base conditions
 - good weather
 - good pavement conditions
 - users familiar with the facility
 - no impediments to traffic flow

Level of Service (LOS)

- A qualitative measure describing operational conditions in a traffic stream and their perception by motorists
- Range – **A** (best) through **F** (worst)
- Determined by measure of effectiveness (MOE) such as speed and travel time, freedom to maneuver, traffic interruptions, and comfort and convenience

Level of Service (freeways)

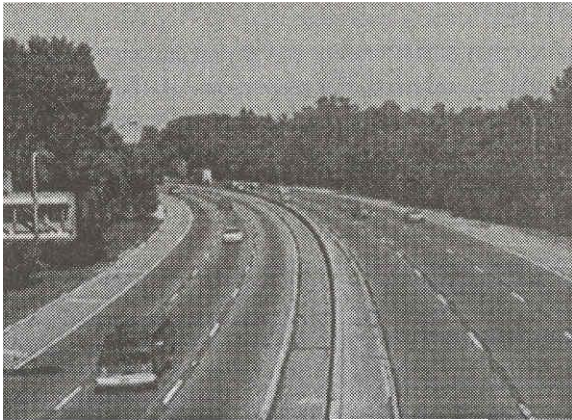


ILLUSTRATION 13-5. **LOS A**

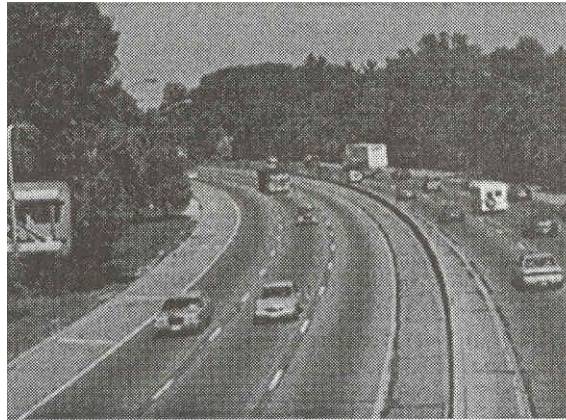


ILLUSTRATION 13-6. **LOS B**

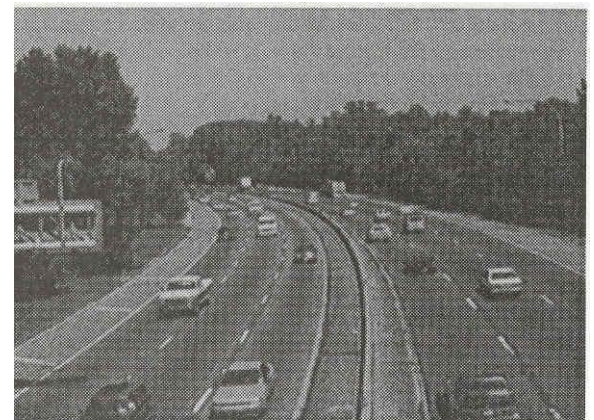


ILLUSTRATION 13-7. **LOS C**

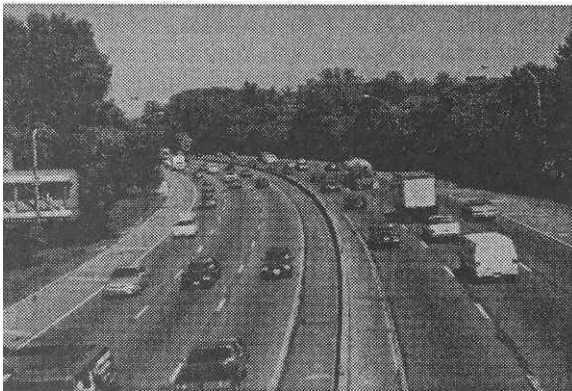


ILLUSTRATION 13-8. **LOS D**

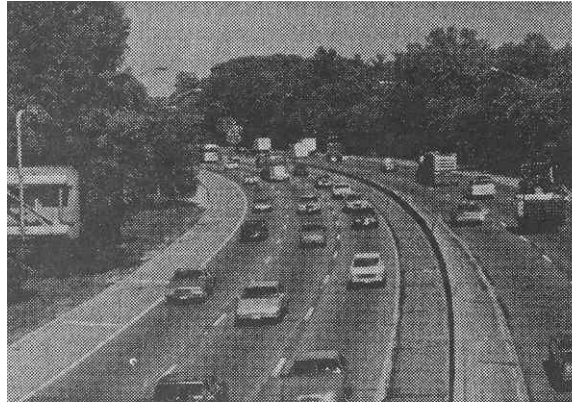


ILLUSTRATION 13-9. **LOS E**

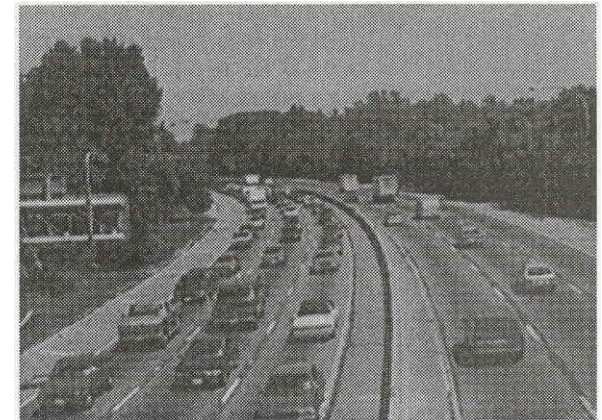


ILLUSTRATION 13-10. **LOS F**

Service Flow Rates

- Maximum flow rate attainable at each level of service (except for LOS F) for a given facility
- Define the flow boundaries between levels of service
- Hourly service flow rate is defined as four times the peak 15-min volume

Capacity Analysis for Freeways

- Only for “basic freeway segments”
 - Where there are no interruptions to the flow of traffic
 - Outside the area of influence of freeway weaving areas and freeway ramp junctions

Capacity Analysis for Freeways

- Base (ideal) conditions
 - Minimum lane widths of 12 ft
 - Minimum right-shoulder lateral clearance of 6 ft
 - Minimum median lateral clearance of 2 ft
 - 100% passenger cars
 - Five or more lanes for one direction
 - Interchange spacing at 2 mi or greater
 - Level terrain (grades no greater than 2%)
 - Drivers primarily regulars

LOS for Freeways

- Defined by density (k)
 - **A**: $k \leq 11$ ($S_{\min}=480$ ft), free flow
 - **B**: $k \leq 18$ ($S_{\min}=290$ ft), reasonably free flow
 - **C**: $k \leq 26$ ($S_{\min}=200$ ft), nearly free flow speed; maneuvers limited; reduced comfort
 - **D**: $k \leq 35$ ($S_{\min}=150$ ft), reduced speeds; limited freedom to maneuver; potential for queuing
 - **E**: $k \leq 45$ ($S_{\min}=120$ ft), at capacity; unstable flow
 - **F**: extensive queuing behind breakdown pts

LOS Criteria

EXHIBIT 23-2. LOS CRITERIA FOR BASIC FREEWAY SEGMENTS

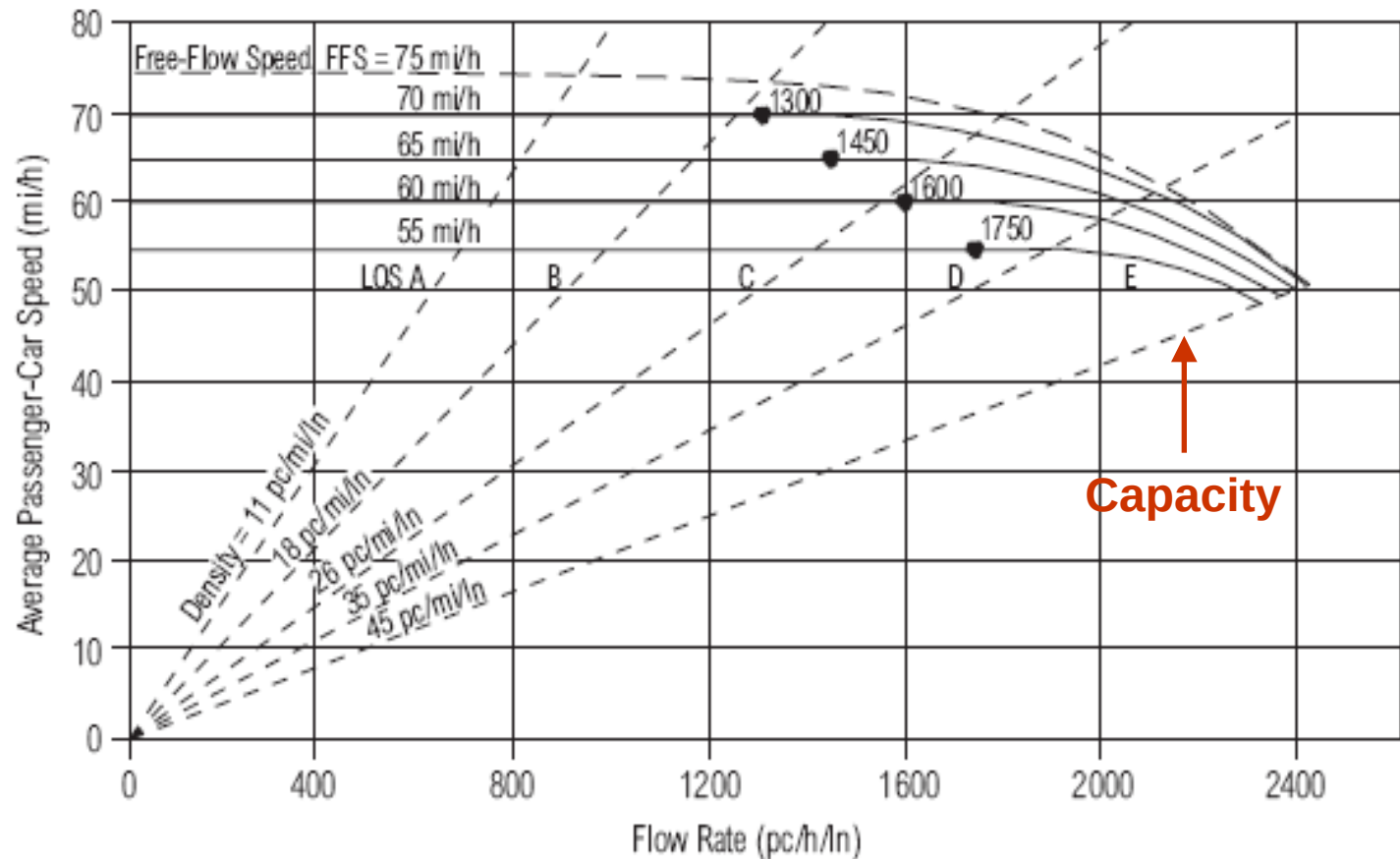
Criteria	LOS				
	A	B	C	D	E
FFS = 75 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	75.0	74.8	70.6	62.2	53.3
Maximum v/c	0.34	0.56	0.76	0.90	1.00
Maximum service flow rate (pc/h/ln)	820	1350	1830	2170	2400
FFS = 70 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	70.0	70.0	68.2	61.5	53.3
Maximum v/c	0.32	0.53	0.74	0.90	1.00
Maximum service flow rate (pc/h/ln)	770	1260	1770	2150	2400
FFS = 65 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	65.0	65.0	64.6	59.7	52.2
Maximum v/c	0.30	0.50	0.71	0.89	1.00
Maximum service flow rate (pc/h/ln)	710	1170	1680	2090	2350
FFS = 60 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	60.0	60.0	60.0	57.6	51.1
Maximum v/c	0.29	0.47	0.68	0.88	1.00
Maximum service flow rate (pc/h/ln)	660	1080	1560	2020	2300
FFS = 55 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	55.0	55.0	55.0	54.7	50.0
Maximum v/c	0.27	0.44	0.64	0.85	1.00
Maximum service flow rate (pc/h/ln)	600	990	1430	1910	2250

Volume-to-capacity
ratio

Speed-flow Curves and LOS for Basic Freeway Segments

EXHIBIT 23-3. SPEED-FLOW CURVES AND LOS FOR BASIC FREEWAY SEGMENTS

$$K = q/v$$



Note:

Capacity varies by free-flow speed. Capacity is 2400, 2350, 2300, and 2250 pc/h/ln at free-flow speeds of 70 and greater, 65, 60, and 55 mi/h, respectively.

Freeway Capacity Analysis

- Determine flow rate
- Determine free flow speed
- Determine level of service

Determining Flow Rate

- Adjusting hourly volumes or estimates, typically reported in veh/h, to arrive at an equivalent passenger-car flow rate in **passenger cars per hour (pc/h)**

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

where

v_p = 15-min passenger-car equivalent flow rate (pc/h/ln),

V = hourly volume (veh/h),

PHF = peak-hour factor,

N = number of lanes,

f_{HV} = heavy-vehicle adjustment factor, and

f_p = driver population factor.

Determining Flow Rate

$$V_p = \frac{V}{PHF * N * f_{HV} * f_p}$$

- Peak Hour Factor (PHF)
 - Accounting for variation in traffic flow within an hour
 - On freeways, typically ranging from 0.80 (rural/off-peak) to 0.95 (urban)
 - If possible, field data should be used

Determining Flow Rate

$$V_p = \frac{V}{PHF * N * f_{HV} * f_p}$$

- Heavy Vehicle Adjustment Factor
 - Accounting for the presence of heavy vehicles (trucks, buses, RVs)

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

where

E_T E_R = passenger-car equivalents for trucks/buses and recreational vehicles (RVs) in the traffic stream, respectively;

P_T P_R = proportion of trucks/buses and RVs in the traffic stream, respectively;
and

f_{HV} = heavy-vehicle adjustment factor.

Passenger-Car Equivalents

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

- Values of E_T and E_R selected for one of the following conditions:
 - Extended freeway segments
 - Specific grades
 - Downgrades

Passenger-Car Equivalents

Extended freeway segments

no one grade of 3% or greater is longer than 0.25 mi or
no one grade of less than 3% is longer than 0.5 mi

EXHIBIT 23-8. PASSENGER-CAR EQUIVALENTS ON EXTENDED FREEWAY SEGMENTS

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

Level: includes short grades of no more than 2%, HV operate at the same speed as PC

Rolling: HV substantially slower than PC but do not operate at crawl speeds for significant length of time

Mountainous: HV operate at crawl speeds for significant length of time

Passenger-Car Equivalents

Specific Grades

grade of more than 0.5 mi for grades less than 3% or
grade of more than 0.25 mi for grades of 3% or more

EXHIBIT 23-9. 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

Passenger-Car Equivalents

Specific Grades

EXHIBIT 23-10. PASSENGER-CAR EQUIVALENTS FOR RVs ON UPGRADES

Upgrade (%)	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	2.0	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	4.0	3.5	3.0	3.0	2.5	2.0

Passenger-Car Equivalents

Downgrades

when trucks must often use low gears to avoid gaining too much speed and running out of control

EXHIBIT 23-11. PASSENGER-CAR EQUIVALENTS FOR TRUCKS AND BUSES ON DOWNGRADES

Downgrade (%)	Length (mi)	E_T			
		Percentage of Trucks			
		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
4–5	> 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

Determining Flow Rate

$$V_p = \frac{V}{PHF * N * f_{HV} * f_p}$$

- Driver Population Factor
 - Accounting for the presence of unfamiliar users
 - Range from 0.85 to 1.00
 - Use 1.00 unless evidence suggests otherwise

Freeway Capacity Analysis

- Determine flow rate
- Determine free flow speed
- Determine level of service



Determining FFS

- FFS: mean speed of passenger cars measured during low to moderate flows
- Two methods:
 - Field measurement
 - Weekday off-peak hours
 - No adjustment needed
 - Estimated based on physical characteristics of the freeway segment

Estimating FFS

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$$

where

- FFS = free-flow speed (mi/h);
- $BFFS$ = base free-flow speed, 70 mi/h (urban) or 75 mi/h (rural);
- f_{LW} = adjustment for lane width from Exhibit 23-4 (mi/h);
- f_{LC} = adjustment for right-shoulder lateral clearance from Exhibit 23-5 (mi/h);
- f_N = adjustment for number of lanes from Exhibit 23-6 (mi/h); and
- f_{ID} = adjustment for interchange density from Exhibit 23-7 (mi/h).

Estimating FFS

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$$

- Adjustment for lane width

EXHIBIT 23-4. ADJUSTMENTS FOR LANE WIDTH

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

Estimating FFS

$$FFS = BFFS - f_{LV} - f_{LC} - f_N - f_{ID}$$

- Adjustment for lateral clearance

EXHIBIT 23-5. ADJUSTMENTS FOR RIGHT-SHOULDER LATERAL CLEARANCE

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	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Estimating FFS

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$$

- Adjustment for number of lanes

EXHIBIT 23-6. ADJUSTMENTS FOR NUMBER OF LANES

Number of Lanes (One Direction)	Reduction in Free-Flow Speed, f_N (mi/h)
≥ 5	0.0
4	1.5
3	3.0
2	4.5

Note: For all rural freeway segments, f_N is 0.0.

Estimating FFS

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$$

- Adjustment for interchange density

EXHIBIT 23-7. ADJUSTMENTS FOR INTERCHANGE DENSITY

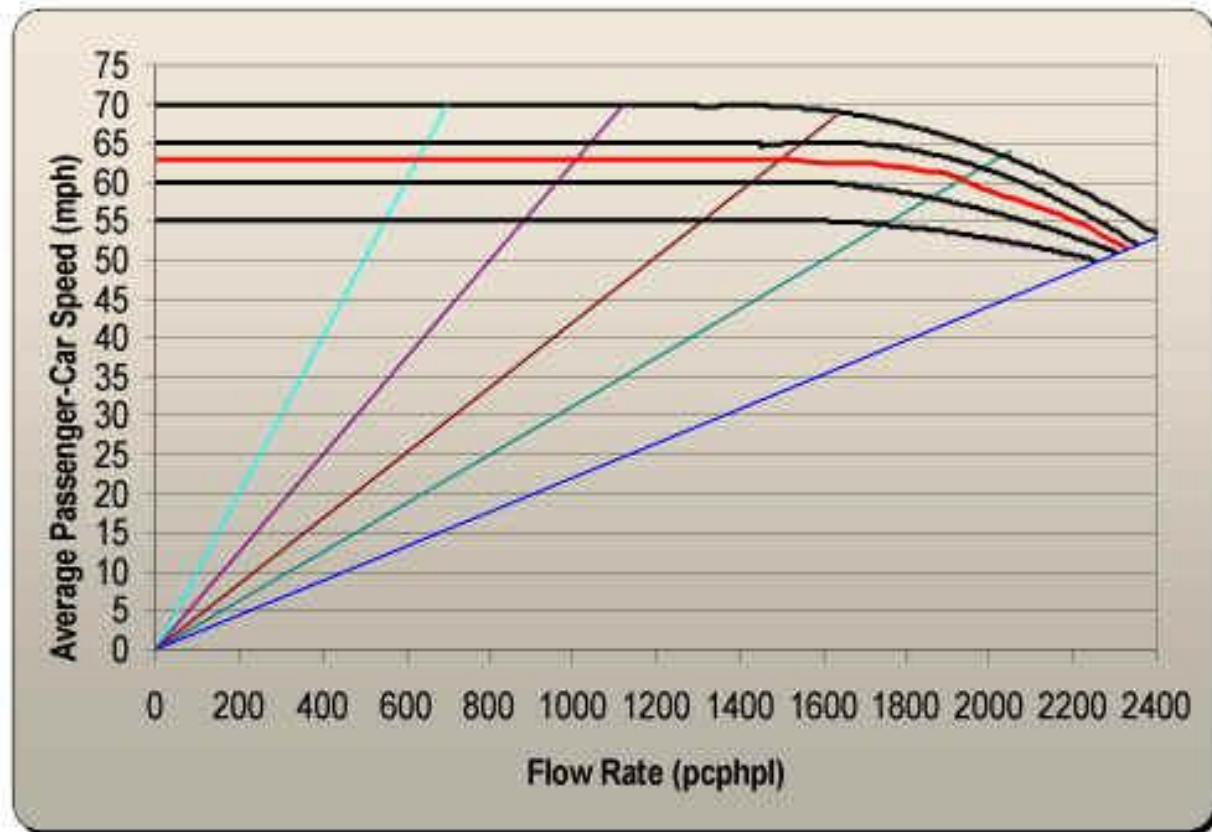
Interchanges per Mile	Reduction in Free-Flow Speed, f_{ID} (mi/h)
0.50	0.0
0.75	1.3
1.00	2.5
1.25	3.7
1.50	5.0
1.75	6.3
2.00	7.5

Freeway Capacity Analysis

- Determine flow rate
- Determine free flow speed
- Determine level of service 

Determining LOS

- Based on the equivalent passenger-car flow rate (V_p) and adjusted free-flow speed (S)
- Step 1



Determining LOS

- Step 2

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

where

D = density (pc/mi/ln),
 v_p = flow rate (pc/h/ln), and
 S = average passenger-car speed (mi/h).

Determining LOS

- Step 3

Compare calculated density with LOS Criteria for Basic Freeway Segments (Table 7-1 of K&L or Exhibit 23-2 of HCM 2000)

EXHIBIT 23-2. LOS CRITERIA FOR BASIC FREEWAY SEGMENTS

Criteria	LOS				
	A	B	C	D	E
FFS = 75 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
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FFS = 65 mi/h					
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Minimum speed (mi/h)	65.0	65.0	64.6	59.7	52.2

Practice Problem

- BFFS = 70 mph (LOS A or B)
- $N = 3$, $LC = 3\text{ft}$, Lane Width = 11ft
- 1 interchange/mi
- $V = 3080$ veh/hr (1-dir)
- $PHF = 0.88$
- 154 Tr & Buses
- Level terrain
- All commuters
- Determine density (D) and LOS