Chapter 12
The Impacts of Congestion on Roadway Traffic Productivity

12.1 Introduction

Road productivity can be defined as the throughput traffic volume (vehicles or persons per hour) of a roadway at a given point, or as the person-miles or vehicle-miles per hour that can be moved on a roadway segment, or on an area-wide road network.

This chapter identifies the various traffic elements (throughput volume, capacity, speed, and density) that determine road productivity. Through illustrative examples it shows how productivity of freeways and arterial streets is impacted by congestion.

12.2 Fundamentals of Traffic Flow

Traffic flow theory provides an analytical means of evaluating capacity, congestion, and productivity. It is useful in analyzing the effects of changes in traffic demand, flow, and speeds over time. For example, it can assist in answering questions such as: what are the congestion and productivity impacts of a new land development along a heavily traveled roadway?

12.2.1 Basic Relationships

Traffic speed is a basic indicator of congestion. Speed depends upon (1) type of roadway (freeway, expressway, arterial, or collector streets); (2) the roadway geometry and controls (from a roadway that is fully accessible from adjacent land use activities, to a roadway with full access control); (3) the nature, extent, and duration of traffic conflicts/incidents that interfere with traffic flow; and (4) the

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traffic demand volume along the roadway at a given time; and (5) the capacity of the road to serve the demand.

Traffic speed varies with traffic volume: as traffic volume increases, speed drops. The speed at which volume reaches its maximum value is the *critical speed*—so called because when speed continues to drop below this critical value the throughput volume of the roadway begins to drop as well. Therefore the critical speed becomes a useful metric in achieving the goal of maximizing/protecting roadway productivity, and it is a useful traffic congestion management tool.

12.3 Freeway and Expressway Productivity

12.3.1 Introduction

Figure 12.1 shows the relationship between average speed and average rate of throughput volume for five freeways with different free-flow speeds: 75, 70, 65, 60, and 55 mph as set forth in the 2010 Highway Capacity Manual, Chap. 11 (2).

These speed-flow curves indicate that traffic speeds on freeways do not begin to drop perceptibly from free flow speed until their volume reaches about 80 % of their maximum throughput volumes or when their respective volume-to-capacity ratio (V/C) = 0.8. When freeways reach their maximum throughput volumes their free flow

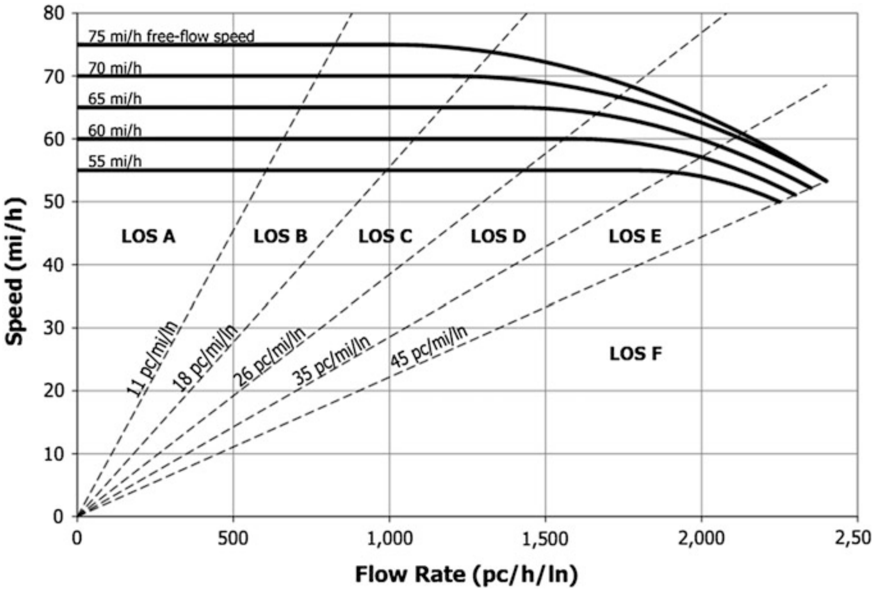

Fig. 12.1 Typical speed-flow curves for freeways when traffic density is below 45 passenger cars per lane-mile. *Source* Reference [1], highway capacity manual 2010, Chap. 11

Table 12.1 Maximum throughput volume (V_m), critical speed (S_c) and critical density (D_c) for freeways with different free-flow design speed (S_f)

Design speed	Maximum throughput volume	Critical speed	Critical density
S_f (mph)	V_m (pcphpl)	S_c (mph)	$D_c = V_m/S_c$ (pcplm)
75 and 70	2,390	53	45
65	2,340	52	45
60	2,290	51	45
55	2,250	50	45

Source Approximate values estimated from Fig. 1

traffic speed drops to from 75 or 70 to 53 mph, from 65 to 52 mph, from 60 to 51 mph, and from 55 to 50 mph, respectively, depending on the initial free-flow speed.

At these maximum throughput volumes (V/C = 1.0) and at their critical speeds (S_c), their critical density (D_c) of 45 passenger cars per lane mile is reached. these relationships are shown in Table 12.1.

When critical density is reached, however, traffic flow becomes unstable, vehicle speeds are apt to drop unpredictably below their critical speed (S_c), and productivity also declines. This speed-flow pattern is shown in Fig. 12.2 for an urban freeway [2]:

Density contours (vehicles per lane per mile) along a freeway have been useful in identifying the location and extent of high densities (i.e., congested flow). The contours can also identify bottleneck points both upstream and downstream of a given location. Density contours such as shown in Fig. 12.3, have been developed

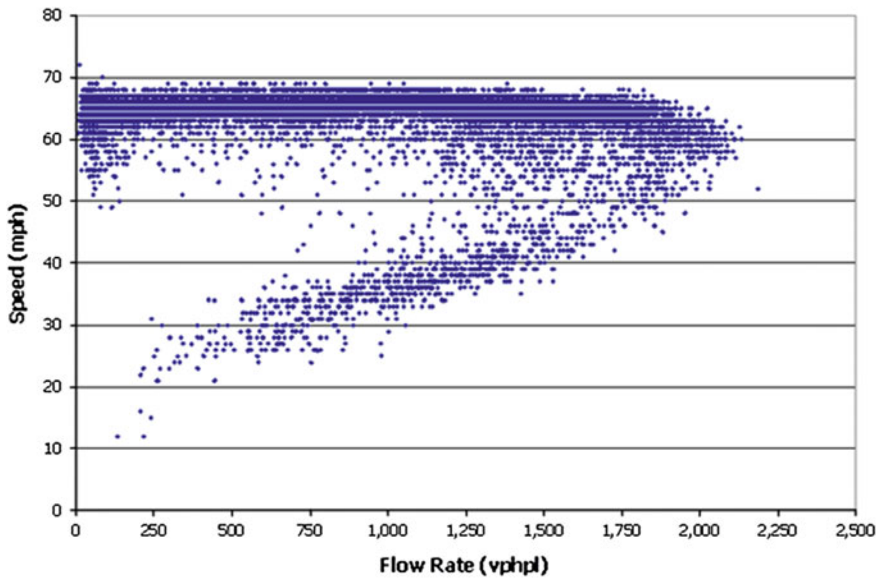

Fig. 12.2 Speed flow data for an urban freeway. *Source* Reference [2], Fig. 5

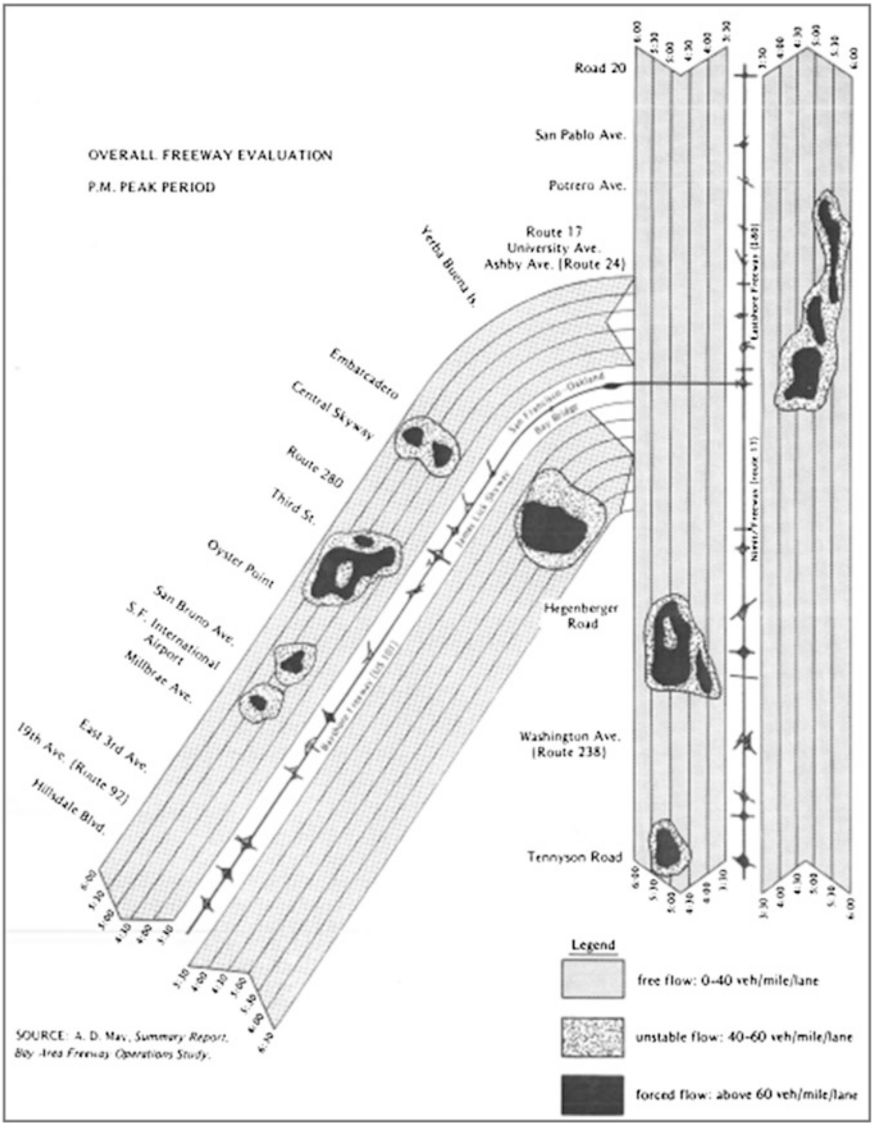

Fig. 12.3 Freeway system evaluation by density contours charts. *Source* Reference [3]

by state transportation and highway agencies. This example defines unstable flow as 40–60 passenger cars per lane per mile, and forced flow (hence reduced productivity) when density exceeds 60 passenger cars per lane-mile [3].

12.3.2 Skycomp Analysis

An example showing what happens to freeway speed when traffic density increases beyond critical density (D_c), was captured through aerial surveys of freeways and expressways in the New York City area by Skycomp (5). These patterns are shown in Fig. 12.4.

From Skycomp's observations, correlations between traffic speed and traffic density were developed to illustrate (1) the impact of increasing traffic density beyond its critical value of 45 pcplpm, on traffic speed; and (2) the impact of traffic speed on productivity (throughput volume) at speeds lower than the critical value of 53 mph. The results are shown in Fig. 12.5 through Fig. 12.8.

- Figure 12.5 shows how freeway speeds decrease once the critical density of 45 vehicles per lane per mile is exceeded.
- Figure 12.6 shows the entire speed-density relationship. In the example the density of 45 passenger cars per lane per mile separates the regions of uncongested and congested flow. The speed—density data for uncongested flow was calculated from Fig. 12.1.

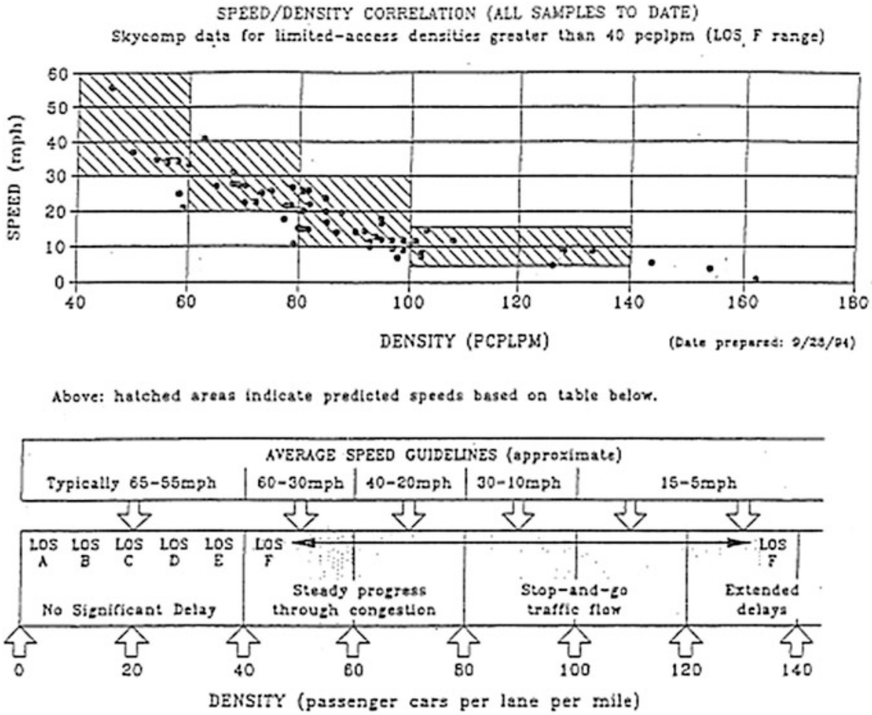

Fig. 12.4 Correlation of speed to vehicle density obtained through aerial surveys. *Source* References [4], p 96, Fig. 27 and [5]

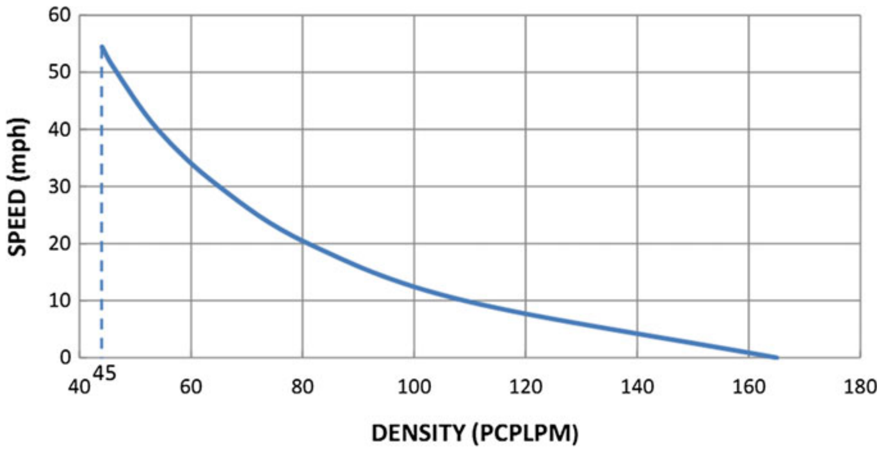

Fig. 12.5 Estimated speed/density relationship for congested freeway flow. *Source* Scale same as in Fig. 12.4

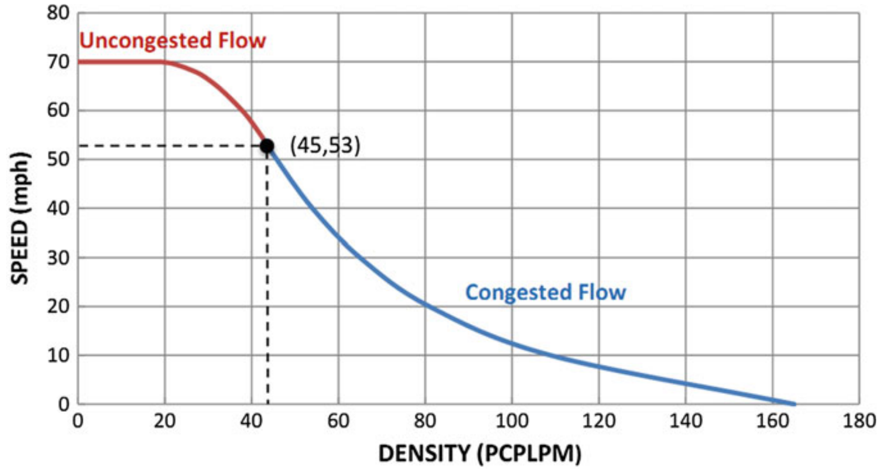

Fig. 12.6 Speed-density relationship for uncongested and congested flow for 70 mph freeway. *Source* Scale as in Figs. 12.4 and 12.5

- Figure 12.7 shows how the throughput volume reaches its maximum of 2,390 passenger cars per hour per lane at a density of 45 cars per lane per mile. Throughput volume then progressively declines to about 1,250 pcphpl as density increases to 100 vehicles per lane per mile, and to about zero flow at 165 pcplpmile.
- Figure 12.8 shows the resulting speed-flow curve. With increasing volume, speed drops minimally from its free-flow speed of 70 mph until it reaches about 1,800 pcphpl [A]. As volume increases beyond this value, traffic speed becomes unstable [B] and susceptible to sudden drops in speed and throughput volume [C].

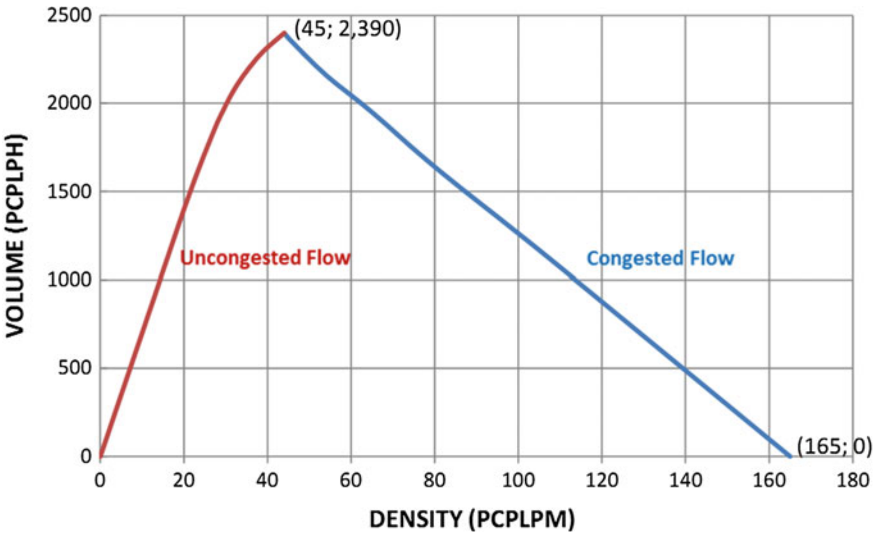

Fig. 12.7 Throughput volume for uncongested and congested flow for 70 mph freeway. *Source* Figure 12.6

The speed volume relationship shown in Fig. 12.8 indicates that: when the V/C = 1.0, the 53 mph traffic speed cannot be sustained for long. At a density of 45 pcplpm, the space between vehicles averages 97 ft [(5,280 ft per mile/45 cars/lane-mile)−20 ft/car]. Many drivers would consider this space too short to merge

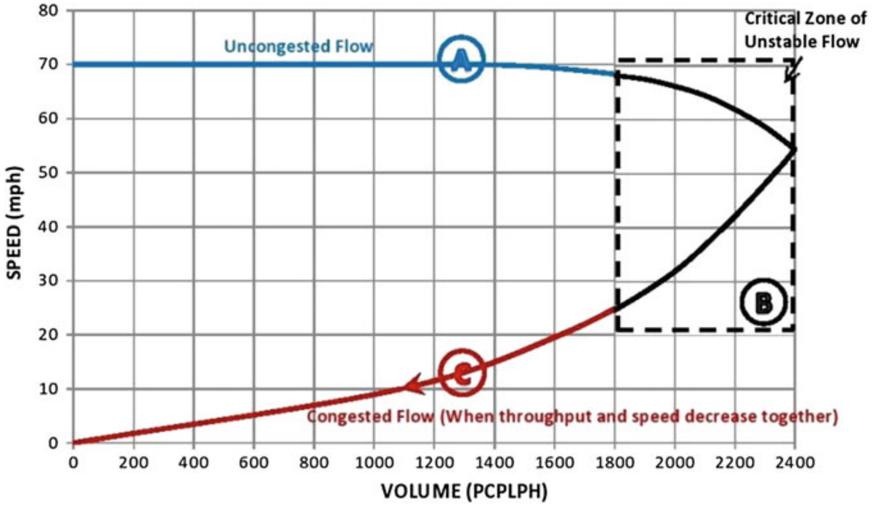

Fig. 12.8 Speed-volume relationship for uncongested and congested flow for 70 mph freeway. *Source* Source scale as in Fig. 12.7

Table 12.2 Percent loss in throughput volume for freeway speeds below critical speed of 53 mph

Average speed (mph)	Throughput volume (pcphpl)	% Loss in throughput volume (from maximum)	Incremental loss in throughput volume (%)
Critical Speed = 53	2,400	0	–
50	2,320	3	3
40	2,150	10	7
30	1,850	23	13
20	1,500	38	15
10	1,050	56	18
0	0	100	44

Source Calculated

into an adjacent lane for a safe lane change needed to maintain a desired speed. As a consequence some vehicles would be delayed by their inability to pass slower-moving vehicles: drivers who cannot make the lane change are forced to drop its speed if the car in front has reduced its speed. This kind of driver response is multiplied in a chain reaction of speed reductions as vehicles come closer to one another. When this occurs the traffic throughput volume of the roadway gets progressively smaller, with a loss rate of 20 vph [2,390/(165–45)] for each unit increase in density above 45 vplm (Fig. 12.8); and when density reaches its maximum (Dj) value, a stop-and-go traffic movement prevails.

The magnitude of the loss in throughput volume for various values of speed below its critical value, is shown in Table 12.2. It may be seen that the incremental loss in throughput increases at a faster rate with each incremental loss in speed.

12.4 Arterial Street Productivity

Arterial streets, in contrast to the uninterrupted flow along freeways, involve "stop and go" operations. Throughput volumes and speeds, are limited by various interruptions along these facilities: signalized intersections result in stop and go traffic that result in delay. Midblock interference from parking movements and other side frictions further impact speeds.

12.4.1 Analysis

The key determinants of travel speed include the frequency, coordination, and timing of traffic signals, the volume and conflicting movements at major intersections, and the number of lanes available on each intersection approach.

The 2010 Highway Capacity Manual (Volume 3) contains detailed procedures for analyzing intersection and roadway performance [1]. The analysis procedures are best suited for evaluating specific locations. Many of the equations are complex and require computerized analysis.

This section, focuses on a general assessment of how traffic speed on arterial roads is impacted by the volumes they carry.

Figure 12.9 shows five types of arterials whose free-flow speed ranges from 40 to 12 mph. Streets with low free-flow speeds (between 20 and 12 mph) are included in the figure, although they are unlikely to function as “arterial streets.”

It can be seen that as traffic volume increases, speeds generally decreases until a critical speed is reached and throughput volume reaches its maximum value (V/C = 1.0). The heavy lines are superimposed on the initial analysis to give a working approximation of how speeds decrease as traffic volumes increase. When the volume-to-capacity ratios are less than 0.60, the speeds change very little. As volume-to-capacity ratio increases, there is a sharp decline in speeds.

Table 12.3 summarizes the relationship between free-flow speed (Sf), and the critical speed (Sc) for maximum throughput volume (Vm)—reached when V/C = 1.0, for each class of arterial streets in Fig. 12.9.

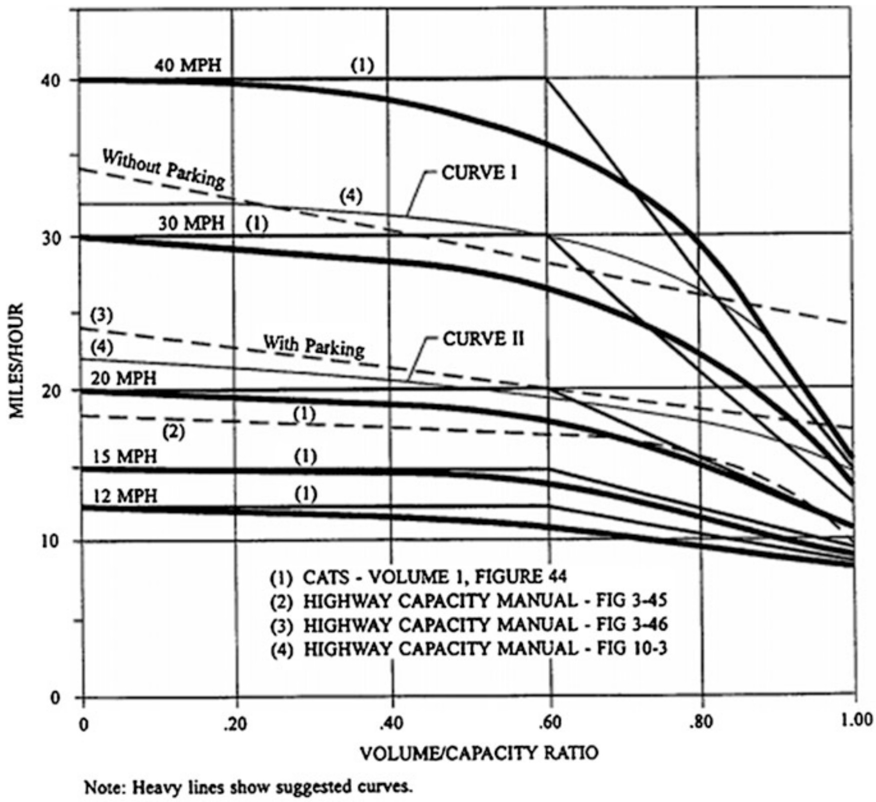

Fig. 12.9 Speed and volume/capacity ratios for arterial streets. *Source* Reference [4], p 30, Fig. 3 and 6

Table 12.3 Free-flow speed and critical speed at maximum throughput volume for arterials of different free-flow speeds

Average free-flow speed (Sf) of arterial streets	Critical speed (Sc) at Vm (V/C = 1.0)
40	17 mph
30	14
20	11
15	9
12	8

Source Figure 12.9

12.4.2 Implications

The preceding speed-flow relationships lead to the following implications:

1. Although Fig. 12.9 does not show what happens to throughput volume when traffic speed drops below its critical value (as shown for freeways), it may be assumed that for arterial streets throughput volumes decrease when speeds drop below their critical value.
2. Therefore critical speed value can be used as the productivity-based threshold speed because arterial streets will reduce their throughput productivity when they operate at speeds lower than critical speed.
3. In these cases sustained traffic demand will exceed the throughput capacity resulting in growing queues (spillback) which will further reduce speeds along the roadway—causing additional productivity losses.

12.5 Conclusions

Traffic demand that exceeds the designated capacity throughput of freeways and arterial streets causes congestion that leads to unstable traffic operations and lowers the roadway's traffic throughput below its designated value. In these cases it is extremely important to reduce losses in capacity throughput due to congestion. Available strategies that can accomplish this goal are described in Part 3 of the book.

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