Chapter 7
Bottlenecks

7.1 Introduction

Travelers and freight movers experience congestion as a result of capacity deficiencies in the roadway system. These congestion problems occur whenever the arrival rate (demand) exceeds the vehicle departure rate (capacity). The demand-capacity imbalance is manifested by a number of conditions: (a) recurring bottlenecks are caused by topographic and physical barriers to movement; the discontinuity of the road network; design and operational deficiencies; (b) nonrecurring bottlenecks are created by incidents, surging demand, inclement weather, work zones/street closures, and driver behavior.

When recurring and nonrecurring bottlenecks happen at the same time their impact on delay is at its worst. The amount of delay caused by recurring events and by nonrecurring events has been estimated by several sources but the estimates provided are not clear as to the amount of congestion produced when recurring and nonrecurring delays overlap.

Table 7.1 shows a national estimate of the causes of recurring and nonrecurring congestion delay for US freeways and expressways.

These estimates represent rough approximations from past and ongoing studies. They show that nonrecurring congestion generates a larger share of delay than recurring congestion (55 vs. 45 %). Incidents cause 45 % of nonrecurring delay and recurring bottlenecks are the most common cause of recurring delay (89 %).

Lockwood [2] breaks down recurring and nonrecurring delay by area type and size of urbanized area. Table 7.2 shows the percentage contribution of recurring and nonrecurring causes to total delay by size and type of area.

Thus the delay in rural areas is predominantly of the nonrecurring type (97 %), while in urban areas nonrecurring delay is a much smaller share of total delay. This share decreases slightly as the size of the area increases (58–72 % in small urban areas versus 55–69 % in areas greater than one million people).

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Table 7.1 Sources of congestion—a national summary

Congestion causes	Recurring (%)	Non-recurring (%)
Bottlenecks	40	–
Poor signal timing	5	–
Traffic incidents	–	25
Work zones	–	10
Bad weather	–	15
Special events/other	–	5
Total	45	55

Source Reference [1]

Table 7.2 Percentage contribution of recurring and nonrecurring causes to total delay, by area type and size

	Cause of delay	Large Urban areas >1 m[a]	Small urban areas 0.1–1.0 m	Rural
Recurring causes	Network demand > capacity	29–37	20–26	0
	Poor signal timing	4–5	7–13	2
Total recurring		33–42	32–33	2
Non-recurring causes	Crashes	35–36	19–26	26
	Breakdowns	6–7	6–10	25
	Work zones	8–19	26–27	39
	Weather	5–6	7–10	7
	Special events/lack of information, other	1	–	0
Total non-recurring		58–67	67	98

[a] Combine estimates for size classes 1–3 m and > 3 m. *Source* Reference [2]. Used by permission

It is important to note that these estimates refer to an area-wide average, and are not intended for estimating conditions at specific highway corridors within the urban area, as these must be estimated from actual experiences. For example, a corridor with older highways and sub-standard designs (e.g., the I-278 corridor in Brooklyn, NY), would experiences higher crash rates, so that the proportion of congestion delay from traffic incidents in the I-278 corridor would be higher than that indicated in the above table.

This chapter describes the various bottleneck factors that contribute to recurring and nonrecurring congestion.

7.2 Recurring Congestion

7.2.1 Physical Bottlenecks

Topographic barriers and physical bottlenecks on streets and highways represent choke points that reduce road capacity and cause peak hour traffic to back up and create congestion of the upstream roadways.

7.2.1.1 Topographic Barriers

A city's physical features can create congestion. Topographic barriers such as hills, mountains, steep grades, and water bodies constrain street patterns and concentrate travel on a limited number of available crossings. Balancing the capacity of the approach roadways with the capacity provided at a limited number of crossings is usually a difficult task seldom achievable. Therefore, in these areas peak hour congestion is a common event on the roadway approaches to bridges, tunnels, and other roadways that traverse such crossings.

Some US examples of topographic barriers in cities illustrate their impact on congestion.

- Manhattan Island in New York City requires motorists to cross the Hudson and East Rivers to reach the business district. AM peak hour inbound traffic backs up forming long queues on the roadways leading to the CBD, often requiring up to 40 min before reaching the crossing. Likewise PM peak hour traffic backs up forming long queues over many blocks on city streets that often require up to 40 min waiting time before reaching the bridge or tunnel crossing.
- San Francisco is located on a peninsula that is separated from Marin County and East Bay communities by San Francisco Bay. Road access from the north and east is limited to the Golden gate and Bay Bridges that constrain traffic demand from the converging freeways leading to the Bay Bridge.
- Los Angeles' San Fernando Valley is separated from the rest of the city by the Santa Monica mountains.
- Seattle is hemmed in by Elliot Bay and Lake Washington.
- Pittsburgh's Golden Triangle is located between the Allegheny and Mongonohela Rivers, and nearby hills to the east and south.
- New Orleans is bounded by the Mississippi River and Lake Ponchatrau.
- The Bronx in New York City, has few continuous east—west streets because of its difficult terrain.

Most cities also have man-made barriers to travel. These include large cemeteries, railroad embankments with infrequent crossings, and large private developments.

7.2.1.2 Design Deficiencies

Traffic bottlenecks are also the outcome of the geometric street layout as well as design deficiencies of critical sections/locations of the street network.

Street Network Geometry

City street patterns are an outgrowth of each city's history, geography and public policy.

1. Pre-automobile Cities—Streets in the central parts of many cities predate the automobile and therefore are not designed to accommodate motor vehicle traffic. Typically they have short, irregular blocks with insufficient capacity in the peak hours for storing vehicles waiting for a green signal. This feature makes these streets prone to spill back traffic creating significant congestion.
2. Many of the post WWII suburban developments have discontinuous street networks and continuous streets that are spaced too far apart with the effect of increasing the number of lanes in each street. This condition concentrate high traffic demand volume where these major streets intersect creating congestion delays.
3. Washington, DC, streets are largely part of the L'Enfant Plan for the National capital. Its combination of multi-direction radial streets superimposed on a rectangle grid creates many complex intersections commonly resulting in traffic congestion. Similar street plans were later adopted in Buffalo, Detroit, and Indianapolis.
4. Converging radial streets are common in many older cities. This pattern often results in peak hour congestion from converging traffic that exceeds the capacity of the intersection.
5. Several cities have a diagonal street system superimposed on a grid. Chicago's for example, has historic plank roads that create six-leg intersections where they cross the grid streets. Historic Broadway in Manhattan cuts across the north-south and east-west grid streets creating complex intersections where it crosses the grid—resulting in reduced intersection capacity.

Facility Design Deficiencies/Constraints

Bottlenecks are created whenever any of the following conditions exist in the road network:

- **Lane Imbalance**: At merge areas, at bridge and tunnel crossings, and where several roadways converge without corresponding increase in travel lanes can create extensive backups and congestion during busy travel periods.

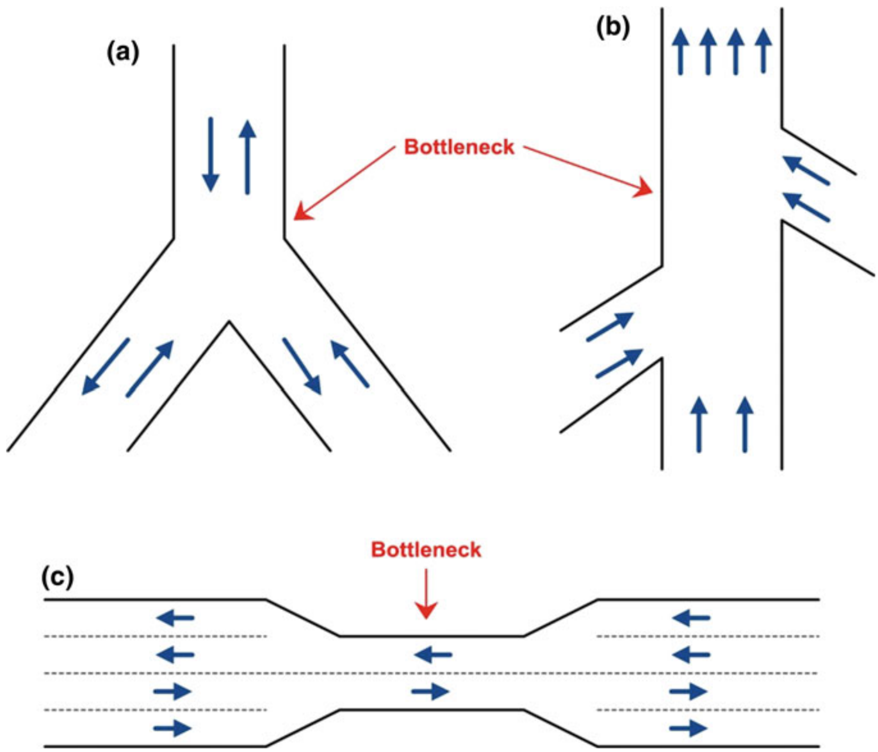


Fig. 7.1 Example of bottlenecks resulting from lane imbalance. **a** Converging roadway two lanes merge into one. **b** Converging roadway six lanes merge into four. **c** Converging roadway four lanes merge into two

Examples of lane imbalance are shown in Fig. 7.1: (a) two travel lanes margining into one; (b) six lanes merging into four; and (c) a 4-lane roadway narrows to 2 lanes for a short distance.

A common source of freeway congestion comes from where the number of entering lanes on two merging freeways exceeds the number of departing lanes (Fig. 7.2). This condition results in recurrent congestion.

A similar problem occurs where a highly traveled entry ramp joins the main freeway lanes without any increase in freeway capacity.

Figure 7.3 shows an example of the lack of lane balance along the Northbound Gowanus Expressway in Brooklyn, NYC. The merge points of the Prospect Parkway and the Belt Parkway with the Gowanus Expressway result in high congestion levels—every weekday morning in the peak hours.

Figure 7.4 shows the pattern of lane convergence along I-95 (southbound) in Connecticut, between Stamford and New Haven. As a result of this condition there is significant amount (intensity, duration, and extent) of daily congestion along this section of the expressway.

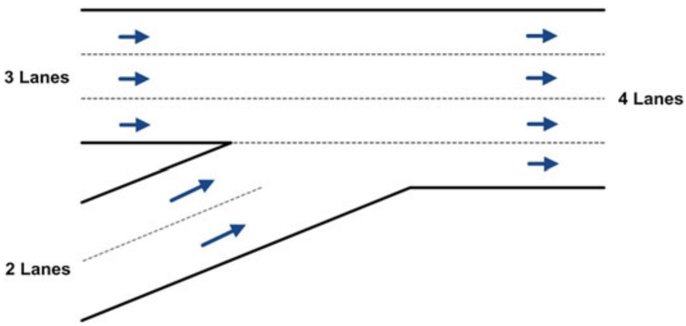
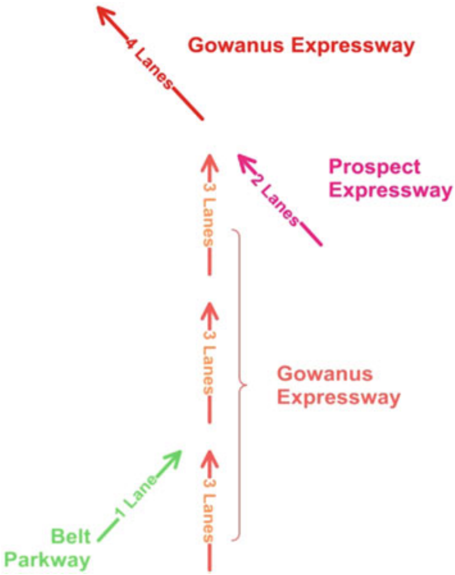


Fig. 7.2 Freeway lane imbalance

Fig. 7.3 Route convergence and lane imbalance along sections of the Gowanus Expressway, Brooklyn, NY



- **Geometric Constraints**: Sharp curves, steep vertical grades, and narrow lanes cause vehicles to slow down (Fig. 7.5). For example, large trucks going on a steep upgrade can create long queues of vehicles in back of the truck.
- **Short Auxiliary Lanes**: Auxiliary lanes on approaches to signalized intersections (Fig. 7.6) are sometimes too short to prevent queued up traffic waiting to turn left or right from blocking the through movement, causing large losses in throughput capacity of the intersection.
- **Inadequate Access Control**: Too many curb cuts and driveways create conflicts between through traffic and vehicles entering/exiting from parking lots/garages or driveways (Fig. 7.7).

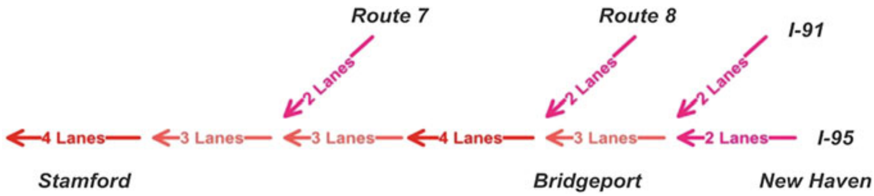
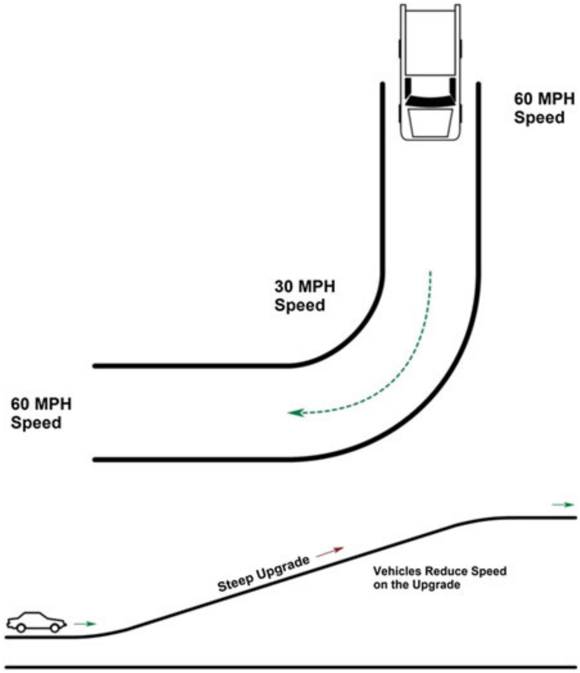


Fig. 7.4 Route convergence and lane imbalances, I-95 southbound (Southern Connecticut)

Fig. 7.5 Examples of sharp *curves* and steep grades



- **Deficient Driveway Geometry**: Commonly found where large entry areas are without lane markings necessary to channel traffic in an orderly way and where the queue space for vehicles entering or leaving the driveway is insufficient to prevent vehicles from spilling back onto the traffic lanes (Fig. 7.8).

Usually there is no provision for protected turning lanes or acceleration lanes along the public road. This condition creates conflicts between vehicles resulting in congested flow and high crash rates. Pedestrian circulation is also problematic due to pedestrian-vehicle conflicts.

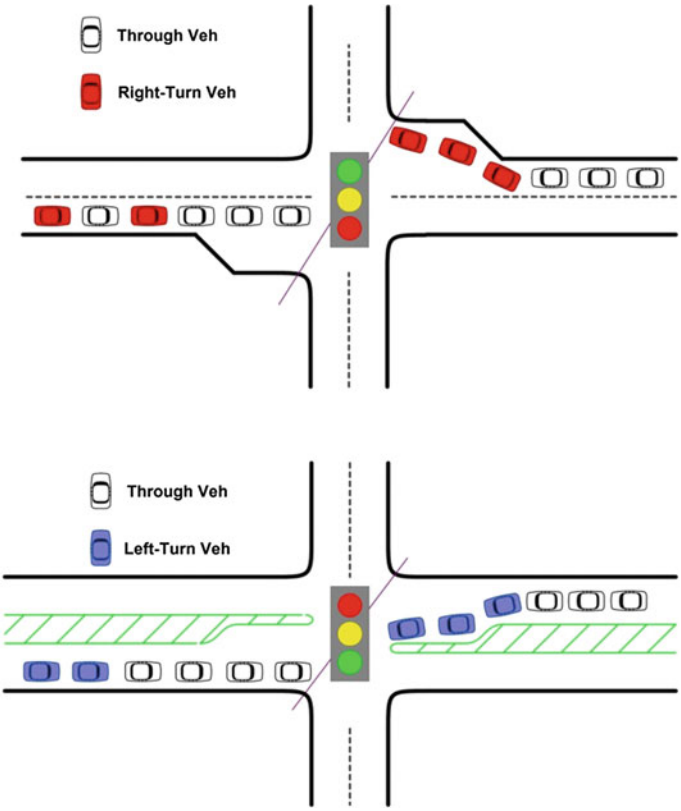


Fig. 7.6 Bottleneck effect of short auxiliary lanes. **a** Traffic queue limits access to auxiliary lane. **b** Right/left-turns back-up onto main travel lane

Fig. 7.7 Varying lot sizes with frequent driveways contribute to congestion

- **Multi-leg Intersections**: In many communities complex multi-leg intersections with more than two intersecting streets are the focal point of congestion. For example, an intersection of three streets requires at least three traffic signal phases—up to six phases if special phasing for left turns is required (Fig. 7.9).

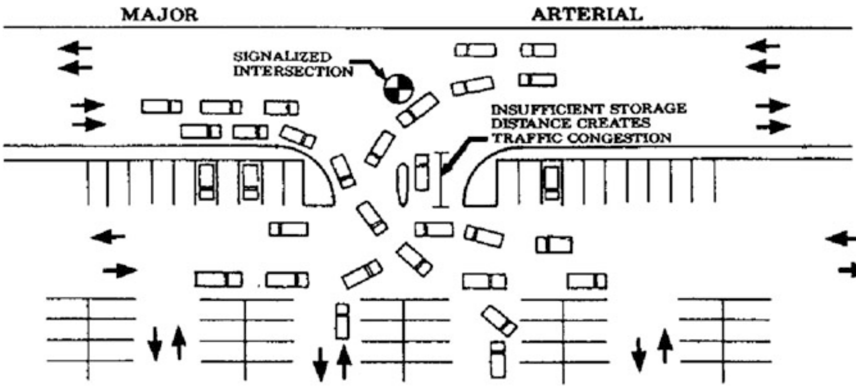
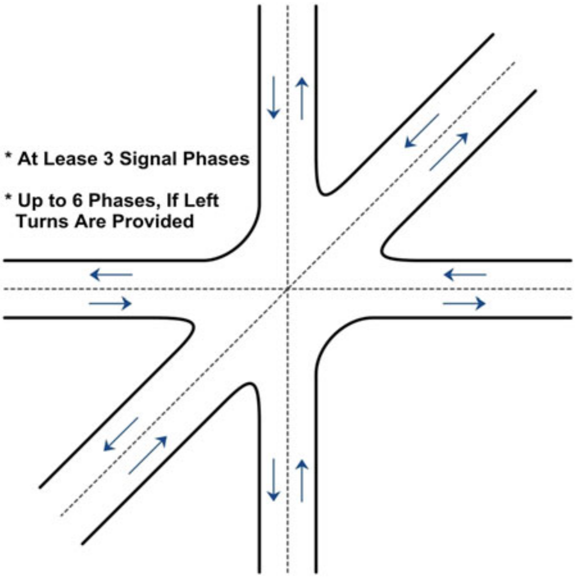


Fig. 7.8 Inadequate driveway geometry creates conflicts and congestion. *Source* Reference [3], p. 86. Fig. 8.32

Fig. 7.9 Six leg intersection



This condition reduces the time available at each approach to serve the approaching volume and creates a capacity deficiency that will result in congested conditions during heavy traffic periods.

- **Offset Intersections**: Offset intersections tend to over-load major roadways, complicating signal timing and sometime creating left-turn storage deficiencies. Examples are shown in (Figs. 7.10 and 7.11).
- **Offset Freeway Alignments**: Offset freeway interchanges result in the double loading of the common freeway segment (Fig. 7.12). Unless carefully designed

Fig. 7.10 Offset intersection with left-turn overload

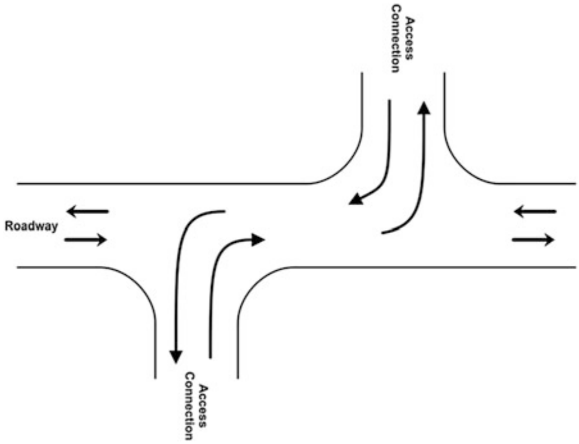
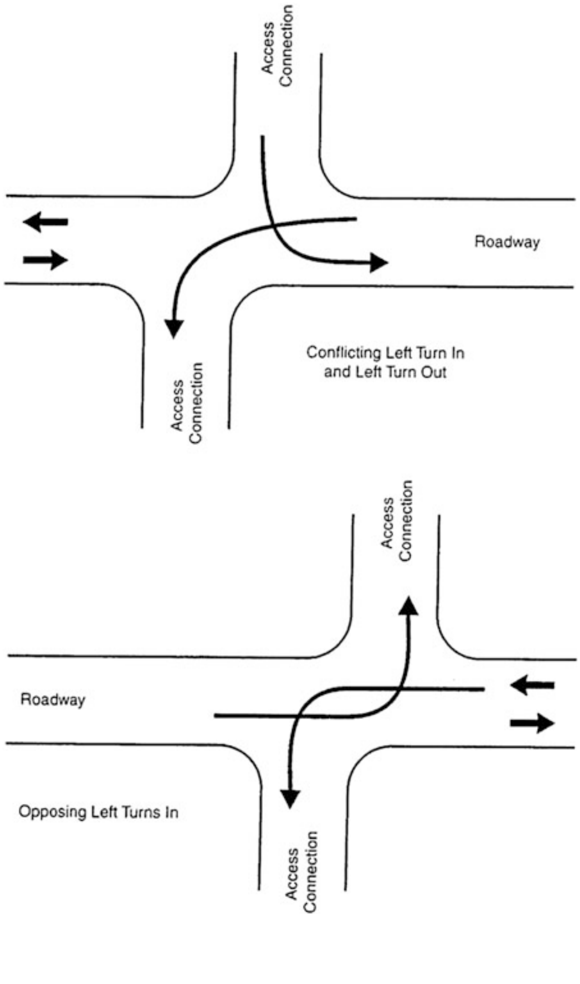


Fig. 7.11 Conflicts arising from closely spaced 'T' access connections. *Source* Reference [4]



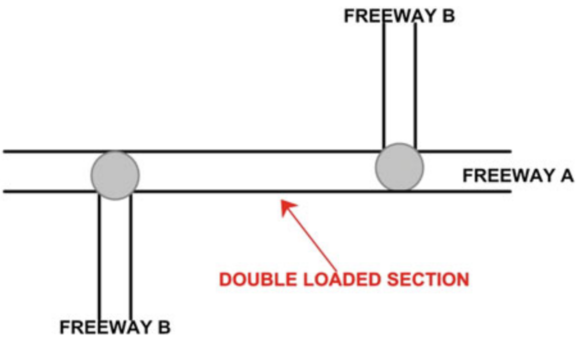


Fig. 7.12 Offset freeway interchange

to prevent cross—weaving maneuvers and lane imbalance, these locations are the source of capacity bottlenecks that cause substantial peak period delays.

- **<u>Complex Weaving Freeway Sections</u>**: Freeway weaving areas, where traffic must merge across several lanes to leave the freeway, can become congestion bottlenecks. This is especially so where the weaving section is too short—requiring traffic to slow down to find acceptable gaps to maneuver between lanes. These weaving conflicts are most problematic where there are left-side entry and right side exit, or right side entry and left side exit ramps, and there are several freeway lanes to cross (Fig. 7.13).
- **<u>Short Freeway On-Ramps</u>**: Short freeway on ramps, especially with inadequate (short) acceleration lanes cause merging traffic to enter gaps by forcing through traffic to slow down. An example is given in Fig. 7.14.
- **<u>Short Freeway Off-Ramps</u>**: Exit ramps with short deceleration lanes require exiting traffic to slow down while still in the through freeway lanes. These

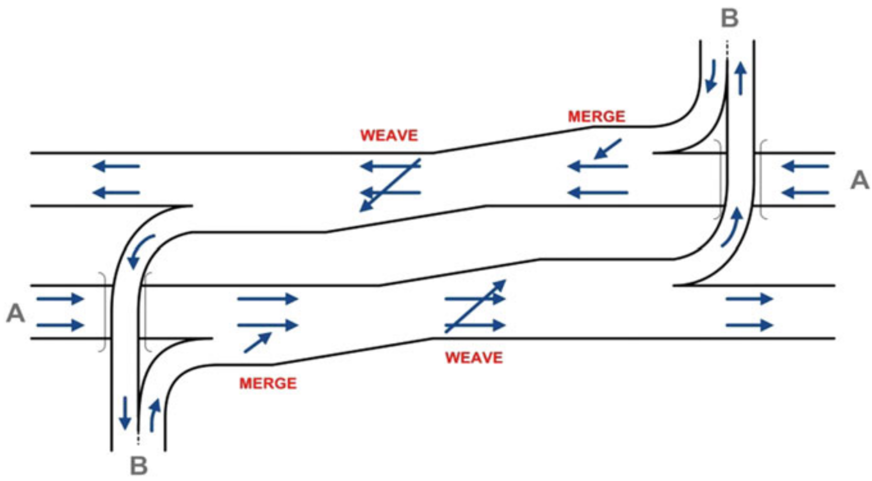


Fig. 7.13 Right side entry ramps and left side exit ramp causing complex weaving maneuvers

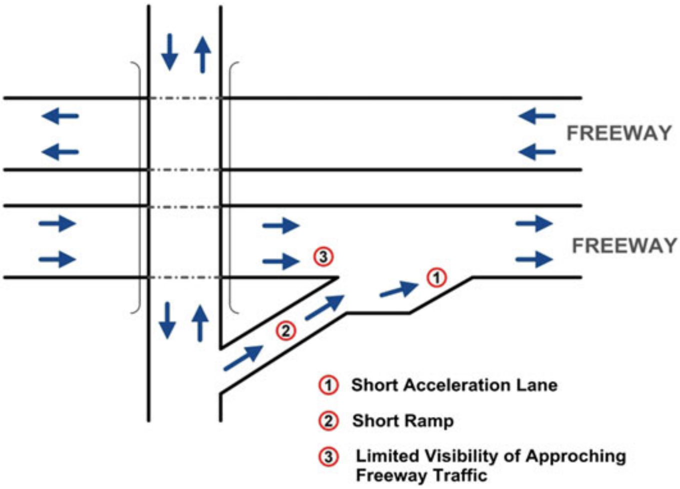


Fig. 7.14 Inadequate freeway on—ramp and acceleration lane

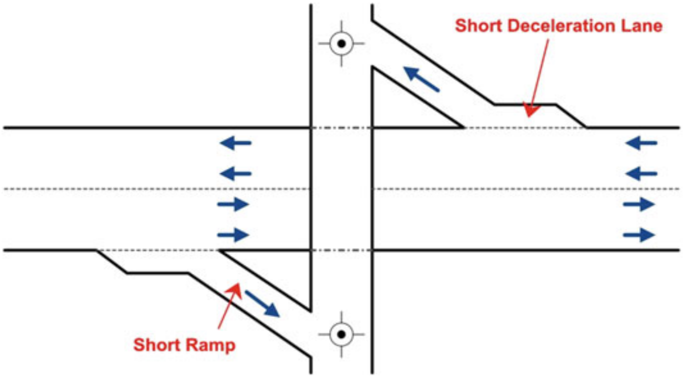


Fig. 7.15 Inadequate freeway exit ramps

maneuvers force through traffic on the freeway lanes to slow down as well. In addition there are cases where the length of the exit ramp approaching a traffic signal is too short to hold the traffic queue generated by the signal. This situation creates backup of queued traffic into the freeway lanes. Figure 7.15 provides an example.

- **Movable Bridge Openings**: Streets and roadways sometimes span water bodies on movable brides. When the watercraft approaches, the bridge is opened to let the motor craft through and motor vehicle traffic is stopped. Traffic backups result as approaching vehicles must wait until the bridge is reopened for their use.

- **Railroad Grade Crossings**: Railroad grade crossings are common in many suburban areas. Whenever trains pass, motor vehicle and pedestrian/bicycle movements are stopped. Also in this situation queues are formed and their length is critical in determining the congestion impacts on the connecting roadways.

7.2.2 *Operational Bottlenecks*

Midblock and intersection conflicts cause bottlenecks that contribute to congestion especially during heavy traffic periods. These conflicts are the result of loading and unloading of goods from the streets and are the result of cross traffic, as well as turning vehicles and pedestrian conflicts at signals.

7.2.2.1 Curb Parking and Goods-Loading Conflicts

On-street curb parking in business districts frequently results in congestion by reducing the number of lanes that are available for moving traffic. In addition, double parking during peak periods—often by delivery and courier vehicles—have an even more detrimental on movement. They block several traffic lanes, and during heavy periods can cause spillback on approaches to the bottleneck.

This condition is generally found where:

- On-street parking is permitted during busy traffic periods
- There is inadequate enforcement of curb parking regulations
- There are frequent double parkers.

Where a street has two lanes in a given direction, and where parked vehicles occupy one lane there is at least a 50 % loss in capacity.

7.2.2.2 Intersection Conflicts

Intersections of major streets are often the focal points of traffic congestion during peak periods of travel. The many conflicts—between pedestrians, cyclists, and motorized traffic; between through and cross traffic, and between through and turning vehicles are major sources of congestion.

As shown in Figs. 7.16 and 7.17, at a typical four-way intersection there are 32 vehicle–vehicle conflict points and 48 pedestrian-vehicle and bicycle-vehicle conflicts.

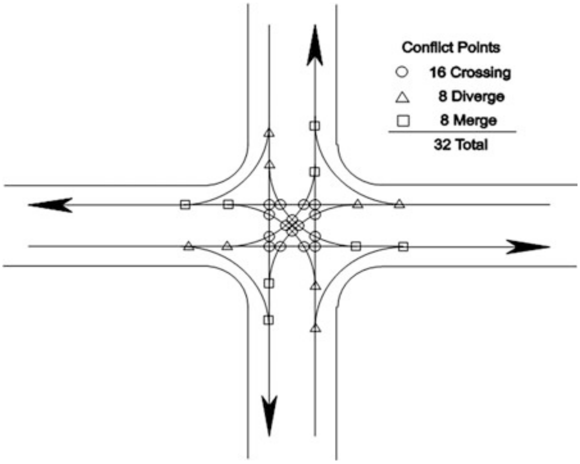


Fig. 7.16 Vehicular conflict points at a typical four-way intersection. *Source* Reference [4]

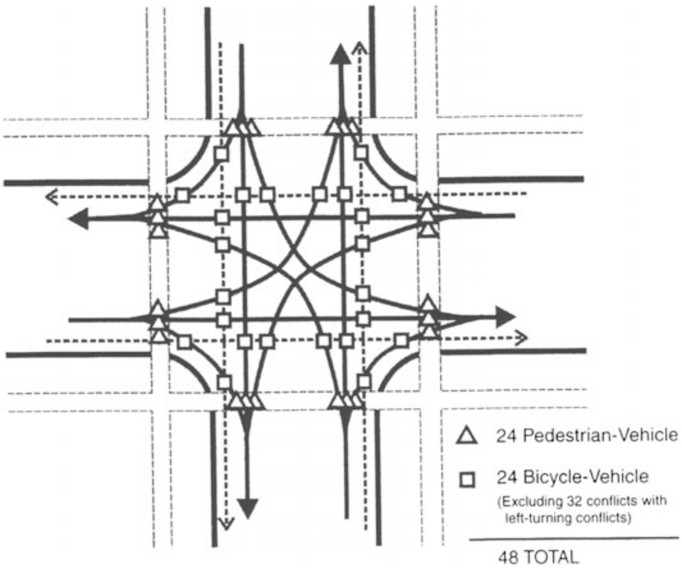


Fig. 7.17 Pedestrian—vehicle and pedestrian- bicycle conflict points at a four-way intersection. *Source* Reference [4]

Conflicting traffic movements through a street intersection are usually separated by a traffic signal that alternatively allocates a proportion (or phase) of the total time available (or cycle) to move traffic and to stop traffic from moving. The stopped time on each approach is a cause of congestion during periods of heavy traffic volume.

The key causes of intersection congestion include:

- an insufficient number of travel lanes on intersection approaches
- the lack of exclusive lanes of adequate length for right and left turns
- heavy traffic volumes and turning movements on the various conflicting approaches
- heavy pedestrian and bicycle movements that conflict with and impede and impeded traffic flow.

7.2.2.3 Traffic Signals

Because traffic signals control conflicting movements they account for much of the traffic delay along streets and roads. Their location, phasing, and timing can substantially increase congestion when:

- the total green time per signal cycle must be shared by conflicting traffic streams
- right-turns conflict with heavy pedestrian volumes
- left-turns operating from a lane shared with through traffic can block through vehicles. When there is one left-turn per cycle, about 40 % of the through vehicles in the shared lane are blocked. When there are three left-turn vehicles per cycle, about 70 % of through traffic is blocked. When protected left turn lanes are provided, there is generally no impedance to through traffic moving in the same direction
- Left turns with exclusive turn lanes must share the green time with the through traffic in the opposing direction.

Traffic signal location, spacing, and timing deficiencies commonly include:

a. Placing signals where they do not fit the progression pattern reduces the width of the through (or green)—band (Fig. 7.18).
b. Although efficient progression can be maintained by increasing the green time on the major street, but this condition would require a reducing the green time on the cross street with a corresponding increase in delay to cross street traffic (4).
c. Providing an excessive number of phases such as a pre-timed exclusive pedestrian phase where there are few pedestrians crossing a highway.
d. Using cycle lengths that are too short to serve peak traffic demands can result in excessive delay.
e. Using cycle lengths that are too long (e.g., over 2 min) make signal coordination difficult to achieve.
f. Operating closely spaced signals that are not coordinated.
g. Operating obsolete traffic signal control systems that limit the ability to establish time-of-day or traffic responsive signal coordination.
h. Locating signals at irregular intervals that limit or preclude coordination.
i. Placing signals too close together, thereby limiting effective coordination and resulting in frequent stops.

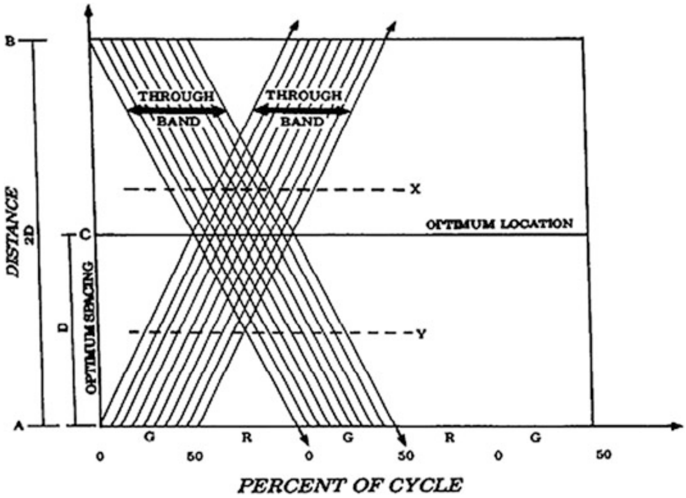


Fig. 7.18 Time-space pattern. *Source* Reference [5]

The key considerations from both capacity and congestion perspectives include (a) the traffic signal cycle, (b) the number of phases, (c) the amount of green time on each phase, and (d) the number of lanes and the traffic volume on each approach. Detailed procedures for estimating intersection capacities, stopped delays at intersections, and "levels of service" are set forth in the 2010 Highway Capacity Manual [6].

Figures 7.19 and 7.20 show the effects of volume-to-capacity ratios and traffic signal spacing on arterial speed. The free-flow speed decreases as the number of signals per mile increases. And the rate of speed drop diminishes after signal density exceeds 5 signals per mile.

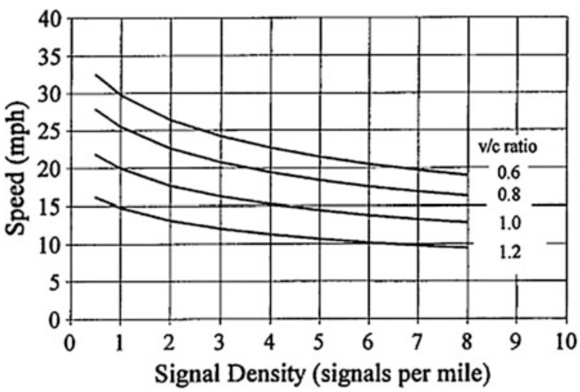


Fig. 7.19 Suggested speed estimation curves as a function of signal spacing and V/C Ratio—Class I arterials. *Source* Reference [7], Fig. 7.10

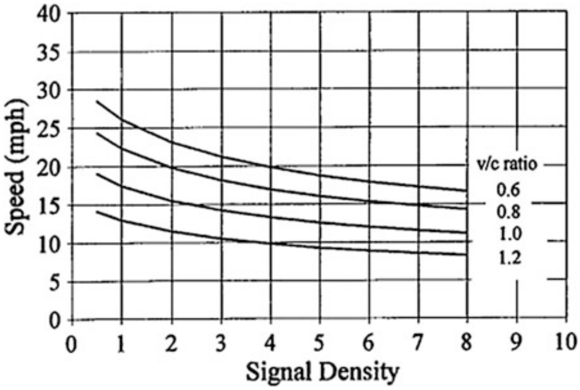


Fig. 7.20 Suggested speed estimation curves as a function of signal spacing and V/C Ratio—Class II and III arterials. *Source* Reference [7], Fig. 7.11

Table 7.3 Percent increase in travel time as a function of traffic signals per mile

Signals per mile	Percent increase in travel time (two signals per mile as base) (%)
3.0	9
4.0	16
5.0	23
6.0	29
7.0	34
8.0	39

Source Reference [8]

The effect of an increase in traffic volume on traffic speed reduction is expressed by a family of curves for various volume-to-capacity (V/C) ratios. For example, for class I arterials, approximately 2 mph drop in speed results for every 0.1 increase in the V/C ratio for roads with fewer than 4 signals per mile. But for roads with 8 signals per mile the drop in speed diminishes to a little over 1 mph for every 0.1 increase in the V/C ratio.

These curves show that traffic signal density has a greater effect on delay than traffic volumes when the volume-to-capacity ratio is less than 0.8. Signal density has its biggest effect of free-flow traffic at 1–3 signals per mile. When traffic demand approaches or exceeds roadway capacity there is a drop in speed at all signal densities.

Using two traffic signals per mile as a base, Table 7.3 provides estimates of the percentage increase in travel time as the signal frequency per mile increases [8].

These relationships suggest that (1) the number of phases should be kept to a minimum, and (2) spacing of signals should permit progression flow to the maximum extent possible.

7.3 Nonrecurring Bottlenecks

7.3.1 Introduction

Nonrecurring congestion results when the roadway capacity is reduced by (1) incidents that remove one or more travel lanes from service, or cause drivers (on both sides of the road) to slow down as they to observe the roadside activities related to the incident; and by (2) headways that are increased by inclement weather, work zones, or driver behavior. Another cause of nonrecurring congestion is a surge in demand in excess of what the roadway can handle (e.g., the exit of spectators at the end of a ball game).

In all cases there is an imbalance between roadway supply and travel demand. In addition to the duration of the above events (e.g., road blockage or demand surge) there is also delay during the recovery time until the normal traffic operation resumes.

7.3.1.1 Traffic Incidents

Traffic incidents reduce roadway capacity and contribute to congestion. The amount of delay depends upon the type/duration of the incident, the number of lanes blocked by the incident, the response times to reach and clear the incident, and the time needed for the roadway (freeway) to resume normal operation.

Traffic incidents reduce roadway capacity [1]. Estimates of the amount of freeway capacity available, as a function of number of lanes blocked by the incident, are provided in Table 7.4, which shows that even when an incident is located at the shoulder of the road it reduces its capacity.

Table 7.4 Freeway capacity available from incident conditions

Number of freeway lanes in each direction	Shoulder disablement	Shoulder accident	Lanes blocked		
			One	Two	Three
2	0.95	0.81	0.35	0	N/A
3	0.99	0.83	0.49	0.17	0
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.25
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

Source Reference [1], pp 1–9, Table 1–2

Table 7.5 Estimated speeds from inclement weather

Precipitation condition	Observed speeds (MPH)	Ratio to no precipitation
No precipitation	64	1
Drizzle	51	0.8
Light rain	50	0.8
Light snow	45	0.7
Rain	48	0.8
Sleet	37	0.6
Snow	37	0.6
Thunder showers	53	0.8
Thunder storm	47	0.7
Strong thunder storm	28	0.5

Source Reference [10]. With permission from ASCE.

7.3.1.2 Surge in Demand

Surges in traffic demand include sports events, seasonal shopping, cultural and recreational events, etc. Vehicle traffic demand in excess of roadway capacity creates queues resulting in lower traffic speeds. Delay lasts longer than the duration of the demand surge.

7.3.1.3 Inclement Weather

Bad Weather: rain and snow reduce visibility and causes drivers to reduce speed. The presence of snow and ice on the road can also reduce speeds. Advances in sensor technologies and continued deployment of intelligent transportation system (ITS) architectures provide the means to anticipate, mitigate, and intervene through various traveler advisory and control measures to better manage traffic flow in periods of inclement weather [9]. Light rain could reduce freeway speeds by 20 %; while severe thunder storms could create a speed reduction of about 50 % (Table 7.5).

The effect of pavement conditions from weather events on traffic speed is summarized in Table 7.6.

7.3.1.4 Work Zones/Street Closures

Road Repair: Construction activities on roadways result in physical changes to the roadway including: narrower lanes, lane shifts, reduction in the number of travel lanes. In addition, slower speed limits are also established in construction zones. These changes increase travel time.

Table 7.6 Effect of weather-generated pavement conditions on traffic speed

Condition	Percent speed reduction (%)
Dry	0
Wet	0
Wet and snowing	13
Wet and slushy	22
Slushy in wheel Paths	30
Snowy and sticking	35
Snowing and packed	42

Source Reference [11]

Street Closures: These events result from emergencies or of planned events (marathon, street fairs, visits by heads of state, etc.). Because they reduce roadway capacity, travel speed drops.

Utility Cuts: In many cities utilities are located below the roadway surface, and their repair often involves closing at least one lane to traffic that reduces capacity and travel speed.

7.3.1.5 Driver Behavior

Erratic and improper driver behavior can contribute to a reduction in traffic speed resulting in congestion.

Examples follow:

a. Use of the passing lane by one slow driver reduces the speed of all drivers.
b. Drivers tend to slow down while passing an incident location in the opposite direction (rubbernecking).
c. Loading or Unloading in moving lanes: the use of moving lanes by commercial vehicles for loading and unloading reduces capacity and forces vehicles to slow down as they change lanes. The same goes for bus drivers that don't pull into the bus stop, and for taxi drivers who pick up or discharge passengers from the moving lane.

7.4 Conclusion

As previously shown in Table 7.2, the proportion of total delay attributed to nonrecurring bottlenecks in urban areas far exceeds that from recurring bottlenecks. As much as 2/3 of the total delay in large and small metropolitan areas is attributable to nonrecurring bottlenecks.

Since nonrecurring congestion is often experienced at the same time and locations where recurring congestion occurs, the severity of nonrecurring delay is highly conditioned by the physical and operational bottlenecks inherent in the roadway system. Therefore effective congestion relief measures should be combined to address both nonrecurring and recurring congestion.

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