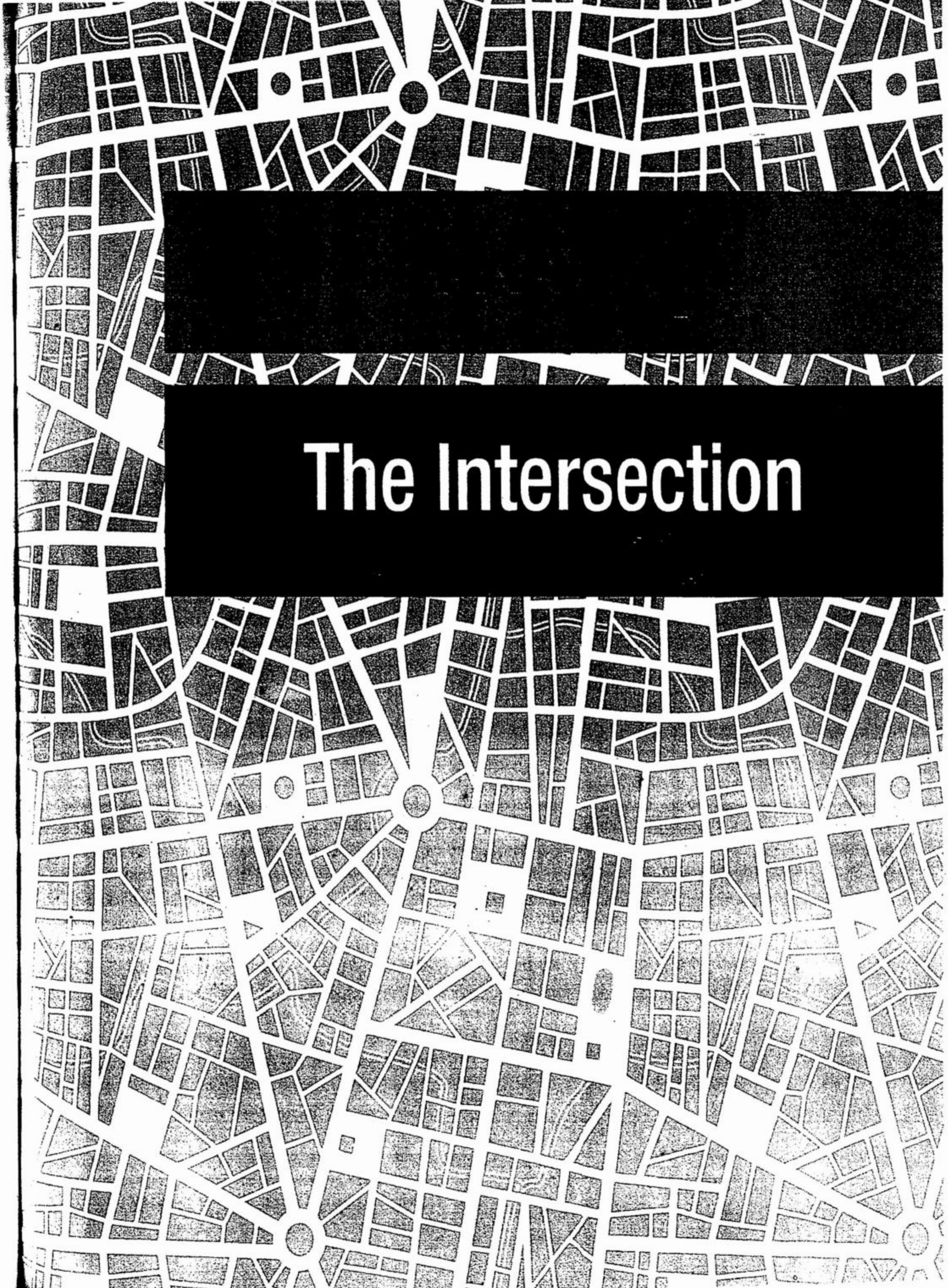

The Intersection

CHAPTER 18

The Hierarchy of Intersection Control

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The most complex individual locations within any street and highway system are at-grade intersections. At a typical intersection of two two-way streets, there are 12 legal vehicular movements (left turn, through, and right turn from four approaches) and four legal pedestrian crossing movements. As indicated in Figure 18.1, these movements create many potential conflicts where vehicles and/or pedestrian paths may try to occupy the same physical space at the same time.

As illustrated, there are a total of 16 potential vehicular crossing conflicts: four between through movements from the two streets, four between left-turning movements from the two streets, and eight between left-turning movements and through movements from the two streets. In addition, there are eight vehicular merge conflicts as right- and left-turning vehicles merge into a through flow at the completion of their desired maneuver. Pedestrians add additional potential conflicts to the mix.

The critical task of the traffic engineer is to control and manage these conflicts in a manner that ensures safety and provides for efficient movement through the intersection for both motorists and pedestrians.

Three basic levels of control can be implemented at an intersection:

- *Level I*—Basic rules of the road
- *Level II*—Direct assignment of right-of-way using YIELD or STOP signs
- *Level III*—Traffic signalization

There are variations within each level of control as well. The selection of an appropriate level of control involves a determination of which (and how many) conflicts a driver should be able to perceive and avoid through the exercise of judgment. Where it is not reasonable to expect a driver to perceive and avoid a particular conflict, traffic controls must be imposed to assist.

Two factors affect a driver's ability to avoid conflicts: (1) a driver must be able to see a potentially conflicting vehicle or pedestrian in time to implement an avoidance maneuver, and (2) the volume levels that exist must present reasonable opportunities for a safe maneuver to take place. The first involves considerations of sight distance and avoidance maneuvers, and the second involves an assessment of demand intensity, the complexity of potential conflicts that exist at a given intersection, and finally, the gaps available in major movements.

A rural intersection of two farm roads contains all of the potential conflicts illustrated in Figure 18.1. However, pedestrians are rare, and vehicular flows may be extremely low. There is a low probability of any two vehicles and/or pedestrians attempting to use a common physical point simultaneously. At the junction between two major urban arterials, the probability of vehicles or pedestrians on conflicting paths arriving simultaneously is quite high. The sections that follow discuss how a determination of an appropriate form of intersection control can be made, highlighting the important factors to consider in making such critical decisions.

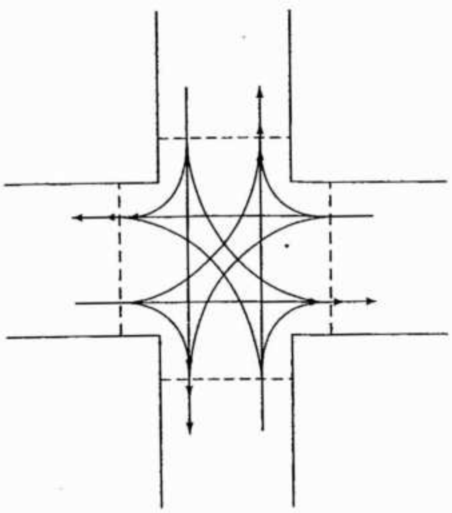


Figure 18.1: Typical Conflicts at a Four-Leg Intersection

18.1 Level I Control: Basic Rules of the Road

Basic rules of the road apply at any intersection where right-of-way is not explicitly assigned through the use of traffic signals, STOP, or YIELD signs. These rules are spelled out in each state's vehicle and traffic law, and drivers are expected to know them. At intersections, all states follow a similar format. In the absence of control devices, the driver on the left must yield to the driver on the right when the vehicle on the right is approaching in a manner that may create an impending hazard. In essence, the responsibility for avoiding a potential conflict is assigned to the vehicle on the left. Most state codes also specify that through vehicles have the right-of-way over turning vehicles at uncontrolled intersections.

Operating under basic rules of the road does not imply that no control devices are in place at or in advance of the intersection, although that could be the case. Use of street-name signs, other guide signs, or advance intersection warning signs do not change the application of the basic rules. They may, however, be able to contribute to the safety of the operation by calling the driver's attention to the existence and location of the intersection.

To safely operate under basic rules of the road, drivers on conflicting approaches must be able to see each other in time to assess whether an "impending hazard" is imposed and to take appropriate action to avoid an accident. Figure 18.2 illustrates a visibility triangle at a typical intersection. Sight distances must be analyzed to ensure that they are sufficient for drivers to judge and avoid conflicts.

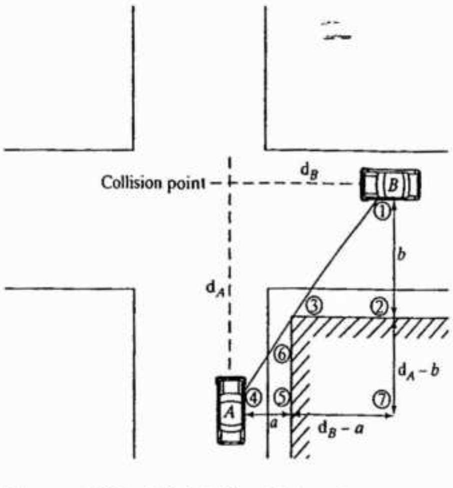


Figure 18.2: Visibility Triangle at an Intersection

At intersections, sight distances are normally limited by buildings or other sight-line obstructions located on or near the corners. There are, of course, four sight triangles at every intersection with four approaches.

All must provide adequate visibility for basic rules of the road to be considered. At the point where the drivers of both approaching vehicles first see each other, Vehicle A is located a distance of d_A from the collision or conflict point, and Vehicle B is located a distance d_B from the collision point. The sight triangle must be sufficiently large to ensure that at no time could two vehicles be on conflicting paths at distances and speeds that might lead to an accident, without sufficient time and distance being available for either driver to take evasive action.

Note that the sight line forms three similar triangles with sides of the sight obstruction: Δ123, Δ147, and Δ645. From the similarity of the triangles, a relationship between the critical distances in Figure 18.2 can be established:

$$\frac{b}{d_B - a} = \frac{d_A - b}{a}$$

$$d_B = \frac{a\, d_A}{d_A - b} \qquad (18\text{-}1)$$

Where: d_A = distance from Vehicle A to the collision point, ft

d_B = distance from Vehicle B to the collision point, ft

a = distance from driver position in Vehicle A to the sight obstruction, measured parallel to the path of Vehicle B, ft

b = distance from driver position in Vehicle B to the sight obstruction, measured parallel to the path of Vehicle A, ft

Thus, when the position of one vehicle is known, the position of the other when they first become visible to each other can be computed. The triangle is dynamic, and the position of one vehicle affects the position of the other when visibility is achieved.

The American Association of State Highway and Transportation Officials (AASHTO) suggests that to ensure safe operation with no control, both drivers should be able to stop before reaching the collision point when they first see each other. In other words, both d_A and d_B should be equal to or greater than the safe stopping distance at the points where visibility is established. AASHTO standards [*1*] suggest that a driver reaction time of 2.5 seconds be used in estimating safe stopping distance and that the 85th percentile speed of immediately approaching vehicles be used. AASHTO does suggest, however, that drivers slow from their midblock speeds when approaching uncontrolled intersections, and it recommends use of an immediate approach speed that is assumed to be lower than the design speed of the facility. From Chapter 2, the safe stopping distance is given by:

$$d_s = 1.47\,S_i t + \frac{S_i^2}{30(0.348 \pm 0.01G)} \qquad (18\text{-}2)$$

where: d_s = safe stopping distance, ft
S_i = initial speed of vehicle, mi/h
G = grade, %
t = reaction time, s
0.348 = standard friction factor for stopping maneuvers

Using this equation, the following analysis steps may be used to test whether an intersection sight triangle meets these sight distance requirements:

1. Assume that Vehicle A is located one safe stopping distance from the collision point (i.e., $d_A = d_s$), using Equation 18-2. By convention, Vehicle A is generally selected as the vehicle on the *minor* street.
2. Using Equation 18-1, determine the location of Vehicle B when the drivers first see each other. This becomes the actual position of Vehicle B when visibility is established, d_{Bact}.
3. Because the avoidance rule requires that both vehicles have one safe stopping distance available, the minimum requirement for d_B is the safe stopping distance for Vehicle B, computed using Equation 18-2. This becomes d_{Bmin}.
4. For the intersection to be safely operated under basic rules of the road (i.e., with no control), $d_{Bact} \geq d_{Bmin}$.

Historically, another approach to ensuring safe operation with no control has also been used. In this case, to avoid collision from the point at which visibility is established, *Vehicle A must travel 18 feet past the collision point in the same time that Vehicle B travels to a point 12 feet before the collision point.* This can be expressed as:

$$\frac{d_A + 18}{1.47\,S_A} = \frac{d_B - 12}{1.47\,S_B}$$

$$d_B = (d_A + 18)\frac{S_B}{S_A} + 12 \qquad (18\text{-}3)$$

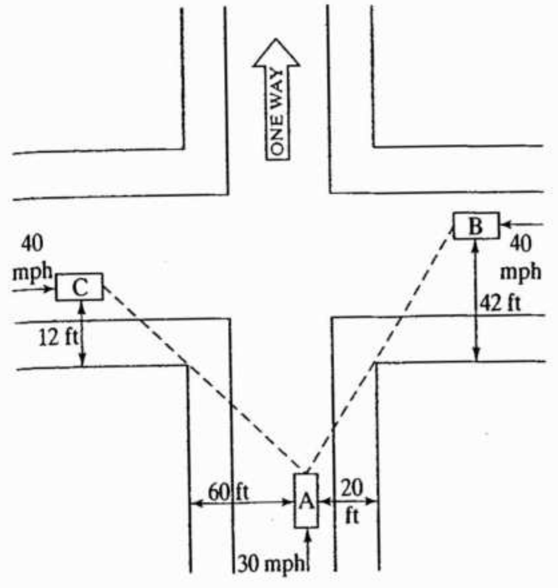
where all variables are as previously defined. This, in effect, provides another means of estimating the minimum required distance, d_{Bmin}. In conjunction with the four-step analysis process outlined previously, it can also be used as a criterion to ensure safe operation.

At any intersection, all of the sight triangles must be checked and must be safe to implement basic rules of the road. If, for any of the sight triangles, $d_{Bact} < d_{Bmin}$, then operation with no control cannot be permitted. When this is the case, there are three potential remedies:

- Implement intersection control, using STOP- or YIELD-control, or traffic signals.
- Lower the speed limit on the major street to a point where sight distances are adequate.
- Remove or reduce sight obstructions to provide adequate sight distances.

The first is the most common result. The exact form of control implemented would require consideration of warrants and other conditions, as discussed in subsequent portions of this chapter. The second approach is viable where sight distances at series of uncontrolled intersections can be remedied by a reduced but still reasonable speed limit. The latter depends on the type of obstruction and ownership rights.

Consider the intersection illustrated in Figure 18.3. It shows an intersection of a one-way minor street and a two-way major street. In this case, two sight triangles must be analyzed. The 85th percentile immediate approach speeds are shown.



(reaction time = 2.5 s, level grade)

Figure 18.3: Sample Problem: Intersection Sight Distance

First, it is assumed that Vehicle A is one safe stopping distance from the collision point:

$$d_A = 1.47 * 30 * 2.5 + \frac{30^2}{30(0.348 + 0)}$$

$$= 110.3 + 86.2 = 196.5 \text{ ft}$$

where 2.5 s is the standard driver reaction time used in safe stopping sight distance computations. Using Equation 18-1, the actual position of Vehicle B when it is first visible to the driver of Vehicle A is found:

$$d_{Bact} = \frac{a\,d_A}{d_A - b} = \frac{20 * 196.5}{196.5 - 42} = \frac{3{,}930}{154.5} = 25.4 \text{ ft}$$

This must be compared with the minimum requirement for d_B, estimated as either one safe stopping distance (Equation 18-2), or using Equation 18-3:

$$d_{Bmin} = 1.47 * 40 * 2.5 + \frac{40^2}{30(0.348 + 0)}$$

$$= 147.0 + 153.3 = 300.3 \text{ ft}$$

or:

$$d_{Bmin} = (196.5 + 18)\frac{40}{30} + 12 = 298.0 \text{ ft}$$

In this case, both of the minimum requirements are similar, and both are far larger than the actual distance of 25.4 ft. Thus the sight triangle between Vehicles A and B fails to meet the criteria for safe operation under basic rules of the road.

Consider the actual meaning of this result. Clearly, if Vehicle A is 196.5 feet away from the collision point when Vehicle B is only 25.4 feet away from it, they will not collide. Why, then, is this condition termed "unsafe?" It is unsafe because there could be a Vehicle B, further away than 25.4 feet, on a collision path with Vehicle A and the drivers would not be able to see each other.

Because the sight triangle between Vehicles A and B did not meet the sight-distance criteria, it is not necessary to check the sight triangle between vehicles A and C. Basic rules of the road may not be permitted at this intersection without reducing major street speeds or removing sight obstructions. This implies that, in many cases, YIELD or STOP control should be imposed on the minor street as a minimum form of control.

Even if the intersection met the sight-distance criteria, this does not mean that basic rules of the road should be applied to the intersection. Adequate sight distance is a *necessary*, but *not sufficient*, condition for adopting a "no-control" option. Traffic volumes or other conditions may make a higher level of control desirable or necessary.

18.2 Level II Control: YIELD and STOP Control

If a check of the intersection sight triangle indicates it would not be safe to apply the basic rules of the road, then as a minimum, some form of level II control is often imposed. Even if sight distances are safe for operating under no control, there may be other reasons to implement a higher level of control as well. Usually, these would involve the intensity of traffic demand and the general complexity of the intersection environment.

The *Manual of Uniform Traffic Control Devices* (MUTCD) [2] gives some guidance as to conditions for which imposition of STOP or YIELD control is justified. It is not very specific, and it requires the exercise of engineering judgment. The warrants shown are taken from the draft of the 2010 MUTCD, which has been available for review on line since December 2007. At this writing, final approval to the contents of this edition has not been obtained. Final approval and official publication is expected in late 2009 or early 2010.

The MUTCD gives some very general "guidance" for the imposition of *either* STOP signs *or* YIELD signs. These shown in Table 18.1.

Table 18.1: Warrants for Using 2-Way STOP or YIELD Control at an Intersection

STOP or YIELD signs should be used at an intersection if one or more of the following conditions exist:

A. An intersection of a less important road with a main road where application of the normal right-of-way rule would not be expected to provide reasonable compliance with the law;

B. A street entering a designated through highway; and/or

C. An unsignalized intersection within a signalized area.

(*Source: Manual on Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, p. 70, available at www.fhwa.com.)

These are very general. The first condition simply addresses a situation in which the sight triangle is insufficient to provide for safety. STOP or YIELD signs can be used to help establish a major or through road. If all unsignalized approaches to a major road are controlled by STOP or YIELD signs, through drivers have a clear right-of-way. The last condition addresses a situation in which virtually *all* intersections in an area or along an arterial are signalized. If a few isolated locations do not need to be signalized, then they should *at least* have STOP or YIELD signs.

18.2.1 Two-Way Stop Control

The most common form of Level II control is the two-way STOP sign. In fact, such control may involve one or two STOP signs, depending on the number of intersection approaches. It is not all-way STOP control, which is discussed later in this chapter.

Under the heading of "guidance," the MUTCD suggests several conditions under which the use of STOP signs would be justified. Table 18.2 shows these warrants.

Warrant A establishes a reasonable level of major street traffic that would require use of a STOP sign to allow minor-street drivers to select an appropriate gap in a busy traffic stream. Warrant B merely restates the need for STOP (or YIELD) control where a sight triangle at the intersection is found to be inadequate. Warrant C establishes criteria for using a STOP sign to correct a perceived accident problem.

Table 18.2: Warrants for STOP Signs

At intersections where a full stop is not necessary at all times, consideration should first be given to using less restrictive measures, such as YIELD signs.

The use of STOP signs on the minor street approaches should be considered if engineering judgment indicates that a stop is always required because of one or more of the following conditions:

A. The vehicular traffic volumes on the through street or highway exceed 6,000 veh/day;

B. A restricted view exists that requires road users on the minor street approach to stop in order to adequately observe conflicting traffic on the through street or highway.

C. Crash records indicate that 3 or more crashes that are susceptible to correction by installation of a STOP sign have been reported within a 12-month period, or that 5 or more such crashes have been reported within a 2-year period. Such crashes include right-angle collisions involving road users on the minor street approach failing to yield the right-of-way to traffic on the through street or highway.

(*Source: Manual of Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, p. 71. available at www.fhwa.com.)

The MUTCD is somewhat more explicit in dealing with inappropriate uses of the STOP sign. Under the heading of a "standard" (i.e., a mandatory condition), STOP (or YIELD) signs *shall not* be installed at intersections where traffic control signals are installed and operating, except where signal operation is a flashing red at all times, or where a channelized right turn exists. This disallows a past practice in which some jurisdictions turned signals off at night, leaving STOP signs in place for the evening hours. During the day, however, an unfamiliar driver approaching a green signal with a STOP sign could become significantly confused. The manual also disallows the use of portable or part-time STOP signs except for emergency and temporary traffic control.

Under the heading of "guidance," STOP signs *should not* be used for speed control, although this is frequently done on local streets designed in a straight grid pattern. In modern designs, street layout and geometric design would be used to discourage excessive speeds on local streets.

In general, STOP signs should be installed in a manner that minimizes the number of vehicles affected, which generally means installing them on the minor street.

AASHTO [*1*] also provides sight distance criteria for STOP-controlled intersections. A methodology based on observed gap acceptance behavior of drivers at STOP-controlled intersections is used. A standard stop location is assumed for the minor street vehicle (Vehicle A in Figure 18.2). The distance to the collision point (d_A) has three components:

- Distance from the driver's eye to the front of the vehicle (assumed to be 8 feet)
- Distance from the front of the vehicle to the curb line (assumed to be 10 feet)
- Distance from the curb line to the center of the right-most travel lane approaching from the left, or from the curb line to the left-most travel lane approaching from the right

Thus:

$$d_{A\text{-}STOP} = 18 + d_{cl} \qquad (18\text{-}4)$$

where: $d_{A\text{-}STOP}$ = distance of Vehicle A on a STOP-controlled approach from the collision point, ft
d_{cl} = distance from the curb line to the center of the closest travel lane from the direction under consideration, ft

The required sight distances for Vehicle B, on the major street for STOP-controlled intersections is found as follows:

$$d_{Bmin} = 1.47 * S_{maj} * t_g \qquad (18\text{-}5)$$

where: d_{Bmin} = minimum sight distance for Vehicle B approaching on major (uncontrolled) street, ft
S_{maj} = design speed of major street, mi/h
t_g = average gap accepted by minor street driver to enter the major road, s

Average gaps accepted are best observed in the field for the situation under study. In general, they range from 6.5 seconds to 12.5 seconds depending on the minor street movement and vehicle type, as well as some of the specific geometric conditions that exist.

For most STOP-controlled intersections, the design vehicle is the passenger car, and the criteria for left-turns are used because they are the most restrictive. Trucks or combination vehicles are considered only when they make up a substantial proportion of the total traffic on the approach. Values for right-turn and through movements are used when no left-turn movement is present. For these typical conditions, AASHTO recommends the use of $t_g = 7.5$ s.

Consider the case of a STOP-controlled approach at an intersection with a two-lane arterial with a design speed of 40 mi/h, as shown in Figure 18.4.

Using Equation 18-4, the position of the stopped vehicle on the minor approach can be determined.

$$d_{A\text{-}STOP}(\text{from left}) = 18.0 + 6.0 = 24.0 \text{ ft}$$
$$d_{A\text{-}STOP}(\text{from right}) = 18.0 + 18.0 = 36.0 \text{ ft}$$

The minimum sight distance requirement for Vehicle B is determined from Equation 18-5, using a time gap (t_g) of 7.5 seconds for typical conditions.

$$d_{Bmin} = 1.47 * 40 * 7.5 = 441 \text{ ft}$$

Now the actual distance of Vehicle B from the collision point when visibility is established is determined using Equation 18-1:

$$d_{Bact}(\text{from left}) = \frac{36 * 24}{24 - 20} = 216 \text{ ft} < 441 \text{ ft}$$
$$d_{Bact}(\text{from right}) = \frac{16 * 34}{36 - 35} = 576 \text{ ft} > 441 \text{ ft}$$

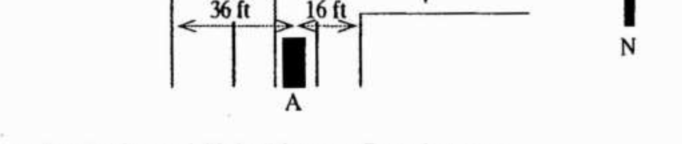


Figure 18.4: Sample Problem in STOP-Control Sight Distance Requirements

In the case of a major street Vehicle B approaching from the left, there is not sufficient sight distance to meet the criteria. The sight distance for Vehicle B approaching from the right meets the criteria. Note that it is possible for d_{Bact} to be negative. This would indicate there was no sight obstruction from the direction analyzed.

Where the STOP-sign sight-distance criterion is not met, it is recommended that speed limits be reduced (with signs posted) to a level that would allow appropriate sight distance to the minor street. Removal or cutting back of sight obstructions is also a potential solution, but this is often impossible in developed areas, where buildings are the principal obstructions.

18.2.2 Yield Control

A YIELD sign assigns right-of-way to the major uncontrolled street. It requires vehicles on the minor approach(es) to slow and yield the right-of-way to any major street vehicle approaching at a distance and speed that would present an impending hazard to the minor street vehicle if it entered the major street. Most state laws require that drivers on YIELD-controlled approaches slow to 8 to 10 mi/h before entering the major street.

Warrants for YIELD control in the MUTCD are hardly definitive, and they are given only under the heading of "options," except for one relatively new mandatory usage. The warrants are summarized in Table 18.3.

The principal uses of the YIELD sign emanate from their mandatory use at roundabouts and Warrants B, C, and E. Warrant B is a common application where medians exist and are wide enough to store at least one crossing vehicle. In such cases, a vehicle crosses the first set of lanes, and may stop again in the median to seek another gap to cross the second set of lanes. Warrant C allows use of the YIELD sign to control channelized right turns at signalized and unsignalized intersections, and Warrant E allows their use at on-ramp or other merge situations. The latter is a frequent use in which adequate sight distance or geometry (i.e., inadequate length of the acceleration lane) make an uncontrolled merge potentially unsafe.

There has been some controversy over the use of YIELD signs at normal crossings. Because YIELD signs require drivers to slow down, the sight triangle may be analyzed using the legal reduced approach speed. In 2000, the Millennium Edition of the MUTCD required that sight distance sufficient for safety at the normal approach speed be present whenever a YIELD sign was used. This greatly discouraged their use at regular intersections. This prescription is expected to be removed in the forthcoming 2010 edition of the manual.

Table 18.3: Warrants for YIELD Signs

A YIELD sign *shall* be used to assign right-of-way at the entrance to a roundabout. YIELD signs at roundabouts *shall* be used to control the approach roadways and *shall not* be used to control the circulatory roadway.

YIELD signs may be installed:

A. On approaches to a through street or highway where conditions are such that a stop is not always required.

B. At the second crossroad of a divided highway, where the median width at the intersection is 30 ft or greater. In this case, a STOP or YIELD sign may be installed at the entrance to the first roadway, and a YIELD sign may be installed at the entrance to the second roadway.

C. On a channelized turn lane that is separated from the adjacent travel lane by an island, even if the adjacent lanes at the intersection are controlled by a highway traffic control signal or by a STOP sign.

D. At an intersection where a special problem exists and where engineering judgment indicates the problem to be susceptible to correction by the use of YIELD signs.

E. Facing the entering roadway for a merge-type movement if engineering judgment indicates that the control is needed because acceleration geometry and/or sign distance is not sufficient for merging traffic operation.

(*Source: Manual of Uniform Traffic Control Devices*, Draft, Federal Highway Administration, Washington DC, p. 73, available at www.fhwa.com.)

18.2.3 Multiway Stop Control

Multiway STOP control, where all intersection approaches are controlled using STOP signs, remains a controversial form of control. Some agencies find it attractive, primarily as a safety measure. Others believe the confusion that drivers often exhibit when confronted by this form of control negates any of the benefits it might provide.

MUTCD warrants and provisions with regard to multiway STOP control reflect this ongoing controversy. Multiway STOP control is most often used where there are significant conflicts between vehicles and pedestrians and/or bicyclists in all directions, and where vehicular demands on the intersecting roadways are approximately equal. Table 18.4 shows the warrants for multiway STOP control.

Note that such control is generally implemented as a safety measure because operations at such locations are often

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Table 18.4: Warrants for Multiway STOP Signs

The following criteria should be considered in the engineering study for a multiway STOP sign:

A. Where traffic control signals are justified, the multiway STOP is an interim measure that can be installed quickly to control traffic while arrangements are being made for the installation of the traffic control signal.

B. Five or more reported crashes in a 12-month period that are susceptible to correction by a multiway STOP installation. Such crashes include right- and left-turn collisions as well as right-angle collisions.

C. Minimum volumes:

1. The vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 veh/h for any 8 hours of an average day, and
2. The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) averages at least 200 units/h for the same 8 hours, with an average delay to minor-street vehicular traffic of at least 30 s/veh during the highest hour, but
3. If the 85th percentile approach speed of the major highway exceeds 40 mi/h, the minimum vehicular volume warrants are 70% of the above values.

D. Where no single criterion is satisfied, but where criteria B., C1. and C2 are all satisfied to 80% of the minimum values. Criterion C3 is excluded from this condition.

(Source: *Manual on Uniform Traffic Control Devices*, Draft, Federal Highway Administration, Washington DC, December 2007, p. 72, available at www.fhwa.com.)

not very efficient. The fourth edition of the *Highway Capacity Manual*, [*3*] includes a methodology for analysis of the capacity and level of service provided by multiway STOP control.

18.3 Level III Control: Traffic Control Signals

The ultimate form of intersection control is the traffic signal. Because it alternately assigns right-of-way to specific movements, it can substantially reduce the number and nature of intersection conflicts as no other form of control can.

If drivers obey the signal, then driver judgment is not needed to avoid some of the most critical intersection conflicts. Imposition of traffic signal control does not, however, remove all conflicts from the realm of driver judgment. At two-phase signals, where all left-turns are made against an opposing vehicular flow, drivers must still evaluate and select gaps in opposing traffic through which to safely turn. At virtually all signals, some pedestrian-vehicle and bicycle-vehicle conflicts remain between legal movements, and driver vigilance and judgment are still required to avoid accidents. Nevertheless, drivers at signalized intersections do not have to negotiate the critical conflicts between crossing vehicle streams, and where exclusive left-turn phases are provided, critical conflicts between left turns and opposing through vehicles are also eliminated through signal control. This chapter deals with the issue of whether or not signal control is warranted or needed. Given that it is needed, Chapter 20 deals with the design of a specific phasing plan and the timing of the signal.

Although warrants and other criteria for STOP and YIELD signs are somewhat general in the MUTCD, warrants for signals are quite detailed. The cost involved in installation of traffic signals (e.g., power supply, signal controller, detectors, signal heads, and support structures, and other items) is considerably higher than for STOP or YIELD signs and can run into the hundreds of thousands of dollars for complex intersections. Because of this, and because traffic signals introduce a fixed source of delay into the system, it is important that they not be overused; they should be installed only where no other solution or form of control would be effective in assuring safety and efficiency at the intersection.

18.3.1 Advantages of Traffic Signal Control

The Millennium Edition of the MUTCD lists the following advantages of traffic control signals that are "properly designed, located, operated, and maintained" [MUTCD, Millennium Edition, p. 4b-2]. These advantages include:

1. They provide for the orderly movement of traffic.
2. They increase the traffic-handling capacity of the intersection if proper physical layouts and control measures are used and if the signal timing is reviewed and updated on a regular basis (every two years) to ensure that it satisfies the current traffic demands.
3. They reduce the frequency and severity of certain types of crashes, especially right-angle collisions.

4. They are coordinated to provide for continuous or nearly continuous movement at a definite speed along a given route under favorable conditions.
5. They are used to interrupt heavy traffic at intervals to permit other traffic, vehicular or pedestrian, to cross.

These specific advantages address the primary reasons why a traffic signal would be installed: to increase capacity (thereby improving level of service), to improve safety, and to provide for orderly movement through a complex situation. Coordination of signals provides other benefits, but not all signals are necessarily coordinated.

18.3.2 Disadvantages of Traffic Signal Control

The description of the second advantage in the earlier list indicates that capacity is increased by a well-designed signal at a well-designed intersection. Poor design of either the signalization or the geometry of the intersection can significantly reduce the benefits achieved or negate them entirely. Improperly designed traffic signals, or the placement of a signal where it is not justified, can lead to some of the following disadvantages [MUTCD, Millennium Edition, p. 4B-3]:

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1. Excessive delay
2. Excessive disobedience of the signal indications
3. Increased use of less adequate routes as road users attempt to avoid the traffic control signal
4. Significant increases in the frequency of collisions (especially rear-end collisions)

Item 4 is of some interest. Even when they are properly installed and well designed, traffic signal controls can lead to increases in rear-end accidents because of the cyclical stopping of traffic.

Where safety is concerned, signals can reduce the number of right-angle, turning, and pedestrian/bicycle accidents; they might cause an increase in rear-end collisions (which tend to be less severe); they will have almost no impact on head-on or sideswipe accidents, or on single-vehicle accidents involving fixed objects.

Excessive delay can result from an improperly installed signal, but it can also occur if the signal timing is inappropriate. In general, excessive delay results from cycle lengths that are either too long or too short for the existing demands at the intersection. Further, drivers tend to assume that a signal is broken if they experience an excessive wait, particularly when there is little or no demand occurring on the cross street.

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18.3.3 Warrants for Traffic Signals

The forthcoming 2009/2010 MUTCD specifies nine different warrants that justify the installation of a traffic signal. The ninth is just being added in this edition. It covers the installation of a signal in coordination with a railroad crossing. Satisfying one or more of the warrants for signalization does *not* require or justify the installation of a signal. The manual *requires,* however, that a comprehensive engineering study be conducted to determine whether or not installation of a signal is justified. The study *must* include applicable factors reflected in the specified warrants but could extend to other factors as well. However, traffic signal control *should not* be implemented if none of the warrants are met. The warrants, therefore, still require the exercise of engineering judgment. In the final analysis, if engineering studies and/or judgment indicate that signal installation *will not* improve the overall safety or operational efficiency at a candidate location, it should not be installed.

Although offered only under the heading of an option, the MUTCD suggests that the following data be included in an engineering study of the need for a traffic signal [2009/2010 MUTCD, Draft, p. 268]:

1. The number of vehicles entering the intersection from each approach during 12 hours of an average day. It is desirable that the hours selected contain the greatest percentage of the 24-hour traffic volume.
2. Vehicular volumes for each traffic movement, from each approach, classified by vehicle type (heavy trucks, passenger cars and light trucks, public-transit vehicles, and in some locations, bicycles), during each 15-minute period of the 2 hours in the morning and 2 hours in the afternoon during which total traffic entering the intersection is greatest.
3. Pedestrian volume counts on each crosswalk during the same periods as the vehicular counts in Item 2 above and during hours of highest pedestrian volume. Where young, elderly, and/or persons with physical or visual disabilities need special consideration, the pedestrians and their crossing times may be classified by general observation.
4. Information about nearby facilities and activity centers that serve the young, elderly, and/or persons with disabilities, including requests from persons with disabilities for accessible parking improvements at the location under study. These persons might not be adequately reflected in the pedestrian volume count if the absence of a signal restrains their mobility.

5. The posted or statutory speed limit or the 85th percentile speed on the uncontrolled approaches to the location.
6. A condition diagram showing details of the physical layout, including such features as intersection geometrics, channelization, grades, sight distance restrictions, transit stops and routes, parking conditions, pavement markings, roadway lighting, driveways, nearby railroad crossings, distance to nearest traffic control signals, utility poles and fixtures, and adjacent land use.
7. A collision diagram showing crash experience by type, location, direction of movement, severity, weather, time of day, date, and day of week for at least one year.

MUTCD also recommends collection of stopped-time delay data and queuing information at some locations where these are thought to be problems.

This data will allow the engineer to fully evaluate whether or not the intersection satisfies the requirements of one or more of the following warrants:

- *Warrant 1:* Eight-Hour Vehicular Volume
- *Warrant 2:* Four-Hour Vehicular Volume
- *Warrant 3:* Peak Hour
- *Warrant 4:* Pedestrian Volume
- *Warrant 5:* School Crossing
- *Warrant 6:* Coordinated Signal System
- *Warrant 7:* Crash Experience
- *Warrant 8:* Roadway Network
- *Warrant 9:* Intersection Near a Highway-Rail Crossing

It also provides a sufficient base for the exercise of engineering judgment in determining whether a traffic signal should be installed at the study location. Each of these warrants is presented and discussed in the sections that follow.

In most cases, an engineering study includes data from an existing location. In some cases, however, consideration of signalization relates to a future situation or design. In such cases, forecast demand volumes may be used to compare with the criteria in the warrants.

Warrant 1: Eight-Hour Vehicular Volume

The eight-hour vehicular volume warrant represents a merging of three different warrants in the pre-2000 MUTCD (old Warrants 1, 2, and 8). It addresses the need for signalization for conditions that exist over extended periods of the day (a minimum of eight hours). Two of the most fundamental reasons for signalization are addressed:

- Heavy volumes on conflicting cross-movements that make it impractical for drivers to select gaps in an uninterrupted traffic stream through which to safely pass. This requirement is often referred to as the "minimum vehicular volume" condition (Condition A).
- Vehicular volumes on the major street are so heavy that no minor-street vehicle can safely pass through the major-street traffic stream without the aid of signals. This requirement is often referred to as the "interruption of continuous traffic" condition (Condition B).

Details of this warrant are shown in Table 18.5. The warrant is met when:

- Either Condition A or Condition B is met to the 100% level.
- Either Condition A or Condition B is met to the 70% level, where the intersection is located in an isolated community of population 10,000 or less, or where the major-street approach speed is 40 mi/h or higher.
- Both Conditions A and B are met to the 80% level.

Note that in applying these warrants, the major-street volume criteria are related to the total volume in both directions, whereas the minor-street volume criteria are applied to the highest volume in one direction. The volume criteria in Table 18.5 must be met for a minimum of eight hours on a typical day. The eight hours do not have to be consecutive, and they often involve four hours around the morning peak and four hours around the evening peak. Major- and minor-street volumes must be for the same eight hours, however.

Either of the intersecting streets may be treated as the "major" approach, but the designation must be consistent for a given application. If the designation of the "major" street is not obvious, a warrant analysis can be conducted considering each as the "major" street in turn. Although the designation of the major street may not be changed within any one analysis, the direction of peak one-way volume for the minor street need not be consistent.

The 70% reduction allowed for rural communities of population 10,000 or less reflects the fact that drivers in small communities have little experience in driving under congested situations. They will require the guidance of traffic signal control at volume levels lower than those for drivers more used to driving in congested situations. The same reduction applies where the major-street speed limit is 40 mi/h or greater. Because gap selection is more difficult through a higher-speed major-street flow, signals are justified at lower volumes.

Table 18.5: Warrant 1: Eight-Hour Vehicular Volume

Condition A: Minimum Vehicular Volume

Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total, both approaches)			Vehicles per hour on higher-volume minor street approach (one direction only)		
Major Street	Minor Street	100%	80%	70%	100%	80%	70%
1	1	500	400	350	150	120	105
2 or more	1	600	480	420	150	120	105
2 or more	2 or more	600	480	420	200	160	140
1	2 or more	500	400	350	200	160	140

Condition B: Interruption of Continuous Traffic

Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total, both approaches)			Vehicles per hour on higher-volume minor street approach (one direction only)		
Major Street	Minor Street	100%	80%	70%	100%	80%	70%
1	1	750	600	525	75	60	53
2 or more	1	900	720	630	75	60	53
2 or more	2 or more	900	720	630	100	80	70
1	2 or more	750	600	525	100	80	70

(*Source:* Used with permission of Federal Highway Administration, US Department of Transportation, *Manual on Uniform Traffic Control Devices*, Millennium Edition, Table 4C-1, p. 4C-5, Washington DC, 2000.)

The various elements of the eight-hour vehicular volume warrant are historically the oldest of the warrants, having been initially formulated and disseminated in the 1930s.

Warrant 2: Four-Hour Vehicular Volume

The four-hour vehicular volume warrant was introduced in the 1970s to assist in the evaluation of situations where volume levels requiring signal control might exist for periods shorter than eight hours. Prior to the MUTCD Millennium Edition, this was old Warrant 9. Figure 18.5 shows the warrant, which is in the form of a continuous graph. Because this warrant is expressed as a continuous relationship between major and minor street volumes, it addresses a wide variety of conditions. Indeed, Conditions A and B of the eight-hour warrant represent two points in such a continuum for each configuration, but the older eight-hour warrant did not investigate or create criteria for the full range of potential conditions.

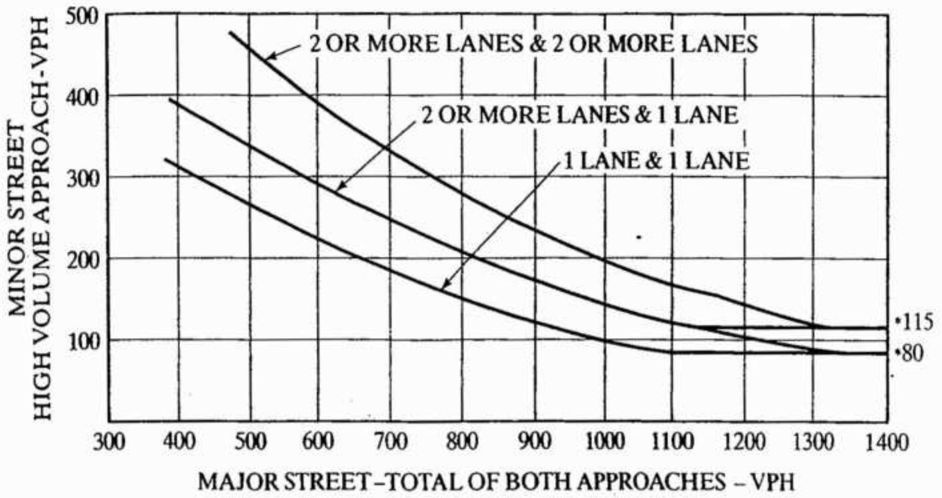
Figure 18.5 (a) is the warrant for normal conditions, and Figure 18.5 (b) reflects the 70% reduction applied to isolated small communities (with population less than 10,000) or where the major-street speed limit is above 40 mi/h. Because the four-hour warrant represents a continuous set of conditions, there is no need to include an 80% reduction for two discrete conditions within the relationship.

To test the warrant, the two-way major-street volume is plotted against the highest one-way volume on the minor street for each hour of the study period. To meet the warrant, at least four hours must plot *above* the appropriate decision curve. The three curves represent intersections of (1) two streets with one lane in each direction, (2) one street with one lane in each direction with another having two or more lanes in each direction, and (3) two streets with more than one lane in each direction. In Case (2), the distinction between which intersecting street has one lane in each direction (major or minor) is no longer relevant, except for the footnotes.

Warrant 3: Peak Hour

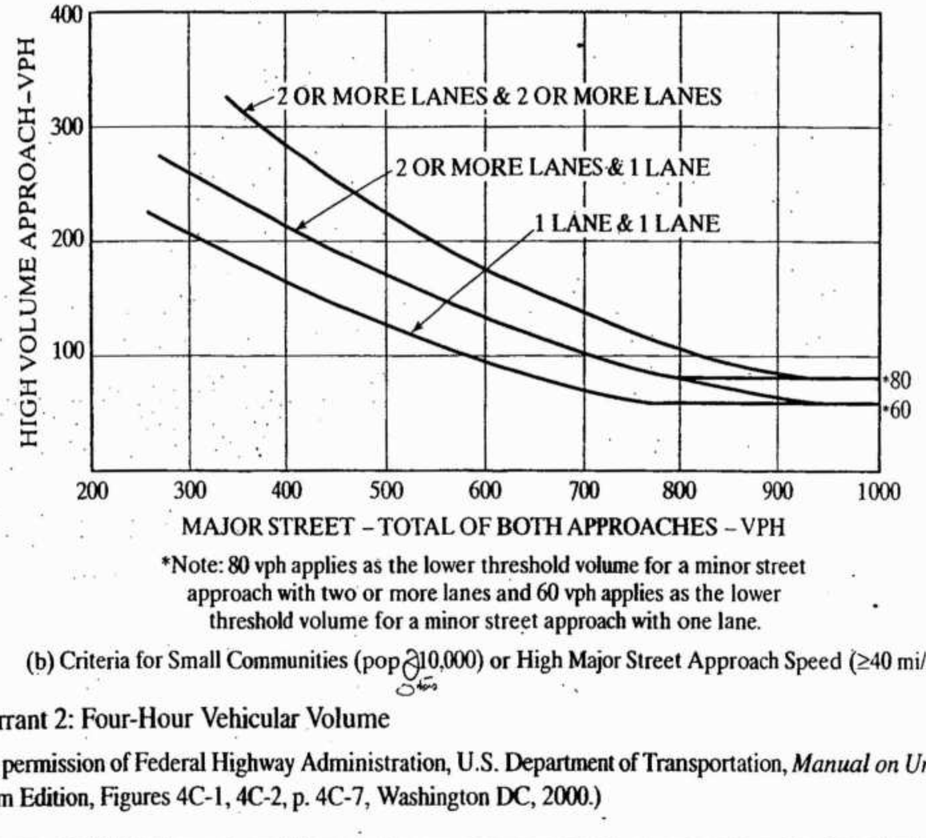
Warrant 3 addresses two critical situations that might exist for only one hour of a typical day. The first is a volume condition similar in form to Warrant 2, and shown in Figure 18.6 (old Warrant 11). The second is a delay warrant (old Warrant 10). If either condition is satisfied, the peak-hour warrant is met.

The volume portion of the warrant is implemented in the same manner as the four-hour warrant. For each hour of



*Note: 115 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 80 vph applies as the lower threshold volume for a minor street approach with one lane.

(a) Normal Conditions



*Note: 80 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 60 vph applies as the lower threshold volume for a minor street approach with one lane.

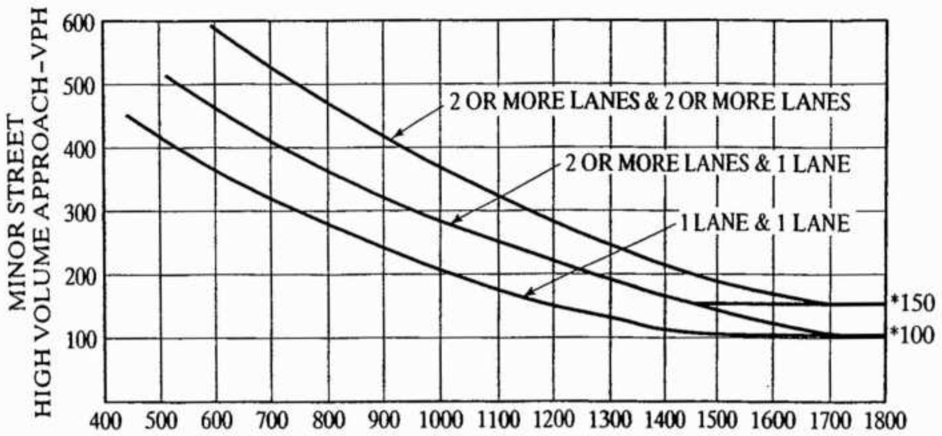
(b) Criteria for Small Communities (pop ≤10,000) or High Major Street Approach Speed (≥40 mi/h)

Figure 18.5: Warrant 2: Four-Hour Vehicular Volume

(*Source:* Used with permission of Federal Highway Administration, U.S. Department of Transportation, *Manual on Uniform Traffic Control Devices*, Millennium Edition, Figures 4C-1, 4C-2, p. 4C-7, Washington DC, 2000.)

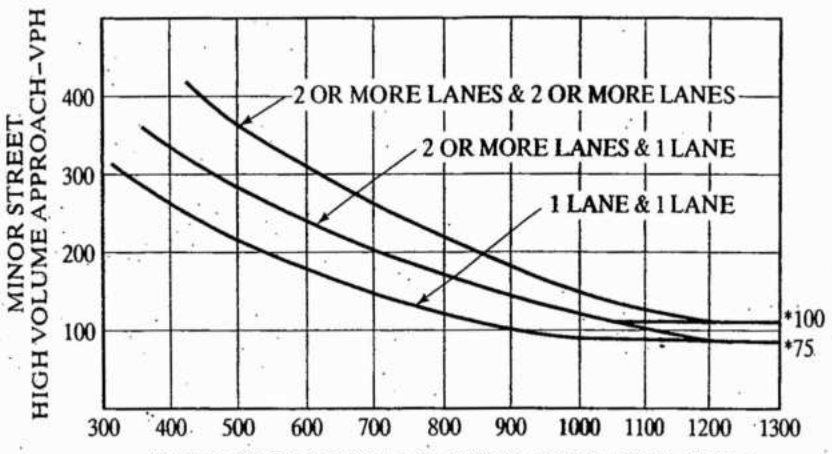
the study, the two-way major street volume is plotted against the high single-direction volume on the minor street. For the Peak-Hour Volume Warrant, however, only one hour must plot above the appropriate decision line to meet the criteria. Criteria are given for normal conditions in Figure 18.6 (a), and the 70% criteria for small isolated communities and high major-street speeds are shown in Figure 18.6 (b). The Peak-Hour Delay Warrant is summarized in Table 18.6.

It is important to recognize that the delay portion of Warrant 3 applies only to cases in which STOP control is already in effect for the minor street. Thus delay during the peak hour is not a criterion that allows going from no control or YIELD control to signalization directly.



*Note: 150 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 100 vph applies as the lower threshold volume for a minor street approach with one lane.

(a) Normal Conditions



*Note: 100 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 75 vph applies as the lower threshold volume for a minor street approach with one lane.

(b) Criteria for Small Communities (Pop <10,000) or High Major Street Approach Speed (≥40 mi/h)

Figure 18.6: Warrant 3A: Peak Hour Volume

(*Source:* Used with permission of Federal Highway Administration, U.S. Department of Transportation, *Manual on Uniform Traffic Control Devices,* Millennium Edition, Figures 4C-3, 4C-4, p. 4C-9, Washington DC, 2000.)

The MUTCD also emphasizes that the Peak-Hour Warrant should be applied only in special cases, such as office complexes, manufacturing plants, industrial complexes, or high-occupancy vehicle facilities that attract or discharge large numbers of vehicles over a short time.

Warrant 4: Pedestrians

The Pedestrian Warrant addresses situations in which the need for signalization is the frequency of vehicle-pedestrian conflicts and the inability of pedestrians to avoid such conflicts due to the volume of traffic present. Signals may be placed under this warrant at midblock locations, as well as at intersections.

This warrant is met when any four hourly plots of total pedestrians crossing the major street and the total major street vehicular traffic falls over the line in Figure 18.7 (a), or when any one similar hourly plot falls above the line in Figure 18.8 (a). If the location is in a built-up area of a small community (population less than 10,000) or where the posted

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Table 18.6: Warrant 3B: Peak-Hour Delay

The need for a traffic control signal shall be considered if an engineering study finds that . . . all three of the following conditions exist for the same 1 hour (any four consecutive 15-minute periods) of an average day:

1. The total stopped-time delay experienced by traffic on one minor street approach (one direction only) controlled by a STOP sign equals or exceeds: 4 veh-hours for a one-lane approach; or 5 veh-hours for a two lane approach, and
2. The volume on the same minor street approach (one direction only) equals or exceeds 100 veh/h for one moving lane of traffic; or 150 veh/h for two moving lanes, and
3. The total entering volume serviced during the hour equals or exceeds 650 veh/h for intersections with three approaches, or 800 veh/h for intersections with four or more approaches.

(*Source: Manual of Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, 2007, p. 270.)

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or statutory speed limit, or the 85th percentile approach speed exceeds 35 mi/h, Figures 18.7 (b) and 18.8 (b) may be used.

The figures address cases in which a steadier pedestrian flow over four hours requires signal control and the case in which a single peak hour has pedestrian-vehicle conflicts that must be signal controlled. The (b) figures apply the same 70% reduction in criteria that is used in conjunction with vehicular volume criteria in Warrants 1, 2, and 3.

If the traffic signal is justified at an intersection by this warrant only, it will usually be at least a semi-actuated signal (a full actuated signal is also a possibility at an isolated intersection) with pedestrian pushbuttons and signal heads for pedestrians crossing the major street. If it is within a coordinated signal system, it would also be coordinated into the system. If such a signal is located in midblock, it will always be pedestrian actuated, and parking and other sight restrictions should be eliminated within 20 feet of both sides of the crosswalk. Standard reinforcing markings and signs should also be provided.

If the intersection meets this warrant but also meets other vehicular warrants, any type of signal could be installed as appropriate to other conditions. Pedestrian signal heads would be required for major-street crossings. Pedestrian pushbuttons would be installed unless the vehicular signal timing safely accommodates pedestrians in every signal cycle.

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A signal would not normally be implemented under this warrant if there is another signal within 300 feet of the location. Placement of a signal so close to another would only be permitted if did not disrupt progressive flow on the major street.

Pedestrian volume criteria may be reduced by as much as 50% if the 15th-percentile crossing speed is less than 3.5 mi/h, as might be the case where elderly, very young, or disabled pedestrians are present in significant percentages.

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Warrant 5: School Crossing

This warrant is similar to the pedestrian warrant but is limited to application at designated school crossing locations, either at intersections or at midblock locations. The warrant requires the study of available gaps to see whether they are "acceptable" for children to cross through. An acceptable gap would include the crossing time, buffer time, and an allowance for groups of children to start crossing the street. The frequency of acceptable gaps should be no less than one for each minute during which school children are crossing. The minimum number of children crossing the major street is 20 during the highest crossing hour.

Traffic signals are rarely implemented under this warrant. Children do not usually observe and obey signals regularly, particularly if they are very young. Thus traffic signals would have to be augmented by crossing guards in most cases. Except in unusual circumstances involving a very heavily traveled major street, the crossing guard, perhaps augmented with STOP signs, would suffice under most circumstances without signalization. Where extremely high volumes of school children cross a very wide and heavily traveled major street, overpasses or underpasses should be provided with barriers preventing entry onto the street.

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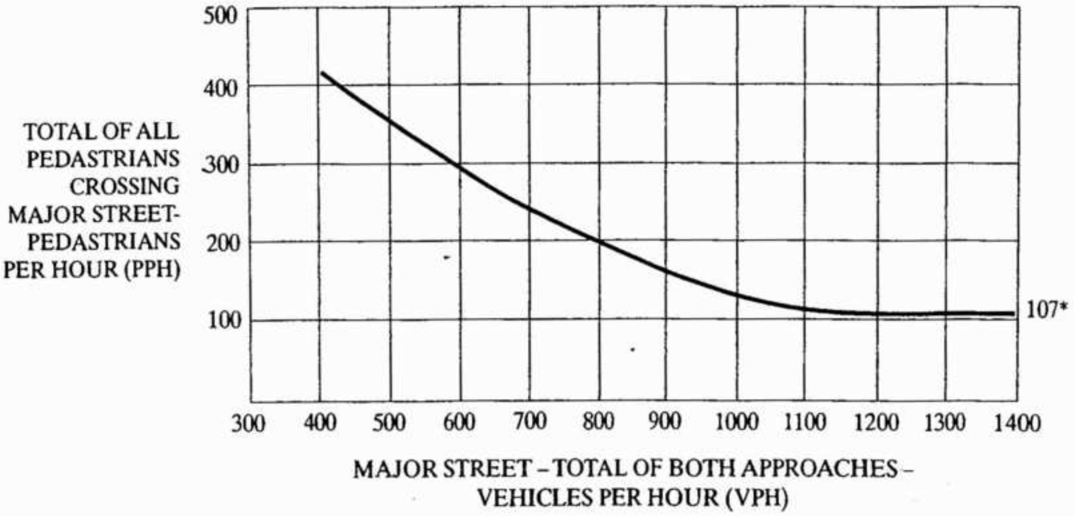
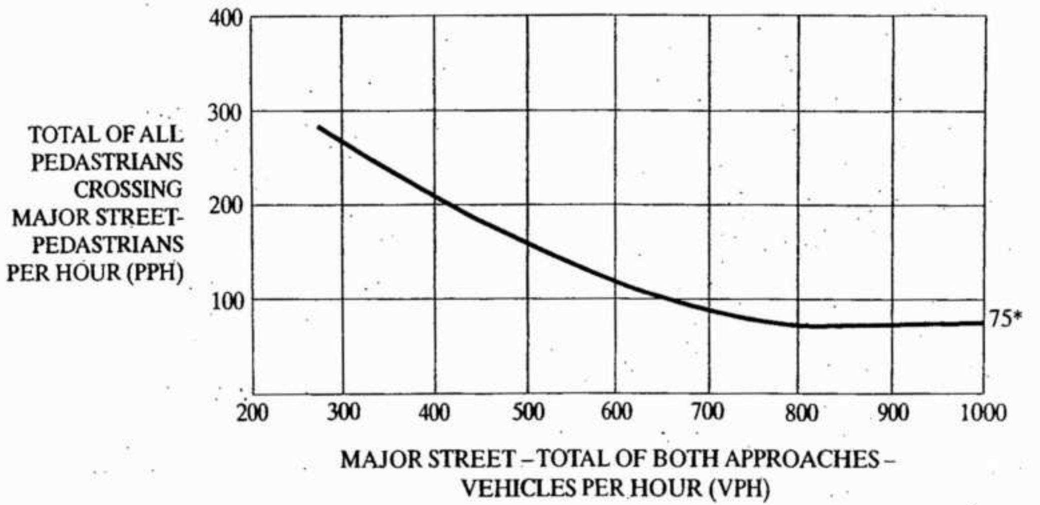
Warrant 6: Coordinated Signal System

Chapters 25 and 26 of this text addresses signal coordination and progression systems for arterials and networks. Critical to such systems is the maintenance of platoons of vehicles moving together through a "green wave" as they progress along an arterial. If the distance between two adjacent coordinated signals is too large, platoons begin to dissipate and the positive impact of the progression is sharply reduced. In such cases, the traffic engineer may place a signal at an intermediate intersection where it would not otherwise be warranted to reinforce the coordination scheme and to help maintain platoon coherence. The application of this warrant, shown in Table 18.7, should not result in signal spacing of



*Note: 107 pph applies as the lower threshold volume.

(a) Normal Criteria.



*Note: 75 pph applies as the lower threshold volume.

(b) Criteria for Small Communities (Pop <10,000) or High Major Street Approach Speed (> 35 mi/h)

Figure 18.7: Four-Hour Pedestrian Warrant

(*Source: Manual of Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, Figures 4C-5 and 4C-7.)

less than 1,000 feet. Such signals, when placed, are often referred to as "spacer signals."

The two criteria are similar but not exactly the same. Inserting a signal in a one-way progression is always possible without damaging the progression. On a two-way street, it is not always possible to place a signal that will maintain the progression in both directions acceptably. This issue is discussed in greater detail in Chapter 25.

Warrant 7: Crash Experience

The Crash Experience Warrant addresses cases in which a traffic control signal would be installed to alleviate an observed high-accident occurrence at the intersection. The criteria are summarized in Table 18.8.

The requirement for an adequate trial of alternative methods means that either YIELD or STOP control is already

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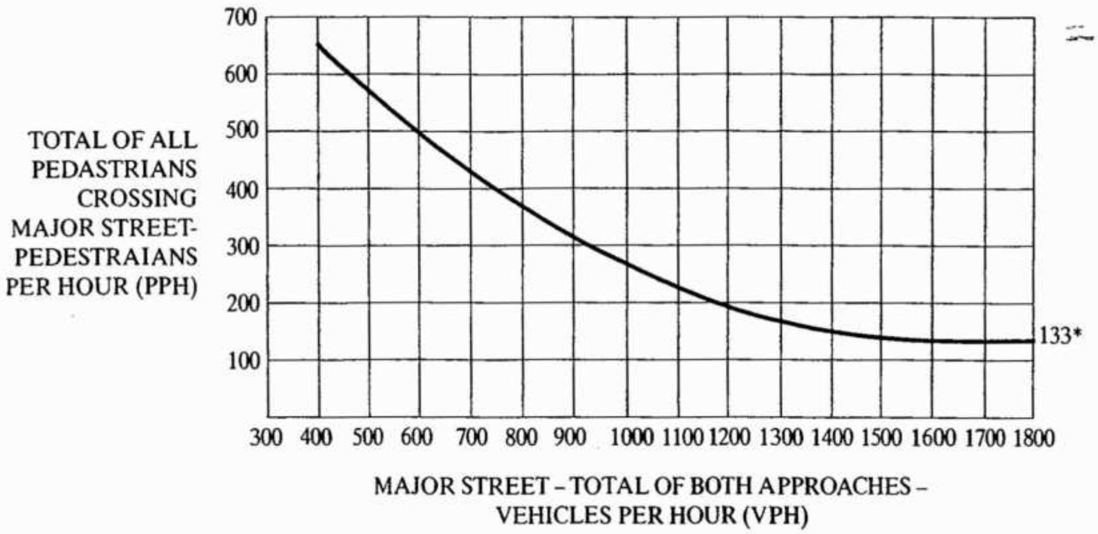
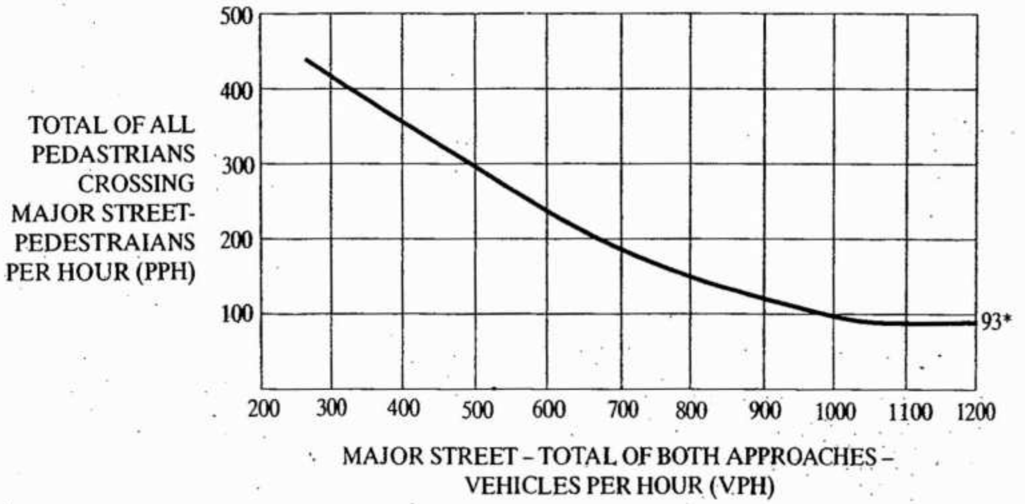


*Note: 133 pph applies as the lower threshold volume.

(a) Normal Criteria.



(b) Criteria for Small Communities (Pop <10,000) or High Major Street Approach Speed (> 35 mi/h)

Figure 18.8: Peak-Hour Pedestrian Warrant

(*Source: Manual of Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, Draft 2007, Figures 4C-6 and 4C-8.)

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in place and properly enforced. These types of control can also address many of the same accident problems as signalization. Thus a signal is justified only when these lesser measures have failed to address the situation adequately.

Accidents that are susceptible to correction by signalization include right-angle accidents, accidents involving turning vehicles from the two streets, and accidents between vehicles and pedestrians crossing the street on which the vehicle is traveling. Rear-end accidents are often increased with imposition of traffic signals (or STOP/YIELD signs) because some drivers may be induced to stop quickly or suddenly. Head-on and sideswipe collisions are not addressed by signalization; accidents between vehicles and fixed objects at corners are also not correctable through signalization.

Table 18.7: Warrant 6: Coordinated Signal System

The need for a traffic control signal shall be considered if an engineering study finds that one of the following criteria is met:

1. On a one-way street or a street that has traffic predominantly in one direction, the adjacent traffic control signals are so far apart that they do not provide the necessary degree of vehicular platooning.
2. On a two-way street, adjacent traffic control signals do not provide the necessary degree of platooning and the proposed and adjacent traffic control signals will collectively provide a progressive operation.

(*Source:* Used by permission of Federal Highway Administration, US Dept. of Transportation, *Manual on Uniform Traffic Control Devices,* Millennium Edition, Washington DC, 2001, p. 4C-12.)

Table 18.8: Warrant 7: Crash Experience

The need for a traffic control signal shall be considered if an engineering study finds that all of the following criteria are met:

1. Adequate trial of alternatives with satisfactory observance and enforcement has failed to reduce the crash frequency, and
2. Five or more reported crashes of types susceptible to correction by a traffic control signal have occurred within a 12-month period, each involving an personal injury or property damage apparently exceeding the applicable requirements for a reportable crash, and
3. For each of any 8 hours of the day, vehicles per hour (vph) given in both of the 80% columns of Condition A (in Warrant 1) or the vph in both of the 80% columns of Condition B (in Warrant 1) exists on the major-street and the higher-volume minor-street approach, respectively, to the intersection, or the volume of pedestrian traffic is not less than 80% of the requirements specified in the Pedestrian Volume warrant. These major-street and minor-street volumes shall be for the same 8 hours. On the minor street, the higher volume shall not be required to be on the same approach during each of the 8 hours.

(*Source: Manual of Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, p. 273.)

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Warrant 8: Roadway Network

This warrant addresses a developing situation (i.e., a case in which present volumes would not justify signalization but where new development is expected to generate substantial traffic that would justify signalization). The MUTCD also allows other warrants to be applied based on properly forecast vehicular and pedestrian volumes.

Large traffic generators, such as regional shopping centers, sports stadiums and arenas, and similar facilities, are often built in areas that are sparsely populated and where existing roadways have light traffic. Such projects often require substantial roadway improvements that change the physical layout of the roadway network and create new or substantially enlarged intersections that will require signalization. Generally, the "existing" situation is irrelevant to the situation being assessed. The warrant is described in Table 18.9.

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Table 18.9: Warrant 8: Roadway Network

The need for a traffic control signal shall be considered if an engineering study finds that the common intersection of two or more major routes meets one or both of the following criteria:

1. The intersection has a total existing, or immediately projected, entering volume of at least 1,000 veh/h during the peak hour of a typical weekday, and has 5-year projected traffic volumes, based upon an engineering study, that meet one or more of Warrants 1, 2 and 3 during an average weekday, or
2. The intersection has a total existing of immediately projected entering volume of at least 1,000 veh/h for each of any 5 hours of a non-normal business day (Saturday or Sunday).

A major route as used in this warrant shall have one or more of the following characteristics:

1. It is part of the street or highway system that serves as the principal roadway network for through traffic flow, or
2. It includes rural or suburban highways outside, entering, or traversing a city, or
3. It appears as a major route on an official plan, such as a major street plan in an urban area traffic and transportation study.

(*Source:* Used by permission of Federal Highway Administration, US Dept. of Transportation, *Manual on Uniform Traffic Control Devices,* Millennium Edition, Washington DC, 2000, pp. 4C-13, 4C-14.)

"Immediately projected" generally refers to the traffic expected on day one of the opening of new facilities and/or traffic generators that create the need for signalization.

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Warrant 9: Intersection Near a Highway-Rail Grade Crossing

(This is a new warrant being added to the forthcoming 2010 MUTCD. It addresses a unique situation: an intersection that does not meet any other warrant for signalization but that is close enough to a highway-railroad crossing to present a hazard. Table 18.10 shows the detailed criteria for the warrant.)

(Figure 18.9 applies when there is only one lane approaching the intersection at the track-crossing location, and Figure 18.10 applied where there are two or more lanes approaching the track-crossing location.)

(The minor-street volume used in entering either Figure 18.9 or 18.10 may be multiplied by up to three adjustment factors: (1) an adjustment for train volume (Table 18.11), (2) an adjustment for presence of high-occupancy buses (Table 18.12), and (3) an adjustment for truck presence (Table 18.13). The base conditions for Figures 18.9 and 18.10 include four trains per day, no buses, and 10% trucks.)

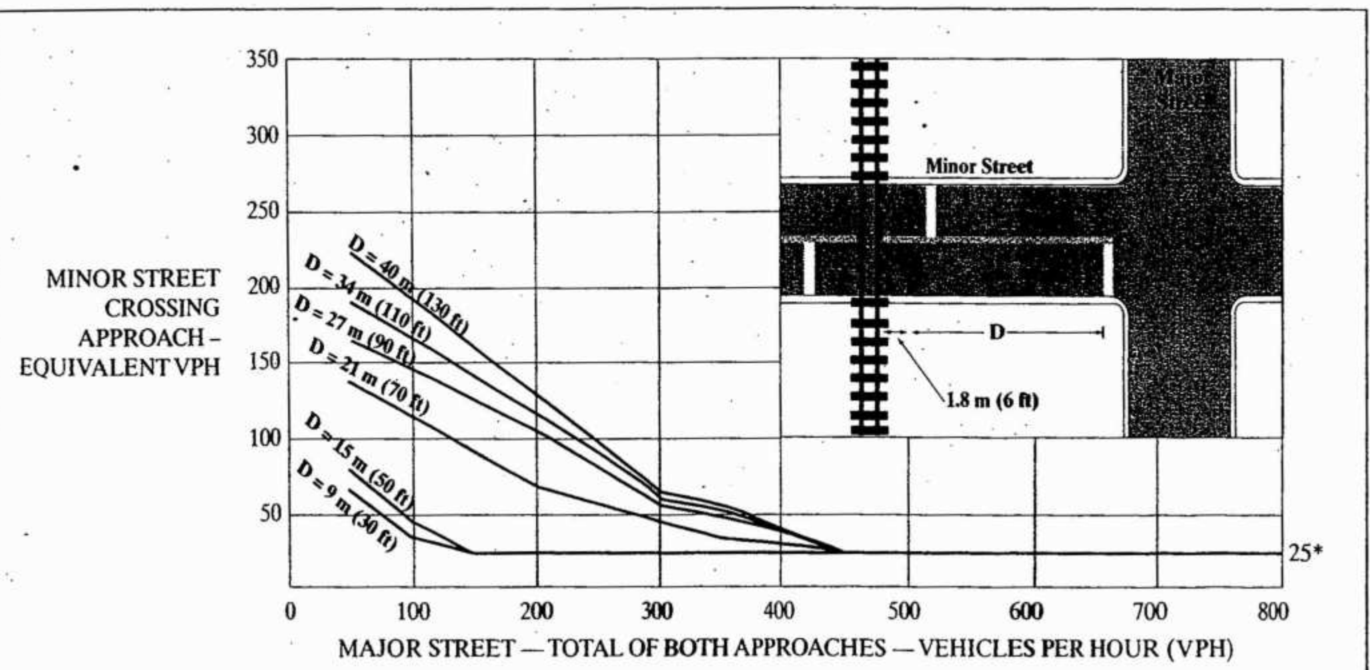
[illegible]

Table 18.10: Warrant 9: Intersection Near a Highway-Rail Grade Crossing

The need for a traffic control signal shall be considered if an engineering study finds that both of the following criteria are met:

1. A highway-rail grade crossing exists on a approach controlled by a STOP or YIELD sign and the center of the track nearest to the intersection is within 140 ft of the stop line on the approach, and
2. During the highest traffic volume hour during which trains use the crossing, the plotted point representing the vehicles per hour on the major street (total of both approaches) and the corresponding vehicles per hour on the minor-street approach that crosses the track (one direction only) falls above the applicable curve in Figure 18.9 or 18.10 for the existing combination of approach lanes over the track and distance D, which is the clear storage distance (between the grade crossing stop line and the near curb line of the major street).

(*Source: Manual of Uniform Traffic Control Devices*, Draft, Federal Highway Administration, Washington DC, December 2007, pp. 273–274.)



*Note: 25 vph applies as the lower threshold volume.

Figure 18.9: Warrant 9: Railroad Crossings for One-Lane Approaches

(*Source: Manual of Uniform Traffic Control Devices*, Draft, Federal Highway Administration, Washington DC, December 2007, Figure 4C-9.)

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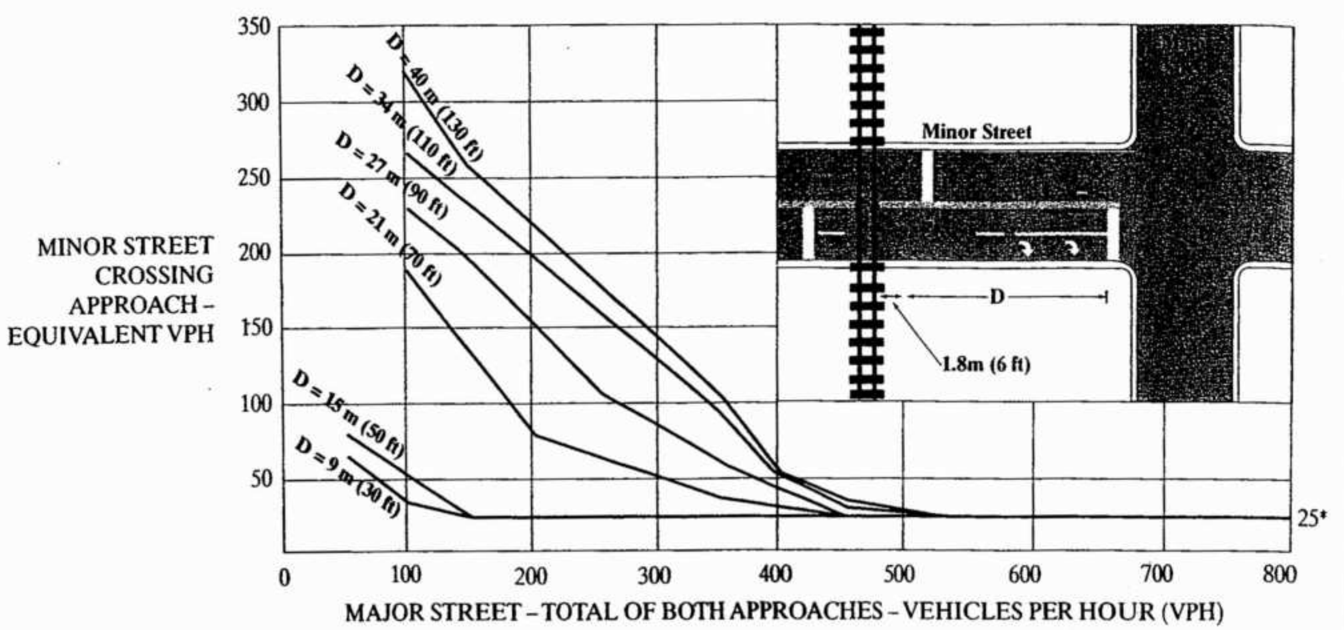

*Note: 25 vph applies as the lower threshold volume.

Figure 18.10: Warrant 9: Railroad Crossings for Two or More-Lane Approaches

(*Source: Manual of Uniform Traffic Control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, Figure 4C-9.)

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Table 18.11: Adjustment Factor for Train Frequency

Trains per Day	Adjustment Factor
1	0.67
2	0.91
3–5	1.00
6–8	1.18
9–11	1.25
12 or more	1.33

(*Source: Manual of Uniform Traffic control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, Table 4C-2.)

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Table 18.12: Adjustment Factor for High-Occupancy Buses

% of High-Occupancy Buses* on Minor-Street Approach	Adjustment Factor
0%	1.00
2%	1.09
4%	1.19
6% or more	1.32

*20 or more persons per bus.

(*Source: Manual of Uniform Traffic control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007. Table 4C-3.)

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18.3.4 Summary

It is important to reiterate the basic meaning of these warrants. No signal should be placed without an engineering study showing that the criteria of at least one of the warrants are met. However, meeting one or more of these warrants *does not* necessitate signalization. Note that every warrant uses the language "The need for a traffic control signal *shall be considered* . . ." (emphasis added). Although the "shall" is a mandatory standard, it calls only for consideration, not placement, of a traffic signal. The engineering study must also convince the traffic engineer that installation of a signal will improve the safety of the intersection, increase the capacity of the intersection, or improve the efficiency of operation at the intersection before the signal is installed. That is why the recommended information to be collected during an "engineering study" exceeds that needed to simply apply the nine warrants of the MUTCD. In the end, engineering judgment is called for, as is appropriate in any professional practice.

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Table 18.13: Adjustment Factor for Tractor-Trailer Trucks

% of Tractor-Trailer Trucks on Minor-Street Approach	Adjustment Factor	
	D Less Than 70 ft	D of 70 ft or More
0%–2.5%	0.50	0.50
2.6%–7.5%	0.75	0.75
7.6%–12.5%	1.00	1.00
12.6%–17.5%	2.30	1.15
17.6%–22.5%	2.70	1.35
22.6%–27.5%	3.28	1.64
More than 27.5%	4.18	2.09

(*Source: Manual of Uniform Traffic control Devices,* Draft, Federal Highway Administration, Washington DC, December 2007, Table 4C-4.)

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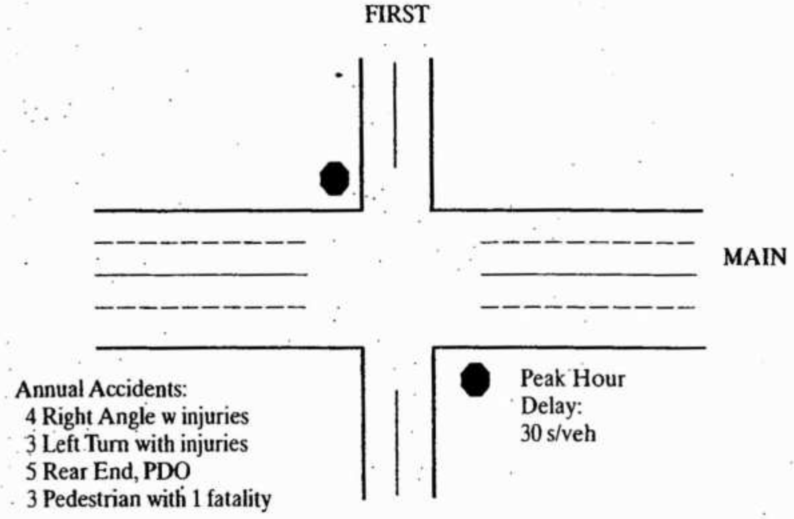
18.3.5 A Sample Problem in Application of Signal Warrants

Consider the intersection and related data shown in Figure 18.11.

Note that the data are formatted in a way that is conducive to comparing with warrant criteria. Thus a column adding the traffic in each direction on the major street is included, and a column listing the "high volume" in one direction on the minor street is also included. Pedestrian volumes are summarized for those crossing the major street because this is the criterion used in the pedestrian warrant. As you will see, not every warrant applies to every intersection, and data for some warrants are not provided. The following analysis is applied:

- *Warrant 1:* There is no indication that the 70% reduction factor applies, so it is assumed that either



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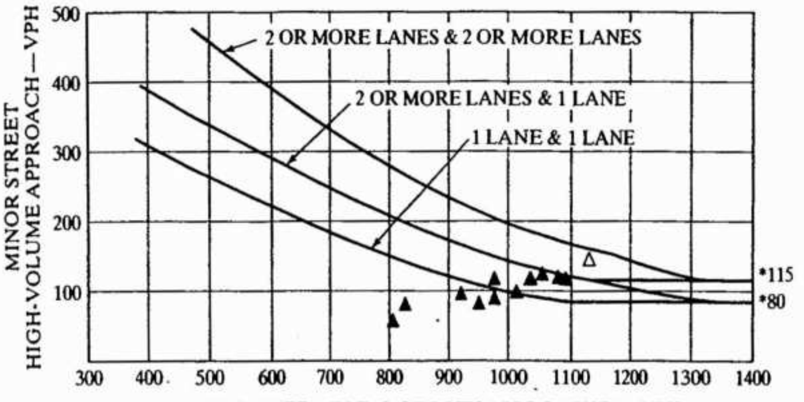
Time	Main Street Volume (veh/h)			First Ave Volume (veh/h)			Ped Volume (ped/h)
	EB	WB	TOT	NB	SB	High Vol	Xing Main
11 AM–12	400	425	**825**	75	80	**80**	115
12–1 PM	450	465	**915**	85	85	**85**	120
1–2 PM	485	500	**985**	90	100	**100**	125
2–3 PM	525	525	**1,050**	110	115	**115**	130
3–4 PM	515	525	**1,040**	100	95	**100**	135
4–5 PM	540	550	**1,090**	90	100	**100**	140
5–6 PM	550	580	**1,130**	110	125	**125**	120
6–7 PM	545	525	**1,070**	96	103	**103**	108
7–8 PM	505	506	**1,011**	90	95	**95**	100
8–9 PM	485	490	**975**	85	75	**85**	90
9–10 PM	475	475	**950**	75	60	**75**	50
10–11 PM	400	410	**810**	50	55	**55**	25

Figure 18.11: Intersection and Data for Sample Problem in Signal Warrant



*Note: 115 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 80 vph applies as the lower threshold volume for a minor street approach with one lane.

Figure 18.12: Example Application of Warrant 2

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Condition A or Condition B must be met at 100%, or both must be met at 80%. Condition A requires 600 veh/h in both directions on the multilane major street and 150 veh/h in the high-volume direction on the one-lane minor street. Although all 12 hours on the major street shown in Figure 18.11 have more than 600 veh/h (total, both directions), none have a one-way volume equal to or higher than 150 veh/h on the minor street. Condition A is not met. Condition B requires 900 veh/h on the major street (both directions) and 75 veh/h on the minor street (one direction). The 10 hours between 12:00 noon and 10:00 PM meet the major-street criterion. The same 10 hours meet the minor-street criterion as well. Therefore, Condition B is met. Because one condition is met at 100%, the consideration of whether both conditions are met at 80% is not necessary. *Warrant 1 is satisfied.*

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- *Warrant 2:* Figure 18.12 shows the hourly volume data plotted against the four-hour warrant graph. The center decision curve (one street with multilane approaches, one with one-lane approaches) is used. Only one of the 12 hours of data is above the criterion. To meet the warrant, four are required. *The warrant is not met.*

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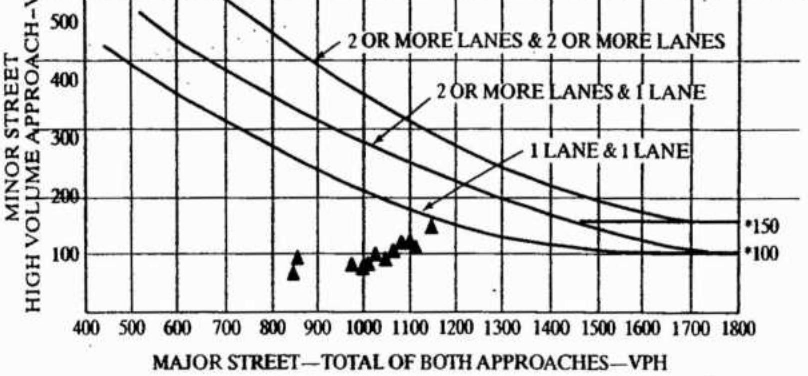

*Note: 150 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 100 vph applies as the lower threshold volume for a minor street approach with one lane.

Figure 18.13: Example Application of Warrant 3

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- *Warrant 3:* Figure 18.13 shows the hourly volume data plotted against the peak-hour volume warrant graph. Again, the center decision curve is used. None of the 12 hours of data is above the criterion. *The volume portion of this warrant is not met.*

The delay portion of the peak-hour warrant requires 4 vehicle-hours of delay in the high-volume direction on a STOP-controlled approach. The intersection data indicate that each vehicle experiences 30 seconds of delay. The peak one-direction volume is 125 veh/h, resulting in 125 * 30 = 3,750 veh-secs of aggregate delay, or 3,750/3,600 = 1.04 veh-hrs of delay. This is less than that required by the warrant. *The delay portion of this warrant is not met.*

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- *Warrant 4:* This warrant includes both a four-hour criterion and a peak-hour criterion, only one of which must be met to satisfy it. Figure 18.14 illustrates the solution.

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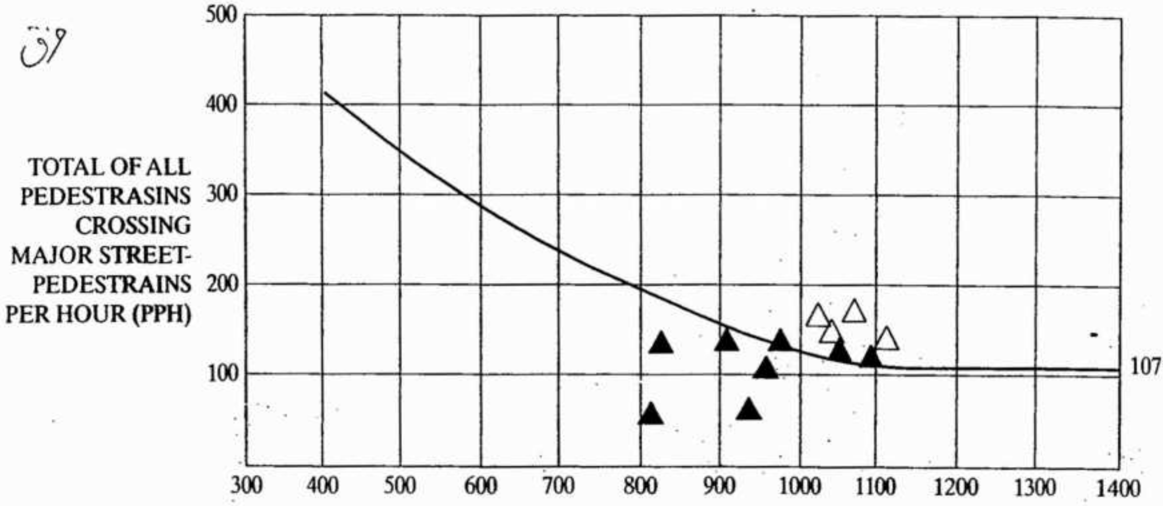

*Note: 107 pph applies as the lower thershold volume.

(a) Four-Hour Pedestrian Warrant

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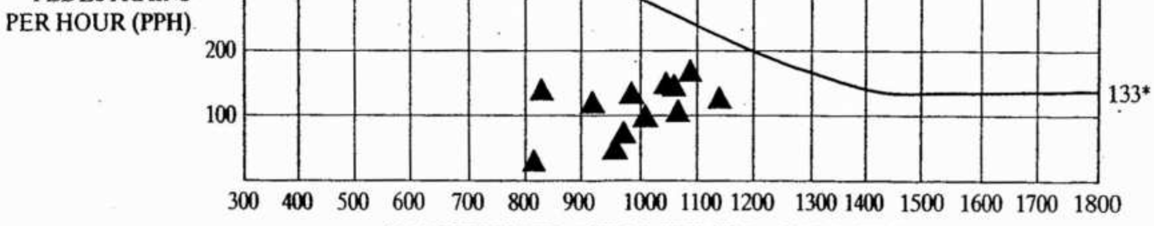

*Note: 133 pph applies as the lower thershold colume.

(b) Peak-Hour Pedestrian Warrant

Figure 18.14: Example Application of Warrant 4

The four-hour pedestrian warrant is met, and the peak-hour pedestrian warrant is not met. Because only one condition must be satisfied, *the pedestrian warrant is met.*

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- *Warrant 5:* The school-crossing warrant does not apply. This is not a school crossing.

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- *Warrant 6:* No information on signal progression is given, so this warrant cannot be applied.

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- *Warrant 7:* The crash experience warrant has several criteria: Have lesser measures been tried? Yes, because the minor street is already STOP-controlled. Have five accidents susceptible to correction by signalization occurred in a 12-month period? Yes—four right-angle, three left-turn, and three pedestrian. Are the criteria for Warrants 1A or 1B met to the extent of 80%? Yes, Warrant 1B is met at 100%. Therefore, *the crash experience warrant is met.*

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- *Warrant 8:* There is no information given concerning the roadway network, and the data reflect an existing situation. This warrant is not applicable in this case.

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- *Warrant 9:* Because this situation is not a highway-rail grade crossing location, this warrant does not apply.

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In summary, a signal should be considered at this location because the criteria for Warrants 1B (Interruption of Continuous Traffic), 4 (Pedestrians), and 7 (Crash Experience) are all met. Unless unusual circumstances are present, it would be reasonable to expect that the accident experience will improve with signalization, and it is, therefore, likely that one would be placed.

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The fact that Warrant 1B is satisfied may suggest that a semiactuated signal be considered. In addition, Warrant 4 requires the use of pedestrian signals, at least for pedestrians crossing the major street. If a semiactuated signal is installed, it must have a pedestrian pushbutton (for pedestrians crossing the major street). The number of left-turning accidents may also suggest consideration of protected left-turn phasing, although this would not be done if a semiactuated signal is used.

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18.4 Closing Comments

In selecting an appropriate type of control for an intersection, the traffic engineer has many factors to consider, including sight distances and warrants. In most cases, the objective is to provide the minimum level of control that will assure safety and efficient operations. In general, providing unneeded or excessive control leads to additional delay to drivers and passengers. With all of the analysis procedures and guidelines, however, engineering judgment is still required to make intelligent decisions. It is always useful to view the operation of existing intersections in the field in addition to reviewing study results before making recommendations on the best form of control.

References

1. *A Policy on Geometric Design of Highways and Streets*, 5th Edition, American Association of State Highway and Transportation Officials, Washington DC, 2004.
2. *Manual on Uniform Traffic Control Devices,* Draft, Federal Highway Administration, U.S. Department of Transportation, Washington DC, 2007.
3. *Highway Capacity Manual,* 4th Edition, Transportation Research Board, National Research Council, Washington DC, 2000.

Problems

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18-1. For the intersection of two rural roads shown in Figure 18.15, determine whether or not operation under basic rules of the road would be safe. If not, what type of control would you recommend, assuming that traffic signals are not warranted?

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18-2. Determine whether the intersection shown in Figure 18.16 can be safely operated under basic rules of the road. If not, what form of control would you recommend, assuming that signalization is not warranted?

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18-3. Determine whether the sight distances for the STOP-controlled intersection shown in Figure 18.17 are adequate. If not, what measures would you recommend to ensure safety?

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18-4–18-7. For each of the intersections shown in the following figures, determine whether the data support each of the nine signal warrants. For each problem, and each warrant, indicate whether the warrant is:

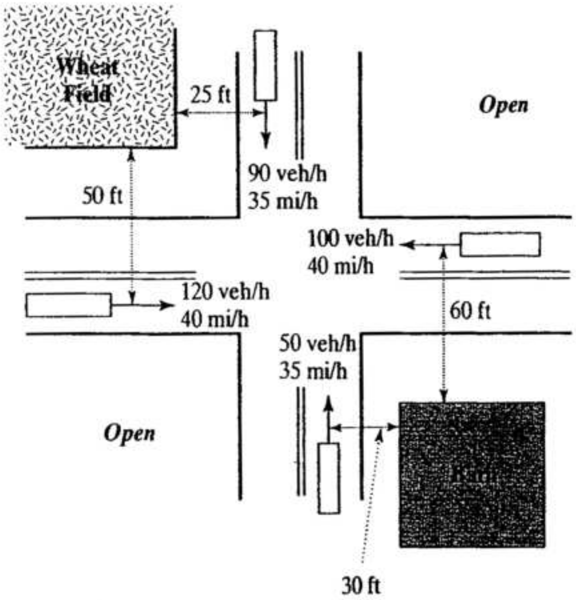
(a) met

(b) not met

(c) not applicable

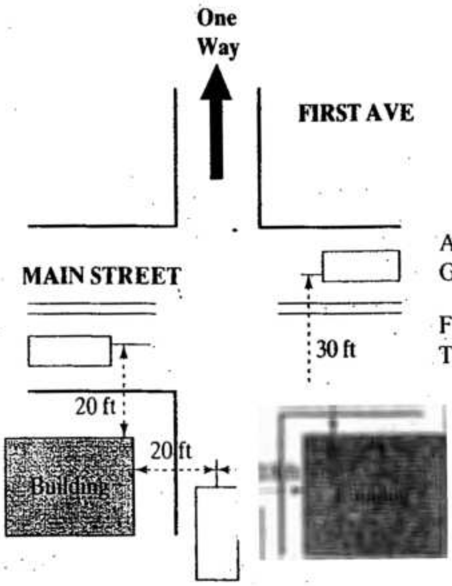
(d) insufficient information given to assess.

For each problem, indicate (a) whether a signal is warranted, (b) the type of signalization that should be



Reaction time, t = 2.5 s
F = 0.348; G = 0.0%

Figure 18.15: Intersection for Problem 18-1



	Main St	First Ave
Approach Speed:	45 mi/h	30 mi/h
Grade:	Level	+4.5%

F = 0.348
T = 2.5 s

Figure 18.16: Intersection for Problem 18.2

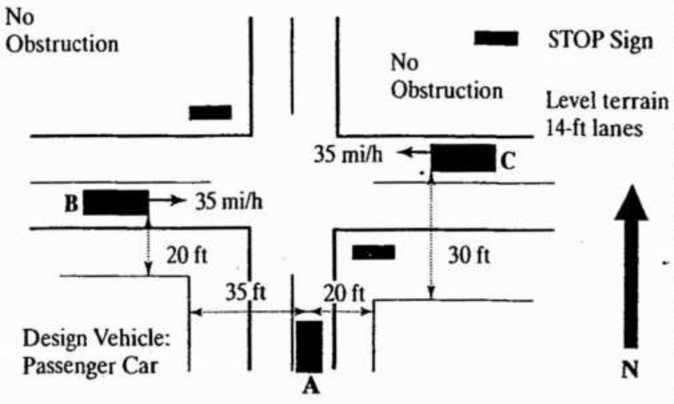


Figure 18.17: Intersection for Problem 18.3

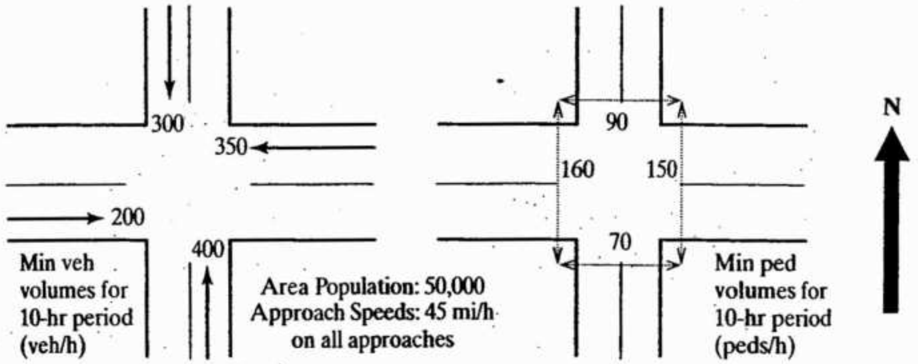
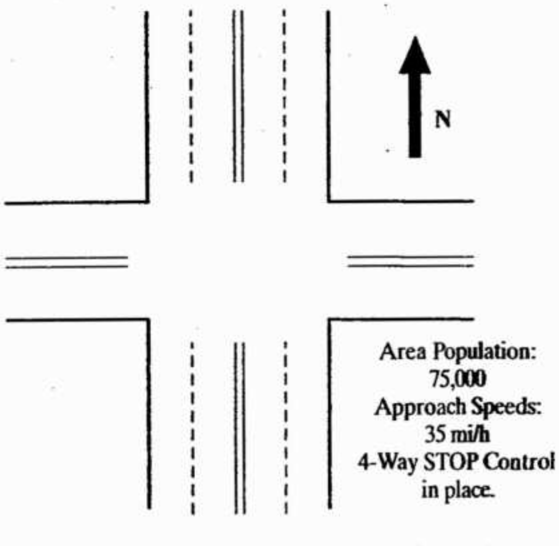
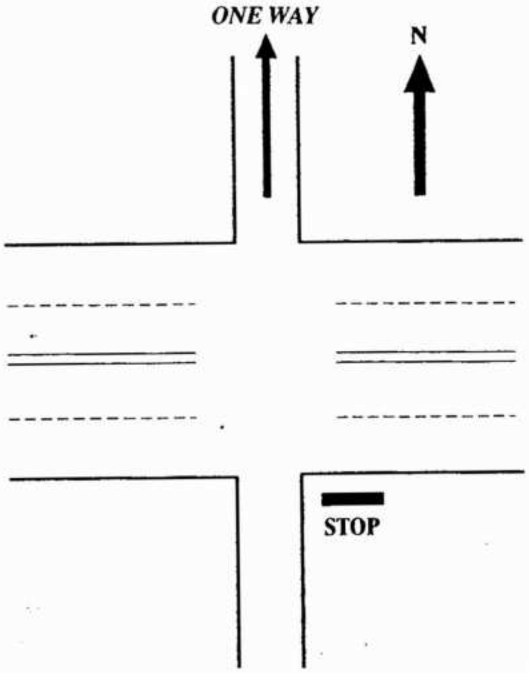


Figure 18.18: Intersection for Problem 18.4



	Volumes (veh/h)			
Hour	**EB**	**WB**	**NB**	**SB**
1	30	30	25	25
2	30	30	50	50
3	50	50	75	100
4	50	50	150	150
5	75	100	250	200
6	100	250	400	300
7	125	400	500	350
8	150	450	500	350
9	200	375	450	300
10	250	300	200	200
11	200	300	150	150
12	150	150	150	150
13	100	100	150	150
14	100	100	150	200
15	100	75	150	200
16	250	100	200	250
17	325	125	350	250
18	375	150	400	300
19	400	150	350	450
20	425	150	350	450
21	325	100	200	200
22	150	75	100	100
23	100	50	50	50
24	50	25	50	50

Figure 18.19: Intersection and Data for Problem 18.5



Area Population = 40.000

Approach Speeds: 45 mi/h (E-W): 30 mi/h (N)

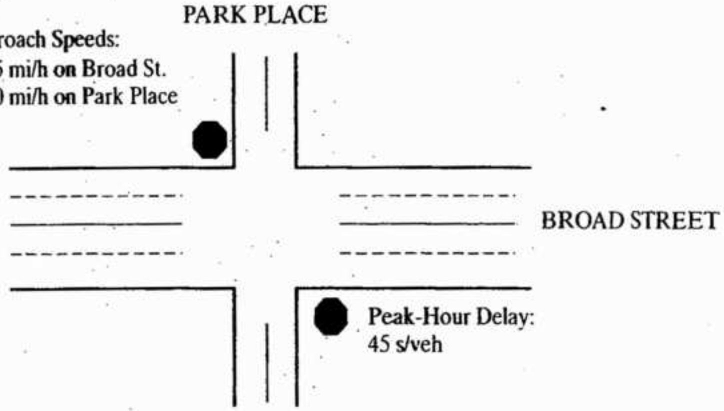
Accidents (Last 12 Months, Reportable):

- 8 right-angle
- 6 rear-end
- 3 left-turn
- 4 pedestrian

Delay to STOP-Controlled Vehicles: 72 s/veh

	Volumes By Hour		
	(Veh/h)	(Veh/h)	(Peds/h)
Time Period	Major St Total	Minor St Total	Peds Xing Major St
1–2 PM	850	100	200
2–3 PM	875	100	210
3–4 PM	1025	130	205
4–5 PM	1050	160	193
5–6 PM	1350	108	180
6–7 PM	1200	135	170
7–8 PM	1000	100	180
8–9 PM	975	85	200
9–10 PM	800	80	150
10–11 PM	900	80	100

Figure 18.20: Intersection and Data for Problem 18.6



Approach Speeds:
45 mi/h on Broad St.
30 mi/h on Park Place

Annual Accidents:

3 Right-Angle with injuries
5 Left-Turn with injuries
4 Rear-End, PDO
6 Pedestrian with 2 fatalities

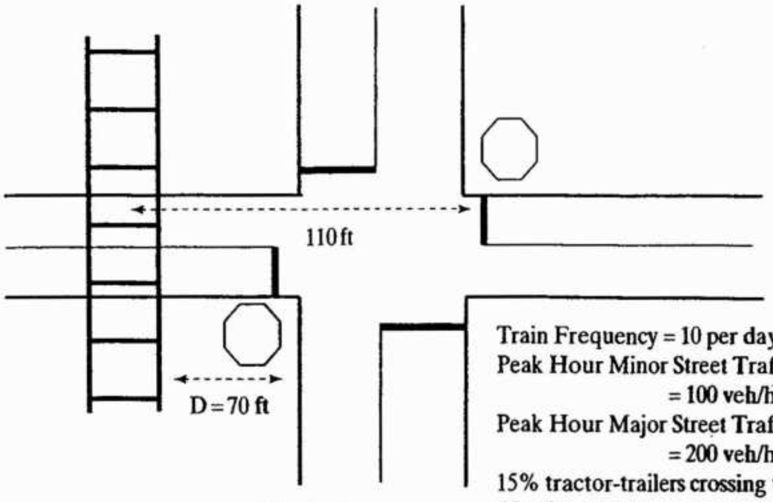
Peak-Hour Delay:
45 s/veh

Time	Broad Street Vol (veh/h)			Park Place Volume (veh/h)			Ped Vol (ped/h) Xing Broad
	EB	WB	TOT	NB	SB	High Vol	
11 AM – 12	300	400	**700**	100	90	**100**	120
12 – 1 PM	325	450	**775**	110	125	**125**	115
1 – 2 PM	400	475	**875**	140	150	**150**	109
2 – 3 PM	450	480	**930**	150	165	**165**	122
3 – 4 PM	455	475	**930**	155	170	**170**	135
4 – 5 PM	445	425	**870**	160	160	**160**	140
5 – 6 PM	400	380	**780**	152	155	**155**	125
6 – 7 PM	385	350	**735**	140	150	**150**	121
7 – 8 PM	350	350	**700**	145	152	**152**	120
8 – 9 PM	350	375	**725**	130	156	**156**	105
9 – 10 PM	325	325	**650**	122	120	**122**	85
10 – 11 PM	300	300	**600**	120	95	**120**	85

Figure 18.21: Intersection and Data for Problem 18.7

considered, and (c) whether pedestrian signals and/or pushbuttons are recommended. In all cases, assume that no warrants are met for the hours that are not included in the study data.

18-8. Figure 18.22 illustrates a STOP-controlled intersection near a highway-railroad grade crossing. Should this intersection be signalized under the new Warrant 9 that applies to such situations?



Train Frequency = 10 per day
Peak Hour Minor Street Traffic Crossing
= 100 veh/h
Peak Hour Major Street Traffic, Both
= 200 veh/h
15% tractor-trailers crossing tracks
No high-occupancy buses crossing tracks.

Figure 18.22: Intersection for Problem 18.18

CHAPTER 19

Elements of Intersection Design and Layout

In Chapter 18, the selection of appropriate control measures for intersections was addressed. Whether signalized or unsignalized, the control measures implemented at an intersection must be synergistic with the design and layout of the intersection. In this chapter, an overview of several important intersection design features is provided. We emphasize that this is only an overview because the details of intersection design could be the subject of a textbook on its own.

The elements treated here include techniques for determining the appropriate number and the use of lanes at an intersection approach, channelization, right- and left-turn treatments, special safety issues at intersections, and location of intersection signs and signal displays. There are a number of standard references for more detail on these and related subject areas, including the AASHTO *Policy on Geometric Design of Highways and Streets* [*1*], the *Manual on Uniform Traffic Control Devices* [2], the *Manual of Traffic Signal Design* [*3*], the *Traffic Detector Handbook* [*4*], and the *Highway Capacity Manual* [*5*].

19.1 Intersection Design Objectives and Considerations

As in all aspects of traffic engineering, intersection design has two primary objectives: (1) to ensure safety for all users, including drivers, passengers, pedestrians, bicyclists, and others, and (2) to promote efficient movement of all users (motorists, pedestrians, bicyclists, etc.) through the intersection. Achievement of both is not an easy task because safety and efficiency are often competing rather than mutually reinforcing goals.

In developing an intersection design, AASHTO [*1*] recommends that the following elements be considered:

- Human factors
- Traffic considerations
- Physical elements
- Economic factors
- Functional intersection area

Human factors must be taken into account. Thus intersection designs should accommodate reasonable approach speeds, user expectancy, decision and reaction times, and other user characteristics. Design should, for example, reinforce natural movement paths and trajectories, unless doing so presents a particular hazard.

Traffic considerations include provision of appropriate capacity for all user demands; the distribution of vehicle types and turning movements; approach speeds; and special requirements for transit vehicles, pedestrians, and bicyclists.

Physical elements include the nature of abutting properties, particularly traffic movements generated by these properties (parking, pedestrians, driveway movements, etc.). They also include the intersection angle, existence and location of traffic control devices, sight distances, and specific geometric characteristics, such as curb radii.

Economic factors include the cost of improvements (construction, operation, maintenance), the effects of improvements on the value of abutting properties (whether used by the expanded right-of-way or not), and the effect of improvements on energy consumption.

Finally, intersection design must encompass the full functional intersection area. The operational intersection area includes approach areas that fully encompass deceleration and acceleration zones as well as queuing areas. The latter are particularly critical at signalized intersections.

19.2 A Basic Starting Point: Sizing the Intersection

One of the most critical aspects of intersection design is the determination of the number of lanes needed on each approach. This is not an exact science because the result is affected by the type of control at the intersection, parking conditions and needs, availability of right-of-way, and a number of other factors that are not always directly under the control of the traffic engineer. Further, considerations of capacity, safety, and efficiency all influence the desirable number of lanes. As is the case in most design exercises, there is no one correct answer, and many alternatives may be available that provide for acceptable safety and operation.

19.2.1 Unsignalized Intersections

Unsignalized intersections may be operated under basic rules of the road (no control devices other than warning and guide signs), or under STOP or YIELD control.

When totally uncontrolled, intersection traffic volumes are generally light, and there is rarely a clear "major" street with significant volumes involved. In such cases, intersection areas do not often require more lanes than on the approaching roadway. Additional turning lanes are rarely provided. Where high speeds and/or visibility problems exist, channelization may be used in conjunction with warning signs to improve safety.

The conditions under which two-way (or one-way at a T-intersection or intersection of one-way roadways) STOP or YIELD control are appropriate are treated in Chapter 18. The existence of STOP- or YIELD-controlled approach(es), however, adds some new considerations into the design process:

- Should left-turn lanes be provided on the major street?
- Should right-turn lanes be provided on the major street?
- Should a right-turn lane be provided on minor approaches?
- How many basic lanes does each minor approach require?

Most of these issues involve capacity considerations. For convenience, however, some general guidelines are presented here.

When left turns are made from a mixed lane on the major street, there is the potential for unnecessary delay to through vehicles that must wait while left-turners find a gap in the opposing major-street traffic. The impact of major-street left turns on delay to all major-street approach traffic becomes noticeable when left turns exceed 150 veh/h. This may be used as a general guideline indicating the probable need for a major-street left-turn lane, although a value as low as 100 veh/h could be justified.

Right-turning vehicles from the major street do not have a major impact on the operation of STOP- or YIELD-controlled intersections. Although they do not technically conflict with minor-street movements when they are made from shared lanes, they may impede some minor-street movements when drivers do not clearly signal that they are turning or approach the intersection at high speed. When major-street right turns are made from an exclusive lane, their intent to turn is more obvious to minor-street drivers. Right-turn lanes for major-street vehicles can be easily provided where on-street parking is permitted. In such situations, parking may be prohibited for 100 to 200 feet from the STOP line, thus creating a short right-turn lane.

Most STOP-controlled approaches have a single lane shared by all minor-street movements. Occasionally, two lanes are provided. Any approach with sufficient demand to

Table 19.1: Guidelines for Number of Lanes at STOP-Controlled Approaches[1]

Total Volume on Minor Approach (veh/h)	Total Volume on Major Street (veh/h)			
	500	**1,000**	**1,500**	**2,000**
100	1 lane	1 lane	1 lane	2 lanes
200	1 lane	1 lane	2 lanes	NA
300	1 lane	2 lanes	2 lanes	NA
400	1 lane	2 lanes	NA	NA
500	2 lanes	NA	NA	NA
600	2 lanes	NA	NA	NA
700	2 lanes	NA	NA	NA
800	2 lanes	NA	NA	NA

[1] Not including multiway STOP-controlled intersections.

NA = STOP control probably not appropriate for these volumes.

require three lanes is probably inappropriate for STOP control. Approximate guidelines for the number of lanes required may be developed from the unsignalized intersection analysis methodology of the *Highway Capacity Manual*. Table 19.1 shows various combinations of minor-approach demand versus total crossing traffic on the major street, along with guidelines as to whether one or two lanes would be needed. They are based on assumptions that (1) all major-street traffic is through traffic, (2) all minor- approach traffic is through traffic, and (3) various impedances and other nonideal characteristics reduce the capacity of a lane to about 80% of its original value.

The other issue for consideration on minor STOP-controlled approaches is whether or not a right-turning lane should be provided. Because the right-turn movement at a STOP-controlled approach is much more efficient than crossing and left-turn movements, better operation can usually be accomplished by providing a right-turn lane. This is often as simple as banning parking within 200 feet of the STOP line, and it prevents right-turning drivers from being stuck in a queue when they could easily be executing their movements. Where a significant proportion of the minor-approach traffic is turning right (>20%), provision of a right-turning lane should always be considered.

Note that the lane criteria of Table 19.1 are approximate. Any finalized design should be subjected to detailed analysis using the appropriate procedures of the HCM 2000 (or the forthcoming HCM 2010).

Consider the following example: two-lane major roadway carries a volume of 800 veh/h, of which 10% turn left and 5% turn right at a local street. Both approaches on the local street are STOP-controlled and carry 150 veh/h, with 50 turning left and 50 turning right. Suggest an appropriate design for the intersection.

Given the relatively low volume of left turns (80/h) and right turns (40/h) on the major street, neither left- nor right-turn lanes would be required, although they could be provided if space is available. From Table 19.1, it appears that one lane would be sufficient for each of the minor-street approaches. The relatively heavy percentage of right turns (33%), however, suggests that a right-turn lane on each minor approach would be useful.

19.2.2 Signalized Intersections

Approximating the required size and layout of a signalized intersection involves many factors, including the demands on each lane group, the number of signal phases, and the signal cycle length.

Determining the appropriate number of lanes for each approach and lane group is not a simple design task. Like so many design tasks, there is no absolutely unique result, and many different combinations of physical design and signal timing can provide for a safe and efficient intersection.

The primary control on number of lanes is the *maximum sum of critical-lane volumes* that the intersection can support. This concept is more thoroughly discussed and illustrated in Chapter 20. The concept involves finding the single lane during a signal cycle that carries the most intense traffic, which means it would be the one that consumes the most green time of all movements to process its demand. Each signal phase has a critical-lane volume, and the cycle length of the signal is set to accommodate the sum of these critical volumes for each phase in the signal plan. This is the equation governing the maximum sum of critical-lane volumes:

$$V_c = \frac{1}{h}\left[3{,}600 - N t_L\left(\frac{3{,}600}{C}\right)\right] \qquad (19\text{-}1)$$

where: V_c = maximum sum of critical-lane volumes, veh/h
h = average headway for prevailing conditions on the lane group or approach, s/veh
N = number of phases in the cycle
t_L = lost time per phase, s/phase
C = cycle length, s

Table 19.2 gives approximate maximum sums of critical-lane volumes for typical prevailing conditions. An average headway of 2.6 s/veh is used, along with a typical lost time per phase of 4.0 s (t_L). Maximum sums are tabulated for a number of combinations of N and C.

Consider the case of an intersection between two major arterials. Arterial 1 has a peak directional volume of 900 veh/h; Arterial 2 has a peak directional volume of 1,100 veh/h. Turning volumes are light, and a two-phase signal is anticipated. As a preliminary estimate, what number of lanes is needed to accommodate these volumes, and what range of cycle lengths might be appropriate?

From Table 19.2, the range of maximum sums of critical-lane volumes is between 1,015 veh/h for a 30-second cycle length and 1,292 veh/h for a 120-second cycle length. The two critical volumes are given as 900 veh/h and 1,100 veh/h. If only one lane is provided for each, then the sum of critical-lane volumes is 900 + 1,100 = 2,000 veh/h, well outside the range of maximum values for reasonable cycle lengths. Table 19.3 shows a number of reasonable scenarios for the number of lanes on each critical approach along with the resulting sum of critical-lane volumes.

Table 19.2: Maximum Sums of Critical-Lane Volumes for a Typical Signalized Intersection

Cycle Length (s)	**No. of Phases**		
	2	**3**	**4**
30	1,015	831	646
40	1,108	969	831
50	1,163	1,052	942
60	1,200	1,108	1,015
70	1,226	1,147	1,068
80	1,246	1,177	1,108
90	1,262	1,200	1,138
100	1,274	1,218	1,163
110	1,284	1,234	1,183
120	1,292	1,246	1,200

With one lane on Arterial 1 and 3 lanes on Arterial 2, the sum of critical-lane volumes is 1,267 veh/h. From Table 19.2, this would be a workable solution with a cycle length over 100 seconds. With two lanes on each arterial, the sum of critical-lane volumes is 1,000 veh/h. This situation would be workable at any cycle length between 30 and 120 seconds. All other potentially workable scenarios in Table 19.3 could accommodate any cycle length between 30 and 120 seconds as well.

This type of analysis does not yield a final design or cycle length because it is approximate. But it does give the traffic engineer a basic idea of where to start. In this case, providing two lanes on each arterial in the peak direction appears to be a reasonable solution. Because peaks tend to be reciprocal (what goes one way in the morning comes back the opposite way in the evening), two lanes would also be provided for the off-peak directions on each arterial as well.

The signal timing should then be developed using the methodology of Chapter 21. The final design and timing should then be subjected to analysis using the *Highway*

Table 19.3: Sum of Critical-Lane Volumes (veh/h) for Various Scenarios: Sample Problem

No. of Lanes on Arterial 2	**Critical-Lane Volume for Arterial (veh/h)**	**No. of Lanes on Arterial[1]**		
		1	**2**	**3**
		900/1 = 900	900/2 = 450	900/3 = 300
1	1,100/1 = 1,100	*2,000*	*1,550*	*1,400*
2	1,100/2 = 550	*1,450*	*1,000*[1]	*850*[1]
3	1,100/3 = 367	*1,267*[1]	*817*[1]	*667*[1]

[1] Acceptable lane plan with V_c acceptable at some cycle length.

Capacity Manual (see Chapter 24) or some other appropriate analysis technique.

The number of anticipated phases is, of course, critical to a general analysis of this type. Suggested criteria for determining when protected left-turn phases are needed are given in Chapter 21. Because there is a critical-lane volume for *each* signal phase; a four-phase signal involves four critical-lane volumes, for example.

Exclusive left-turn lanes must be provided whenever a fully protected left-turn phase is used and is highly desirable when compound left-turn phasing (protected + permitted or vice versa) is used.

19.3 Intersection Channelization

19.3.1 General Principles

Channelization can be provided through the use of painted markings or by installation of raised channelizing islands. The AASHTO *Policy on Geometric Design of Highways and Streets* [*1*] gives a number of reasons for considering channelization at an intersection:

- Vehicle paths may be confined so that no more than two paths cross at any one point.
- The angles at which merging, diverging, or weaving movements occur may be controlled.
- Pavement area may be reduced, decreasing the tendency to wander and narrowing the area of conflict between vehicle paths.
- Clearer indications of proper vehicle paths may be provided.
- Predominant movements may be given priority.
- Areas for pedestrian refuge may be provided.
- Separate storage lanes may be provided to permit turning vehicles to wait clear of through-traffic lanes.
- Space may be provided for the mounting of traffic control devices in more visible locations.
- Prohibited turns may be physically controlled.
- Vehicle speeds may be somewhat reduced.

The decision to channelize an intersection depends on a number of factors, including the existence of sufficient right-of-way to accommodate an effective design. Factors such as terrain, visibility, demand, and cost also enter into the decision. Channelization supplements other control measures but can sometimes be used to simplify other elements of control.

19.3.2 Some Examples

It is difficult to discuss channelization in the abstract. A selection of examples illustrates the implementation of the principles noted previously.

Figure 19.1 shows the intersection of a major street (E–W) with a minor crossroad (N–S). A median island is provided on the major street. Partial channelization is provided for the southbound (SB) right turn, and a left-turn lane is provided for the eastbound (EB) left turn. The two channelized turns are reciprocal, and the design reflects a situation in which these two turning movements are significant. The design illustrated minimizes the conflict between SB right turns and other movements and provides a storage lane for EB left turns, removing the conflict with EB through movements. The lack of any channelization for other turning movements suggests they have light demand. The design does not provide for a great deal of pedestrian refuge, except for the wide median on the east leg of the intersection. This suggests that pedestrian volumes are relatively low at this location; if this is so, the crosswalk markings are optional. The channelization at this intersection is appropriate for both an unsignalized and a signalized intersection.

Figure 19.2 shows a four-leg intersection with similar turning movements as in Figure 19.1. In this case, however, the SB-EB and EB-SB movements are far heavier and require a more dramatic treatment. Here channelization is used to create two additional intersections to handle these dominant turns. Conflicts between the various turning movements are minimized in this design.

Figure 19.3 is a similar four-leg intersection with far greater use of channelization. All right turns are channelized,

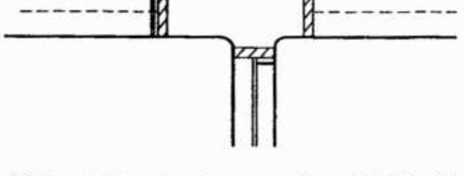


Figure 19.1: A Four-Leg Intersection with Partial Channelization for SB-EB and EB-SB Movements

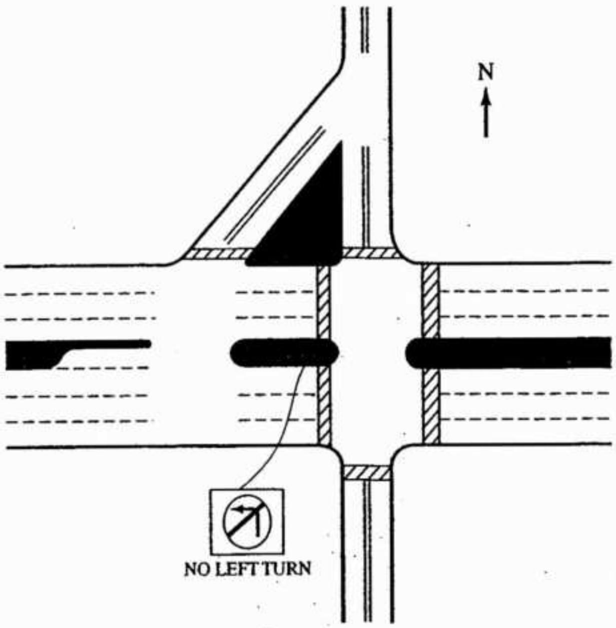


Figure 19.2: A Four-Leg Intersection Channelization for Major SB-EB and EB-SB Movements

and both major street left-turning movements have an exclusive left-turn lane. This design addresses a situation in which turning movements are more dominant. Pedestrian refuge is provided only on the right-turn channelizing islands, which may be limited by the physical size of the islands. Again, the

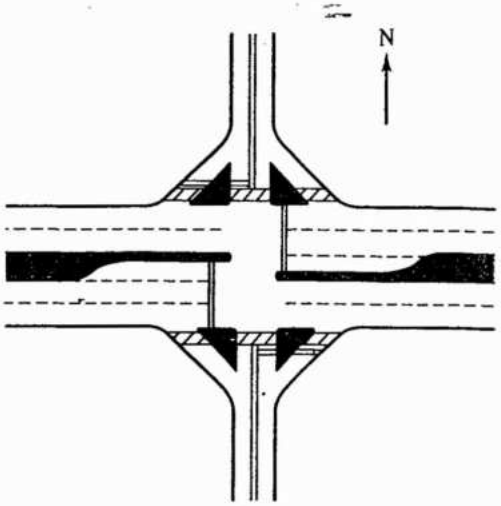


Figure 19.3: A Four-Leg Intersection with Full Channelization of Right Turns

channelization scheme is appropriate for either signalized or unsignalized control.

Channelization can also be used at locations with significant traffic volumes to simplify and reduce the number of conflicts and to make traffic control simpler and more effective. Figure 19.4 illustrates such a case.

In this case, a major arterial is fed by two major generators, perhaps two large shopping centers, on opposite sides of the roadway. Through movements across the arterial are

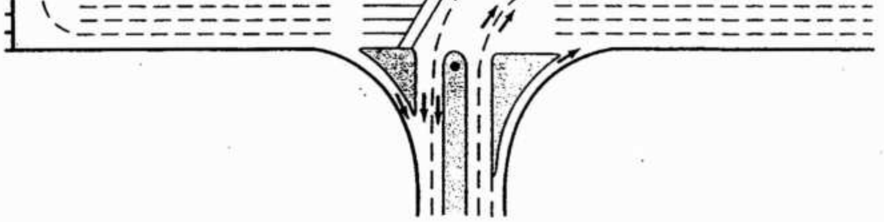


Figure 19.4: Channelization of a Complex Intersection

(*Source:* Used with permission of Institute of Transportation Engineers, R.P. Kramer, "New Combination of Old Techniques to Rejuvenate Jammed Suburban Arterials," *Strategies to Alleviate Traffic Congestion,* Washington DC, 1988.)

prevented by the channelization scheme as are left turns from either generator onto the arterial. The channelization allows only the following movements to take place:

- Through movements on the arterial
- Right-turn movements into either generator
- Left-turn movements into either generator
- Right-turn movements onto the arterial

Double-left-turn lanes on the arterial are provided for storage and processing of left turns entering either generator. A wide median is used to nest a double U-turn lane next to the left-turn lanes. These U-turn lanes allow vehicles to exit either generator and accomplish either a left-turning movement onto the arterial or a through movement into the opposite generator. In this case, it is highly likely the main intersection and the U-turn locations would be signalized. However, all movements at this complex location could be handled with two-phase signalization because the channelization design limits the signal to the control of two conflicting movements at each of the three locations. The distance between the main intersection and the U-turn locations must consider the queuing characteristics in the segments between intersections to avoid spill back and related demand starvation issues. From these examples, you can see that channelization of intersections can be a powerful tool to improve both the safety and the efficiency of intersection operation.

19.3.3 Channelizing Right Turns

When space is available, it is virtually always desirable to provide a channelized path for right-turning vehicles. This is especially true at signalized intersections where such channelization accomplishes two major benefits:

- Where "right-turn on red" regulations are in effect, channelized right turns minimize the probability of a right-turning vehicle or vehicles being stuck behind a through vehicle in a shared lane.
- Where channelized, right turns can effectively be removed from the signalization design because they would, in most cases, be controlled by a YIELD sign and would be permitted to move continuously.

The accomplishment of these benefits, however, depends on some of the details of the channelization design.

Figure 19.5 shows three different schemes for providing channelized right turns at an intersection. In Figure 19.5 (a), a simple channelizing triangle is provided. This design has limited benefits for two reasons: (1) through vehicles in the right lane may queue during the "red" signal phase, blocking access to the channelized right-turn lane, and (2) high right-turn volumes may limit the usefulness of the right-hand lane to through vehicles during "green" phases.

In the second design, shown in Figure 19.5 (b), acceleration and deceleration lanes are added for the channelized right turn. If the lengths of the acceleration and deceleration lanes are sufficient, this design can avoid the problem of queues blocking access to the channelized right turn.

In the third design, Figure 19.5 (c), a very heavy right-turn movement can run continuously. A lane drop on the approach leg and a lane addition to the departure leg provide a continuous lane and an unopposed path for right-turning vehicles. This design requires unique situations in which the lane drop and lane addition are appropriate for the arterials involved. To be effective, the lane addition on the departure leg cannot be removed too close to the intersection. It should be carried for at least several thousand feet before it is dropped, if necessary.

Right-turn channelization can simplify intersection operations, particularly where the movement is significant. It can also make signalization more efficient because channelized right turns, controlled by a YIELD sign, do not require green time to be served.

19.4 Special Situations at Intersections

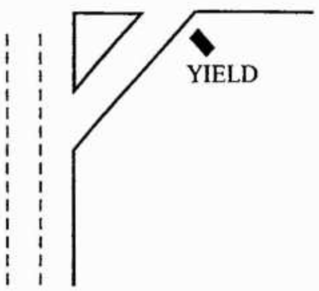
This section deals with four unique intersection situations that require attention: (1) intersections with junction angles less than 60° or more than 120°, (2) T-intersections, (3) offset intersections, and (4) special treatments for heavy left-turn movements.

19.4.1 Intersections at Skewed Angles

Intersections, both signalized and unsignalized, work best when the angle of the intersection is 90°. Sight distances are easier to define, and drivers tend to expect intersections at right angles. Nevertheless, in many situations the intersection angle is not 90°. Such angles may present special challenges to the traffic engineer, particularly when they are less than 60° or more than 120°. These occur relatively infrequently. Drivers are generally less familiar with their special characteristics, particularly vis-à-vis sight lines and distances.

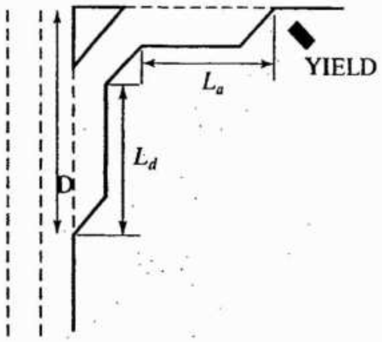
Skewed-angled intersections are particularly hazardous when uncontrolled and combined with high intersection-approach speeds. Such cases generally occur in rural areas

- No acceleration or deceleration lanes.
- Problem: queued vehicles may block access to right-turn lane.



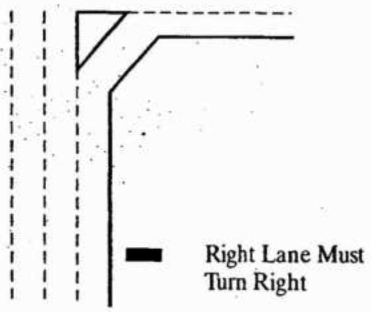
(a) Simple Channelized Right Turn

- "D" should be long enough to encompass the longest expected queue plus one vehicle.
- L_d allows right-turning vehicles to decelerate.
- L_a allows right-turning vehicles to accelerate.



(b) Channelized Right Turn with Acceleration and Deceleration Lanes

- Generally requires a RT demand of 500 veh/h or more.



(c) Channelized Right Turn with Lane Drop and Lane Addition

Figure 19.5: Three Ways to Channelize a Right Turn

and involve primary state and/or county routes. The situation illustrated in Figure 19.6 provides an example.

The example is a rural junction of two-lane, high-speed arterials, Routes 160 and 190. Given relatively gentle terrain, low volumes, and the rural setting, speed limits of 50 mi/h are in effect on both facilities. Figure 19.6 also illustrates the two movements representing a hazard. The conflict between the WB movement on Route 160 and the EB movement on Route 190 is a significant safety hazard. At the junction shown, both roadways have similar designs. Thus there is no visual cue to the driver indicating which route has precedence or right-of-way. Given that signalization is rarely justifiable in low-volume rural settings, other means must be considered to improve the safety of operations at the intersection.

The most direct means of improving the situation is to change the alignment of the intersection, making it clear which of the routes has the right-of-way. Figure 19.7 illustrates the two possible realignments. In the first case, Route 190 is given clear preference; vehicles arriving or departing on the east leg

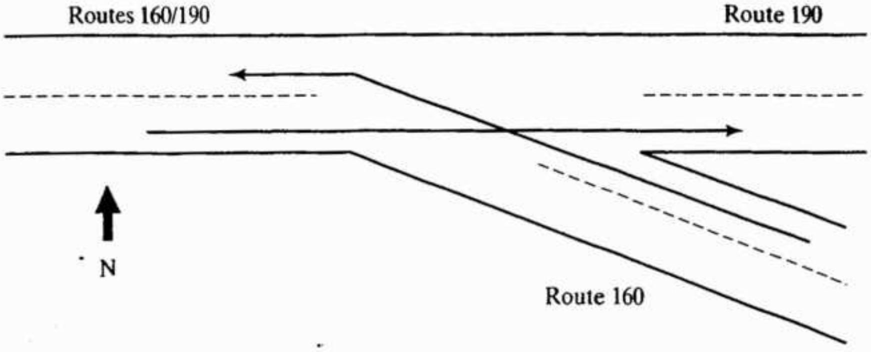


Figure 19.6: A Skewed-Angle Rural Intersection

of Route 160 must go through a 90° intersection to complete their maneuver. In the second case, Route 160 is dominant, and those arriving or departing on the east leg of Route 190 go through the 90° intersection. In either case, the 90° intersection would be controlled using a STOP sign to clearly designate right-of-way.

Although basic realignment is the best solution for high-speed odd-angle intersections, it requires that right-of-way be available to implement the change. Even in a rural setting, sufficient right-of-way to realign the intersection may not always be available. Other solutions can also be considered. Channelization can be used to better define the intersection movements, and control devices can be used to designate right-of-way. Figure 19.8 shows another potential design that requires less right-of-way than full realignment. 160

In this case, only the WB movement on Route 106 was realigned. Although this would still require some right-of-way, the amount needed is substantially less than for full realignment. Additional channelization is provided to separate EB movements on Routes 106 and 109. In addition to the regulatory signs indicated in Figure 19.8, warning and directional guide signs would be placed on all approaches to the intersection. In this solution, the WB left turn from Route 109 must be prohibited; an alternative route would have to be provided and appropriate guide signs designed and placed.

The junction illustrated is, in essence, a three-leg intersection. Skewed-angle four-leg intersections also occur in rural, suburban, and urban settings and present similar problems. Again, total realignment of such intersections is the most desirable solution. Figure 19.9 shows an intersection and the potential realignments that would eliminate the odd-angle junction. Where a four-leg intersection is involved, however, the realignment solution creates two separate intersections. Depending on volumes and the general traffic environment of the intersection, the realignments proposed in Figure 19.9 could result in signalized or unsignalized intersections.

In urban and suburban settings, where right-of-way is a significant impediment to realigning intersection, signalization of the odd-angle intersection can be combined with channelization to achieve safe and efficient operations. Channelized right turns would be provided for acute-angle turns, and left-turn lanes (and signalization) would be provided as needed.

In extreme cases, where volumes and approach speeds present hazards that cannot be ameliorated through normal traffic engineering measures, consideration may be given to providing a full or partial interchange with the two main roadways grade-separated. Providing grade separation would also involve some expansion of the traveled way, and overpasses in some suburban and urban surroundings may involve visual pollution and/or other negative environmental impacts.

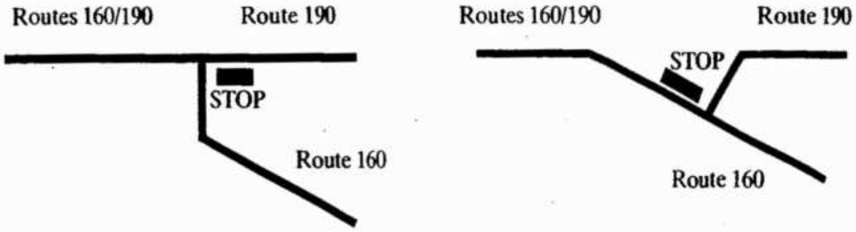


Figure 19.7: Potential Realignment for Rural Intersection

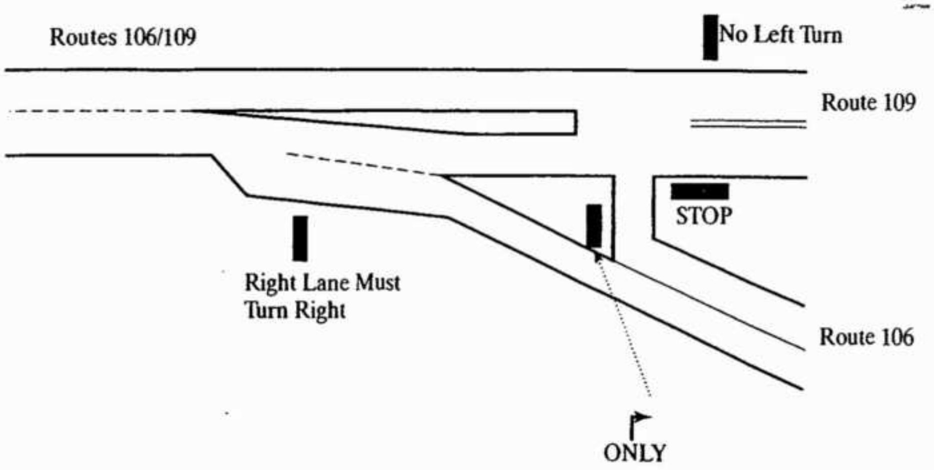


Figure 19.8: An Alternative Solution Using Channelization

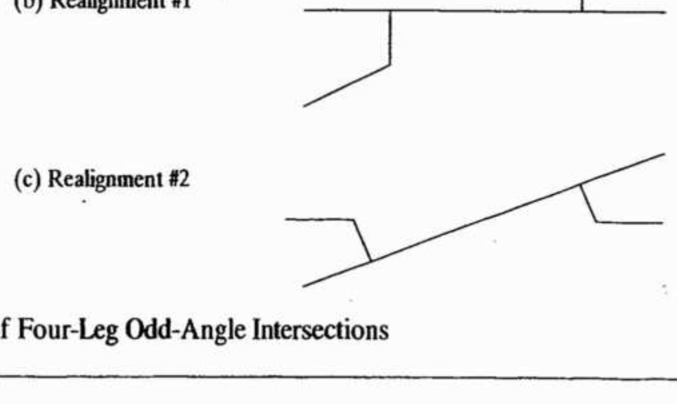
19.4.2 T-Intersections: Opportunities for Creativity

In many ways, T-intersections are far simpler than traditional four-leg intersections. The typical four-leg intersection contains 12 vehicular movements and 4 crossing pedestrian movements. At a T-intersection, only six vehicular movements exist and there are only three crossing pedestrian movements. These are illustrated in Figure 19.10.

Note that in the set of T-intersection vehicular movements, there is only one opposed left turn—the WB left-turn movement in this case. Because of this, conflicts are easier to manage, and signalization, when necessary, is easier to address.

Control options include all generally applicable alternatives for intersection control:

- Uncontrolled (warning and guide signs only)
- STOP or YIELD control
- Signal control


(a) Original Odd-Angle Intersection

(b) Realignment #1

(c) Realignment #2

Figure 19.9: Realignment of Four-Leg Odd-Angle Intersections

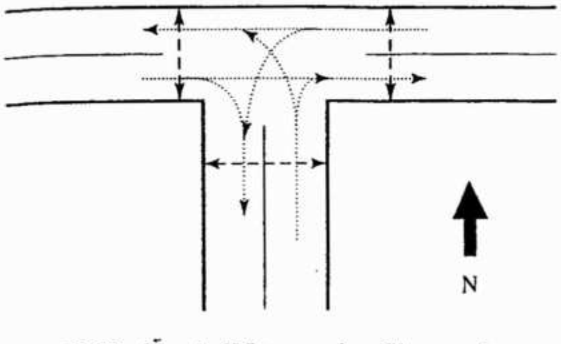


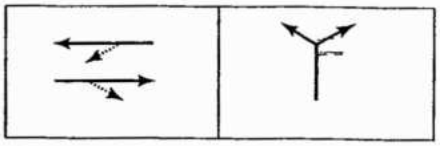
Figure 19.10: Simple T-Intersection Illustrated

The intersection shown in Figure 19.10 has one lane for each approach. There are no channelized movements or left-turn lanes. If visibility is not appropriate for uncontrolled operation under basic rules of the road, then the options of STOP/YIELD control or signalization must be considered. The normal warrants would apply.

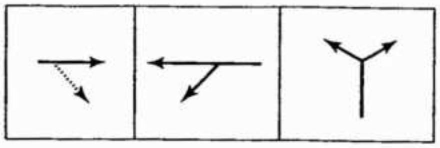
The T-intersection form, however, presents some relatively unique characteristics that influence how control is applied. STOP-control is usually applied to the stem of the T-intersection, although it is possible to apply two-way STOP control to the cross street if movements into and out of the stem dominate.

If needed, the form of signalization applied to the intersection of Figure 19.10 depends entirely on the need to protect the (WB) opposed left turn. A protected phase is normally suggested if the left-turn volume exceeds 200 veh/h or the cross-product of the left-turn volume and the opposing volume per lane exceeds 50,000. If left-turn protection is not needed, a simple two-phase signal plan is used. If the opposed left-turn must be protected and there is no left-turn lane available (as in Figure 19.10), a three-phase plan must be used. Figure 19.11 illustrates the possible signal plans for the T-intersection of Figure 19.10. The three-phase plan is relatively inefficient because a separate phase is needed for each of the three approaches.

Where a protected left-turn phase is desirable, the addition of an exclusive left-turn lane would simplify the signalization. Channelization and some additional right-of-way would be required to do this. Channelization can also be applied in other ways to simplify the overall operation and control of the intersection. Channelizing islands can be used to create separated right-turn paths for vehicles entering and leaving the stem via right turns. Such movements would be YIELD-controlled, regardless of the primary form of intersection control.



(a) A Two-Phase Signal Plan for the T-Intersection of Figure 19.10 (Permitted Left Turns)



(b) A Three-Phase Signal Plan for the T-Intersection of Figure 19.10 (Protected Left Turns)

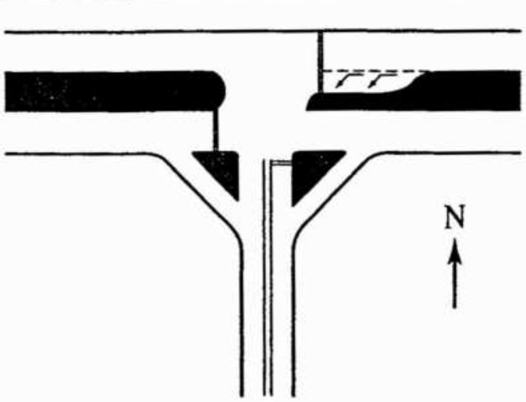
Figure 19.11: Signalization Options for the T-Intersection of Figure 19.10

Figure 19.12 shows a T-intersection in which a left-turn lane is provided for the opposed left turn. Right turns are also channelized. Assuming that a signal with a protected left turn is needed at this location, the signal plan shown could be implemented. This plan is far more efficient than that of Figure 19.11 because EB and WB through flows can move simultaneously. Right turns move more or less continuously through the YIELD-controlled channelized turning roadways. The potential for queues to block access to the right-turn roadways, however, should be considered in timing the signal.

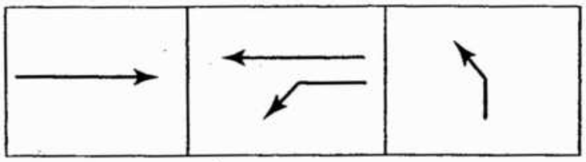
Right turns can be completely eliminated from the signal plan if volumes are sufficient to allow lane drops or additions for the right-turning movements, as illustrated in Figure 19.13. Right turns into and out of the stem of the T-intersection become continuous movements.

19.4.3 Offset Intersections

One of the traffic engineer's most difficult problems is the safe operation of high-volume offset intersections. Figure 19.14 illustrates such an intersection with a modest right offset. In the case illustrated, the driver needs more sight distance (when compared with a perfectly aligned 90° intersection) to observe vehicles approaching from the right. The obstruction caused by the building becomes a more serious problem because of this. In addition to sight-distance problems, the offset intersection distorts the normal trajectory of all movements, creating accident risks that do not exist at aligned intersections.



(a) A Channelized T-Intersection



(b) Signal Plan with Protected Left Turn and YIELD-Controlled Right Turns

Figure 19.12: A Channelized T-Intersection with Improved Signalization

Offset intersections are rarely consciously designed. They are necessitated by a variety of situations, generally involving long-standing historic development patterns. Figure 19.15 illustrates a relatively common situation in which offset intersections occur.

In many older urban or suburban developments, zoning and other regulations were (and in some cases, still are) not particularly stringent. Additional development was considered to be an economic benefit because it added to the property tax base of the community involved. Firm control over the specific design of subdivision developments, therefore, is not always exercised by zoning boards and authorities.

The situation depicted in Figure 19.15 occurs when Developer A obtains the land to the south of a major arterial and lays out a circulation system that will maximize the number of building lots that can be accommodated on the parcel. At a later time, Developer B obtains the rights to

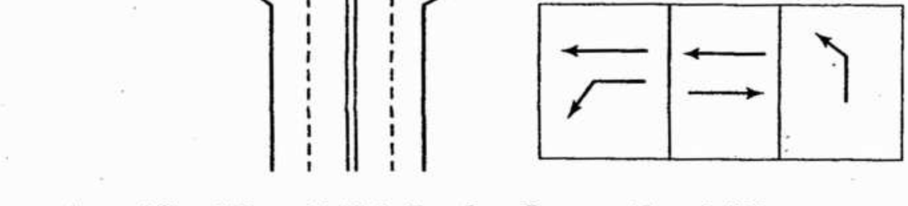


Figure 19.13: T-Intersection and Signal Plan with Right-Turn Lane Drops and Lane Additions

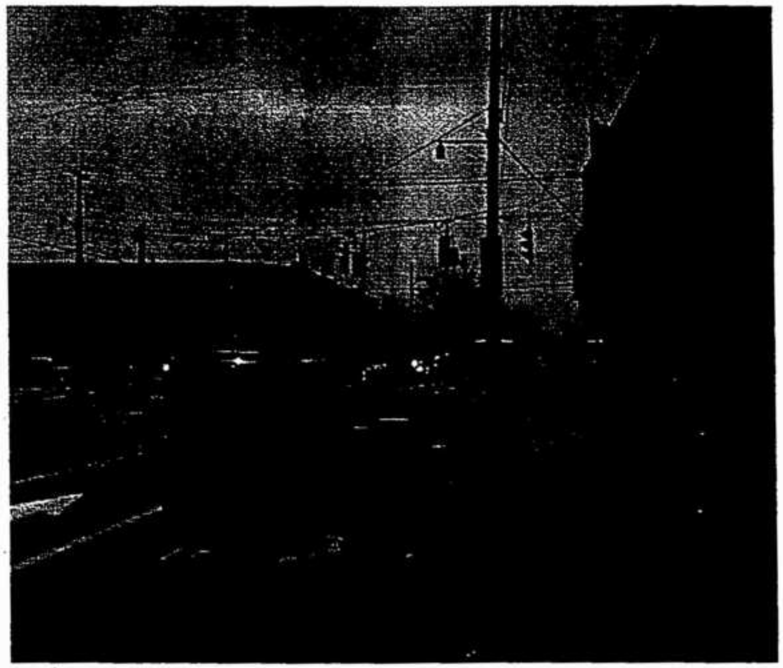


Figure 19.14: Offset Intersection with Sight Distance and Trajectory Problems

land north of the same arterial. Again, an internal layout that provides the maximum number of development parcels is selected. Without a strong planning board or other oversight group requiring it, there is no guarantee that opposing local streets will "line up." Offsets can and do occur frequently in such circumstances. In urban and suburban environments, it is rarely possible to acquire sufficient right-of-way to realign the intersections; therefore, other approaches to control and operation of such intersections must be considered.

Two major operational problems are posed by a right-offset intersection, as illustrated in Figure 19.16. In Figure 19.16 (a), the left-turn trajectories from the offset legs involve a high level of hazard. Unlike the situation with an aligned intersection, a vehicle turning left from either offset leg is in conflict with the opposing through vehicle almost immediately after crossing the STOP line. To avoid this conflict, left-turning vehicles must bear right as if they were going to go through to the opposite leg, beginning their left turns only when they are approximately halfway through the intersection. This, of course, is not a natural movement, and a high incidence of left-turn accidents often result at such intersections.

In Figure 19.16 (b), the hazard to pedestrians crossing the aligned roadway is highlighted. Two paths are possible, and both are reasonably intuitive for pedestrians: They can cross from corner to corner, following an angled crossing path, or they can cross perpendicularly. The latter places one end of

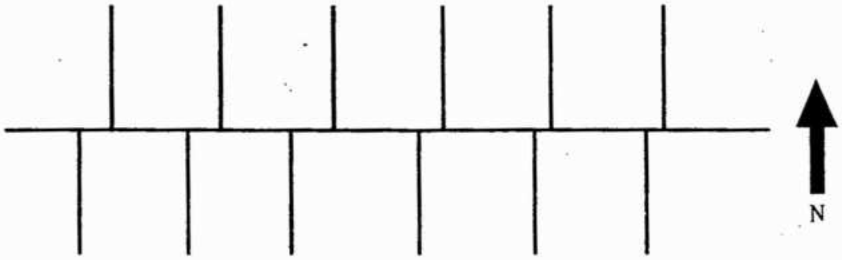
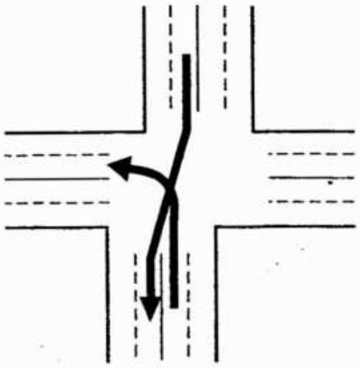
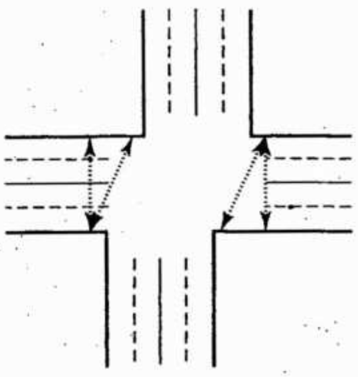


Figure 19.15: A Common Situation for Offset Intersections



(a) Left-Turn Trajectory Problems Illustrated



(b) Pedestrian Path Problems Illustrated

Figure 19.16: Special Problems at Offset Intersections

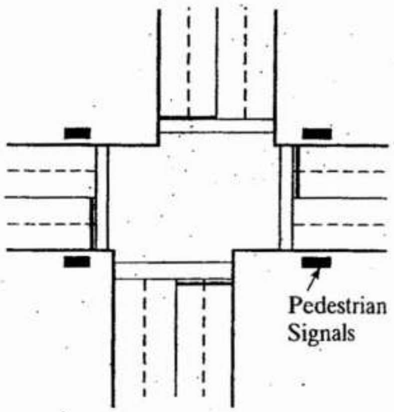
their crossing away from the street corner. Perpendicular crossings, however, minimize the crossing time and distance. However, right-turning vehicles encounter the pedestrian conflict at an unexpected location, after they have virtually completed their right turn. Diagonal crossings increase the exposure of pedestrians, but conflicts with right-turning vehicles are closer to the normal location.

Yet another special hazard at offset intersections, not clearly illustrated by Figure 19.16, is the heightened risk of sideswipe accidents as vehicles cross between the offset legs. Because the required angular path is not necessarily obvious, more vehicles will stray from their lane during the crossing.

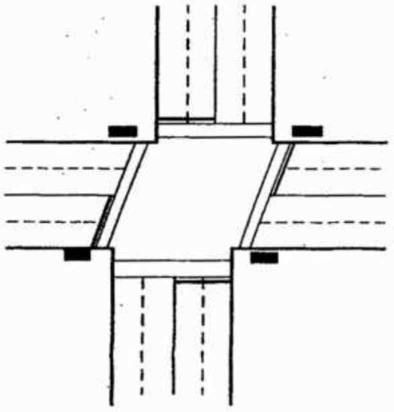
There are, however, remedies that will minimize these additional hazards. Where the intersection is signalized, the left-turn conflict can be eliminated through the use of a fully protected left-turn phase in the direction of the offset. In this case, the left-turning vehicles will not be entering the intersection area at the same time as the opposing through vehicles. This requires, however, that one of the existing lanes be designated an exclusive turning lane or that a left-turn lane can be added to each offset leg. If this is not possible, a more extreme remedy is to provide each of the offset legs with an exclusive signal phase. Although this separates the left-turning vehicles from the opposing flows, it is an inefficient signal plan and can lead to four-phase signalization if left-turn phases are needed on the aligned arterial.

For pedestrian safety, it is absolutely necessary that the traffic engineer clearly designate the intended path they are to take. This is done through proper use of markings, signs, and pedestrian signals, as shown in Figure 19.17.

Crosswalk locations influence the location of STOP-lines and the position of pedestrian signals, which must be located in the line of sight (which is the walking path) of pedestrians. Vehicular signal timing is also influenced by the crossing paths implemented. Where perpendicular crossings are used, the distance between STOP-lines on the aligned street can be considerably longer than for diagonal crossings.



(a) Markings for Perpendicular Pedestrian Crossings



(b) Markings for Diagonal Pedestrian Crossings

Figure 19.17: Signing, Markings, and Pedestrian Signals for a Right-Offset Intersection

This increases the length of the all-red interval for the aligned street and adds lost time to the signal cycle.

In extreme cases, where enforcement of perpendicular crossings becomes difficult, barriers can be placed at normal street corner locations, preventing pedestrians from entering the street at an inappropriate or unintended location.

To help vehicles follow appropriate paths through the offset intersection, dashed lane and centerline markings through the intersection may be added, as illustrated in Figure 19.18. The extended centerline marking would be yellow, and the lane lines would be white.

Left-offset intersections share some of the same problems as right-offset intersections. The left-turn interaction with the opposing through flow is not as critical, however. The pedestrian–right-turn interaction is different but potentially just as serious. Figure 19.19 illustrates.

The left-turn trajectory through the offset intersection is still quite different from an aligned intersection, but the left-turn movement does not thrust the vehicle immediately into the path of the oncoming through movement, as in a right-offset intersection. Sideswipe accidents are still a risk, and extended lane markings would be used to minimize this risk.

At a left-offset intersection, the diagonal pedestrian path is more difficult because it brings the pedestrian into immediate conflict with right-turning vehicles more quickly than at an aligned intersection. For this reason, diagonal crossings are generally not recommended at left-offset intersections. The signing, marking, and signalization of perpendicular pedestrian crossings is similar to that used at a right-offset intersection.

When at all possible, offset intersections should be avoided. If sufficient right-of-way is available, basic realignment should be seriously considered. When confronted with such a situation, however, the traffic engineering approaches discussed here can ameliorate some of the fundamental concerns associated with offset alignments. The traffic engineer should recognize that many of these measures will negatively affect capacity of the approaches due to the additional signal phases and longer lost times often involved. This is, however, a necessary price paid to optimize safety of intersection operation.

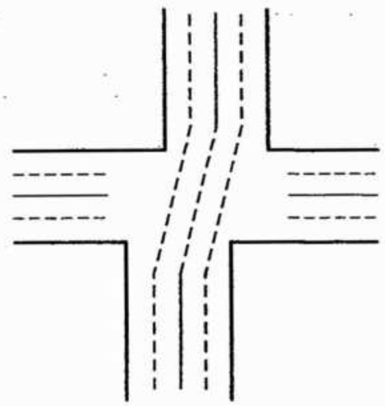


Figure 19.18: Dashed Lane and Centerline Through an Offset Intersection

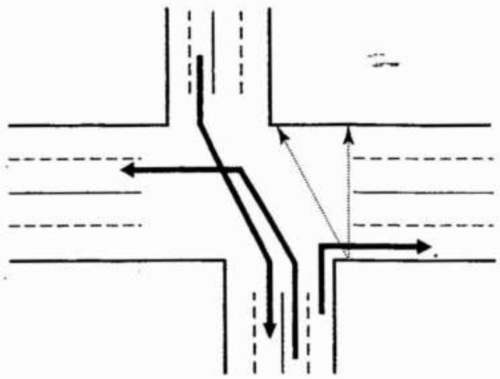


Figure 19.19: Conflicts at a Left-Offset Intersection

19.4.4 Special Treatments for Heavy Left-Turn Movements

Some of the most difficult intersection problems to solve involve heavy left-turn movements on major arterials. Accommodating such turns usually requires the addition of protected left-turn phasing, which often reduces the effective capacity to handle through movements. In some cases, adding an exclusive left-turn phase or phases is not practical, given the associated losses in through capacity.

Alternative treatments must be sought to handle such left-turn movements, with the objective of maintaining two-phase signalization at the intersection. Several design and control treatments are possible, including:

- Prohibition of left turns
- Provision of jug-handles
- Provision of at-grade loops and diamond ramps
- Provision of a continuous-flow intersection
- Provision of U-turn treatments

Prohibition of left turns is rarely a practical option for a heavy left-turn demand. Alternative paths would be needed to

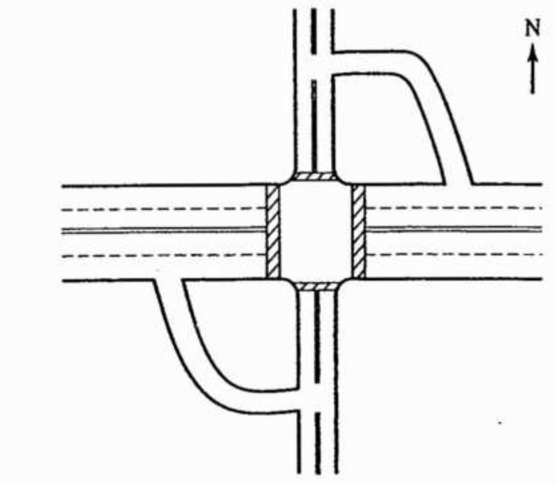


Figure 19.20: Jug-Handle Design for Left-Turning Vehicles

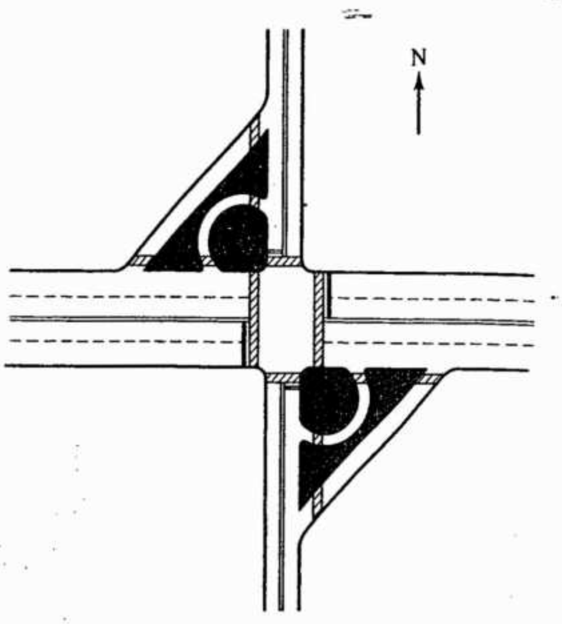


Figure 19.21: Surface Loop Ramp Design for Left Turns

accommodate the demand for this movement, and diversion of a heavy flow onto an "around-the-block" or similar path often creates problems elsewhere.

Figure 19.20 illustrates the use of jug-handles for handling left turns. In effect, left-turners enter a surface ramp on the right, executing a left turn onto the cross street. The jug-handle may also handle right-turn movements. The design creates two new intersections. Depending on volumes, these may require signalization or could be controlled with STOP signs. In either case, queuing between the main intersection and the two new intersections is a critical issue. Queues should not block egress from either of the jug-handle lanes. The provision of jug-handles also requires sufficient right-of-way available to accommodate the solution. In some extreme cases, existing local streets may be used to form a jug-handle pattern.

Figure 19.21 illustrates the use of surface loop ramps to handle heavy left-turning movements at an arterial intersection. These are generally combined with surface diamond ramps to

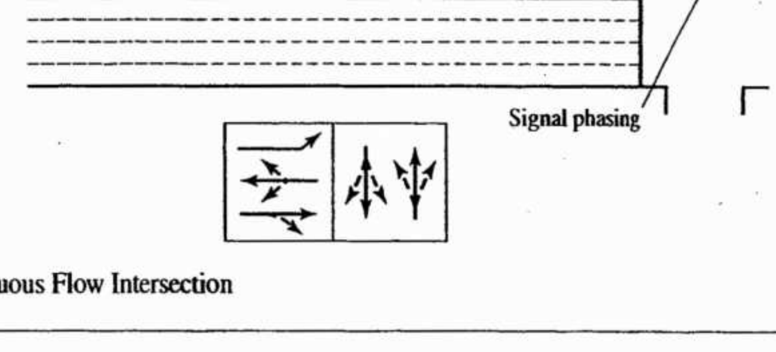


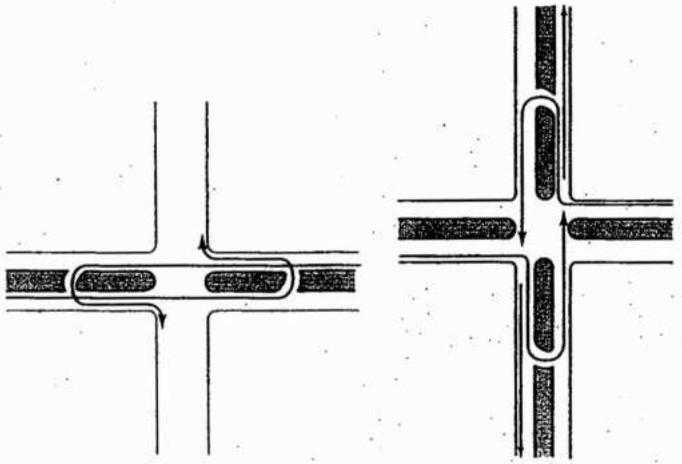
Figure 19.22: A Continuous Flow Intersection

handle right turns from the cross street, thus avoiding the conflict between normal right turns and the loop ramp movements on the arterial. Once again, queuing could become a problem if left-turning vehicles back up along the loop ramp far enough to affect the flow of vehicles that can enter the loop ramp. This option also consumes considerable right-of-way and may be difficult to implement in high-density environments.

Figure 19.22 illustrates a continuous-flow intersection, a relatively novel design approach developed during the late 1980s and early 1990s. The continuous-flow intersection [*6*] takes a single intersection with complex multiphase signalization and separates it into two intersections, each of which can be operated with a two-phase signal and coordinated. At the new intersection, located upstream of the left-turn location, left-turning vehicles are essentially transferred to a separate roadway on the left side of the arterial. At the main intersection, the left turns can then be made without a protected phase, regardless of the demand level. The design requires sufficient right-of-way on one side of the arterial to create the new left-turn roadway and a median that is wide enough to provide one or two left-turning lanes at the new intersection. Queuing from the main intersection can become a problem if left-turning vehicles are blocked from entering the left-turn lane(s) at the new upstream intersection.

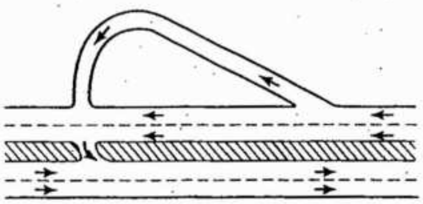
Although a few continuous-flow intersections have been built, they have not seen the widespread use that was originally anticipated. In most cases, right-of-way restrictions make this solution somewhat impractical.

As a last resort, left turns may be handled in a variety of ways as U-turn movements. Figure 19.23 illustrates four

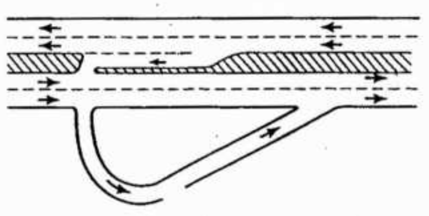


(a) Left turns handled as U-turns on the primary arterial.

(b) Left turns handled as U-turns on the cross street.



(c) Left turns handled as U-turns using a right-side U-turn roadway.



(d) Left turns handled as U-turns using a left-side U-turn roadway.

Figure 19.23: Left Turn Options Handled as U-Turns

potential designs for doing this. In Figure 19.23 (a), left-turning vehicles go through the intersection and make a U-turn through a wide median downstream. The distance between the U-turn location and the main intersection must be sufficient to avoid blockage by queued vehicles and must provide sufficient distance for drivers to execute the required number of lane changes to get from the median lane to right lane. In Figure 19.23 (b), left-turning vehicles turn right at the main intersection, then execute a U-turn on the cross street. Queuing and lane-changing requirements are similar to those described for Figure 19.23 (a). Where medians are narrow, the U-turn paths of (a) and (b) cannot be provided. Figures 19.23 (c) and (d) use U-turn roadways built to the right and left sides of the arterial (respectively) to accommodate left-turning movements. These options require additional right-of-way.

The safe and efficient accommodation of heavy left-turn movements on arterials often requires creative approaches that combine both design and control elements. The examples shown here are intended to be illustrations, not a complete review of all possible alternatives.

19.5 Street Hardware for Signalized Intersections

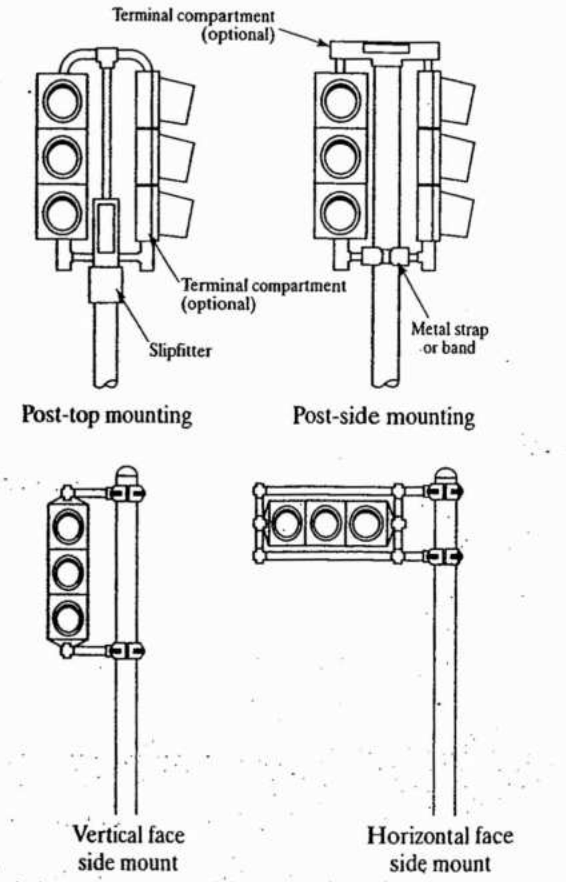
In Chapter 4, the basic requirements for display of signal faces at a signalized intersection were discussed in detail. These are the key specifications:

- A minimum of two signal faces should be visible to each primary movement in the intersection.
- All signal faces should be placed within a horizontal 20° angle around the centerline of the intersection approach (including exclusive left- and/or right-turn lanes).
- All signal faces should be placed at mounting heights in conformance with MUTCD standards, as presented in Figure 4.20 of Chapter 4.

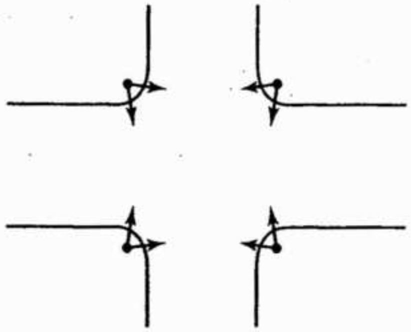
The proper location of signal heads is a key element of intersection design and critical to maximizing observance of traffic signals.

Three general types of signal-head mountings can be used alone or in combination to achieve the appropriate location of signal heads: post-mounting, mast-arm mounting, and span-wire mounting.

Figure 19.24 illustrates post-mounting. The signal head can be oriented either vertically or horizontally, as shown. Post-mounted signals are located on each street corner. A post-mounted signal head generally has two faces, oriented such that a driver sees two faces located on each of the far intersection corners. Because they are located on street



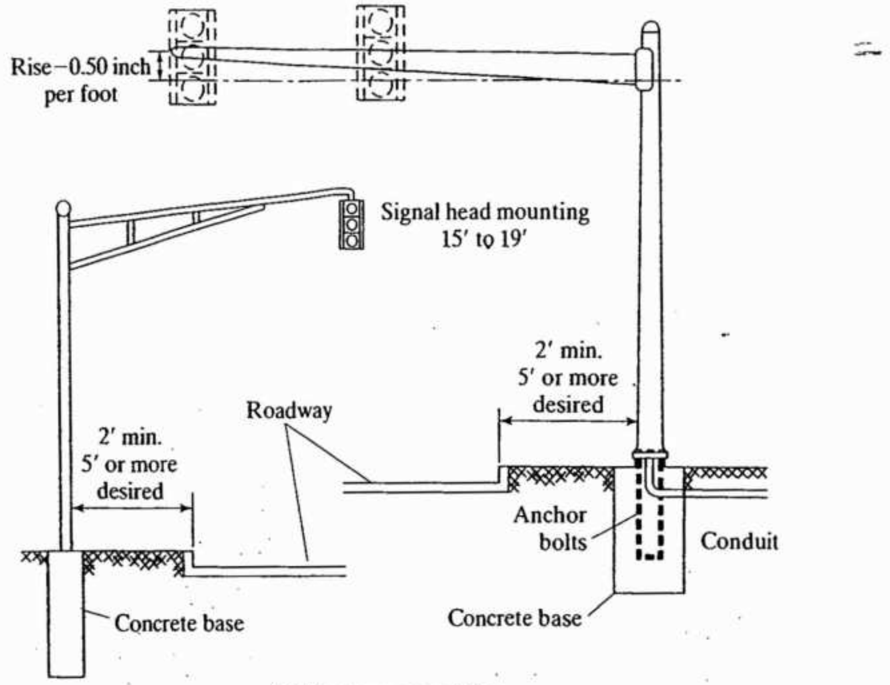
(a) Post-mounting alternatives



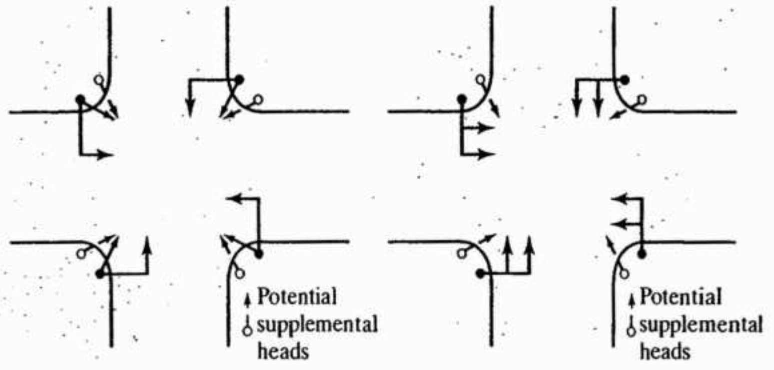
(b) Standard post-mounting locations

Figure 19.24: Post-Mounting of Signal Heads

(*Source:* Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., *Manual of Traffic Signal Design*, 2nd Edition, 1991, p. 44.)



(a) Mast-arm assemblies



(b) Typical mast-arm locations

Figure 19.25: Mast-Arm Mounting of Signal Heads

(*Source:* Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., *Manual of Traffic Signal Design,* 2nd Edition, 1991, p. 57.)

corners, care must be taken to ensure that post-mounted signals fall within the required 20° angle of the approach centerline. Post-mounted signals are often inappropriate for use at intersections with narrow streets because street corners in such circumstance lie outside of the visibility requirement.

Figure 19.25 illustrates mast-arm mounting of signal heads. Typically, the mast arm is perpendicular to the intersection approach. They are located so that drivers are looking at a signal face or faces on the far side of the intersection. Mast arms can be long enough to accommodate two signal heads, but they are rarely used for more than two signal heads.

Figure 19.26 shows two typical mast-arm signal installations. The first (a) shows mast-arm signals at a four-leg intersection, with the mast-arm oriented perpendicular to the direction of traffic. Note that the mast-arm signal heads are supplemented by a post-mounted signal in the gore of the four-leg intersection. The second (b) represents a very efficient scheme for mounting signal heads at a simple intersection of two two-lane streets. Two mast

(a) Mast-Arm Mounted Signals at a Y-Intersection

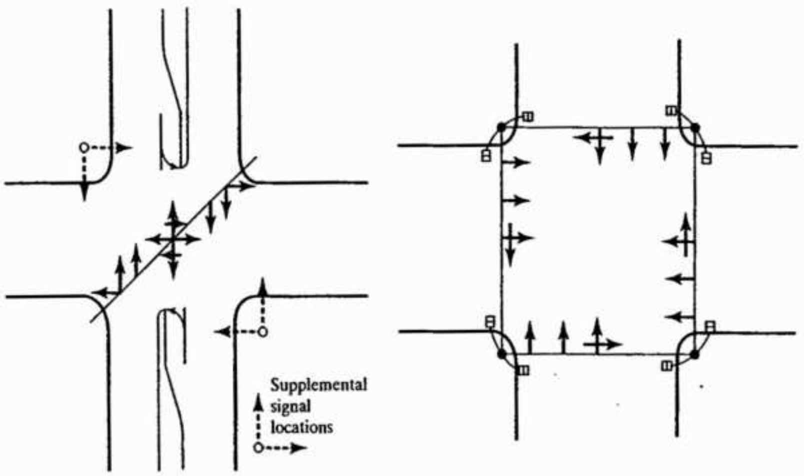
(b) Mast-Arm Mounted Signals at the Intersection of Two 2-Lane Streets

Figure 19.26: Two Examples of Mast-Arm Mounted Signals

arms are used, each extending diagonally across the intersection. Only two signal heads are used, each with a full four faces. In this way, using only two signal heads, all movements have two signal faces displaying the same signal interval.

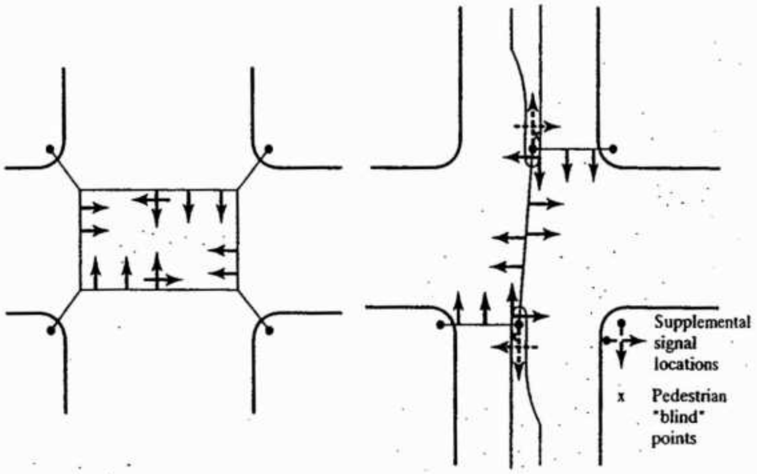
In the case of both post-mounted and mast-arm–mounted signal heads, power lines are carried to the signal head within the hollow structure of the post or mast arm.

The most common method for mounting signal heads is span wire because it is the most flexible and can be used in a variety of configurations. Figure 19.27 shows four basic configurations in which span wires can be used. The first is a single diagonal span wire between two intersection corners. The span wire allows the installation of a number of signal heads, each having between one and three faces, depending on the exact location. Such installations are generally supplemented by post-mounted signals on the two other intersection corners. The second installation illustrated is a "box" design. Four span wires are installed across each intersection leg. Signal heads are oriented much in the same way as with mast arms. Most signal heads have a single face and are visible from the far side of the intersection. The third example is a "modified box," in which the box is suspended over the middle of the intersection. This is done to accomplish signal-face locations that are more visible and more clearly aligned with specific lanes of each intersection approach. The final example of Figure 19.27 is a "lazy Z" pattern in which the primary span wire is anchored on



Simple two-pole span with left-turn display

Simple box span with left-turn display



Modified box span

Typical Z-span

Figure 19.27: Span-Wire Mounting of Signal Heads

(*Source:* Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., *Manual of Traffic Signal Design,* 2nd Edition, 1991, pp. 51–53.)

opposing medians. This latter design is possible only where opposite medians exist.

Span wire allows the traffic engineer to place signal faces in almost any desired position and is often used at complex intersections where a signal face for each entering lane is desired.

Figure 19.28 illustrates how signal heads are anchored on span wires. In general, the main cable supports each signal head from above. Signal heads so mounted can and do sway in the wind. Where wind is excessive or where the exact orientation of the signal face is important, a tether wire may be attached to the bottom of the signal head for restraint. This is most important where Polaroid signal lenses are used. These lenses are visible only when viewed from a designated angle. They are often used at closely spaced signalized intersections, where the traffic engineer uses them to prevent drivers from reacting to the next downstream signal.

Figure 19.29 illustrates how power is supplied to a span-wire mounted signal head. A shielded power cable is wrapped around the primary support wire and connected to each signal head.

Figure 19.30 shows a typical field installation of span-wire mounted signals. In this case, a single span wire supports six signal heads that are sufficient to control all movements, including a left-turn phase on the major street.

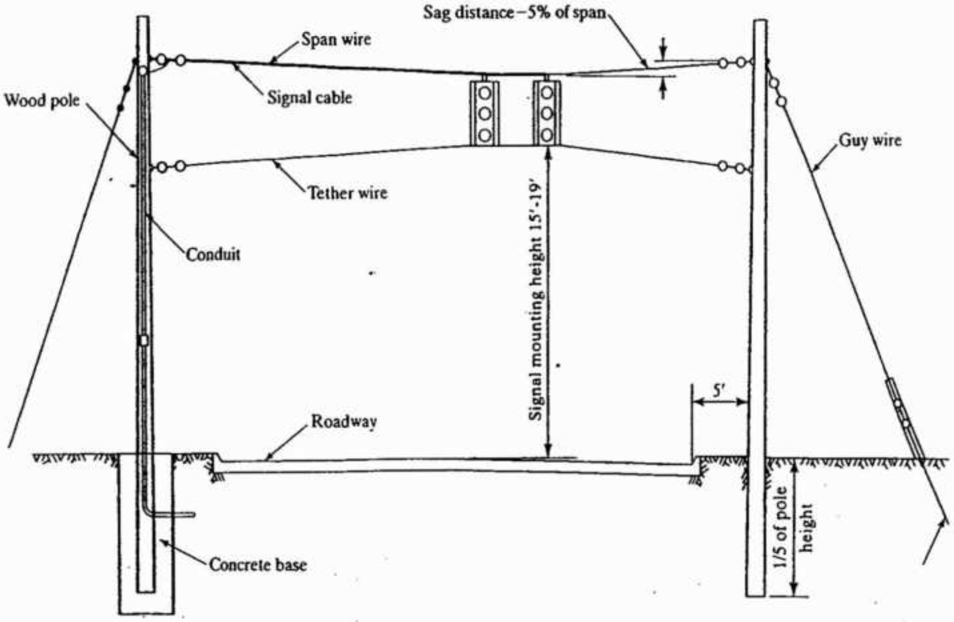


Figure 19.28: Use of Span Wire and Tether Wire Illustrated

(*Source:* Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., *Manual of Traffic Signal Design*, 2nd Edition, 1991.)

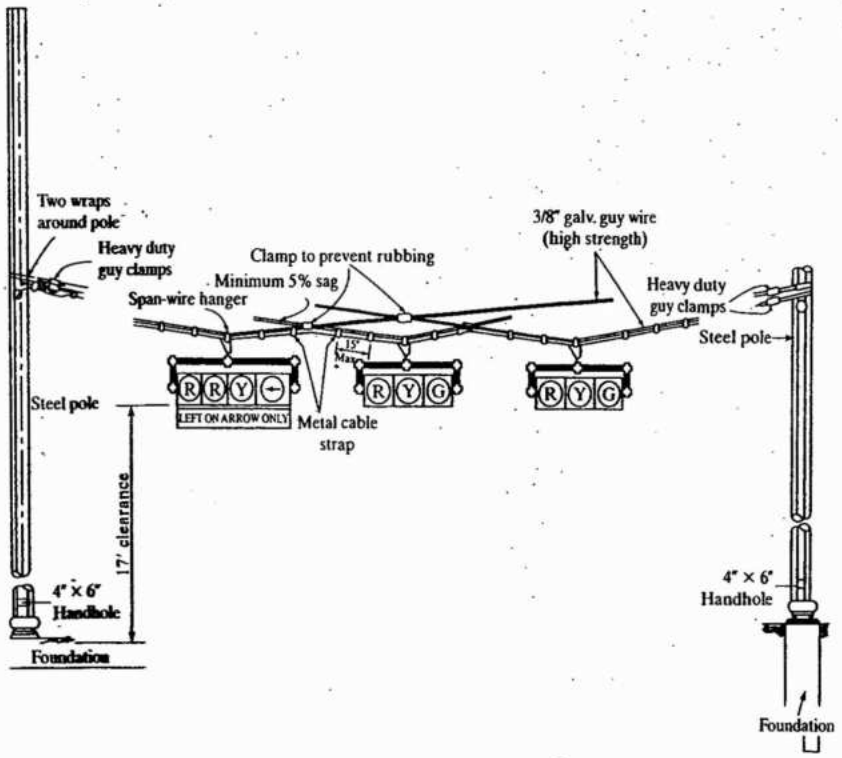


Figure 19.29: Providing Power to Span-Mounted Signals

(*Source:* Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., *Manual of Traffic Signal Design*, 2nd Edition, 1991.)

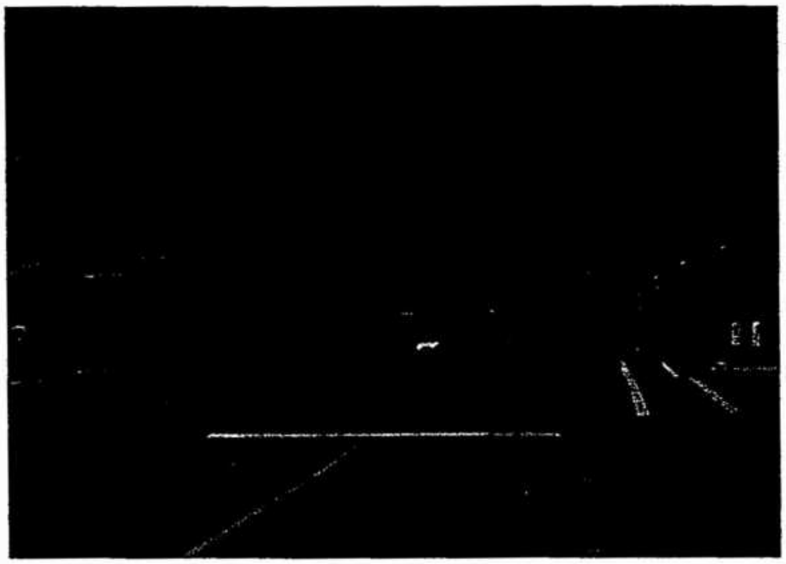


Figure 19.30: A Typical Span-Wire Signal Installation

Using the three signal mounting options (post mounted, mast-arm mounted, span-wire mounted), either alone or in combination, the traffic engineer can satisfy all of the posting requirements of the MUTCD and present drivers with clear and unambiguous operating instructions. Achieving this goal is critical to ensuring safe and efficient operations at signalized intersections.

19.6 Closing Comments

This chapter has provided an overview of several important elements of intersections design. It is not intended to be exhaustive, and we encourage you to consult standard references for additional relevant topics and detail.

References

1. *A Policy on Geometric Design of Highways and Streets,* 5th Edition, American Association of State Highway and Transportation Officials, Washington DC, 2004.
2. *Manual of Uniform Traffic Control Devices,* Federal Highway Administration, U.S. Department of Transportation, 2009.
3. Kell, J., and Fullerton, I., *Manual of Traffic Signal Design,* 2nd Edition, Institute of Transportation Engineers, Washington DC, 1991.
4. *Traffic Detector Handbook,* JHK & Associates, Institute of Transportation Engineers, Washington DC, n.d.
5. *Highway Capacity Manual,* 4th Edition, Transportation Research Board, Washington DC, 2000.
6. Hutchinson, T., "The Continuous Flow Intersection: The Greatest New Development Since the Traffic Signal?" *Traffic Engineering and Control,* 36, no. 3, Printhall Ltd., London, UK, 1995.

Problems

19-1–19-2. Each of the sets of demands shown in Figures 19.31 and 19.32 represent the forecast flows (already adjusted for peak hour factor) expected at new intersections that are created as a result of large new developments. Assume that each intersection will be signalized. In each case, propose a design for the intersection, including a detailing of where and how signal heads would be located.

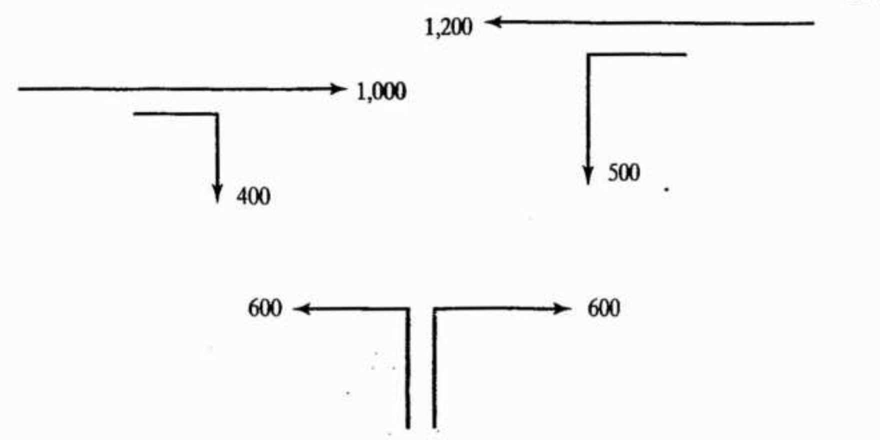


Figure 19.31: Demands for Problem 19-1

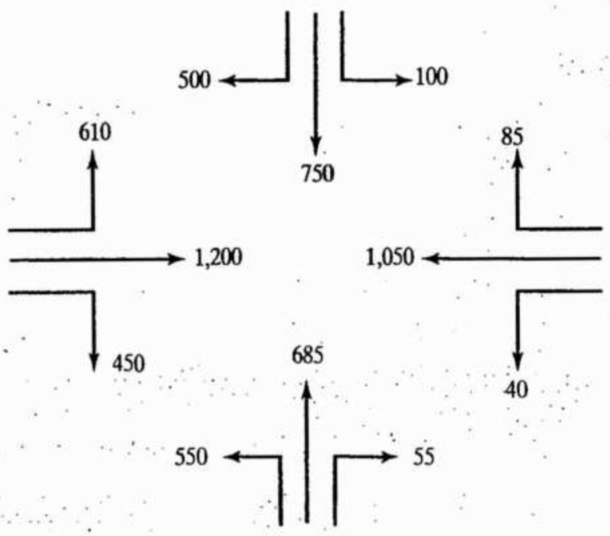


Figure 19.32: Demands for Problem 19-2