Chapter 11

INDIVIDUAL MOVEMENT TREATMENTS

TABLE OF CONTENTS

LIST OF EXHIBITS

11.0 INDIVIDUAL MOVEMENT TREATMENTS

This section identifies treatments for vehicle movements at signalized intersections. This section will start with left- and right-turn lanes, including multiple turning lanes. Relocating or prohibiting movements will be the next treatment discussed. Information related to through lane treatments will follow. Finally, this chapter will cover treatments to be used sparingly, but are available in response to unusually heavy traffic conditions (e.g., variable and reversible lane usage). The treatments in this section primarily address the following safety and operational concerns facing practitioners:

- Choosing appropriate treatment that addresses common crash types at signals.
- Impacts to all users are considered when choosing a treatment.
- An intersection that operates with nominal delay and queuing.

11.1 LEFT-TURN TREATMENTS

This section discusses the key safety, operational, and design characteristics associated with left-turn treatments that range in scope from a single left-turn lane to multiple left-turn lanes.

Left-turning vehicles encounter conflicts from several sources: pedestrians; bicyclists; opposing through traffic; through traffic in the same direction; and crossing traffic. These conflicts can cause angle-, sideswipe, left-turn, and rear-end crashes.

The demand for left-turn movements also affects the amount of green time that is allocated to other traffic movements. Operational treatments may be justified to minimize the amount of green time that is allocated to left-turn movements. This will allow the practitioner to reallocate time to other critical movements.

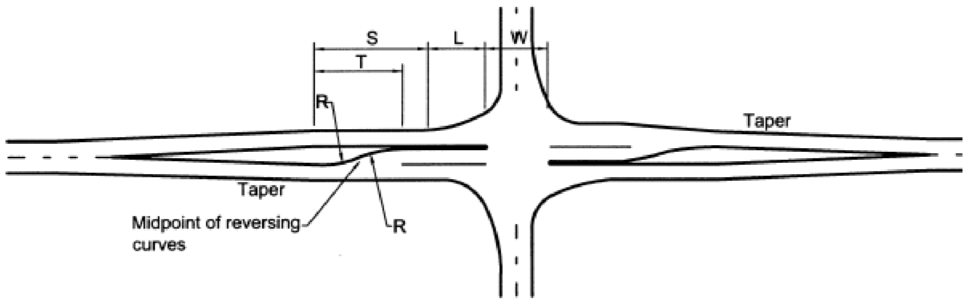
11.1.1 Add Single Left-Turn Lane

Adding a single left-turn lane at an approach that currently has shared through and left-turn movements is one the most common approaches to improve the safety and reduce delay. An example of a typical left-turn lane is shown in Exhibit 11-1. Installing a left-turn lane on one approach does not necessarily mean that a left-turn lane for the opposing left is necessary. If one left-turn lane is installed, the practitioner should ensure that the traveling path of through traffic transitions through the signal into the correct lane

Left-turning vehicles stopped in traffic while waiting for a gap in opposing traffic are prone to rear-end crashes. Separate left-turn lanes provide a refuge while waiting for a gap. Reviewing the crash history collision diagrams or the results of a traffic conflict study can provide the basis for adding a left-turn lane or changing left-turn phasing. Practitioners should look for a history of rear ends or left-turn crashes on any given approach.

A left-turn lane provides left-turning vehicles space to safely decelerate away from through traffic. Reducing this conflict directly impacts rear end collisions. If practicable, the left-turn lane should be long enough to accommodate most of the deceleration needed to stop at the intersection.

Left-turn lanes can help improve signals' efficiency. Separating through movements from left-turning vehicles can decrease the headway between vehicles and improve the flow rate through the signal for both movements. Different phasing options can be utilized to accommodate fluctuating traffic flow occurring throughout the day. For example, a lagging left turn needed for the morning commuters reverting back to simultaneous lefts for the rest of the day. The practitioner should always consider impacts to non-motorized travel. The typical impact is the additional pavement that pedestrians must cross and the walk time that must be added to signal's timing plan.



L = Storage length
R = Radius of reversing curve
S = Stopping sight distance for a speed of (0.7)(operating speed of highway)
T = Tangent distance required to accommodate reversing curve
W = Minimum distance of 12 m (40 ft)

Exhibit 11-1. Diagram of a single left-turn lane.[181]

Applicability

Review local agencies' adopted guidelines and practices should be reviewed to determine whether left-turn lane warrants are in place for a particular roadway. Key elements to consider when determining whether a left-turn lane is warranted include:

- **Significant intersections.** A left-turn lane should be considered at the intersections of higher class facilities (i.e., arterials and principal arterials) and other public roads equal to a collector or higher classification to accommodate both higher approach speeds and expected growth in traffic volumes.
- **Prevailing approach speeds**. An increase in speed differentials between through and slower-speed left-turning vehicles may lead to an increase in rear-end collisions.
- **Capacity of an intersection.** The addition of a left-turn lane can increase the number of vehicles the intersection can serve.
- **Proportion of approach vehicles turning left**. Higher volumes of left-turn traffic result in increased conflicts and delay to through vehicles.
- **Volumes of opposing through vehicles**. High volumes of opposing vehicles reduce the number of gaps available for a left-turn movement (assuming permissive phasing), thus increasing conflicts and delay with approaching through movements.
- **Design conditions**. A left-turn lane may be needed to improve sight distance.
- **Crash history associated with turning vehicles**. A left-turn lane should be considered if there is a disproportionate amount of collisions involving left-turning vehicles on the approach.

In the absence of site-specific data, the *HCM 2010* indicates the probable need for a left-turn lane if the left-turn volume is greater than 100 vehicles in a peak hour, and the probable need for dual left-turn lanes if the volume exceeds 300 vehicles per hour.[2] The HCM also indicates a left-turn lane should be provided if a left-turn phase is warranted.

Exhibit 11-2 highlights several rule-of-thumb intersection capacities for various scenarios where exclusive left-turn treatments may be required on one or both approaches to an intersection. In general, exclusive left-turn lanes are needed when a left-turn volume is greater than 20 percent of total approach volume or when a left-turn volume is greater than 100 vehicles per hour in peak periods.[48]

Case I: No Exclusive Left-Turn Lanes

Assumed critical signal phases*	2
Left-turn volumes	Critical major approach:** ≤ 125 veh/hr Critical minor approach: ≤ 100 veh/hr

Planning-level capacity (veh/hr), sum of critical approach volumes***		Number of basic lanes,**** major approach		
		2	3	4
Number of basic lanes, minor approach	1	1,700	2,300	—
	2	2,400	3,000	—
	3	—	—	—

Case II: Exclusive Left-Turn Lane on Major Approaches Only

Assumed critical signal phases	3
Left-turn volumes	Critical major approach: 150-350 veh/hr Critical minor approach: ≤ 125 veh/hr

Planning-level capacity (veh/hr), sum of critical approach volumes		Number of basic lanes, major approach		
		2	3	4
Number of basic lanes, minor approach	1	1,600	2,100	2,300
	2	2,100	2,600	2,800
	3	2,700	3,000	3,200

Case III: Exclusive Left-Turn Lane on Both Major and Minor Approaches

Assumed critical signal phases	4
Left-turn volumes	Critical major approach: 150-350 veh/hr Critical minor approach: 150-250 veh/hr

Planning-level capacity (veh/hr), sum of critical approach volumes		Number of basic lanes, major approach		
		2	3	4
Number of basic lanes, minor approach	1	1,500	1,800	2,000
	2	1,900	2,100	2,400
	3	2,200	2,300	2,800

Notes: *Critical signal phases are non-concurrent phases
**A critical approach is the higher of two opposing approaches (assumes same number of lanes)
***Use fraction of capacity for design purposes (e.g., 85 or 90 percent)
****Basic lanes are through lanes, exclusive of turning lanes
Adapted from NCHRP 279, figure 4-11[48]

Exhibit 11-2. Rule-of-thumb intersection capacities assuming various exclusive left-turn treatments.

Key Design Features

Key design elements of an exclusive left-turn lane include: entering taper, storage length, lane width, and offset. Design criteria for left-turn lanes are presented in the AASHTO *A Policy on Geometric Design for Highways and Streets* as well as in the policies of individual highway agencies.[3]

Entering taper. Entering tapers should be designed to: (1) allow vehicles to depart the through travel lane with minimum braking; and (2) provide adequate length to decelerate and join the back of queue. In practice, some deceleration (10 mph) is considered acceptable in the through lane prior to entering the turn lane. An appropriate combination of deceleration and taper length will vary according to the situation at individual intersections. A relatively short taper and a longer deceleration length may be applicable at busier intersections where speeds are slower during peak hours. This allows more storage space during peak hours and reduces the potential for spillover into the adjacent through lane. However, off-peak conditions should be considered when vehicle speeds may be higher, thus requiring a longer deceleration length.

AASHTO indicates a taper rate of 8:1 for 30 mph to 15:1 for 50 mph or greater is common for high-speed roadways. Using a taper that is too short may require a vehicle to stop suddenly, thus increasing the potential for rear-end collisions. Using too long of a taper may result in drivers inadvertently drifting into the left-turn lane, especially if located within a horizontal curve. AASHTO indicates that municipalities and urban counties are increasingly adopting the use of taper lengths such as 100 ft for a single turn lane and 150 ft for a dual turn lane.[3]

Storage length. The length of the left-turn bay should be sufficient to store the number of vehicles likely to accumulate during a critical period so the lane may operate independent of the through lanes. The storage length should be sufficient to prevent vehicles spilling back from the auxiliary lane into the adjacent through lane. Storage length is a function of the cycle length, signal phasing, rate of arrivals and departures, and vehicle mix. As a rule-of-thumb, the left-turn lane should be designed to accommodate one and one-half to two times the average number of vehicle queues per cycle, although methods vary by jurisdiction. The HCM can also be used to estimate queues, as noted in Chapter 7.[2] Traffic models used to develop signal timing can provide an accurate estimate on queue length.

Lane width. Lane width requirements for left-turn lanes are largely based on operational considerations. Generally, lane widths of 12 ft are desirable to maximize traffic flow; however, right-of-way or non-motorized needs may dictate the use of a narrower lane width. For situations where it is not possible to achieve the standard width for a left-turn lane, providing a less-than-ideal lane is likely an improvement over providing no left-turn lane. Lane widths less than 9 ft are not recommended for new design. However, in some very constrained retrofit situations on lower speed roadways, lane widths as low as 8 ft for some left-turning movements may be a better choice than not providing any left-turn lane or having too few left-turn lanes. Achieving more lanes through restriping from 12-ft lanes to narrower lanes should be considered where appropriate.[57],[182] Exhibit 11-3 shows an example from Montgomery County, Maryland, where a narrow left-turn lane has been used effectively.

Exhibit 11-3. Narrow left-turn lanes may be used effectively in retrofit situations.

Offset. A left-turning driver's view of opposing through traffic may be blocked by left-turning vehicles on the opposite approach. When left-turning traffic has a permissive signal phase, this can lead to collisions between vehicles turning left and through vehicles on the opposing approach. In a situation with a negative offset or no offset, left-turning motorists can be blocked by opposing left turners (see Exhibit 11-4(a)). This should be avoided when possible.

The practitioner should consider left-turn lanes with a positive offset that allow drivers to see oncoming traffic without obstruction (see Exhibit 11-4(c)).

This practice helps improve safety and operations of the left-turn movement by improving driver acceptance of gaps in opposing through traffic and eliminating the potential for vehicle path overlap. This is especially true for older drivers who have difficulty judging gaps in front of oncoming vehicles. AASHTO policy recommends that medians wider than 18 ft should have positive offset left-turn lanes. However, providing any amount of offset that moves obstructing vehicles out of the way should be pursued. One method for laterally shifting left-turning vehicles is to narrow the turn-lane width using pavement markings.

Positive offsetting has other benefits. Positive offsetting of left-turn lanes ensures that the turning radii for opposing left-turning vehicles do not overlap each other. This allows these movements to be concurrent phases. Also, positive offsetting of the left-turn lanes can be useful for staged improvements. For example, dual lefts can be built on the major street approach, but cannot be utilized until the minor streets are widened. The outside turn lane is striped out to provide positive offset.

Offset left-turn lanes should remain parallel to the through travel route if practical. Exhibit 11-4 illustrates a positive offset at an intersection.[1]

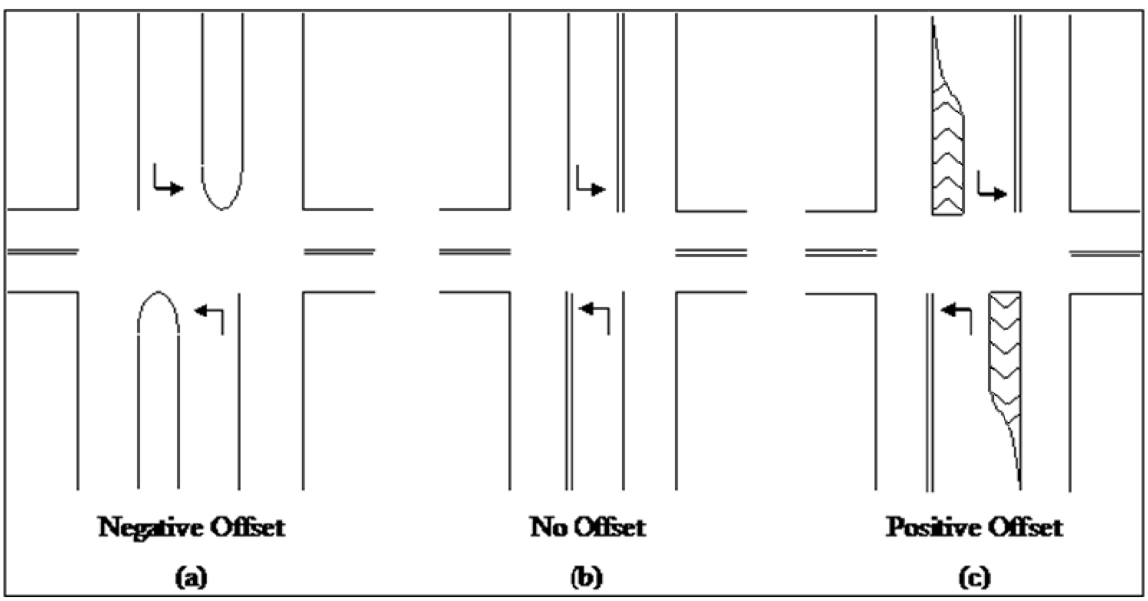


Exhibit 11-4. Illustration of negative, no, and positive offset left-turn lanes. Positive offset is preferred.[183]

Exhibit 11-5. Example of positive offset left-turn lane.

Dropped Lane. In constrained areas, through lanes are sometimes converted to left-turn lanes. This type of lane is sometimes referred to as a "dropped" lane. The traffic control used to alert or raise awareness by the driver in this situation is critical especially at locations with higher speeds or congested areas. For this reason, the MUTCD requires the use of a wide dotted white lane line to distinguish the drop lane from the adjacent through lane (refer to MUTCD Section 3B.04).

Channelization

Physical channelization of left turns emphasizes separation of left-turning vehicles from the through traffic stream. It guides drivers through an intersection approach, increasing capacity and driver comfort.

A left-turn channelization design should incorporate consideration of the design vehicle, roadway cross section, traffic volumes, vehicle speeds, type and location of traffic control, pedestrians, and bus stops. In addition to these design criteria, consideration should be given to the travel path; drivers should not have to sharply change direction in order to follow the channelization. Channelizing devices should not cause drivers to make turns with angles that vary greatly from 90 degrees. If median treatments are used to channelize the left turn, pedestrian needs identified in Chapter 8 should be considered. Additional guidance is provided in the AASHTO policy.(3)

Channelization can be provided using curbed concrete, painted islands, or delineators. The appropriateness of raised or flush medians depends on conditions at a given intersection. Painted channelization provides guidance to drivers without presenting an obstruction in the roadway, and would be more appropriate where vehicles may be proceeding through the intersection at high speeds or where the design vehicle can be better accommodated. However, paint is more difficult to see at night, especially at intersections that are not lighted.

Raised curbed islands should provide guidance in the intersection area but should not present a significant obstruction to vehicles. Safety advantages of left-turn lanes with raised channelization include:

- Turning paths are clearly defined within an expansive median opening.
- Improved visibility for left-turning drivers.
- Simultaneous opposing left-turn lanes are offset from one another.
- Sideswipe collisions due to motorists' changing from left-turn to through lanes or vice versa are prevented.
- Median refuge for pedestrians providing a two stage crossing.
- Median islands can used to control speed across crosswalks.

Raised pavement markings and "flex-post" delineators should be considered when use of raised channelization is not possible.

Operational Features

The type of signal phasing used for a left-turn movement directly affects the safety and operational performance of the turn. The practitioner should always strive to utilize the smallest number of phases. To accomplish this, less-restrictive phasing schemes are preferable where appropriate because these phases result in lower delay to all users of the intersection. However, the responsible agency for the signal's performance should review the operation and safety of the intersection on an annual basis to ensure the intersection is operating within expectations.

Exhibit 11-6 presents suggested guidelines for determining whether left-turn phasing is appropriate, and Exhibit 11-7 presents suggested guidelines for determining the type of left-turn phasing. Current signal equipment allows practitioners the flexibility to alter timing and phasing throughout the day as conditions warrant. Exhibit 11-8 presents the minimum recommended sight distance for permissive left turns. Note that many agencies have adopted similar guidelines with localized variations to reflect State policy. Examples of deviations include the following:

- Some States have a policy to always use protected-only left-turn phasing where the left-turn movement crosses three lanes, while other States allow the use of permissive phasing or protected-permissive phasing in those situations.
- Some States use values in the criteria that are more conservative than provided here, such as lower crash frequency thresholds for protected-only left-turn phasing.
- Some municipalities (Tucson, AZ; Denver, CO) allow the use of protected-permissive phasing at double left turns, while most States use protected-only phasing for those locations.

Left-turn phasing (protected-permissive, permissive-protected, or protected-only) should be considered if any one of the following criteria is satisfied:

1. A minimum of 2 left-turning vehicles per cycle and the product of opposing and left-turn hourly volumes exceeds the appropriate following value:
   a. Random arrivals (no other traffic signals within 0.5 mi):

      One opposing lane: 45,000 Two opposing lanes: 90,000
   b. Platoon arrivals (other traffic signals within 0.5 mi):

      One opposing lane: 50,000 Two opposing lanes: 100,000
2. The left-turning movement crosses 3 or more lanes of opposing through traffic.
3. The posted speed of opposing traffic exceeds 45 mph.
4. Recent crash history for a 12-month period indicates 5 or more left-turn collisions that could be prevented by the installation of left-turn signals.
5. Sight distances to oncoming traffic are less than the minimum distances in Exhibit 11-7.
6. The intersection has unusual geometric configurations, such as five legs, when an analysis indicates that left-turn or other special traffic signal phases would be appropriate to provide positive direction to the motorist.
7. An opposing left-turn approach has a left-turn signal or meets one or more of the criteria in this table.
8. An engineering study indicates a need for left-turn signals. Items that may be considered include, but are not necessarily limited to, pedestrian volumes, traffic signal progression, freeway interchange design, maneuverability of particular classes of vehicles, and operational requirements unique to preemption systems.

Exhibit 11-6. Guidelines for use of left-turn phasing.[184],[185]

The type of phasing to use can be based on the following criteria:

1. Insignificant number of adequate gaps in opposing traffic to complete a left turn.
2. Permissive left-turn phasing may be considered at sites that do not satisfy any of the left-turn phasing criteria listed in Exhibit 11-6.
3. Protected-permissive left-turn phasing may be considered at sites that satisfy one or more of the left-turn phasing criteria listed in Exhibit 11-6 but do not satisfy the phasing criteria for protected-only phasing (see criterion 4 below). Protected-permissive phasing is not appropriate when left-turn phasing is installed as a result of an accident problem.
4. Permissive-protected left-turn phasing may be considered at sites that satisfy the criteria for protected-permissive phasing and one of the following criteria:
    a. The movement has no opposing left turn (such as at a T-intersection) or the movement is prohibited (such as at a freeway ramp terminal).
    b. A protected-permissive signal display is used that provides the left-turning vehicle with an indication of when the driver must yield to opposing traffic, a flashing yellow arrow, or other such devices.
5. Protected-only left-turn phasing should be considered if any one of the following criteria is satisfied:
    a. A minimum of 2 left-turning vehicles per cycle and the product of opposing and left-turn hourly volumes exceed 130,000-150,000 for one opposing lane or 300,000 for two opposing lanes.
    b. The posted speed of opposing traffic exceeds 45 mph.
    c. Left-turning crashes per approach (including crashes involving pedestrians) equal 4 or more per year, or 6 or more in 2 years, or 8 or more in 3 years.
    d. The left-turning movement crosses three or more lanes of opposing through traffic.
    e. Multiple left-turn lanes are provided.
    f. Sight distances to oncoming traffic are less than the minimum distances in Exhibit 11-8.
    g. The signal is located in a traffic signal system that may require the use of lead-lag left-turn phasing. This criterion does not apply if:
        i. An analysis indicates lead-lag phasing is not needed.
        ii. An analysis indicates that protected-permissive phasing reduces total delay more than lead-lag phasing.
        iii. A protected-permissive signal display is used that allows a permissive left turn to operate safely opposite a lagging protected left-turn phase (see Chapter 2 for discussion of left-turn trap).
    h. An engineering study indicates a need for left-turn signals. Items that may be considered include, but are not necessarily limited to, pedestrian volumes, traffic signal progression, freeway interchange design, maneuverability of particular classes of vehicles, number of older drivers, and operational requirements unique to preemption systems.

Exhibit 11-7. Guidelines for selection of type of left-turn phasing.[184,185]

Design Speed (mph)	Design Intersection Sight Distance for Passenger Cars* (ft)
20	165
25	205
30	245
35	285
40	325
45	365
50	405
55	445
60	490
65	530

* For a passenger car making a left turn from an undivided highway. For other conditions and design vehicles, the time gap should be adjusted and the sight distance recalculated.
Source: Adapted from (3), exhibit 9-67

Exhibit 11-8. Minimum recommended sight distance for allowing permissive left turns.

Safety Performance

The HSM contains information that allows practitioners to quantify the safety impacts of left-turning phasing and/or left-turn lanes. Exhibits 11-9 and 11-10 identify CMFs used to calculate the number of crashes per year. The exhibits show favorable impacts towards safety through the addition of a lane and exclusive left-turn movements.

The presence of a left-turn lane could create situations where vehicles are more likely to off-track. Large trucks and buses are more likely to off-track than passenger cars particularity if short tapers are used to shift through traffic. Off-tracking increases the likelihood of sideswipe and head on crashes between left-turning and adjacent through vehicles and between opposing left-turning vehicles. These impacts to large vehicles can be reduced with proper lengths of tapers and appropriate pavement markings.

In providing left-turn lanes, vehicles in opposing left-turn lanes may block their respective drivers' view of approaching vehicles in the through lanes. This potential problem can be resolved by offsetting the left-turn lanes.

Exhibit 11-9 shows safety benefits of left-turn geometric improvements. All collision modification factors suggest safety improvements associated with providing a left-turn lane at a signalized intersection. Collision types that would particularly benefit from a left-turn lane are rear-end and left-turn collisions. Provision of a left-turn lane in conjunction with protected left-turn phasing would appear to provide the most benefit.

Crash Modification Factor (CMF_{1i}) for Installation of Left-Turn Lanes on Intersection Approaches					
Intersection Type	**Intersection traffic control**	**Number of approaches with left-turn lanes [a]**			
		One approach	**Two approaches**	**Three approaches**	**Four approaches**
3 Approaches	Traffic signal	0.93	0.86	0.80	0.80
4 Approaches	Traffic signal	0.90	0.81	0.73	0.66

Exhibit 11-9. Safety benefits associated with left-turn lane improvements for four approach, urban and suburban intersection.
Source: Highway Safety Manual.[(11)]

Potential Crash Effects of Modifying Left-Turn Phase at Urban Signalized Intersections (8,15,22)

Treatment	**Setting (Intersection Type)**	**Traffic Volume AADT (veh/day)**	**Crash Type (Severity)**	**CMF**	**Std. Error**
Change to protected phasing (8,15)	Urban (Four- and three-leg signalized)	Unspecified	Left-turn crashes on treated approach (All severities)	**0.01***	**0.01**
			All types (All severities)	**0.94***+	**0.1**
Change from permissive to protected/permissive or permissive/protected phasing (15,22)	Urban (Four-leg signalized)	Major road 3,000 to 77,000 and minor road 1 to 45,500	Left-turn (Injury)	**0.84**	**0.02**
Change from permissive to protected/permissive or permissive/protected phasing (15)	Urban (Four-leg signalized)	Unspecified	All types (All severities)	0.99	N/A*

Base Condition: For changing to protected phasing, the base condition is permissive, permissive/protected, or protected/permissive phasing. For changing to permissive/protected or protected/permissive phasing, the base condition is permitted phasing.

NOTE: Bold text is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less.
* Observed variability suggests that this treatment could result in an increase, decrease, or no change in crashes. See Part D—Introduction and Applications Guidance.
* Standard error of CMF is unknown.
\+ Combined CMF, see Part D—Introduction and Applications Guidance.

Exhibit 11-10. Crash effects of modifying left-turn phases
Source: Highway Safety Manual (11)

Operational Performance

The addition of a left-turn lane increases capacity for the approach by removing left-turn movements from the through traffic stream. The addition of a left-turn lane may allow for the use of a shorter cycle length or allocation of green time to other critical movements.

The additional pavement width associated with the left-turn lane increases the crossing width for pedestrians and may increase the minimum time required for pedestrians to cross. In addition, the wider roadway section likely will increase the amount of clearance time required for the minor street approach. Restriping the roadway with narrower lanes can minimize this problem.

If a left-turn lane is excessively long, through drivers may enter the lane by mistake without realizing it is a left-turn lane. Effective signing and marking of the upstream end of the left-turn lane should remedy this problem.

Practitioners considering adding protected left turn phasing should evaluate the impacts to other movements at the intersection. Other movements may experience increases in queue lengths, and stopped approach delay for all users. Impacts to coordination also should be evaluated prior to implementation of additional left turn phasing.

Multimodal Impacts

For cases where widening is required to add a left-turn lane, the pedestrians will need to walk further to cross the street increasing the conflict between vehicles and pedestrians. Consider pedestrian refuges (along with push buttons) for wide roadway sections (approximately 75 ft).(186)

Practitioners should consider the volumes of truck and bus traffic using the lane in the design of a left-turn lane.

Physical Impacts

Adding a left-turn lane will increase the footprint of the intersection if no median is currently present, except when the approach is restriped with narrower lanes. The approach to the intersection will be wider to accommodate the auxiliary lane.

Designers should also use caution when considering restriping a shoulder to provide or lengthen a left-turn lane. Part of the safety benefits of installing the turn lane may be lost due to a loss of shoulder, less proximity to roadside objects, and a reduction in intersection sight distance. In addition, the shoulder may not have been designed and constructed to a depth that will support considerable traffic volumes and may require costly reconstruction.

Socioeconomic Impacts

The potential reduction in travel time and in vehicle emissions is a benefit of left-turn lanes. A certain degree of comfort is provided to drivers when they are able to wait to turn outside of the through traffic stream, since they are not delaying other vehicles and can wait for a comfortable gap.

The cost of construction and the accompanying signing, striping, and additional signal equipment are one of the main economic disadvantages to installing a left-turn lane. Also, access to properties adjacent to the intersection approach may need to be restricted when a left-turn lane is installed.

Enforcement, Education, and Maintenance

Given that left-turn lanes are common at signalized intersections, no education should be needed to prepare drivers for installation of a lane at an intersection.

Maintenance issues for left-turn lanes and phasing will be the same as for other areas of the intersection. Pavement markings, signs, and indications should be kept visible and legible. Pavement skid resistance should be maintained. Detection systems should be checked for any call failures. In addition, ongoing reviews through intersection counts, observations, and periodic checks of performance goals related to crashes, delay, and network compatibility are needed.

Summary

Exhibit 11-11 provides a summary of the issues associated with left-turn lanes.

Characteristic	Potential Benefits	Potential Concerns
Safety	Separation of left-turn vehicles from though movements.	Increased pedestrian exposure.
Operations	Additional capacity. Potential for shorter cycle lengths and/or allocation of green to other movements.	Spillback; inadequacy of design.
Multimodal	Left-turn lane may result in shorter pedestrian delays due to shorter cycle length.	Depending on design, may result in longer crossing time and exposure for pedestrians.
Physical	None identified.	Increased intersection size. *
Socioeconomic	Travel time reduced. Vehicle emissions reduced.	Right-of-way and construction costs. *
Enforcement, Education, and Maintenance	None identified.	None identified. Adding signals without funding adjustment reduces ability to properly maintain all intersections.

* Applies to situations where the left-turn lane is added by physical widening rather than restriping.

Exhibit 11-11. Summary of issues for left-turn lanes.

11.1.2 Multiple Left-Turn Lanes

Multiple left-turn lanes are widely used at signalized intersections where traffic volumes have increased to the point that signal timing cannot alleviate excessive queues and delay with the current number of lanes.

Multiple left-turn lanes allow for the allocation of green time to other critical movements or utilize a shorter cycle length. Using multiple left-turn lanes helps reduce the queue waiting to turn left; the practitioner will need to estimate how many vehicles may be in each lane. Rarely will there be an even distribution among the turn lanes, which can dramatically impact the signal timing.

Applicability

Double and triple left-turn lanes are appropriate at intersections with high left-turn volumes that cannot be adequately served in a single lane. As a rule-of-thumb, consider dual left-turn lanes when left-turn volumes exceed 300 vehicles per hour (assuming moderate levels of opposing through traffic and adjacent street traffic). A left-turn demand exceeding 600 vehicles per hour indicates a triple left-turn may be appropriate. Lane distribution for triple lefts is critical to operational success. (187)

While effective in improving intersection capacity, double or triple lefts are not appropriate where:

- A high number of vehicle-pedestrian conflicts occur.
- Left-turning vehicles are not expected to evenly distribute themselves among the lanes.
- Channelization may be obscured.
- Sufficient right-of-way is not available to provide for the design vehicle.
- Other alternative intersections may be a more appropriate option.
- An insufficient number of departure lanes exist.

Design Features

The design of multiple left-turn lanes is similar to that of single turn lanes. In addition, the interaction between vehicles in adjacent lanes and also the width of the receiving lanes should be considered. The following are design considerations for triple left-turn lanes provided by Ackeret.[188] These same considerations apply for double left-turn lanes:

- Widths of receiving lanes.
- Width of intersection (to accommodate three vehicles abreast).
- Clearance between opposing left-turn movements during concurrent maneuvers.
- Pavement marking and signing visibility.
- Placement of stop lines for left-turning and through vehicles.
- Weaving movements downstream of turn.
- Potential for pedestrian conflict.

The previous section provided criteria for selecting the type of signal phasing to be used. In general, protected-only left-turn phasing is used for most double-lane and triple-lane left-turn movements, although some agencies have used protected-permissive phasing for double left turns.

Operational Features

Drivers may be confused when attempting to determine their proper turn path on an approach with multiple left-turn lanes. Providing positive guidance for the driver in the form of pavement markings can help eliminate driver confusion and eliminate vehicle conflict by channeling vehicles in their proper turn path.

Delineation of turn paths is especially useful to drivers making simultaneous opposing left turns, as well as in some cases where drivers turn right when a clear path is not readily apparent. This strategy is also appropriate when the roadway alignment may be confusing or unexpected.

Delineation of turn paths is expected to improve intersection safety, though the effectiveness has not been well evaluated. The additional guidance in the intersection will help separate vehicles making opposing left turns, as well as vehicles turning in adjacent turn lanes.

Additional operational features of dual and triple left-turn lanes are identified below.

- Prominent and well-placed signing, located over each lane if feasible, should be used with triple left-turn movements, especially in advance of the intersection. The signing will help maximize the benefits of triple lefts. Lane distribution for triple left-turn lanes should be estimated as close as possible. Practitioners should reevaluate marking and signing immediately after the triple lefts are constructed for any necessary adjustments.
- The excess green time for left-turn movements resulting from the additional lane should be allocated to other critical movements or removed from the entire cycle to reduce the cycle length.
- Triple left turns should not include a permissive phase; they should be protected only at all times of day.

Safety Performance

A literature review shows that dual left-turn lanes with protected-only phasing generally operate with minimal negative safety impacts. Common crash types in multiple turn lanes are sideswipes between vehicles in the turn lanes. Turn path delineation guides drivers through their lane and can help reduce sideswipes at left-turn maneuvers.

A study of double and triple left-turn lanes in Las Vegas, NV, showed that about 8 percent of intersection-related sideswipes occur at double lefts, and 50 percent at triple lefts.[189] These sideswipes are 1.4 and 9.2 percent of all crashes at the intersections with double and triple lefts, respectively. Turn path geometry and elimination of downstream bottlenecks are important considerations for reducing sideswipes.

One study indicates that triple left-turn lanes have been shown to operate well, and drivers do not have trouble understanding the triple left turns.(190) In addition, construction of triple left-turn lanes has not resulted in unexpected or unacceptable crash experiences. Another study showed that 10 percent of the crashes at intersections with triple lefts occurred in the approach for the triple left. These are angle crashes that occur when left-turning vehicles collide with through traffic on the cross street. These crashes are attributed to short change and clearance intervals and limited sight distance, not operation of the triple left.

Exhibit 11-12 presents selected findings of the safety benefits of multiple left-turn lanes.

Treatment	Finding
Double left-turn lane.(163)	29 percent estimated reduction in all fatal/injury collisions. 26 percent estimated reduction in all PDO collisions. 29 percent estimated reduction in fatal/injury rear-end collisions. 47 percent estimated reduction in fatal/injury left-turn collisions. 20 percent estimated reduction in angle fatal/injury collisions.
Triple left –turn lanes.	Texas study found triple lefts did not raise any major safety issues.

Exhibit 11-12. Safety benefits associated with double left-turn lanes: selected findings.

Operational Performance

Multiple left-turn lanes can improve intersection operations by reducing the time allocated to the signal phase for the left-turn movement. Triple left-turn lanes have been constructed to meet the left-turn capacity demand without having to construct an interchange. This configuration can accommodate left-turn volumes of more than 600 vehicles per hour. Vehicle delays, intersection queues, and green time for the left-turn movement are all reduced, improving operation of the entire intersection.

To achieve this level of performance, these turning movements should still be serviced through normal phasing sequences. If these turns require split-phasing and/or independent phasing, the advantages mentioned in the previous paragraph will not be long term. Evaluation of the signal timing necessary for the triple left-using traffic software and simulation is key to a successful implementation of multiple left-turn lanes. The practitioner may need to compare triple lefts with other alternative intersection designs.

While dual left-turn lanes are largely operated with protected-only phasing, some agencies use protected-permissive signal phasing. This signal phasing improves capacity for the left-turn movements, particularly during nonpeak times when opposing traffic volumes are lower. Many agencies have safety concerns regarding permissive left-turns in a double turn lane. In fact, many agencies only allow dual left-turn lanes to be run as protected-only phasing. However, some agencies overcome this concern by offsetting the dual left-turn lanes.

Multimodal Impacts

Adding turn lanes increases the crossing distance for pedestrians, as well as their exposure to potential conflicts if roadway widening is required. One method to mitigate this exposure is the use of median refuge islands for pedestrians. The islands reduce the walking distance and provide safe areas for pedestrians and bicyclists to wait. These refuge islands also allow for a two stage crossing.

Physical Impacts

Installation of a second or third turn lane will increase the footprint of the intersection, except when additional lanes can be accommodated through restriping. As with single left-turn lanes, practitioners should consider right-of-way costs and access to adjacent properties.

Socioeconomic Impacts

A shorter green time for left-turning vehicles, made possible by multiple turn lanes, can provide more green time to other movements. As this reduces delay, it will also reduce vehicle emissions.

Enforcement, Education, and Maintenance

Little or no education should be needed for multiple left-turn lanes that operate with protected-only or split phasing other than lane assignment signing and markings. Some public information may be needed to educate drivers regarding a permissive movement at a double left-turn lane.

Summary

Exhibit 11-13 summarizes the issues associated with multiple left-turn lanes.

Characteristic	Potential Benefits	Potential Concerns
Safety	Potential reduction in collisions.	Permissive phasing can increase the opportunity for left turn crashes.
Operations	Potential improvement in capacity.	Unbalanced lane utilization.
Multimodal	None identified	Longer crossing distance and more exposure.
Physical	None identified.	Multiple turn lanes may increase the footprint of the intersection.
Socioeconomic	Potential reduction in vehicle emissions due to lower delay.	None identified.
Enforcement, Education, and Maintenance	None identified.	Maintaining more equipment, pavement, marking, signing. Enforcement of triple lefts may be an issue.

Exhibit 11-13. Summary of issues for multiple left-turn lanes.

11.2 RIGHT-TURN TREATMENTS

The purpose of this section is to highlight what strategies are available to practitioners for right-turning movements. Significant volumes of right-turning vehicles can adversely impact the operations and safety of a signalized intersection. Typical improvements used to offset these adverse impacts range from channelizing islands to right-turn lanes. This section will move from lower to higher impact improvements related to additional property.

Practitioners should consider phasing overlaps for right-turning movements. The ability to share green time with compatible movements at the intersection can reduce the need for some of the following treatments.[(187)]

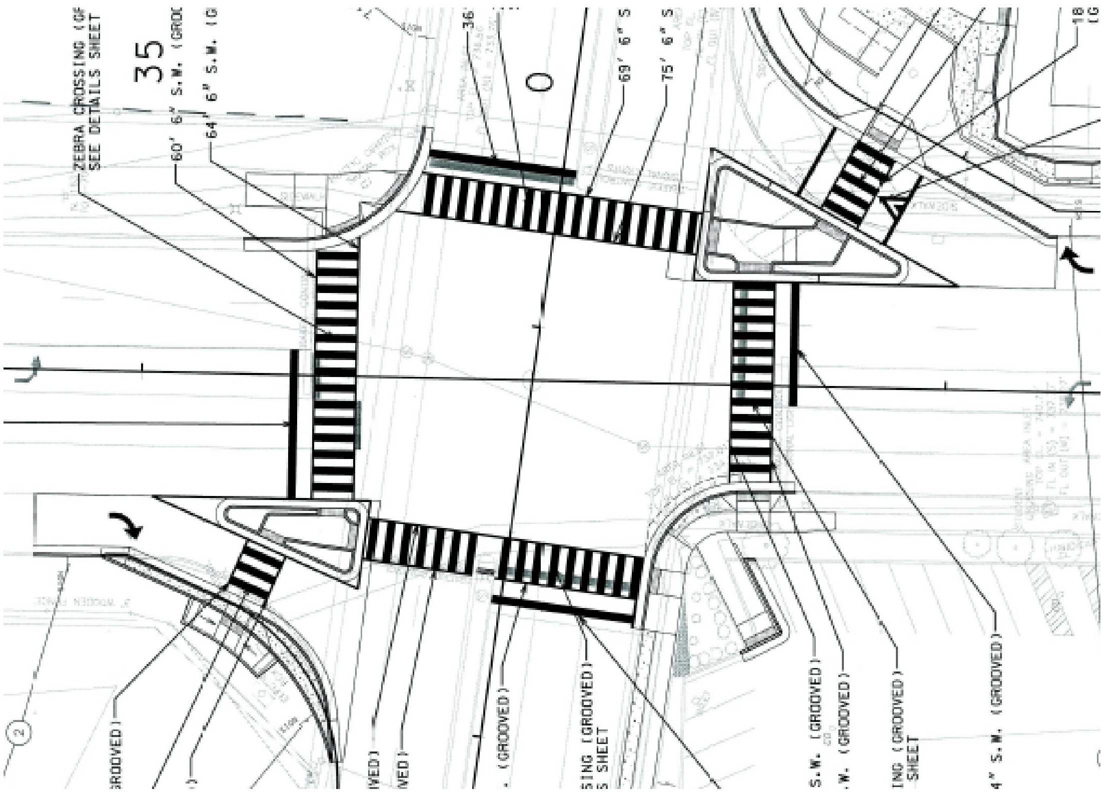
11.2.1 Channelizing Islands

Channelizing islands that physically separate through and right-turning movements are constructed to improve the operations and/or safety of an intersection. These islands can be constructed as standalone improvements or built in combination with a right-turn lane.

Applicability

Channelization of the right turn with a raised or painted island can provide larger turning radii to accommodate large design vehicles. A larger turning radius also allows higher turning speeds. These higher speeds help increase the efficiency of the right-turning vehicles. The island allows some queuing of through traffic and provides access for right-turning vehicles to travel through the intersection.

Agencies increasingly install raised channelized islands to provide an area for pedestrian refuge. Crosswalks with long crossing distances can be reduced somewhat by providing these islands.



(11-14a) (a. City of Columbia, MO)

Exhibit 11-14. Channelized islands.

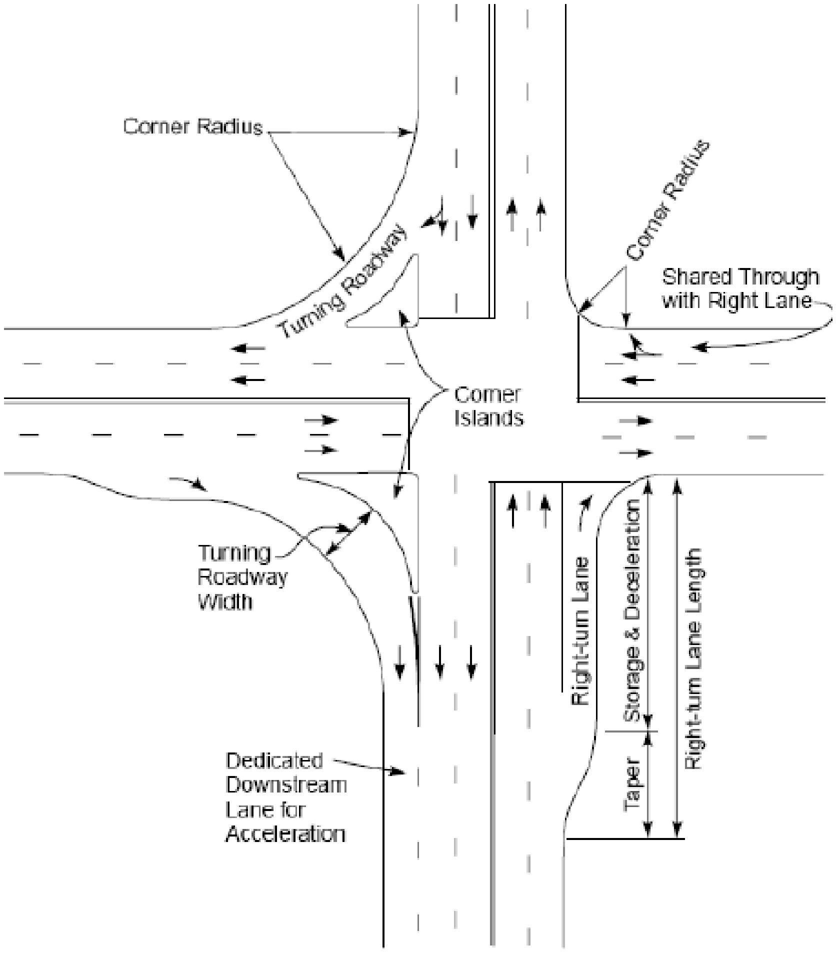


Figure 2-20. Right-Turn Lane and Right Turning Roadway Examples.
Source: Fitzpatrick and Schneider (2004)

(11-14b) [200]

Exhibit 11-14. Channelized islands (cont'd).

Key Design Features

Channelizing islands can be raised or flush with the pavement. A Georgia study evaluated the effects of right-turn channelization in the form of painted islands, small raised islands, and large raised islands.[191] Results show that traffic islands appear to reduce the number of right-turn angle crashes, and the addition of an exclusive turn lane appears to correspond to an increased number of sideswipe crashes given the introduction of a lane change.

Raised channelized islands using simple curves find high incidences of rear-end and pedestrian crashes. As driver's focus to their left anticipating on-coming traffic, they lose sight of the vehicle they were following who chooses to yield. To aid driver's line of sight while turning right, an "Australian" right is used. A large radius allows a right turn vehicle to maneuver by the island, but allows viewing all of the details in front of them.

Exhibit 11-15 illustrates a channelized right-turn lane.

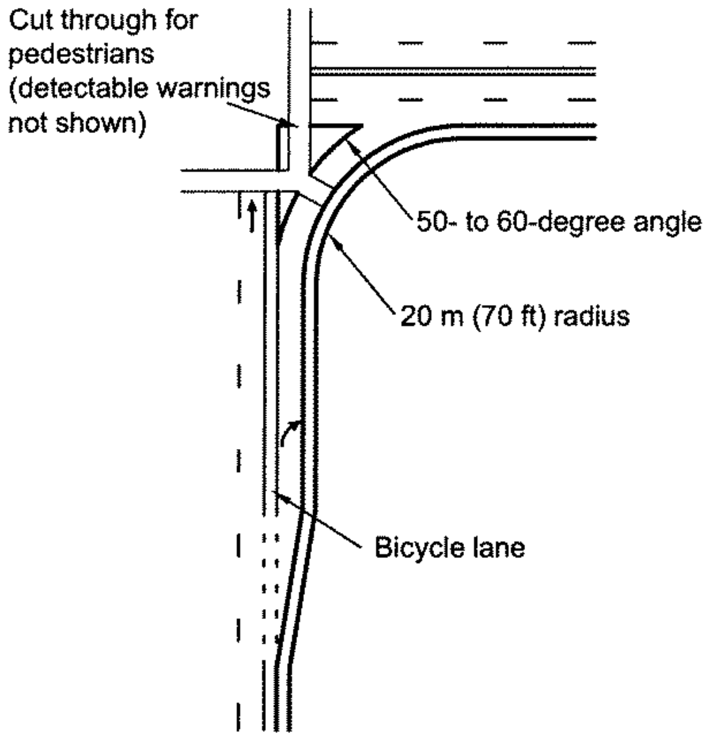


Exhibit 11-15. Example illustration of a channelized right-turn lane.

Channelized right-turn lanes apply for intersections with a high volume of right-turning vehicles that experience excessive delay due to the traffic signal. The larger the turn radius, the higher vehicle speeds can be. An important consideration is the desired speed of the turning vehicles as they enter the crossroad. The turn radius can be used to control speed, especially if the speed varies greatly from the road the vehicle is turning from. Additionally, larger turn radii and higher speeds can pose a pedestrian safety issue.

A channelized right-turn lane will have a larger footprint than an intersection with a conventional right-turn lane. Additional right-of-way may be needed to accommodate the larger corner radius. Constructing a departure auxiliary lane to allow for a downstream merge may also increase right-of-way costs.

Operational Features

The right turn may operate as a free flow movement if an acceleration lane is provided on the cross street, or the movement may be controlled by a YIELD sign where the turning roadway enters the cross street. Periodic enforcement may be needed to ensure drivers obey any traffic control devices used for the right-turn roadway (such as a YIELD sign).

Visibility of channelizing islands is very important. Islands can be difficult for drivers to see, especially at night and in inclement weather. This is particularly true for older drivers. Raised islands have been found to be more effective than flush painted islands at reducing nighttime collisions, because they are easier to see.

Older drivers, in particular, benefit from channelization as it provides a better indication of the proper use of travel lanes at intersections. However, older drivers often find making a right turn without the benefit of an acceleration lane on the crossing street to be particularly difficult.

Safety Performance

A reduction in rear-end collisions involving right-turning vehicles and following through vehicles could be expected after construction of a right-turn roadway. Turning vehicles will not need to decelerate as much as they would for a standard right-turn lane, and therefore the speed differentials between turning and through vehicles would not be as great.

The potential for rear-end and sideswipe crashes on the departure lanes may increase as the vehicles turning onto the crossroad merge with the vehicles already on the road.

Higher speeds and a possibly longer crossing distance and exposure could lead to an increase in crashes involving pedestrians, and the resulting crashes will likely have more serious consequences.

Safety benefits of right-turn channelization are shown in Exhibit 11-16.

Exhibit 11-16. Safety benefits associated with right-turn channelization: selected findings.[200]

Treatment	Finding
Channelization	25 percent decrease in all collisions 50 percent decrease in right-turn collisions

Operational Performance

Through vehicles will experience less delay if right-turning vehicles do not have to decelerate in a through lane. If the volume of right turns is significant enough that the right turn is the critical movement on an approach, provision of a right-turn roadway may increase capacity enough that more green time can be provided for other movements.

Multimodal Impacts

Curbed islands offer a pedestrian refuge. Crossing paths should be clearly delineated, and the island itself should be made as visible as possible to passing motorists.

Right-turn roadways can reduce the safety of pedestrian crossings if an area is not provided for pedestrian refuge. Right-turn roadways increase crossing distances and pedestrian exposure to traffic. Elderly and mobility-impaired pedestrians may have difficulty crossing intersections with large corner radii. Right-turn channelization also makes it more difficult for pedestrians to cross the intersection safely, adequately see oncoming traffic that will turn right, and know where to cross. Proper delineation of the turning roadway may help, particularly at night.

Larger turn radii result in higher vehicle speeds. In areas with significant pedestrian traffic, consideration should be given to minimizing the curb radii while still accommodating the turning path of the design vehicle. Minimizing the curb radii will reduce vehicular turning speeds, minimize pedestrian crossing distances, and reduce the potential severity of vehicle-pedestrian collisions.

Socioeconomic Impacts

Access to adjacent properties may need to be restricted to provide a merge area. Owners of adjacent property should be involved in early discussions regarding the plans.

Summary

Exhibit 11-17 summarizes the issues associated with channelized right-turn lanes.

Characteristics	Potential Benefits	Potential Liabilities
Safety	Separation of decelerating right-turn vehicles.	Potential for sideswipes and rear-end collisions on departure leg. Pedestrian crosswalk design compatibility.
Operations	Higher right-turn capacity. Shorter green time. Less delay for following through vehicles.	None identified. "Australian Right" may not accommodate large vehicles
Multimodal	Pedestrian refuge area.	Longer pedestrian crossing distance and exposure. Higher vehicle speeds.
Physical	Smaller impact than a lane along the right-of-way	Larger intersection footprint.
Socioeconomic	Support a mixed use, walkable community	Right-of-way costs. Access restrictions to property.
Enforcement, Education, and Maintenance	None identified.	Higher maintenance of islands, marking, signing

Exhibit 11-17. Summary of issues for channelized right-turn lanes.

11.2.2 Right-Turn Lanes

Turning vehicles' deceleration creates a speed differential between them and the through vehicles. This can lead to delay for the through vehicles, as well as rear-end crashes involving both movements.

In addition to providing safety benefits for approaching vehicles, right-turn lanes at signalized intersections can reduce vehicular delay and increase intersection capacity.

Exhibit 11-18 illustrates the operational impacts of a right-turn lane.

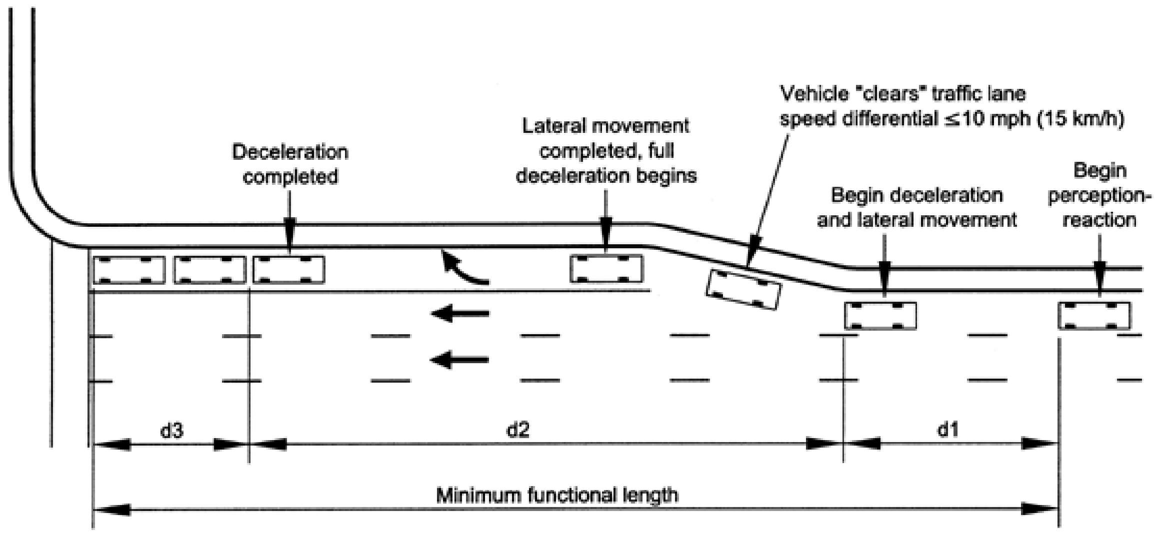


Exhibit 11-18. Diagram of a typical right-turn lane.(adapted from 192)

Right-Turn Lane Warrants

Similar to left-turn lane warrants, review the adopted guidelines and practices from local agencies when determining if a right-turn lane is warranted. Factors to consider include vehicle speeds, turning and through volumes, percentage of trucks, approach capacity, desire to provide right-turn-on-red operation, type of highway, arrangement/frequency of intersections, crash history involving right turns, pedestrian conflicts, and available right-of-way.

NCHRP 279 identifies warrants for right-turn lanes on four-lane, high-speed roadways, shown in Exhibit 11-19.[48] These warrants are based on the percentage of vehicles turning right (as a percentage of through vehicles) during the peak period.

State	Conditions Warranting Right-Turn Lane off Major (Through Highway)		
	Through Volume	Right-Turn Volume	Highway Conditions
Alaska	N/A	DHV = 25 vph	
Idaho	DHV = 200 vph	DHV = 5 vph	2 lanes
Michigan	N/A	ADT = 600 vpd	2 lanes
Minnesota	ADT = 1,500 vpd	All	Design speed > 70 km/h (45 mph)
Utah	DHV = 300 vph	Crossroad ADT = 100 vpd	2 lanes
Virginia	DHV = 500 All DHV = 1,200 vph All	DHV = 40 vph DHV = 120 vph DHV = 40 vph DHV = 90 vph	2 lanes Design speed > 70 km/h (45 mph) 4 lanes
West Virginia	DHV = 500 vph	DHV = 250 vph	Divided highways
Wisconsin	ADT = 2,500 vpd	Crossroad ADT = 1,000 vpd	2 lanes

Notes: DHV = design hourly volume; ADT = average daily traffic; vph = vehicles per hour; vpd = vehicles per day

Exhibit 11-19. Right-turn lane volume warrants.[48]

Design features

The key design criteria for right-turn lanes are: entering taper; deceleration length; storage length; lane width; corner radius; and sight distance. *A Policy on Geometric Design for Highways and Streets* and agencies' policies describe the design criteria for selecting an appropriate right-turn lane length.[3]

Entering taper and deceleration length. Determine the entering taper and deceleration length based on vehicle speed. Design the storage length to accommodate the maximum vehicle queue expected for the movement under design year conditions. From a functional perspective, the entering taper should allow for a right-turning vehicle to decelerate and brake outside of the through traffic lanes. This is particularly important at higher vehicle speeds. In urban areas, this is often difficult to achieve and some deceleration of a turning vehicle is expected in the through travel lane.

Storage length. Make right-turn lanes sufficiently long to store the number of vehicles likely to accumulate during a critical period. The storage length should be sufficient to prevent vehicles from spilling back from the auxiliary lane into the adjacent through lane. At signalized intersections, the storage length required is a function of the cycle length, signal phasing arrangement, and rate of arrivals and departures. As a rule-of-thumb, design the auxiliary lane to accommodate 1.5 to 2 times the average number of vehicle queues per cycle, although methods vary by jurisdiction. See Chapter 7 for additional discussion regarding methodologies for estimating queue lengths/storage requirements.

In some cases, a right-turn lane may already exist, but increased traffic volumes may necessitate lengthening it, which can help improve operations and safety by providing additional storage for right-turning vehicles. If the length of a right-turn lane is inadequate, right-turning vehicles will spill back into the through traffic stream, thus increasing the potential for rear-end collisions. Longer entering tapers and deceleration lengths can reduce this potential.

Lane width. Lane width requirements for right-turn lanes are largely based on operational considerations. Generally, lane widths of 12 ft maximize traffic flow; however, right-of-way or pedestrian needs may dictate use of a narrower lane width. Consider restriping from 12 ft-lanes to narrower lanes in order to create more travel lanes where appropriate.[57] Exhibit 11-20 shows an example from Montgomery County, MD, where a narrow right-turn lane has been used effectively.

Exhibit 11-20. Narrow (8 ft) right-turn lanes may be used effectively in retrofit situations.

Corner Radius. The corner radius influences the turning speed of vehicles. Large corner radii allow vehicles to turn at higher speeds. If low-speed, right-turn movements are desired, particularly in locations where pedestrian crossings occur, the curb radius should be minimized, yet still accommodate the turning path of the design vehicle. Pedestrian crossing distances will be minimized if curb radius is minimized. In addition, lower vehicle speeds can reduce the probability of a crash.

A larger curb radius is appropriate for situations where it is desirable for right-turning vehicles to exit the through traffic stream quickly. The right turn may operate as a free-flow movement if an acceleration lane is provided on the cross street, or the movement may be controlled by a yield sign where the turning roadway enters the cross street.

Increasing the turning radius can reduce the potential for sideswipe or rear-end collisions by reducing lane encroachments as a vehicle approaches a turn and as it enters the cross street. Also, some older drivers and drivers of large vehicles may have difficulty maneuvering; the rear wheels of their vehicles may ride up over the curb or swing out into other lanes where traffic may be present. For situations where a large turning radius is desired, the use of a channelization island may be appropriate to reduce unused pavement area. Unused pavement area contributes to driver confusion regarding the appropriate path through the intersection.

Sight distance. Adequate sight distance should be provided for vehicles in the right-turn lane or channelized right-turn movement. If right turns on red are permitted, drivers turning right should be able to view oncoming traffic from the left on the crossroad.

Safety Performance

Right-turn lanes are often used to preclude the undesirable effects resulting from the deceleration of turning vehicles. ITE's *Transportation and Land Development* indicates that a vehicle traveling on an at-grade arterial at a speed 10 mph slower than the speed of the normal traffic stream is 180 times more likely to be involved in a crash than a vehicle traveling at the normal traffic speed.[89] Right-turn channelization demonstrably reduces right-turn angle crashes. However, the addition of a right-turn lane may result in an increase in sideswipe crashes. From a vehicular operations standpoint, larger curb radii generally result in vehicle turning paths that are in line with the pavement edge. In addition, larger curb radii produce higher vehicle speeds that can negatively impact the safety of pedestrians and bicyclists.

The provision of right-turn lanes minimizes collisions between vehicles turning right and following vehicles, particularly on high-volume and high-speed major roads. A right-turn lane may be appropriate in situations with an unusually high number of rear-end collisions on a particular approach. Installation of a right-turn lane on one major road approach at a signalized intersection is expected to reduce total crashes by 2.5 percent, and crashes are expected to decrease by 5 percent when right-turn lanes are constructed on both major-road approach.[(190)]

Selected findings of safety benefits associated with various right-turn lane improvements are given in Exhibit 11-21.

Crash Modification Factor (CMF_{3i}) for Installation of Right-Turn Lanes on Intersection Approaches

Intersection Type	Intersection traffic control	Number of approaches with right-turn lanes [a]			
		One approach	Two approaches	Three approaches	Four approaches
3 Approaches	Traffic signal	0.96	0.92	--	--
4 Approaches	Traffic signal	0.96	0.92	0.88	0.85

Exhibit 11-21. Safety benefits associated with right-turn improvements.
Source: Highway Safety Manual, Chapter 12.[(11)]

Operational Performance

Right-turn lanes remove decelerating and slower-moving vehicles from the through traffic stream, which reduces delay for following through vehicles. Lin concluded that a right-turn lane may reduce vehicle delays substantially, even with the percentage of right-turns as low as 10 percent.[(193)]

Installation of a right-turn lane can create other safety or operational problems at the intersection. For example, vehicles in the right-turn lane may block the cross street drivers' view of through traffic; a significant issue where right turns on red are permitted on the cross street. If a right shoulder is restriped to provide a turn lane, there may be adverse impacts on safety due to the decrease in distance to roadside objects. Carefully consider delineation of the turn lane to provide adequate guidance through the intersection.

If a right-turn lane is excessively long, through drivers may enter the lane by mistake without realizing it is a right-turn lane. Effective signing and marking the upstream end of the right-turn lane may remedy this.

Also, if access to a right-turn lane is blocked by a queue of through vehicles at a signal, drivers turning right may block the movement of through traffic if the two movements operate on separate phases. This could lead to unsafe lane changes and added delay.

Multimodal Impacts

The speed of turning vehicles is a risk to pedestrian safety.

The addition of a turn lane increases the crossing distance for pedestrians and may require additional time for the pedestrian change (upraised hand) interval phase. Other issues to consider when designing a right-turn lane include potential conflicts between turning vehicles and bicyclists proceeding through the intersection. Also, right-turning drivers from the inside right-turn lane might not see pedestrians in a parallel crosswalk that has a concurrent WALK signal.

Transit stops may have to be relocated from the near side of an intersection, due to possible conflicts between through buses and right-turning vehicles.

Physical Impacts

Addition of a right-turn lane will increase the footprint of the intersection, unless the shoulder is restriped to create a turn lane. The approach to the intersection will be wider to accommodate the auxiliary lane.

Designers should use caution when considering restriping a shoulder to provide or lengthen a right-turn lane. Part of the safety benefits of installing the turn lane may be lost due to loss of shoulder, the greater proximity of traffic to roadside objects, and a possible reduction in intersection sight distance.

Socioeconomic Impacts

Installing or lengthening a right-turn lane on an intersection approach may involve restricting right turns in and out of driveways on that approach. Techniques include signing or construction of a raised median.

The cost of construction (including relocation of signal equipment) and right-of-way acquisition is the main disadvantage to installation of a turn lane. Also, access to properties adjacent to the intersection approach may need to be restricted when a turn lane is installed.

Enforcement, Education, and Maintenance

Periodic enforcement may be needed to prevent red light violations, especially if right turns on red are prohibited.

Right-turn lanes are common, and minimal education should be needed to prepare drivers for their installation. Drivers may need a reminder that they should be watching for pedestrians crossing the departure lanes.

Maintenance issues for right-turn lanes will be the same as for other areas of the intersection. Pavement markings and signs should be kept visible and legible. Pavement skid resistance should be maintained.

Summary

Exhibit 11-22 summarizes the issues associated with right-turn lanes.

Characteristic	Potential Benefits	Potential Liabilities
Safety	Separation of right-turn vehicles.	Higher speed of right-turning vehicles increases risk to pedestrians.
Operations	Higher right-turn capacity. Shorter green time. Less delay for following through vehicles. Additional storage for approach queues.	Potential for off-tracking of large vehicles.
Multimodal	None identified.	Longer pedestrian crossing distance, time, and exposure. May require transit stop relocation.
Physical	None identified.	Larger intersection footprint.
Socioeconomic	None identified.	Right-of-way/construction costs. Access restrictions to property.
Enforcement, Education, and Maintenance	None identified.	Periodic enforcement may be needed to prevent red light violations, especially if right turns on red are prohibited.

Exhibit 11-22. Summary of issues for right-turn lanes.

11.2.3 Provide Double Right-Turn Lanes

High volumes of right-turning vehicles may support double right-turn lanes to increase capacity for the turns and reduce delay for other movements at the intersection. Double right-turn lanes can reduce both the length needed for turn lanes and the green time needed for that movement.

Approaches with right-turn volumes that cannot be accommodated in a single turn lane without excessively long green times (and delays for other approaches) may be appropriate locations for double turn lanes. Also, locations where right-of-way is not available to provide a long turn lane but there is space for two shorter turn lanes may be ideal for double turn lanes. Clearly, multiple turn lanes are not appropriate where only one receiving lane is available; however, consideration may be given to providing a departing auxiliary lane to allow for double right turns with a downstream merge.

As with single right-turn lanes, the design vehicle should be considered when determining length, width, and taper of the turn lane. The receiving lane should accommodate the turning radius of a large vehicle. Delineation of the turn path will guide drivers through the maneuver and help reduce crossing over into adjacent lanes while turning.

Based on the subjective assessment of the authors, the safety experience of double right-turn lanes should be similar to that of single right-turn lanes. Rear-end collisions of decelerating right-turn vehicles and following through vehicles may be reduced after construction of the additional turn lane, because the turn lanes have a higher capacity for the slower vehicles. Even though the double turn lanes increase capacity, some deceleration may occur in the through lanes, depending on the length of the turn lanes. This could lead to rear-end crashes.

Sideswipes between turning vehicles are a possibility at double turn lanes. This is especially an issue if the turn radius is tight and large vehicles are likely to be using the turn lanes. Delineation of turn paths should help address this.

Construction of an additional right-turn lane can be reasonably expected to improve the operation of the intersection, provided that the affected right-turn movement is a critical movement. The additional deceleration and storage space should help prevent spillover into adjacent through lanes. Less green time should be needed for right-turn traffic, and this time thus can be allocated to other movements. However, a double turn lane will result in a wider footprint for the intersection and increase the distance pedestrians must cross, which increases their exposure to potential conflicts with vehicular traffic.

Acquisition of right-of-way to provide an additional turn lane may be expensive. If a departure auxiliary lane is to be constructed to allow for a downstream merge, this may also increase right-of-way costs. Access to adjacent properties may need to be restricted to provide a merge area. Owners of adjacent property should be involved in early discussions regarding the plans.

Lane use signing and signs prohibiting right turns on red from the inside turn lane should convey all the information that drivers would need. In some cases the outside lane will be handled with yield control while the inside right-turn lane is under signal control. Periodic enforcement may be needed to ensure drivers obey any right turn on red prohibitions.

Summary

Exhibit 11-23 summarizes the issues associated with double right-turn lanes.

Characteristics	Potential Benefits	Potential Liabilities
Safety	Separation of right-turn vehicles.	Potential for sideswipes.
Operations	Higher right-turn capacity. Shorter green time. Less delay for following through vehicles.	Off-tracking of large vehicles.
Multimodal	None identified.	Longer pedestrian crossing distance, time, and exposure.
Physical	Potentially shorter intersection footprint than needed for single turn lane.	Wider intersection footprint.
Socioeconomic	None identified.	Right-of-way costs. Access restrictions to property.
Enforcement, Education, and Maintenance	None identified.	None identified.

Exhibit 11-23. Summary of issues for double right-turn lanes.

11.2.4 Restricting Turns, U-Turns

One of the easiest methods to improve the operation of signals is reducing the number of phases or movements. Typically, these restrictions relate to a turning movement; however, any movement like through movements from the minor street could be restricted. Safety and operations at some signalized intersections can be enhanced by restricting turning maneuvers, particularly left turns, during certain periods of the day (such as peak traffic periods) or by prohibiting particular turning movements altogether. Signing or channelization can be implemented to restrict or prohibit turns at intersections.

Prohibiting or restricting left turns should practically eliminate crashes related to the affected turning maneuver. Analyze alternative routes to ensure crash rates and operational problems do not increase due to diversion of traffic to these alternatives. Also, the benefit of restricting turns may be reduced by an increase in accidents related to formation of queues (rear-end collisions).

Restricting right turns on red is a commonly done due to the number of pedestrians crossing at the intersection. Certain vehicles, such as school buses, have policies in place to prohibit drivers from turning right on red. The HSM equation 12-35 calculates a CMF using this formula: $CMF = 0.98^n$, in which n is the number of approaches that have the prohibition.

The key to success is how well the prohibition is communicated through signing, marking, and may require public outreach to inform drivers.

Managing access near signals is often problematic. Adding medians and restricting existing entrances to right in, right out can improve operational efficiency. Providing a U-turn at the signal for access can help offset these restrictions. Note that U-turning vehicles proceed through an intersection at a slower speed than left-turning vehicles and can adversely affect both operations and safety at the intersection. Consider prohibition of U-turns at intersections with high volumes of movement with which U-turns interfere. Slower moving U-turning traffic will reduce the capacity of a left-turn movement. Drivers attempting to make a U-turn during a permitted left-turn phase may interfere with opposing through traffic. Rear-end crashes involving U-turning vehicles followed by left-turning or through vehicles may be a sign of operational problems with the U-turn maneuver.

Consider sight distance limitations. If opposing left-turning vehicles waiting in a turn lane block a U-turning driver's view of oncoming through traffic, prohibition of U-turn (as well as left-turn) maneuvers on a permissive left-turn phase may be appropriate.

Accommodate the turning radius of the design vehicle by a combination of median and receiving lane width. A shorter turn radius will cause slower speeds for U-turning vehicles, and will result in more delay to following vehicles.

One study suggests adjusting for U-turns differently from left-turns when determining saturation flow rates of left-turn lanes, to account for their larger effect on operations.(194)

Summary

Exhibit 11-24 summarizes the issues associated with turn prohibitions.

Characteristic	Potential Benefits	Potential Liabilities
Safety	Potential reduction in collisions.	None identified.
Operations	Potential increase in capacity and reduction in delay due to reduction of the number of phases.	Could adversely affect adjacent intersections.
Multimodal	Fewer conflicts with turning vehicles. Lower delay to all users.	None identified.
Physical	Could reduce the footprint of intersection.	Upkeep of delineators, marking, and islands to restrict movements.
Socioeconomic	Part of a traffic calming measure while enhancing main street efficiency. Reduce emissions.	Impacts from adverse travel.
Enforcement, Education, and Maintenance	None identified.	Enforcement of turn restrictions may be needed.

Exhibit 11-24. Summary of issues for turn prohibitions.

11.2.5 Provide Auxiliary Through Lanes

Adding auxiliary through lanes (i.e., additional through lanes with limited length) at signalized intersections can provide added capacity for through movements. The amount of added capacity achieved depends on the extent to which through vehicles use the auxiliary lane. Various factors (such as the length of the auxiliary lane, turn volumes, and overall operation of the intersection) contribute to how many vehicles will use an auxiliary lane.

Description

Auxiliary lanes are generally provided on the approaches of a signalized intersection in advance of the intersection, reduced downstream of the intersection, or dropped at a subsequent intersection. Right-turn traffic may share the outside lane with a portion of the through vehicles, or there may be a separate exclusive right-turn lane. The auxiliary lane may also serve as an acceleration lane for vehicles turning right from the adjacent approach. Exhibit 11-25 illustrates an auxiliary through lane.

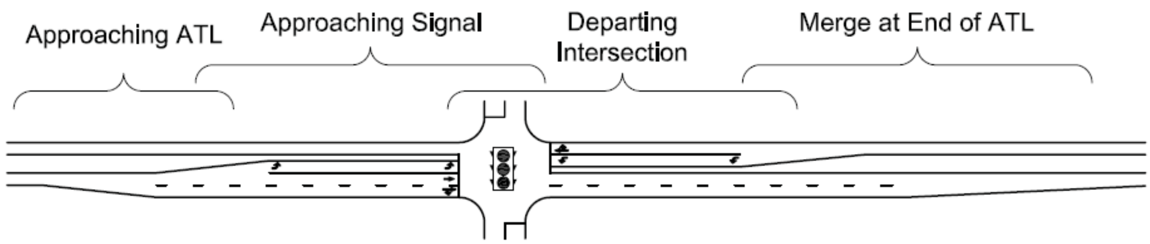


Exhibit 11-25. Diagram of an auxiliary through lane.
Source: NCHRP Report 707.[195]

Applicability

Auxiliary through lanes are applicable for arterials that have adequate capacity along midblock segments but require additional capacity at signalized intersection locations. The full benefit of an auxiliary through lane will not be realized if a bottleneck or constraint exists on the arterial upstream or downstream of the intersection.

Design Features

The length of the auxiliary through lane on both sides of an intersection helps determine whether the lane will be used; longer lanes get more use by through vehicles than do shorter ones. Ideally, the lane should be of sufficient length to allow a smooth merge once the lane is reduced.

Clearly communicating when the lane will end also determines how well the auxiliary lane will be used.[196] The reduction of the auxiliary lane downstream should be signed and marked according to the MUTCD.[1] If not properly signed and marked, motorists can become trapped near the end of the reduced lane, without advance notice of the reduction. Therefore, pay particular attention should be made to discontinuing the lane line at the ¾d distance from the end of the full width lane (see MUTCD Figure 3B-14). Note that "d", placement of the warning sign, is found in MUTCD Table 2C-4.

Operational Features

Unless a separate right-turn lane is provided, both through and right-turning vehicles may use the additional lane. More vehicles are likely to use the auxiliary through lane if there is not adequate green time to clear the signal from the inside through lane. Using relatively short green times for the approach will clear vehicle queues and likely result in a higher utilization of the outside auxiliary through lane due to compressed gaps in the through movement.

Safety Performance

Based on the subjective assessment of the authors, the safety experience of an intersection with auxiliary through lanes should not significantly differ from conventional intersections without the additional lane. The downstream merge maneuver this design requires may lead to an increase in merge-related collisions (sideswipes), but studies have not evaluated this.

Again, the length of the auxiliary through lane impacts the safety of the intersection. Drivers not comfortable with an auxiliary lane will stay in the through lane. No reduction in rear end crashes at the signal should be expected. Right-turning vehicles off the minor street may conflict with the vehicles on the main street using the auxiliary lane. The right-turning vehicles may use the auxiliary lane as an acceleration lane and not properly yield to the major street. This could lead to right turn, right angle crashes or right turn rear end crashes.

NCHRP 707 lists the following elements as critical to its safe operation:[195]

- Downstream length should be sufficient to allow enough acceleration to merge back into through movement easily.

- Access control is necessary to reduce the number of conflicting movements along the lane.
- Sight distance should be adequate to view all signing, marking, merge area, and judge traffic flow.
- Queuing downstream of the auxiliary through lane merge should be prevented if possible from bottlenecks.
- Taper design should match AASHTO Green Book standards.
- Signing, marking, and lighting of the auxiliary through lane should be in accordance with MUTCD guidelines, should be clear and concise, and should accommodate nighttime operations.

Operational Performance

NCHRP 707 contains a step by step procedure to estimate the usage of a proposed auxiliary lane. This example is for the additional of a single auxiliary lane adjacent to a single, continuous through lane.[195]

$$X_T = \frac{V_T}{S_T \times \frac{g}{C}}$$

where: V_T = 15 - minute through - movement demand flow rate on the approach, expressed in vehicles per hour;

S_T = A adjusted through saturation flow rate per lane on the approach, in vehicles per hour;

g = Effective green time for the approach, in seconds; and

C = Intersection cycle length, in seconds.

$$V_{ATL} = 20.226 + 81.791 \times X_T^2 + 1.65 \times \frac{V_T^2}{10{,}000}$$

where: V_{ATL} = The predicted through movement flow rate in the auxiliary through lane (in vehicles per hour), and all other variables are as previously defined.

Remaining volume traveling in the continuous through lanes is $V_{CTL} = V_T - V_{ATL}$.

Multimodal Impacts

Wider intersections result in longer crossing times for pedestrians and bicyclists, as well as increased exposure to vehicle conflicts.

Physical Impacts

Adding an auxiliary through lane will increase the footprint of the intersection if no median is currently present. The approach to the intersection will be wider to accommodate the auxiliary lane.

Socioeconomic Impacts

Driver perception of the benefits of the auxiliary through lane will determine how often the lane is used by through vehicles. If right-turn volumes are high enough that drivers do not benefit from using the lane, capacity of the through movement will not improve significantly.

The cost of construction and the accompanying signing and striping are among the main economic disadvantages to installation of an auxiliary lane. Also, access to properties adjacent to the intersection approach should be restricted when another lane is constructed. Property owners affected by the restrictions, especially business owners, may be opposed to the auxiliary lanes.

Enforcement, Education, and Maintenance

Auxiliary through lanes do not present any special enforcement issues.

No public education should be needed to inform drivers how to proceed through the intersection. Only critical, location-specific signs should be located within the downstream auxiliary through lane area due to the merge and reduction demand on the driver. Markings and signing for lane use and arrangement are generally sufficient upstream, and lane reduction signing and markings are sufficient downstream.

Maintenance issues for through auxiliary lanes will be the same as for other areas of the intersection. Pavement markings and signs should be kept visible and legible.

Summary

Exhibit 11-26 summarizes the issues associated with auxiliary through lanes.

Characteristic	Potential Benefits	Potential Liabilities
Safety	May reduce rear-end crashes due to improved signal operation.	Potential for sideswipes downstream of merge. Right-turn crashes with minor street.
Operations	Decreased delay for through vehicles.	Improper use of auxiliary lane downstream; under use of auxiliary lane upstream.
Multimodal	Reduces queues may decrease overall cycle length	Longer pedestrian crossing time and exposure.
Physical	None identified.	Larger intersection footprint.
Socioeconomic	None identified.	Construction costs. Driver perception of delay. Access to properties.
Enforcement, Education, and Maintenance	None identified	Enforcement responding to crashes from rear ends and side swipes. Right-turning drivers not yielding to through movement.

Exhibit 11-26. Summary of issues for auxiliary through lanes.

11.2.6 Delineate Through Path

At complex intersections where the correct path through the intersection may not be immediately evident to drivers, pavement markings may be needed to provide additional guidance. The same markings are used to delineate turning paths through intersections for multiple turn lanes. These markings are a continuation of the longitudinal lane stripes, but have a different stripe and skip pattern. An example of these markings is given in Exhibit 11-27.

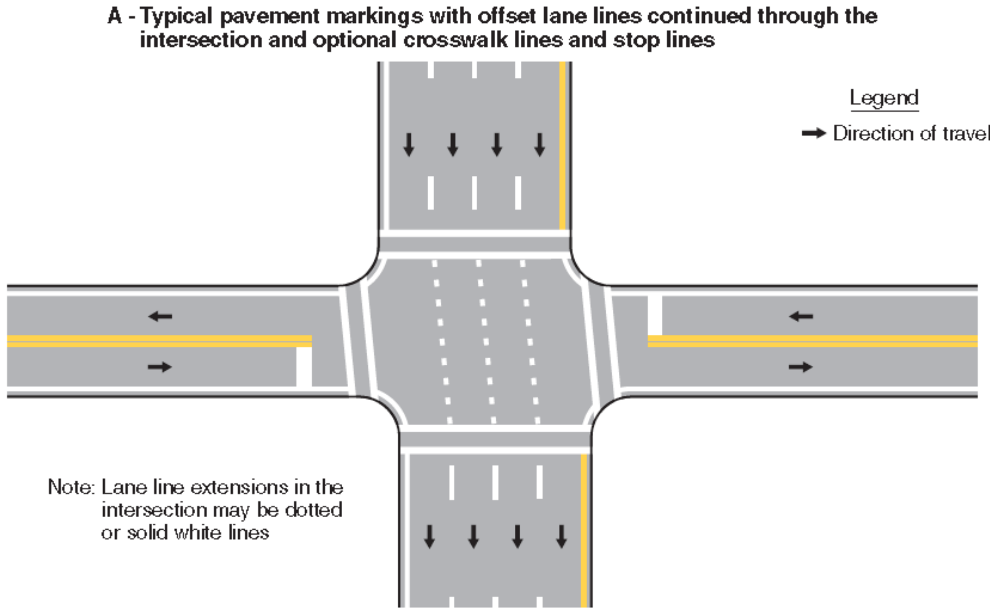


Exhibit 11-27. Example of delineated paths.
Source: MUTCD 2009 Fig 3B-13.[1]

Intersections where through vehicles cannot proceed through the intersection in a straight line may benefit from pavement markings that guide drivers along the appropriate path. Skewed intersections, intersections where opposing approaches are offset, and multi-leg intersections may all present situations where additional guidance can improve safety and operations.

Delineating the through path should help reduce driver confusion in the intersection, which will reduce erratic movements as drivers steer into or out of the appropriate path. This would reduce the potential for sideswipe, rear-end, and head-on crashes.

Pavement markings through the intersection should account for off-tracking of large (design) vehicles. The markings should be spaced far enough apart to allow off-tracking without crossing over the markings.

The cost of installing and maintaining the pavement markings should be the only costs of this treatment, and should be similar to that of other pavement markings on the approaches.

Summary

Exhibit 11-28 summarizes the issues associated with path delineation.

Characteristic	Potential Benefits	Potential Liabilities
Safety	Fewer erratic maneuvers.	None identified.
Operations	Fewer erratic maneuvers.	None identified.
Multimodal	None identified.	Potential off-tracking of large vehicles.
Physical	None identified.	Installation costs.
Socioeconomic	None identified.	Maintenance costs.
Enforcement, Education, and Maintenance	None identified.	None identified.

Exhibit 11-28. Summary of issues for path delineation.

11.3 VARIABLE LANE USE TREATMENTS

11.3.1 Provide Reversible Lanes

Reversible lanes increase capacity without additional widening when flows during peak periods are highly directional. These peak periods could be regular occurrences, as with normal weekday morning and evening peak traffic, or with special events, as with roadways near major sporting venues. Reversible lanes often extend for a considerable length of an arterial through multiple signalized intersections.

According to the MUTCD, reversible lanes are governed by signs (Section 2B.25) and/or the following lane use control signals (section 4J.02): [1]

- DOWNWARD GREEN ARROW.
- YELLOW X.
- WHITE TWO-WAY LEFT-TURN ARROW.
- WHITE ONE-WAY LEFT-TURN ARROW.
- RED X.

At least three sources provide good information on the implementation of reversible lanes. First, the MUTCD provides guidance on the allowable applications of these lane use control signs and signals, as well as when lane use signals should be used instead of signs. Second, the *Traffic Control Devices Handbook* provides additional information on signal control transition logic that can be used when reversing the directional flow of a lane or changing a lane to or from two-way left-turn operation.[68] Third, the *Traffic Safety Toolbox* provides further discussion on planning and implementation considerations, in addition to a discussion of the effects on capacity and safety.[10]

Safety Performance

Reversible lanes help reduce congestion and likely reduce rear-end collisions. As reported in the *Traffic Safety Toolbox*, "Studies of a variety of locations where reversible lanes have been implemented have found no unusual problem with head-on collisions compared to other urban facilities. Typically, the reversible lanes will have either no effect on safety conditions or will achieve small but statistically significant reductions in accident rates on the facility." [10, p. 130]

Reversible lanes may preclude the use of median treatments as an access- management technique along an arterial street.

Operational Performance

Reversible lanes directly benefit operational performance by allowing better matching of the available right-of-way to peak direction demands.

Multimodal Impacts

The operation of a reversible lane precludes the use of a fixed median to physically separate opposing travel directions. Therefore, reversible lane operation precludes the use of medians as a refuge area for pedestrians, thus requiring pedestrians to cross the arterial in one stage.

Physical Impacts

Reversible lanes may postpone or eliminate the need to widen a facility.

Socioeconomic Impacts

Reversible lanes are a relatively low-cost treatment compared to the cost of physically widening a facility. This type of facility may not be viewed as conducive to the type of development along the route.

Summary

Exhibit 11-29 summarizes of the issues associated with reversible lanes.

Characteristics	Potential Benefits	Potential Concerns
Safety	Typically achieves small but statistically significant accident reductions due to reduced congestion.	May preclude access management techniques.
Operations	Provides additional capacity to accommodate peak direction flows.	Potential confusion by drivers during off peak times.
Multimodal	None identified.	Reversible lanes may prevent the use of median pedestrian refuges.
Physical	May postpone or eliminate the need to widen a facility.	None identified.
Socioeconomic	Relatively low cost.	May not be compatible with adjacent property uses.
Enforcement, Education, and Maintenance	None identified.	New treatment to the area would require some communication.

Exhibit 11-29. Summary of issues for reversible lanes.

11.3.2 Provide Variable Lane Use Assignments

The concept of variable lane use treatments at signalized intersections is similar to that of the reversible lane but is typically applied locally to a single intersection. Variable treatments change individual lane assignments at a signalized intersection by time of day and thus can be used to accommodate turning movements with highly directional peaking characteristics.

Issues to consider when implementing variable lane use assignments include: [57]

- Adequate turning radius for the number of turning lanes intended during each mode of operation.
- Adequate receiving lanes for each mode of operation.
- Compatible signal phasing to accommodate each lane configuration.

- The use of similar variable advance lane use signs to provide adequate notice to drivers of the lane use in effect.

Impacts to signal timing and phasing require special attention when implementing variable lane use assignments. Variable lane assignments should be evaluated using traffic software and simulations. While not necessary for all variable lane use operations, split phasing allows any legal combination of lanes to be implemented, provided that the other factors cited above are accommodated. Other techniques that could be used include variable left-turn phasing treatments (e.g., protected-only operation during some times of day, and protected-permissive operation during others). Today's traffic software and simulation programs allow the practitioner to evaluate different scenarios prior to implementing this strategy on the street.

Exhibits 11-30 and 11-31 provide examples from Montgomery County, Maryland, where variable lane use signs have been provided for additional left and right turns, respectively. These signs have been employed in conjunction with advance variable lane use signs provided several hundred feet before the intersection. The signs are compliant with the MUTCD, which allows changeable message signs to use the reverse color pattern when displaying regulatory messages (Sections 2A.07 and 6F.52).[1] They are reported as being well received by the public and effective in reducing peak-period queuing.[57]

(a) Double left turn during morning peak and off-peak periods.

(b) Triple left turn during evening peak period.

Exhibit 11-30. Example use of variable lane use sign to add a third left-turn lane during certain times of day.

Exhibit 11-31. Example use of variable lane use sign to add a second right-turn lane along a corridor during certain times of day.

Summary

Exhibit 11-32 summarizes the issues associated with variable lane use.

Characteristics	Potential Benefits	Potential Concerns
Safety	None identified.	None identified.
Operations	Improved peak-period utilization of existing right-of-way. Reduced queuing during peak periods.	None identified.
Multimodal	None identified.	Barrier to adding bike lanes.
Physical	Reduces or eliminates need for additional right-of-way.	None identified.
Socioeconomic	Lower cost than adding lanes.	None identified.
Enforcement, Education, and Maintenance	None identified.	Communicate any changes to the public. Maintain additional equipment

Exhibit 11-32. Summary of issues for variable lane use.