Alternative Intersections/Interchanges: Informational Report (AIIR)

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FOREWORD

Today's transportation professionals, with the limited resources available to them, are challenged to meet the mobility needs of an increasing population. At many highway junctions, congestion continues to worsen, and drivers, pedestrians, and bicyclists experience increasing delays and heightened exposure to risk. Today's traffic volumes and travel demands often lead to safety problems that are too complex for conventional intersection designs to properly handle. Consequently, more engineers are considering various innovative treatments as they seek solutions to these complex problems.

This report covers four intersection and two interchange designs that offer substantial advantages over conventional at-grade intersections and grade-separated diamond interchanges. It also provides information on each alternative treatment covering salient geometric design features, operational and safety issues, access management, costs, construction sequencing, environmental benefits, and applicability. The six alternative treatments covered in this report are displaced left-turn (DLT) intersections, restricted crossing U-turn (RCUT) intersections, median U-turn (MUT) intersections, quadrant roadway (QR) intersections, double crossover diamond (DCD) interchanges, and DLT interchanges.

Raymond Krammes
Acting Director, Office of Safety
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Today's transportation professionals are challenged to meet the mobility needs of an increasing population with limited resources. At many highway junctions, congestion continues to worsen. Drivers, pedestrians, and bicyclists experience longer delays and greater exposure to risk. Today's traffic and safety problems are more complex and complicated. Conventional intersection/ interchange designs are sometimes found to be insufficient to mitigate transportation problems. Consequently, many engineers are investigating and implementing innovative treatments in an attempt to think outside the box. This report covers four intersection designs and two interchange designs that may offer additional benefits compared to conventional at-grade intersections and grade-separated diamond interchanges. The six alternative treatments covered in this report are displaced left-turn (DLT) intersections, restricted crossing U-turn (RCUT) intersections, median U-turn (MUT) intersections, quadrant roadway (QR) intersections, double crossover diamond (DCD) interchanges, and DLT interchanges. The information presented in this report provides knowledge of each of the six alternative treatments including salient geometric design features, operational and safety issues, access management issues, costs, and construction sequencing and applicability.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER 1. INTRODUCTION

Today's transportation professionals are challenged to meet the mobility needs of an increasing population with limited resources. At many highway junctions, congestion continues to worsen. Drivers, pedestrians, and bicyclists experience longer delays and greater exposure to risk. Today's traffic and safety problems are more complex and complicated than ever, and conventional intersection designs are sometimes found to be insufficient to mitigate transportation problems. Consequently, many engineers are investigating and implementing innovative treatments in an attempt to improve mobility for roadway users.

This report describes alternative intersection and interchange designs that may offer additional benefits compared to conventional at-grade intersections and grade-separated diamond interchanges. The objective of this report is to present information on selected alternative designs. This report is not a guidebook, and it does not constitute a standard, specification, or required practice. It is an attempt at disseminating information about selected treatments that may not be generally considered for implementation during the alternatives analysis phase. The intended audience of this report is the group of transportation professionals engaged in the planning, design, and operation of interchanges and intersections.

The six alternative treatments presented in this report are identified in table 1. In addition, the general locations where these treatments have been or will be implemented are also presented in table 1. Figure 1 shows illustrations of the four alternative intersection configurations.

Table 1. Installations of selected alternative intersection and interchange treatments in the United States and other countries.

Alternative Intersection/Interchange Treatment	Installations
Displaced left-turn (DLT) intersection	Maryland, New York, Louisiana, Utah, Mexico, and United Kingdom.
Median U-turn (MUT) intersection	Michigan, Florida, and Louisiana.
Restricted crossing U-turn (RCUT) intersection	Maryland and North Carolina.
Quadrant roadway (QR) intersection	No known U.S. implementations yet although variants exist.
Double crossover diamond (DCD) interchange	Three locations in France and an implementation by the Missouri Department of Transportation.
DLT interchange	No known U.S. implementations yet.

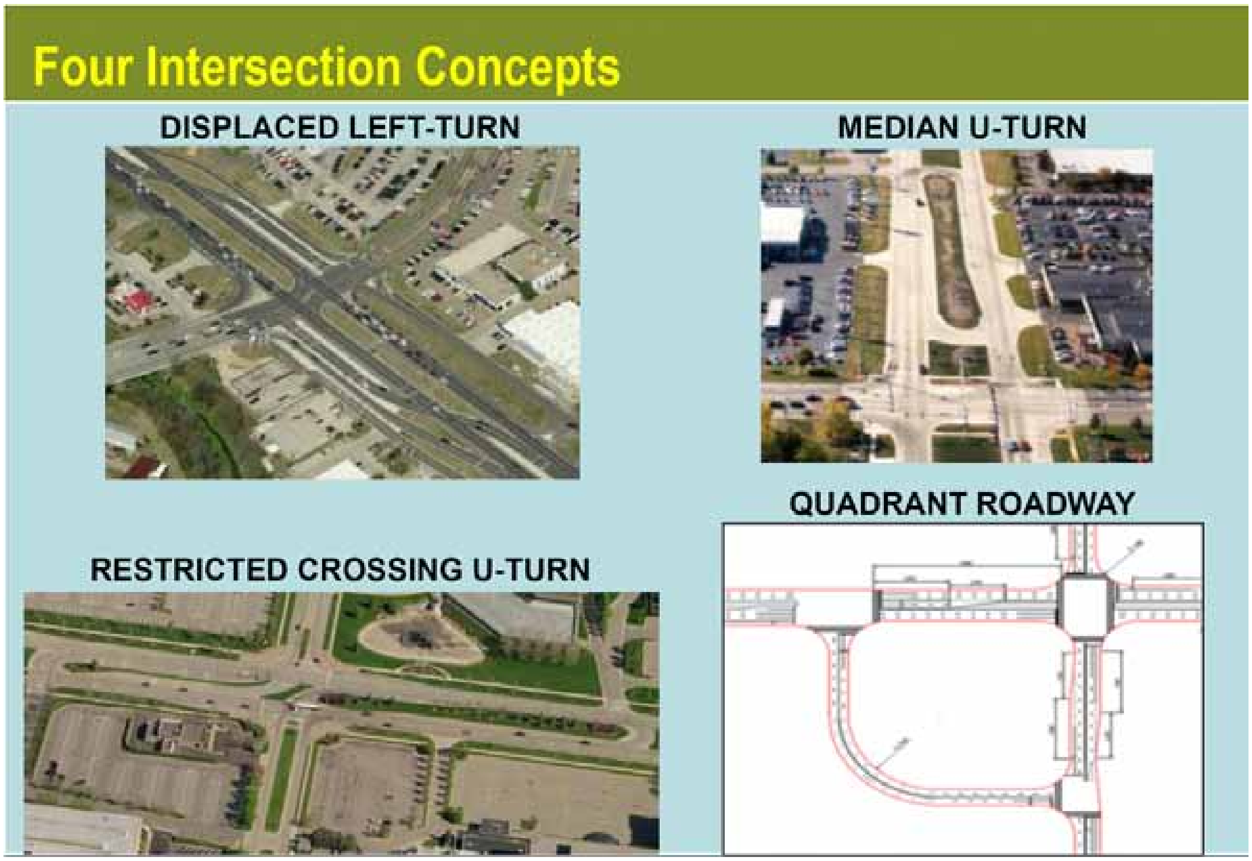


Figure 1. Photo. Four alternative intersection configurations.

While the four alternative at-grade intersection designs are noticeably different from each other, there is common aspect among them. These alternative designs all attempt to remove one or more of the conventional left-turn movements from the major intersection. By removing one or more of the critical conflicting traffic maneuvers from the major intersection, fewer signal phases are required for signal operation. This can result in shorter signal cycle lengths, shorter delays, and higher capacities compared to conventional intersections.

DLT intersections are also referred to as continuous flow intersections (CFI) and crossover displaced left-turn intersections (XDL). At conventional intersections, left-turn movements are frequently made from separate left-turn lanes directly onto the crossroad. Drivers turning left must cross the path of the oncoming through traffic from the opposite direction. At a displaced left-turn (DLT) intersection, left-turn traffic is laterally displaced. In other words, left-turning traffic crosses over the opposing through movement at a location that is several hundred feet upstream of the major intersection. This upstream crossover location is typically signal controlled. The left-turning traffic then travels on a separated roadbed, which is on the outside of the opposing through lanes, as those vehicles proceed toward the major intersection. When these left-turning motorists reach the major intersection, they can proceed without conflict concurrently with the opposing through traffic.

The median U-turn (MUT) intersection, which is also referred to as Michigan lefts, has been used extensively in Michigan. At an MUT intersection, left turns are not allowed at the major intersection. Rather, drivers turning left from the major approach must first proceed through the intersection. At a location that is several hundred feet downstream of the major intersection, these drivers can make a U-turn, travel back toward the intersection, and then subsequently execute a right turn onto the crossroad. This type of treatment is most effective on boulevard-type streets with wide medians. The MUT intersection can be classified as either a partial MUT intersection or a full MUT intersection. At a partial MUT intersection, the side road approaches operate in a manner similar to the side road approaches at conventional intersections. Specifically, left-turn movements can be made directly from left-turn lanes on the side road approaches. For partial MUT intersections, left turns from the major road at the intersection with the crossing side road are prohibited. At a full MUT intersection, no left turns are permitted from either the major road or the intersecting side road.

The restricted crossing U-turn (RCUT) intersection, also known as a super street intersection, is similar to the MUT intersection treatment in that left-turning traffic from the minor-road approach must first turn right and then execute a U-turn maneuver downstream. The distinguishing characteristic is that the through and left-turn maneuvers are not allowed from the side road. Rather, all traffic approaching the major road on the side road must first turn right onto the major road, travel a short distance downstream on the major road, and then make a U-turn on the major road. Drivers on the side street who want to go through on the side road can then make a right turn from the major roadway onto the side road. While conventional intersections can be converted to RCUT intersections at individual spot locations, the RCUT intersection treatment is more applicable as a treatment applied to arterial segments. Another form of the RCUT intersection is the J-turn intersection, named by the Maryland State Highway Administration (MDSHA). At a J-turn intersection, traffic signal control is not installed, but all traffic from the side road must turn right onto the arterial. Left turns from the major arterial are still permitted at the crossroad similar to a conventional intersection. This treatment is typically implemented where left-turn volumes and side road volumes are relatively low. The benefit of the J-turn intersection is that it allows the major arterial through traffic to proceed without stopping for traffic signal control.

The quadrant roadway (QR) intersection is a design at which the mainline left-turn movements are relocated to a connector roadway that is located in one of the quadrants. The connector roadway provides a separate connection between the major road and the crossroad. Drivers who want to turn left from the major road at a conventional intersection turn left onto this connector roadway at a location upstream from the major intersection. They then turn left again from the connector roadway to the cross street. At the time of this report, there are no known QR intersections in the United States if held to the strict definition that no left turns are allowed at the primary intersection. However, there are many locations where one or more left-turn movements have been prohibited at the primary intersection and directed via existing streets in the local roadway network. The removal of even one left-turn movement from a heavily congested intersection can reduce delays and improve flow through the intersection. Therefore, the QR intersection, in its purest form, removes all left turns from the primary intersection in an attempt to maximize throughput on both the major and minor intersecting roadways.

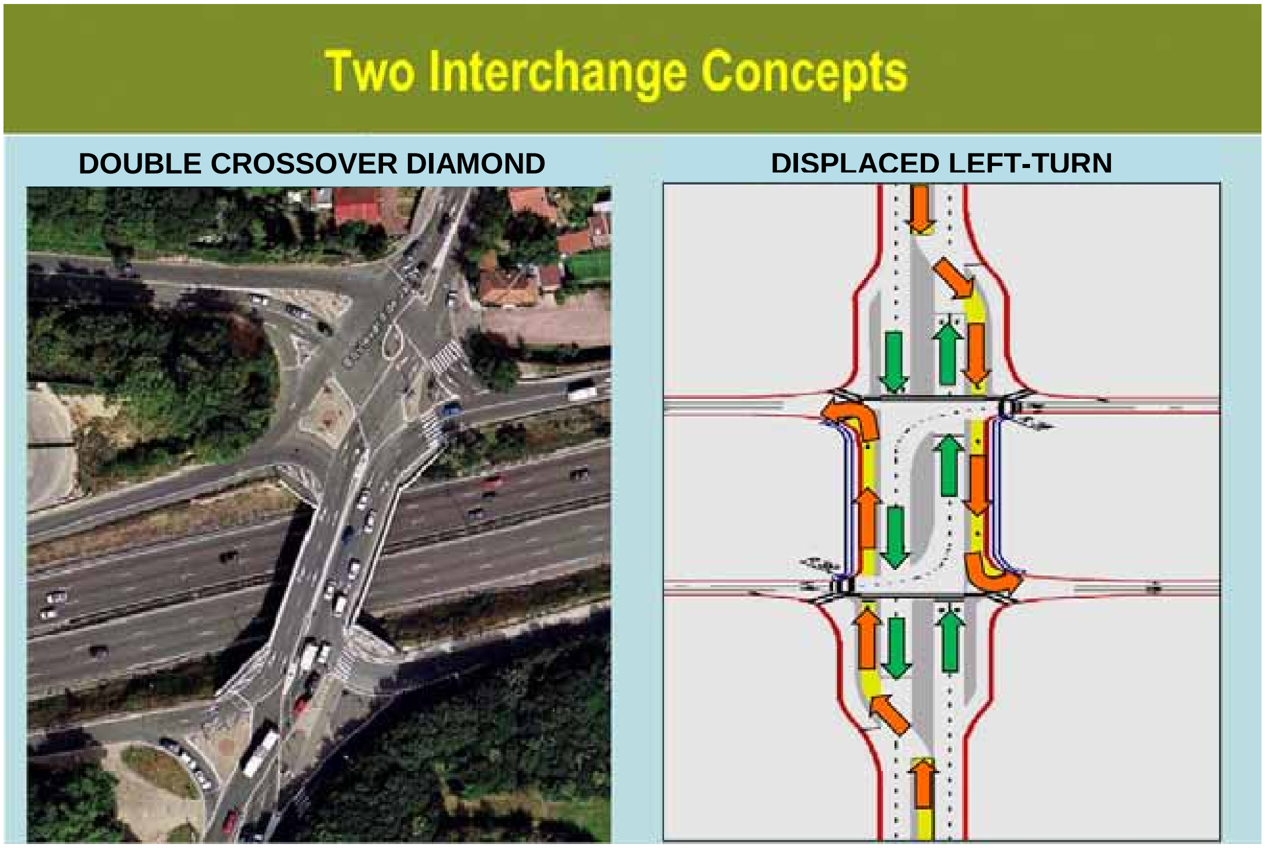


Figure 2. Photo. Two alternative interchange configurations.

The two alternative interchange treatments examined in detail in this report are alternatives for a conventional diamond interchange, which are shown in figure 2. The double crossover diamond (DCD) interchange, also referred to as diverging diamond interchange (DDI), features a reversal of the directional traffic movements on the crossing arterial roadway through the interchange area. At a conventional diamond interchange, left turns are executed across the path of opposing through traffic. By flipping the traffic streams within the interchange area, the conflict between the left turn from the major road and the opposing through movement can be removed. Left-turning traffic from the major road onto an on-ramp to the freeway can be made without conflict from the opposing traffic. This resulting movement is analogous to a right turn from the major road to a ramp at a conventional diamond interchange.

The other alternative interchange treatment documented in this report is the DLT interchange. Operationally, it is analogous to a DLT intersection and can be thought of as a DLT intersection implemented at a diamond interchange. The treatment removes the conflict between the left turn onto the on-ramp and the opposing through movement. By displacing the left turn, opposing through movements can move concurrently during the same signal phase when traffic is turning left to the ramp. However, as opposed to the DCD interchange, the DLT interchange does not require the reversal of the directional through movements.

Among the intersections in this report, DLT intersections have been implemented at five locations in the United States, with several implementations in Mexico and some in the United Kingdom. The MUT intersections are the most common form within the United States, with many existing implementations in Michigan and some in Florida and Louisiana. The RCUT intersection has been implemented in both the signalized and unsignalized forms in North Carolina. In Maryland, they are in the unsignalized form and are referred to as J-turns. Although several variations of QR intersections exist in the United States, there are no known pure forms of this intersection.

Regarding the two interchange forms detailed in this report, the DCD interchange exists at a known location in Versailles, France, and two other locations near Paris, France. The designs for two DCD interchanges have been prepared and are expected to be constructed in Kansas City, MO, and Springfield, MO.

This report discusses the following main topics:

- Alternative intersection treatments (chapters 2 through 6).
- Alternative interchange treatments (chapters 7 through 9).
- Processes to assist transportation professionals in selecting alternative intersection/ interchange treatments (chapter 10).

Chapters 2 through 6 discuss the alternative at-grade intersections and provide knowledge of each intersection treatment including its salient geometric design features, operational and safety issues, access management issues, costs, construction sequencing, and applicability. Additional alternative intersections not discussed in detail in this report are briefly described at the end of chapter 6.

Chapters 7 through 9 discuss the two alternative grade-separated interchanges and provide knowledge of each interchange treatment including its salient geometric design features, operational and safety issues, access management issues, costs, construction sequencing, and applicability. Chapter 9 provides descriptions of two grade-separated interchanges that are popular among designers, namely, the compressed or tight urban diamond interchange (TUDI) and the single point urban interchange (SPUI). Additional innovative interchanges not discussed in detail in this report are described briefly in chapter 9.

Chapter 10 presents a process that transportation professionals could use to identify and assess alternative at-grade intersection designs. The process was devised so that potentially feasible alternative intersection designs that are often not considered would be included at a sketch planning level during an alternative analysis stage. The assessment procedure uses a set of criteria that cover operational, safety, right-of-way, and pedestrian issues. The criteria presented in chapter 10 could encourage the advancement of a broader range of alternative intersection designs to subsequent phases in project planning and preliminary design processes.

CHAPTER 2. DISPLACED LEFT-TURN INTERSECTION

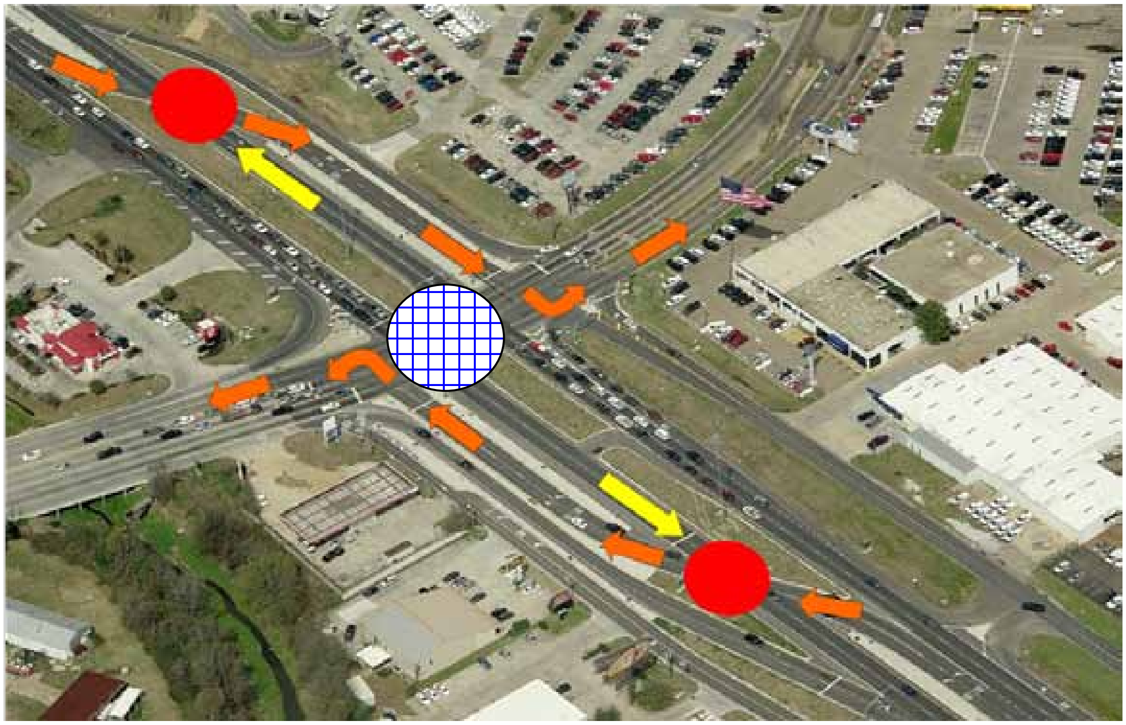
2.1 INTRODUCTION

The DLT intersection, also known as a CFI and a XDL intersection, has been implemented at several locations in the United States to reduce congestion. The reduction in the numbers of traffic signal phases and conflict points at DLT intersections can result in improved traffic operations and safety.

The main feature of this alternative intersection is the relocation of the left-turn movement on an approach to the other side of the opposing roadway, which consequently eliminates the left-turn phase for this approach at the main intersection. As shown in figure 3, traffic that would normally turn left at the main intersection first crosses the opposing through lanes at a signal-controlled intersection several hundred feet upstream of the main intersection. Left-turning vehicles then travel on a new roadway parallel to the opposing lanes and execute the left-turn maneuver simultaneously with the through traffic at the main intersection.(1) Traffic signals are present at the main intersection and at the locations of the left-turn crossovers. The traffic signals are operated in a coordinated manner. The left-turn crossover movement, opposing through movements, and signal control at the crossovers and the main intersection are shown in figure 4. In the figure, the red circle indicates a signal-controlled crossover, the blue hatched circle indicates a signal-controlled main intersection, the orange arrows indicate left-turn crossover movements, and the yellow arrows indicate opposing through movement at a signal-controlled crossover.

Source: Google™ Earth

Figure 3. Photo. Left-turn crossover movement at a three-legged partial DLT intersection in Shirley, NY.



Source: Microsoft® Windows Local Live

Figure 4. Photo. Left-turn crossover movement at a partial DLT intersection in Baton Rouge, LA.

Figure 4 is a partial DLT intersection where the DLT movements have been implemented on two opposing approaches on the major road in this case. In most cases, the DLTs are on the major roadway. The left-turn movements for the minor road continue to take place at the main intersection. There are three junctions with traffic signal control—the main intersection (shown as the blue hatched circle in figure 4) and the two left-turn crossovers (shown as red circles).

For the full DLT intersection, the left-turn movements are relocated to crossovers on all four approaches, as shown in figure 5. In the figure, the red circle indicates a signal-controlled crossover, the blue hatched circle indicates a signal-controlled main intersection, the orange arrows indicate left-turn crossover movements, and the yellow arrows indicate opposing through movement at a signal-controlled crossover. There are five junctions with traffic signal control at a full DLT intersection—the main intersection (shown as the blue hatched circle) and the four left-turn crossovers (shown as red circles).

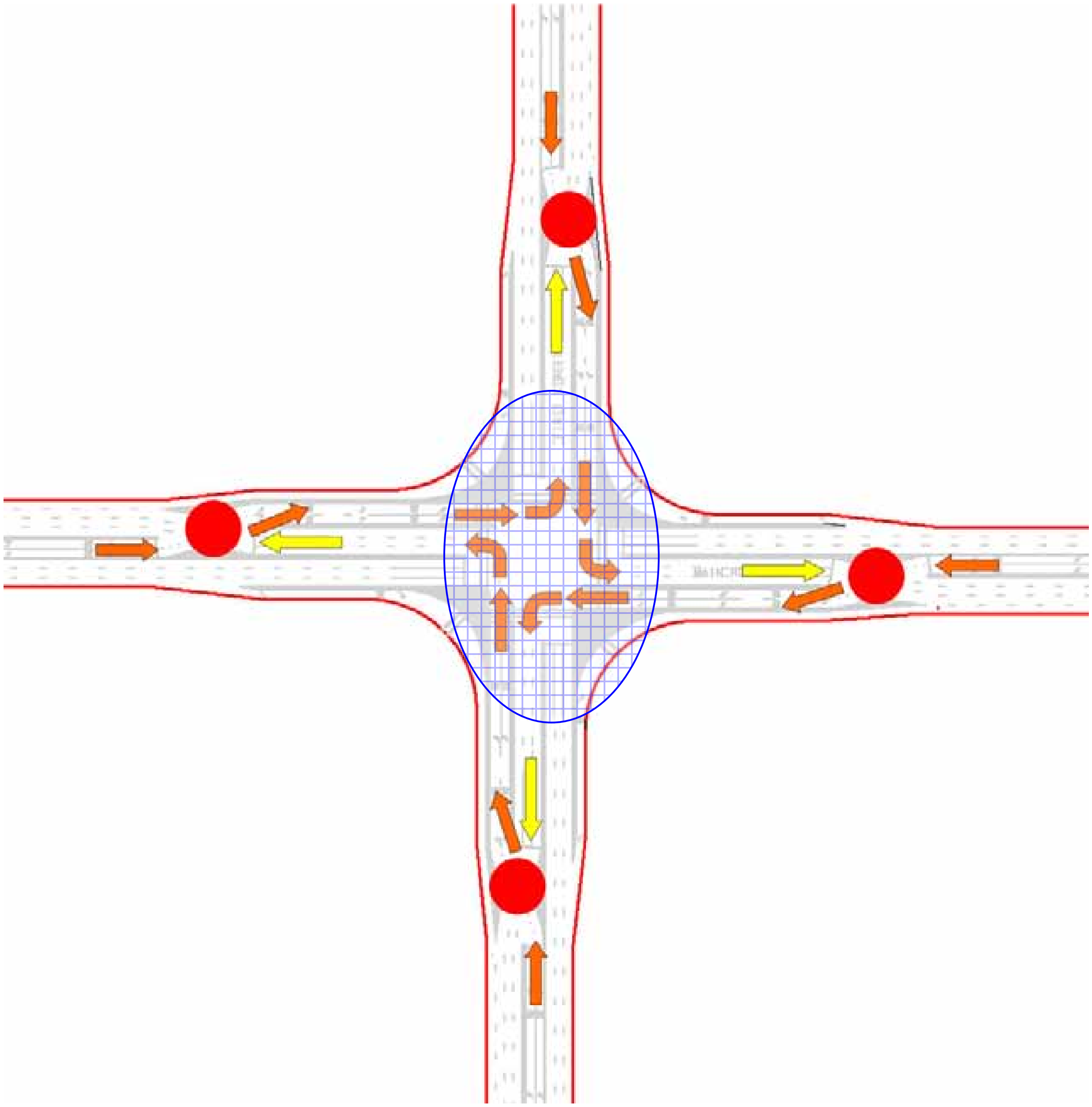


Figure 5. Illustration. Left-turn crossover movements in a full DLT intersection.

Another at-grade variation of the DLT intersection is the parallel flow, which is also known as the paraflow intersection. The parallel flow intersection is described in greater detail in chapter 6. In England, DLT intersections are also known as displaced right-turn intersections. One such intersection was opened in August 2002 in Swindon, UK.[2]

The accommodation of pedestrians at a DLT intersection is an important issue because DLT intersections are suited for urban settings where higher pedestrian activity is likely. Pedestrians crossing at a DLT intersection must cross travel lanes carrying traffic in potentially counterintuitive directions. Depending on pedestrian and traffic volumes, the DLT intersection may not be an appropriate option for some locations due to increased exposure for pedestrian conflicts. For many DLT intersections, pedestrian crossings are possible in multiple signal phases with median islands providing a refuge. This issue is discussed in more detail in section 2.5.

The conversion from a conventional intersection to a DLT intersection offers some advantages over expanding capacity at a conventional intersection or constructing a grade-separated interchange. A DLT intersection is less expensive compared to a grade-separated interchange and can be constructed much faster.(1) In terms of safety, DLT intersections have fewer conflict points compared to conventional intersections. At most volume scenarios, DLT intersections have the potential to considerably reduce average intersection delays. Simultaneous movement of the left-turn and through traffic promotes improved progression of traffic platoons on the arterial and increases vehicular throughput.

A DLT intersection has some disadvantages. Specifically, it has a larger footprint compared to a conventional intersection, which may be a significant factor in the decision not to construct one in an urban area where right-of-way is limited and costly. Access to land parcels located in the quadrants of the intersection can be restricted, and U-turn movements may have to be eliminated at the intersection.(1) In addition, pedestrians cannot cross all four legs as at conventional intersections, and the intersection design can present challenges to pedestrians with visual impairments since the pedestrian paths and some of the traffic movements are not typical. The use of accessible pedestrian signals (APS) is recommended wherever appropriate to better accommodate pedestrians with visual impairments. Unlike a conventional intersection, the DLT intersection has internal conflict points at the left-turn crossover points.

Several DLT intersections have been built in the United States. At the time of this report, DLT intersections are present at the following locations:

- A DLT intersection prototype was constructed as a T-intersection at the intersection of William Floyd Parkway and the entrance of Dowling College National Aviation Technology (NAT) Center in Shirley, NY, in 1995. An aerial view of the intersection was shown previously in figure 3.

- The intersection of Route 210 (Indian Head Highway) and Route 228 (Berry Road) in Accokeek, MD, is also a T-intersection. It operates under traffic signal control and was constructed in 2001. The DLT movement is on the side street approach to the intersection rather than on the major road approach as with the DLT intersection in Shirley, NY. The intersection aerial is shown in figure 6.

- A partial DLT intersection was implemented at the four-legged intersection of U.S. 61 (Airline Highway) at Seigen Lane and South Sherwood Forest Road in Baton Rouge, LA. The DLT intersection was opened in March 2006. The aerial perspective view of this intersection was shown previously in figure 4.

- The intersection of 3500 South and Bangerter Highway in Salt Lake City, UT, was converted in September 2007. It is also a partial DLT intersection with left-turn crossovers on the approaches of Bangerter Highway.

- The latest addition to the list of DLT intersections in the United States is the intersection of U.S. Route 30 and Summit Drive in Fenton, MO, which opened in September 2007. This partial DLT intersection, with left-turn crossovers on the approaches of U.S. Route 30, is shown in figure 7. The figure shows how the DLT intersection can be constructed on the outside of the through lanes and how the existing median width can be preserved without a shift in the through lanes.

Source: Google™ Maps

Figure 6. Photo. DLT intersection at the intersection of Indian Head Highway (MD 210) and Berry Road (MD 228) in Accokeek, MD.

Source: Missouri Department of Transportation

Figure 7. Photo. DLT intersection at the intersection of U.S. Route 30 and Summit Drive in Fenton, MO.

2.2 GEOMETRIC DESIGN CONSIDERATIONS

Figure 8 and figure 9 illustrate typical designs for DLT intersections. The design in figure 8 is for a full version, which has DLT movements on all four approaches. This design reflects a shift of the through traffic lanes into the median in an attempt to minimize the need for additional right-of-way. At several locations where DLT intersections have been implemented as a retrofit to an existing conventional at-grade intersection, the existing median has been preserved, and there is no shift in the through lanes. Figure 9 illustrates a DLT movement at a three-legged intersection with the displacement on the major road.

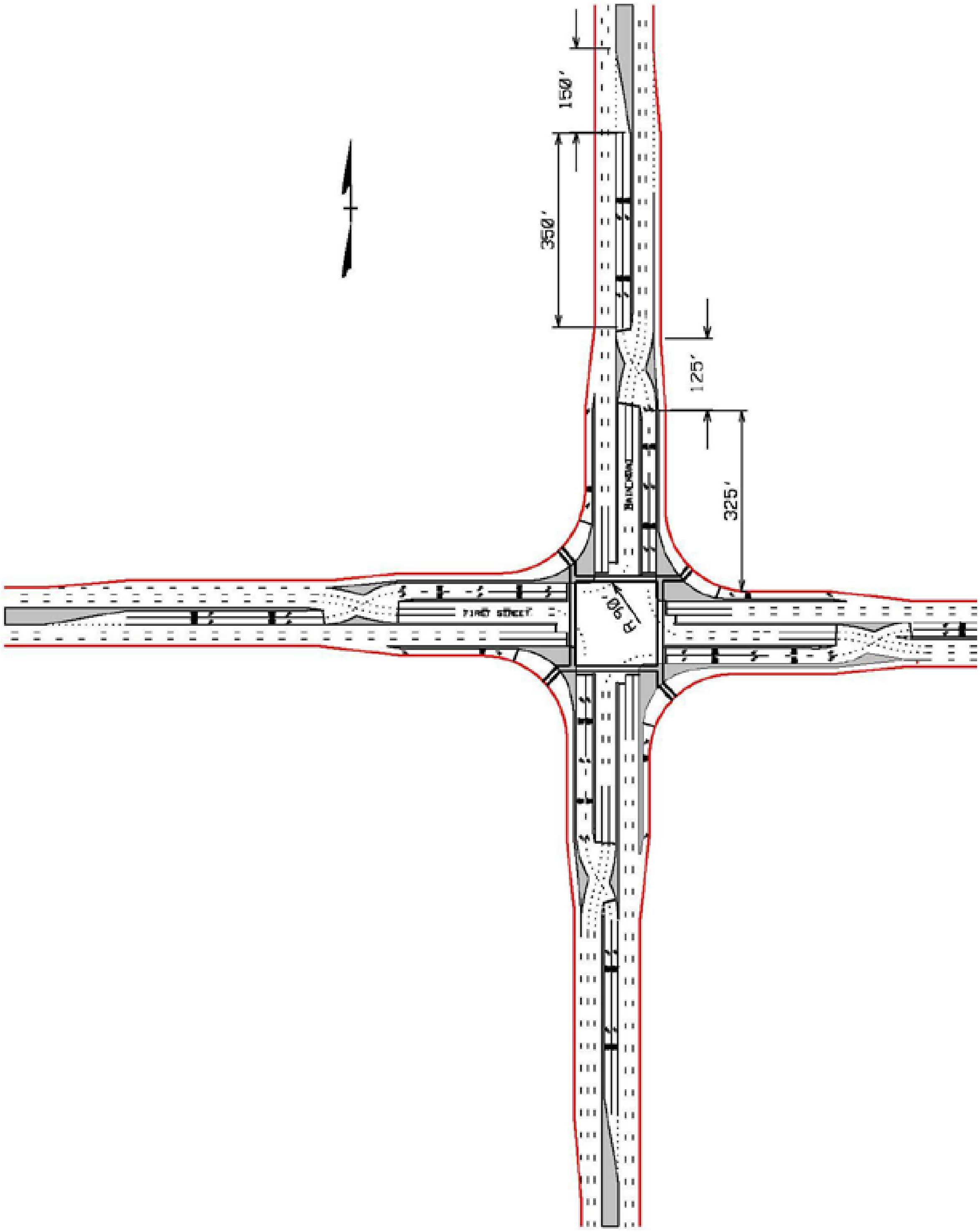
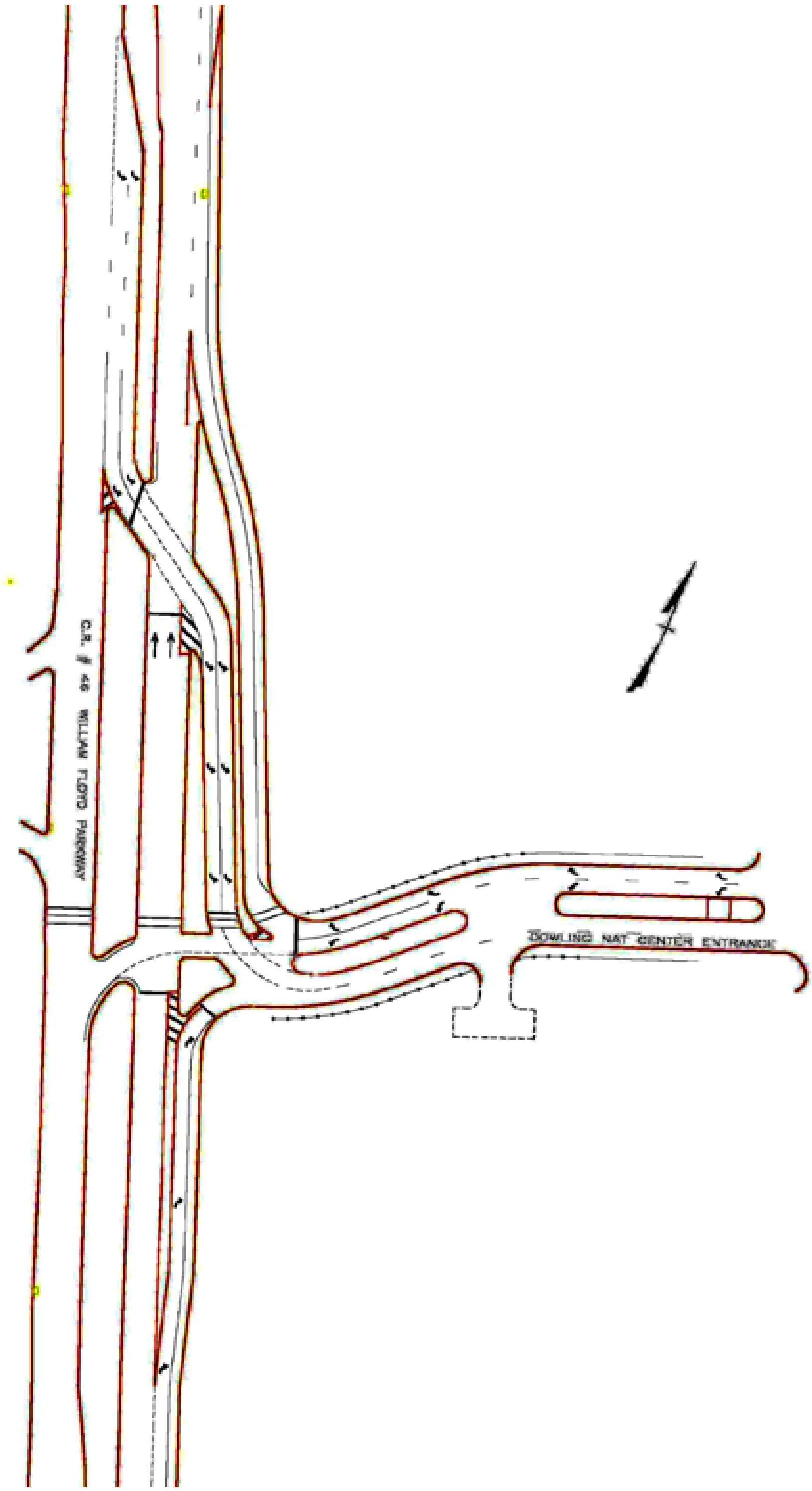


Figure 8. Illustration. Typical full DLT intersection plan view with DLTs on all approaches.



Source: LKM Associates, PC

Figure 9. Illustration. Example of a partial DLT intersection plan view at Dowling NAT Center in Shirley, NY, with DLTs on major road approaches.

Removal of conflict between the left-turn movement and the oncoming traffic at the main intersection is the primary design element in a DLT intersection.(3) The DLT vehicles typically cross the opposing through traffic approximately 300–400 ft upstream of the main intersection under the control of another traffic signal as shown in figure 10 and figure 11. Research performed by the MDSHA shows that the appropriate upstream distance is dependent on queuing from the main intersection and on costs involved in constructing a left-turn storage area for the crossed-over left turn movement.(4) Radii of the crossover movements can range from 150 to 200 ft (see figure 11), while the radius of the next left-turn movement at the main intersection is dependent on the turning movement of the design vehicle.(5) Lane widths at the crossover reverse curve should be wider than 12 ft to accommodate larger design vehicles. Consideration should also be given to having wider lane widths (e.g., up to 15 ft) for the receiving crossroad.

The angle between the DLT intersection left-turn lanes and the main through lanes is referred to as the crossover angle and is influenced by the median width and the alignment of the mainline lanes. The Louisiana Department of Transportation and Development (LA DOTD) recommends an angle of 10–15 degrees.(6)

Figure 10. Illustration. Left-turn crossover movement view in a DLT intersection driver simulator.

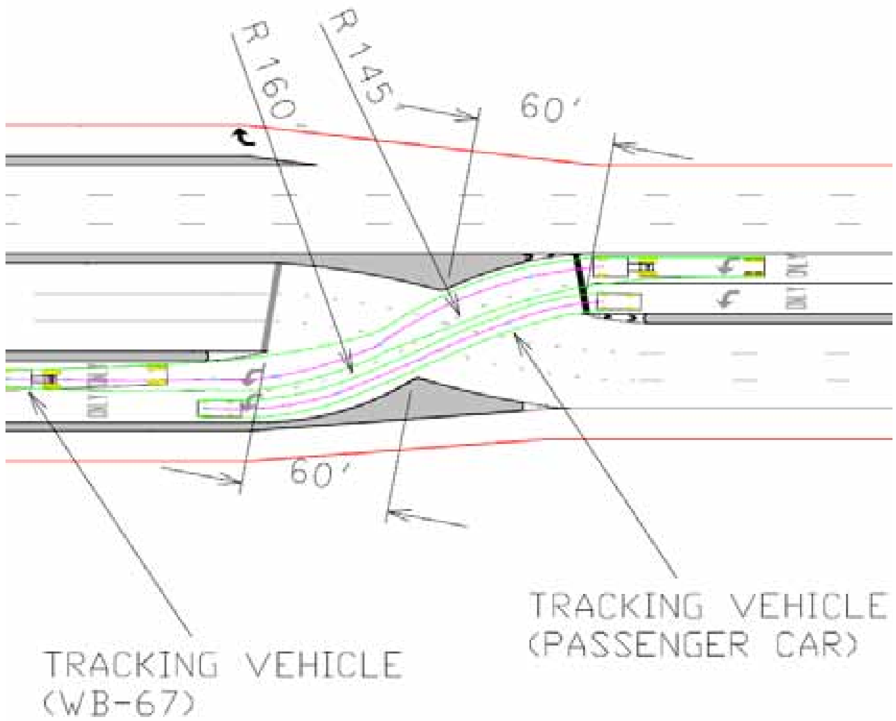


Figure 11. Illustration. Left-turn crossover movement in a DLT intersection.

Right-of-way constraints are an issue common in urban environments. The DLT intersection design helps minimize right-of-way acquisition by occupying far less space compared to grade-separated interchanges. However, due to the presence of left-turn crossovers, a DLT intersection has a larger footprint compared to a conventional at-grade intersection. To minimize the footprint, median widths can be reduced, but they still need to be adequate to accommodate signs. Designers can obtain minimum median widths from the American Association State Highway and Transportation Officials (AASHTO) *A Policy on Geometric Design of Highways and Streets*, referred to as the *Green Book*.[7] Designers should also take into account the possibility of installing post-mounted signs in these medians for safe and effective channelization of traffic. Offsets for signs should be in accordance with the *Manual of Uniform Traffic Control Devices* (*MUTCD*).[8] A wide median can be counterproductive for several reasons, including the following:

- Wide medians can result in large walking distances for pedestrians at the intersection. This can result in long pedestrian clearance intervals, which can be counterproductive to the efficient signal operation.
- Wide medians resulting in a wide intersection footprint lead to longer yellow and all-red clearance times for the intersection and consequently longer cycle lengths.

If the existing arterial has a wide median, the median can be narrowed through the use of transition curves and guidance from the AASHTO *Green Book*.[7] Similarly, minimum turning radius criteria for the appropriate design vehicles and shoulder placement can be obtained from the AASHTO *Green Book* and applied as appropriate.[7] *NCHRP Synthesis 225*, "Left-Turn Treatments at Intersections—A Synthesis of Highway Practice," describes several design features for DLT intersections including channelizing islands, overhead lane controls, and raised pavement markers for lane delineation and traffic flow separation.(9)

With the elimination of left-turn movements at the main intersection, U-turns should also be prohibited at the main intersection of a DLT intersection. However, if the median's width is sufficient, then U-turn movements on the major road can be executed at the left-turn crossover.(10) Designers of the DLT intersection in Baton Rouge, LA, implemented a U-turn crossover with truck restrictions between the main intersection and the left-turn crossover, as depicted in figure 12.

Sight distance and driver expectancy are other issues related to the design of a DLT intersection. Left-turning drivers may be confused when they negotiate the DLT intersection. This can be counterintuitive to unfamiliar drivers. Hence, unambiguous signing is needed.

The DLT intersection in Louisiana was designed and constructed based on the following criteria:(11)

- Design speed of 50 mi/h with 12-ft lanes and 8-ft shoulders on U.S. 61 (Airline Highway).
- Lane width of 12 ft was on all lanes except the frontage roads.
- The median width on U.S. 61 (Airline Highway) was 43 ft.
- Shoulders of 8 ft in width on both sides of U.S. 61.
- The separation between the left-turn crossover and the opposing through traffic was 20 ft.

A 12-ft-wide separation was maintained between the left-turn crossover and the opposing right-turning traffic. Some of the other design guidelines used in the Louisiana DLT intersection were as follows:(11)

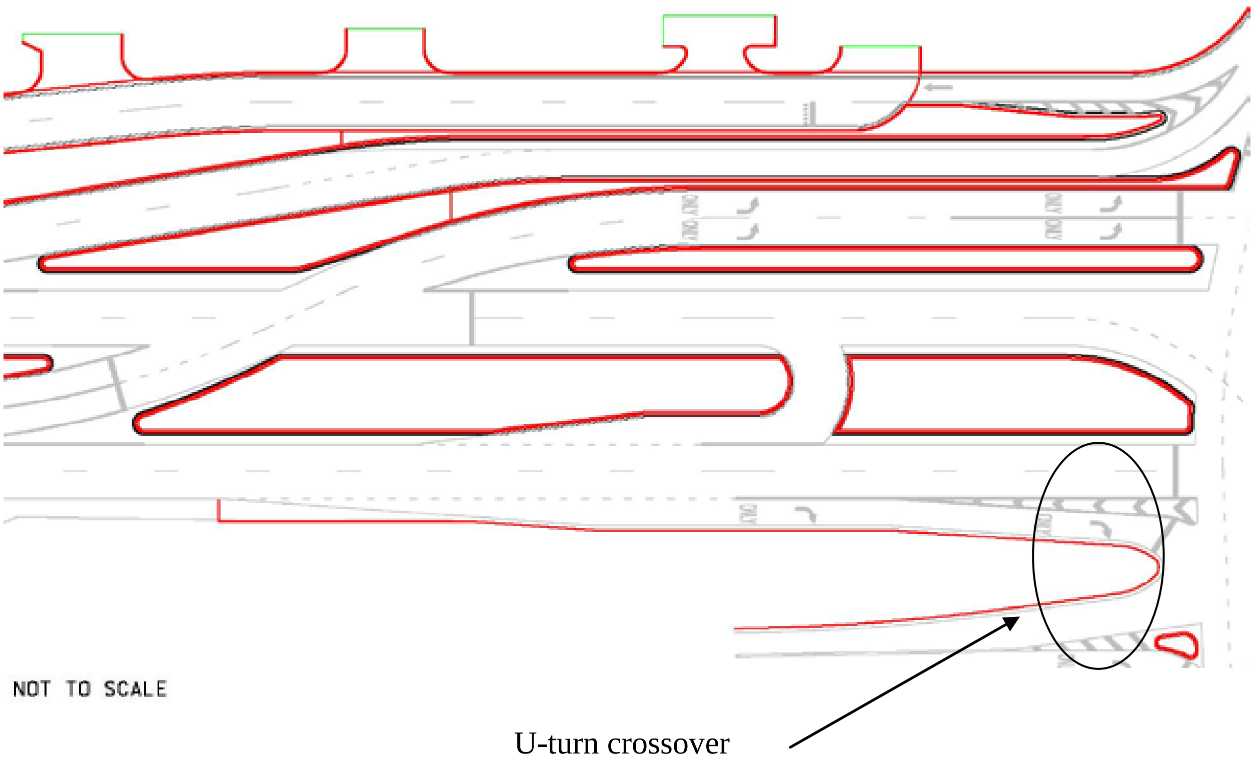
- The angle of crossing for DLT vehicles was as great as possible to help reduce the possibility of wrong-way entry and to reduce crossing time.
- Right-turn lanes were provided on intersection legs approaching DLT roadways.

Widening or adding lanes at a DLT intersection in the future could be difficult. Additional lanes that may be needed in the future should be planned during the initial design of a DLT intersection.(11)

2.3 ACCESS MANAGEMENT CONSIDERATIONS

Full DLT intersection implementation typically places restrictions on direct access to parcels situated in the corners of an intersection. Access to these parcels is possible from right-in and right-out configurations. The *NCHRP Report 420*, "Impacts of Access Management Techniques," discusses design, location, and spacing of driveways in detail.(12)

As mentioned in the previous section, U-turn movements are prohibited at the main intersection of a DLT intersection. To facilitate egress and easy movement of traffic from driveways in either direction of the approach, U-turn crossovers can be provided between the main intersection and the left-turn crossover. One such U-turn movement using a median opening along with the appropriate signing and marking is shown in figure 12 and was implemented in Baton Rouge, LA. Median width at the U-turn crossover should be sufficient to facilitate U-turning of the design vehicle.



Source: Louisiana Department of Transportation and Development

Figure 12. Illustration. Location of U-turn at DLT intersection in Baton Rouge, LA.

Since direct access to adjacent businesses is restricted in a DLT intersection design, the use of frontage roads can provide access to these businesses. General features of frontage roads and their typical layouts are detailed in the AASHTO *Green Book*.(7) Outer separation should be maintained per the AASHTO *Green Book* recommendations.(7)

Chapter 10 of the *NCHRP Report 420* also discusses application guidelines for one-way and two-way frontage roads and their key features.(12) Figure 13 shows the frontage road design at the DLT intersection in Baton Rouge, LA. According to designers of the Louisiana DLT intersection, two-way frontage roads might be required in some quadrants to provide local access to business sites in the quadrant.(6)

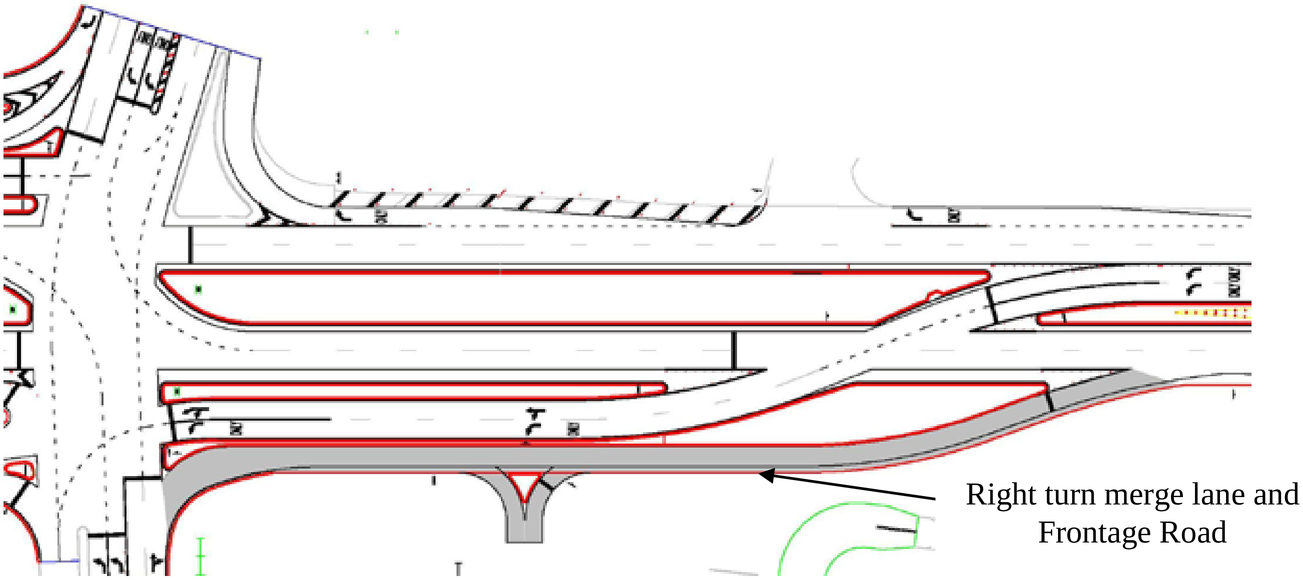
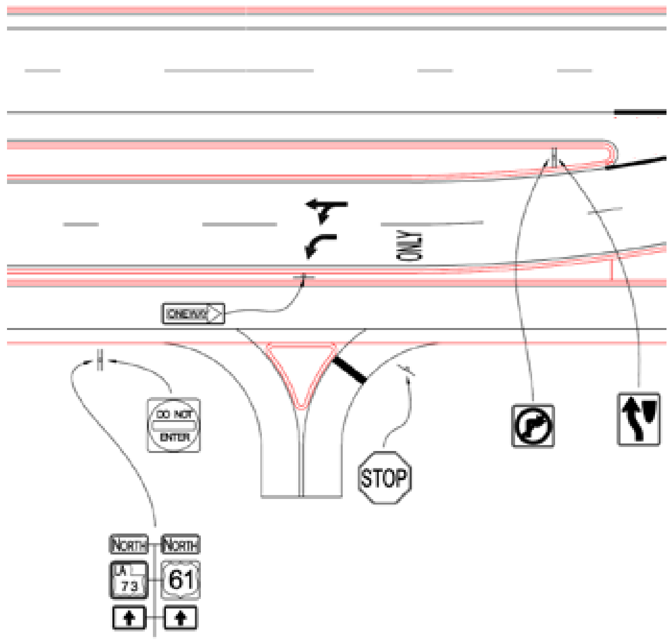


Figure 13. Illustration. Right-turn merge lane/frontage road at DLT intersection in Baton Rouge, LA.

With restricted access to parcels located close to the main intersection, the optimal placement of driveway openings in the vicinity of a DLT intersection is an important issue. Approaches at the DLT intersection that have the left-turn crossovers cannot accommodate median breaks typically within a distance of 600–700 ft of the main intersection depending on the design of the left-turn crossovers. Therefore, driveways on the approaches to the main intersection need to be right-in and right-out only.

Driveway widths, other dimensions, and sight distance requirements can be determined using local and national design guidelines, such as the AASHTO *Green Book*.(7) Other potentially applicable design guidance can be found in the *Institute of Transportation Engineers (ITE) Guidelines for Driveway Location and Design.*(13) Figure 13 through figure 15 show the location of one such driveway at the DLT intersection in Baton Rouge, LA, with a channelizing “pork-chop” island and driveway signing.



Source: Louisiana Department of Transportation and Development

Figure 14. Illustration. Location of driveway and signage at the DLT intersection in Baton Rouge, LA.

Figure 15. Photo. Right-in, right-out driveway accessible via the right-turn merge lane/frontage road at the DLT intersection in Baton Rouge, LA.

2.4 TRAFFIC SIGNALIZATION TREATMENTS

A DLT intersection has traffic signal control at the main intersection and the left-turn crossovers, as shown in figure 16. At a full DLT intersection with left-turn crossovers on all four approaches, the signal control for each of the five locations operates each location as two-phase signal-controlled intersections. Since there are only two signal phases, optimal cycle lengths are typically between 60 and 90 s. At a partial DLT intersection that handles minor road left turns at the main intersection, the signal control at the main intersection operates with three signal phases and cycle lengths typically between 80 and 110 s. When multiple signal controllers are used at a DLT intersection to control each signalized intersection separately, coordination of the traffic signal controllers is necessary.

DLT intersections have shorter cycle lengths because of the reduced number of phases. Therefore, if a DLT intersection exists within a corridor and if the cycle lengths for the other intersections in the system are different from the cycle length for the DLT intersection, then the DLT intersection is operated as an isolated intersection. However, if the cycle length of the DLT intersection is the same as or half of the signal cycle length of the other intersections in the system, then progression is achieved. The DLT intersection design also has to consider the progression on an arterial, which is done by preserving the background cycle and a guaranteed green time during that cycle for the major street. Depending on the specific turning movement volumes and geometry, it is possible to establish timings that result in the following:

- Reductions in delay for the through vehicles.
- Reductions in delay for vehicles waiting to turn left.
- Reductions in delay for drivers of vehicles who have entered the DLT lane and are traveling toward the main intersection to eventually turn left.
- Reductions in delay for drivers of vehicles who have turned left and are traveling to the final crossing on the through approach.
- Reductions in the number of stops for all vehicles.
- Increase in efficiency for pedestrian crossings on all intersection legs.

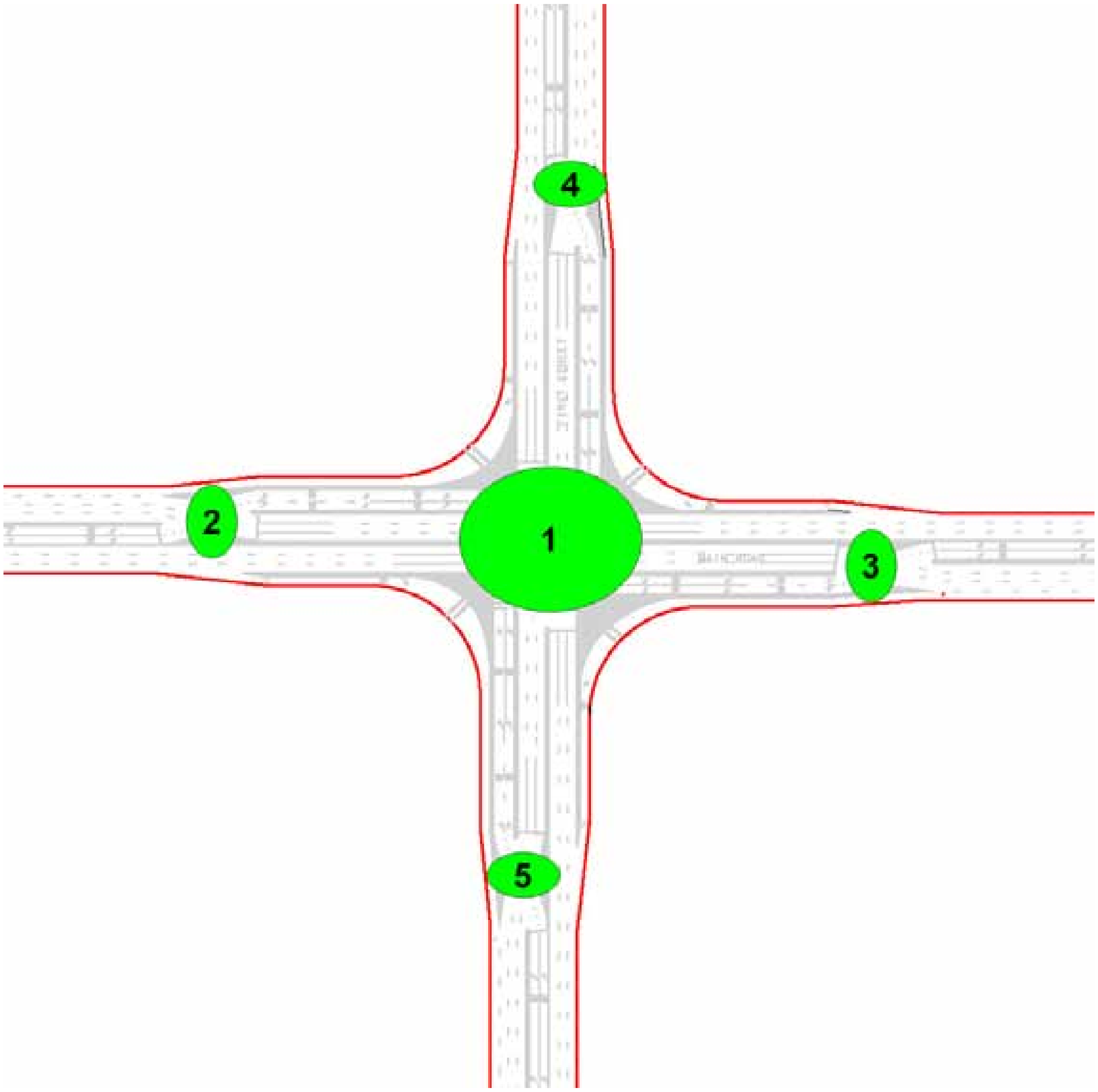


Figure 16. Illustration. Typical DLT intersection signal locations.

2.4.1 Signal Design

Since DLT intersections are appropriate for intersections with high through and left-turning volumes, signals are likely warranted both at the main intersection and the left-turn crossovers. Figure 16 shows the typical location of the signals at the main intersection and the left-turn crossovers. The green circles in the figure indicate typical signal locations.

Signal control at a DLT intersection may be operated in a fully actuated mode to minimize delay. Detectors can be installed to cover all of the crossovers, the minor street approaches, and the major street approaches. The five signals, as shown earlier in the full DLT intersection, can be operated either with separate controllers or with a single controller. The signal phasing for a DLT intersection where five separate signal controllers are used is depicted in figure 17. The signal phasing for a DLT intersection where one signal controller is used is depicted in figure 18. The signal phasing scheme for the partial DLT intersection is shown in figure 19.

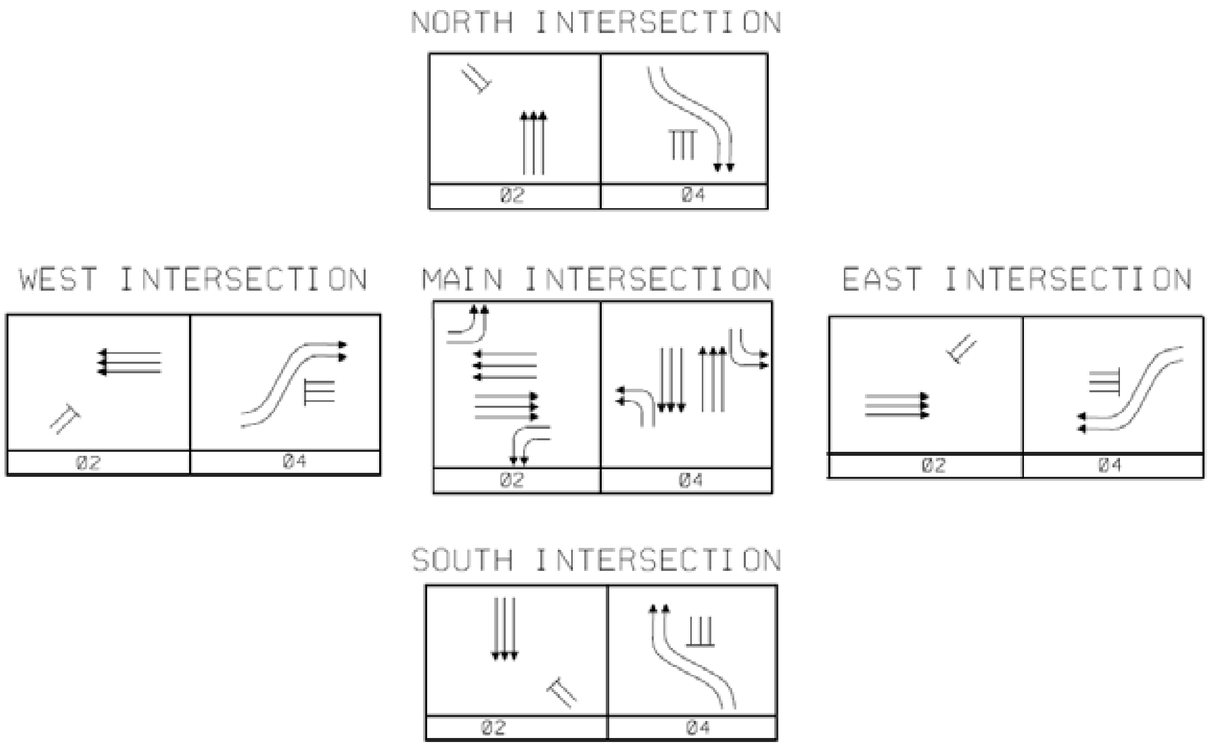


Figure 17. Illustration. Two-phase signal phasing at the five separately controlled signalized intersections within a full DLT intersection.

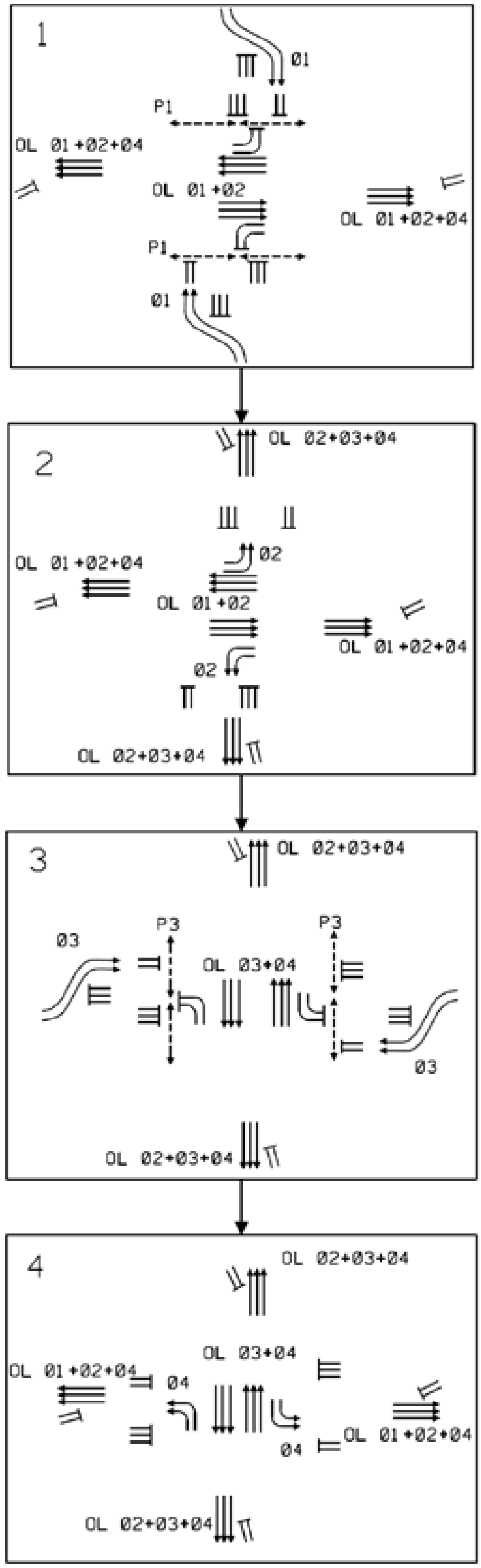


Figure 18. Illustration. Signal phasing for a full DLT intersection with a single controller.

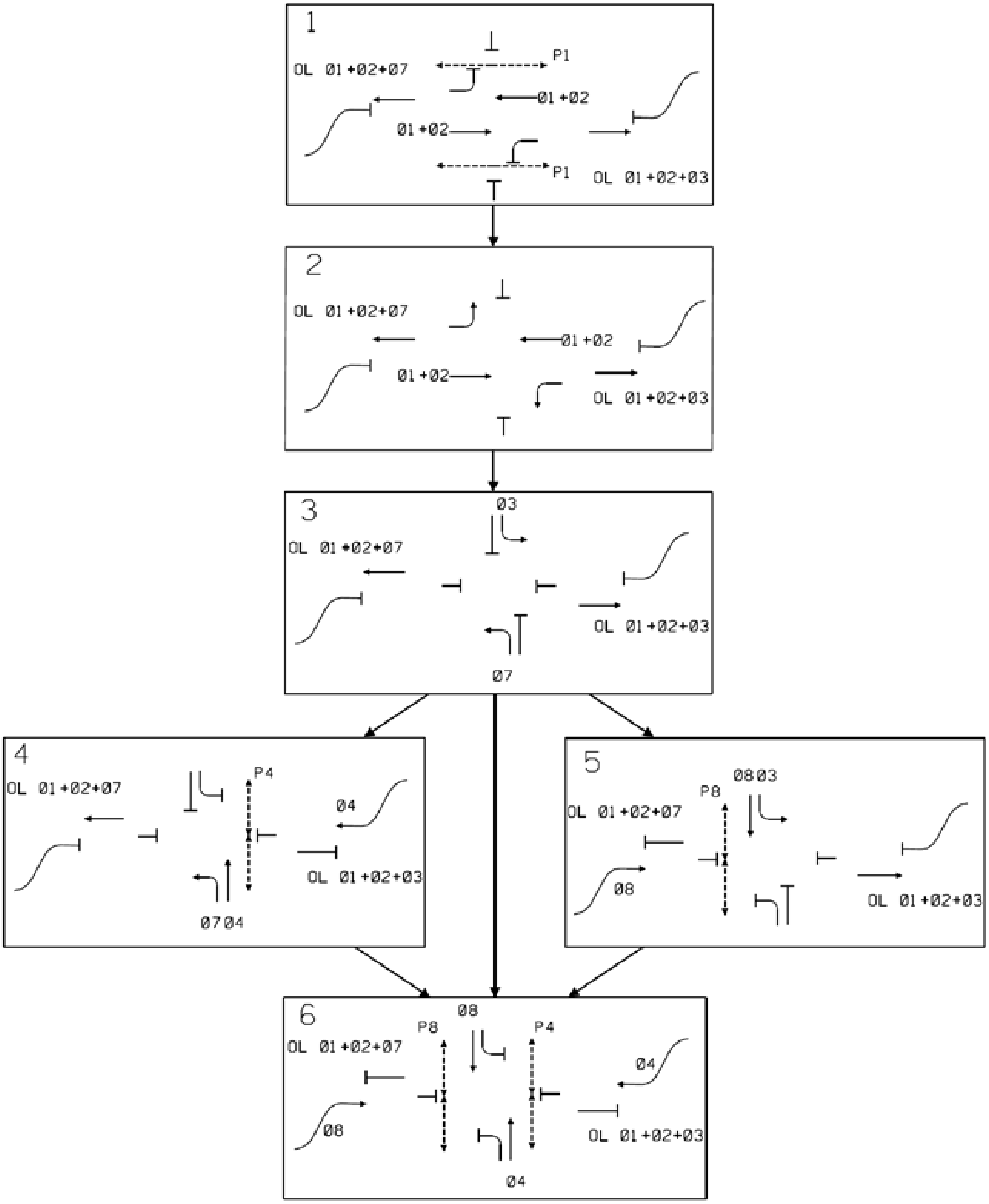


Figure 19. Illustration. Signal phasing for a partial DLT intersection with a single phase crossing for pedestrians.

Figure 20 is a schematic of suggested signal pole and mast arm locations in a box layout scheme for a full DLT intersection. One possible set of locations for pedestrian push-buttons is depicted in figure 20, and the reader is referred to section 4E.08 of *MUTCD* for further information.[8] Figure 21 shows an alternative strategy that was used for an existing DLT intersection at the junction of William Floyd Parkway and the entrance of Dowling NAT Center in Shirley, NY. It is a span wire system with pedestal poles located on one of the median islands for pedestrian push-buttons. Detectors were not installed for the right-turn movements or for the opposing through movement at the left-turn crossover. Figure 22 shows the suggested typical signal pole and mast arm locations in a box layout scheme for a partial DLT intersection.

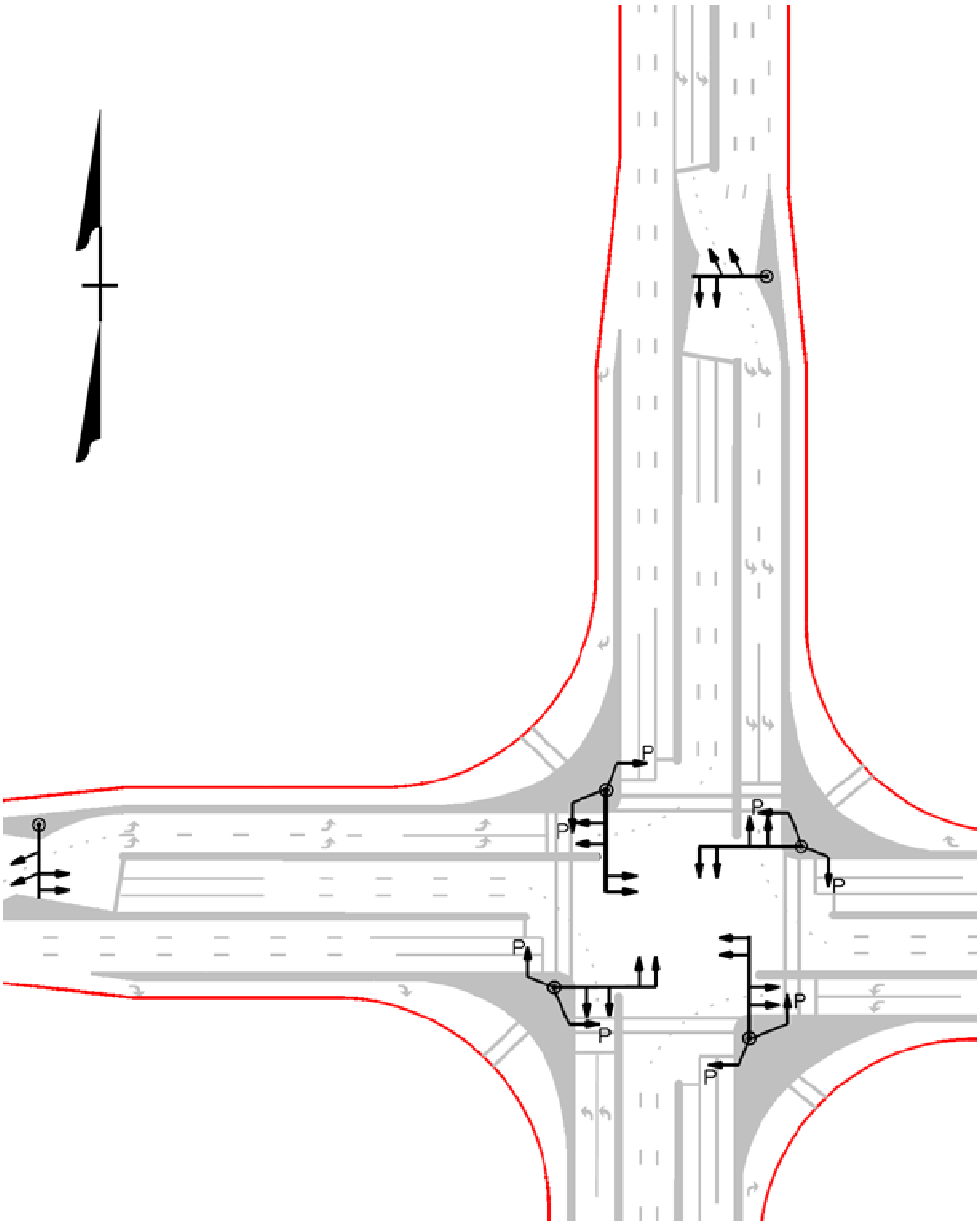
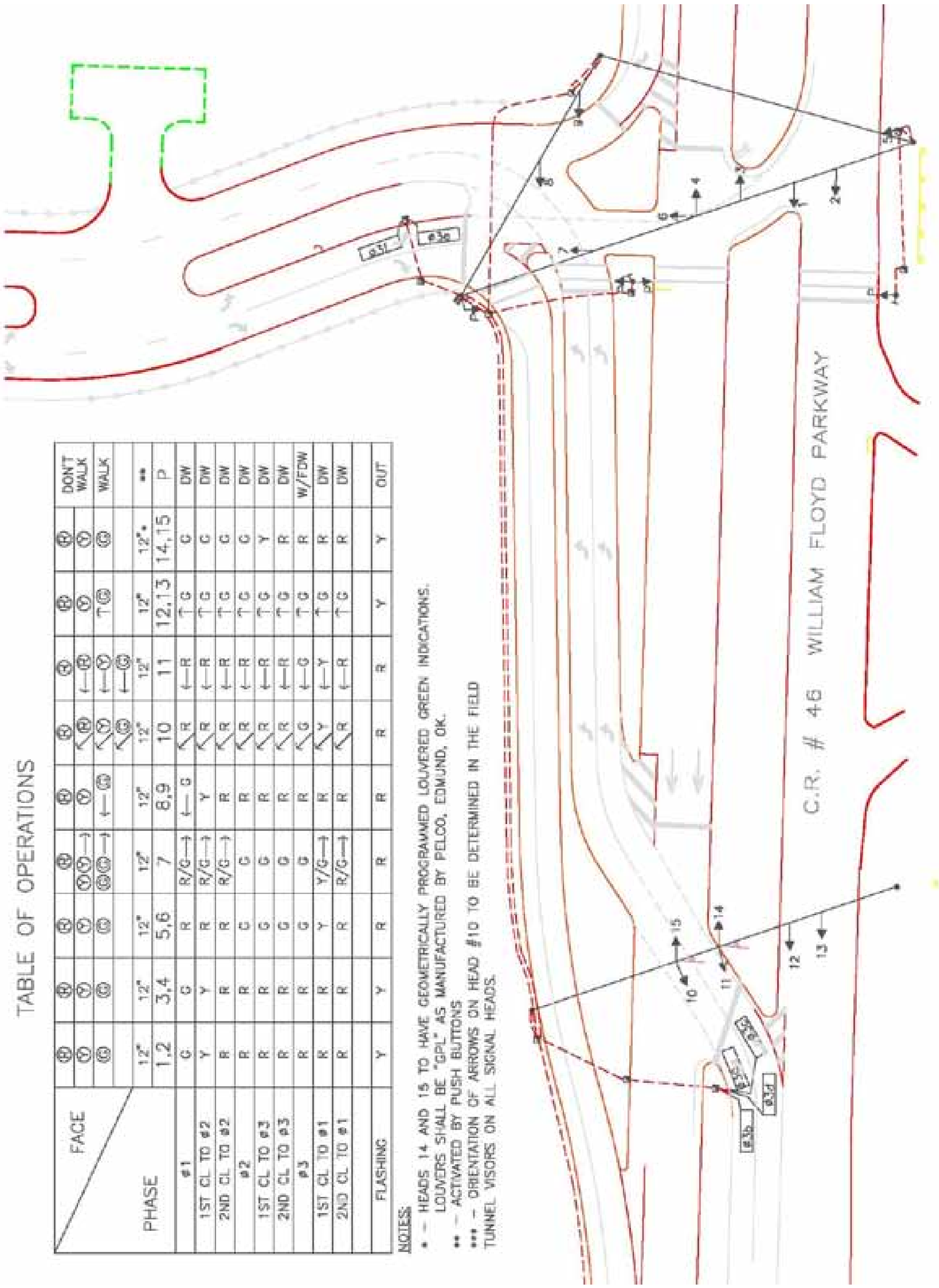


Figure 20. Illustration. Conceptual box layout signal pole and mast arm locations for a DLT intersection.



Source: LKM Associates, PC

Figure 21. Illustration. Existing span wire system at entrance of Dowling NAT Center in Shirley, NY.

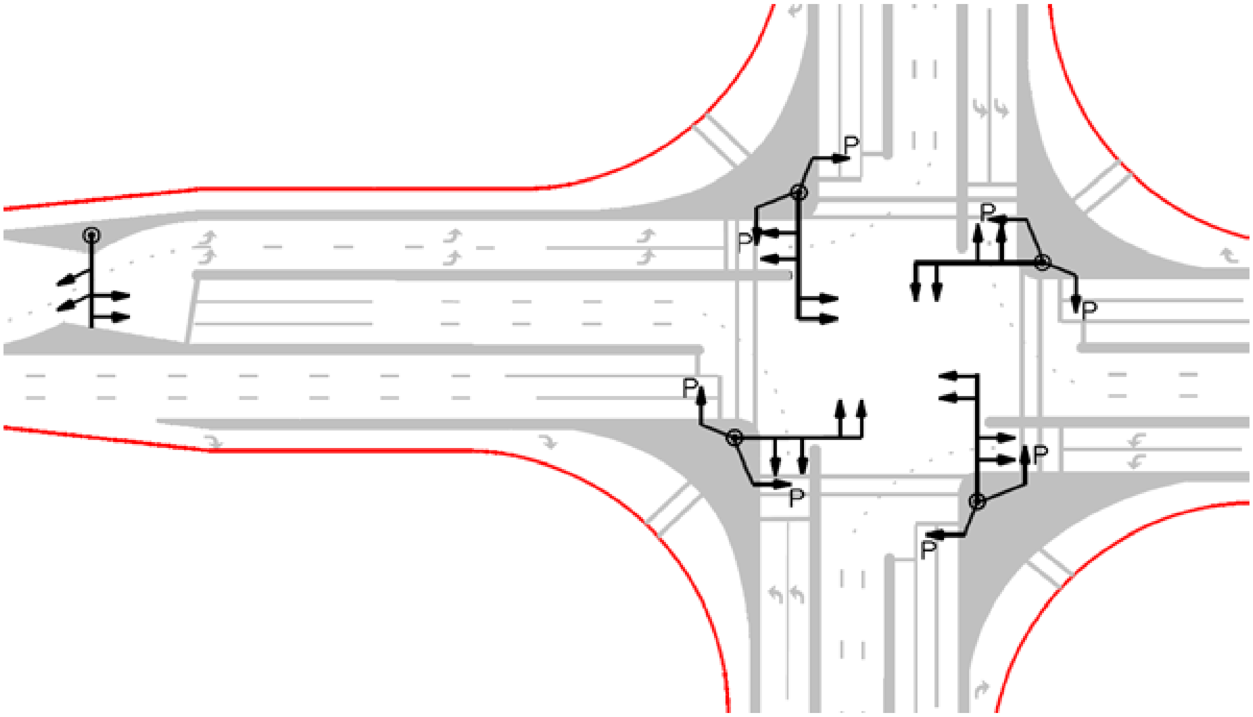


Figure 22. Illustration. Conceptual box layout signal pole and mast arm locations for DLT intersection.

Detector actuation depends on the type of operation. Figure 23 and figure 24 show the possible in-pavement, loop detector placement for multiple controllers and single controller for a full DLT intersection, respectively. Figure 25 shows the possible placement and detection technique for a partial DLT intersection. The DLT intersection at the intersection of U.S. Route 30 and Summit Drive uses video detection technology. An angular arrow signal display, as shown in figure 26, can be used to direct traffic at the left-turn crossovers.

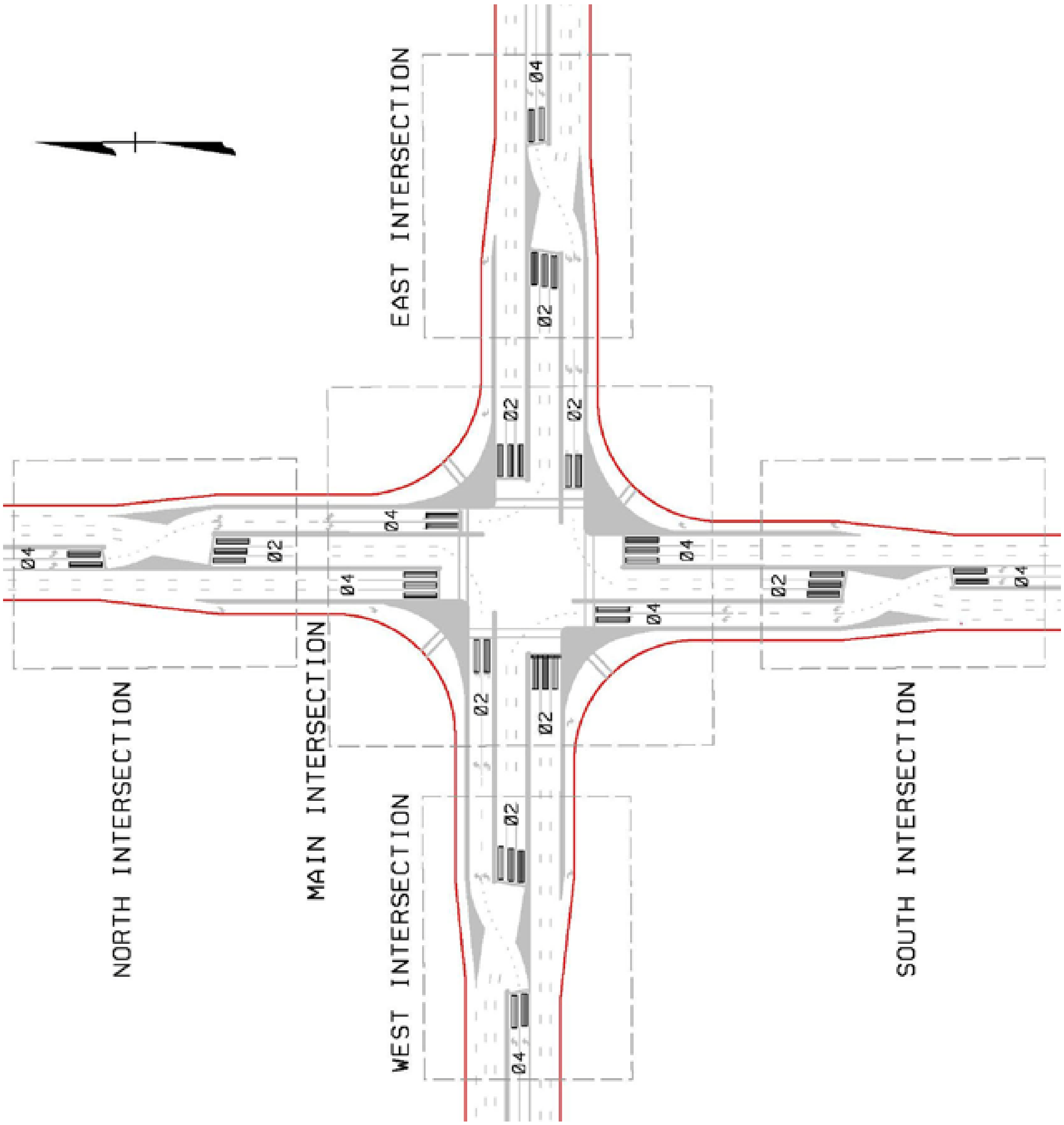


Figure 23. Illustration. Possible detector placement locations for DLT intersection with five separate controllers.

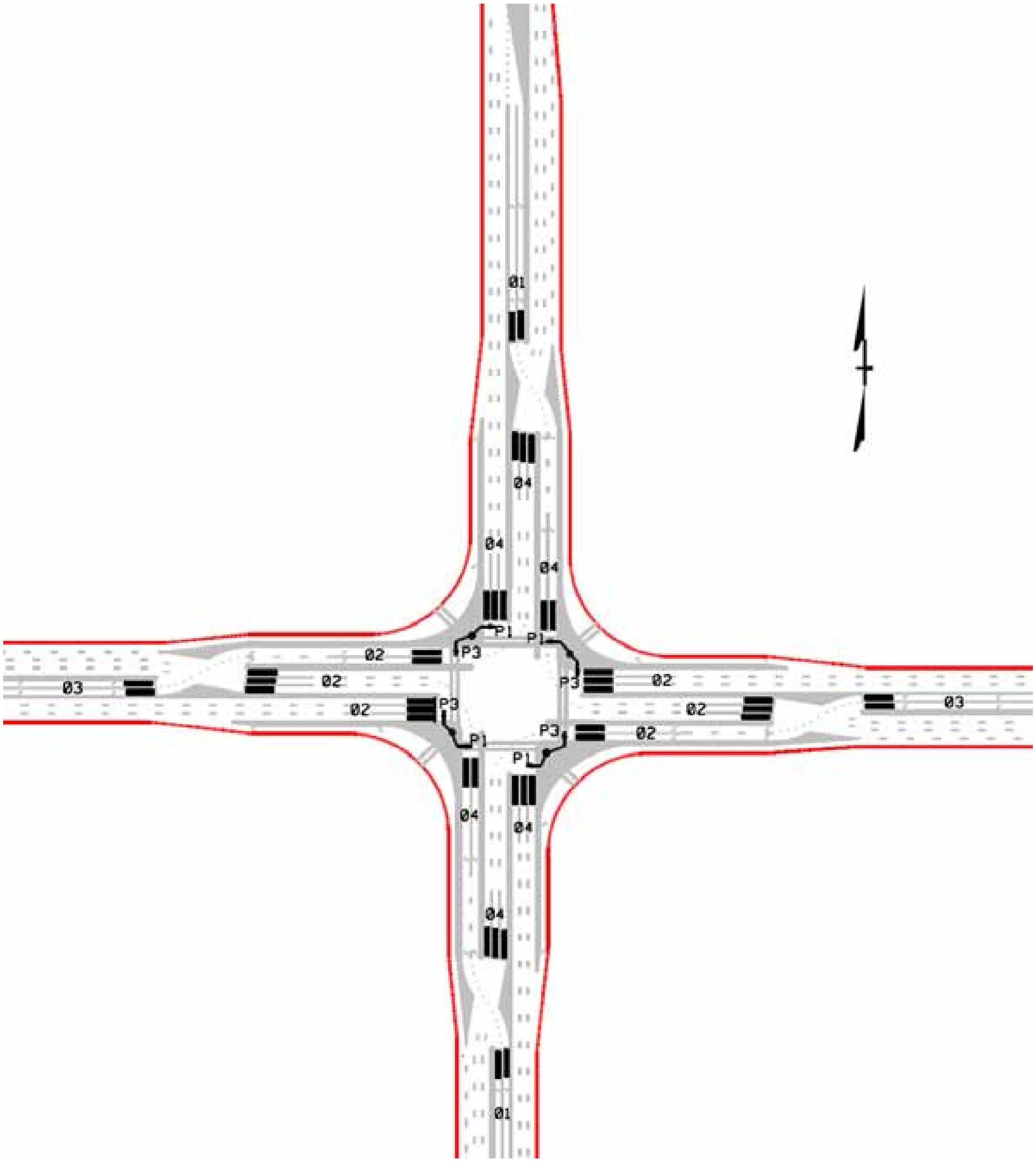


Figure 24. Illustration. Possible detector placement locations for a full DLT intersection with a single controller.

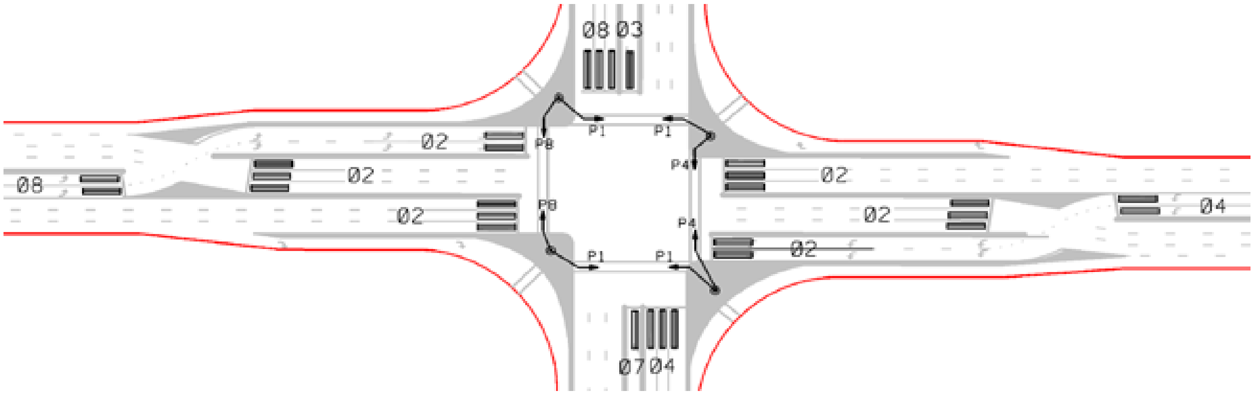


Figure 25. Illustration. Possible detector placement locations for a partial DLT intersection.

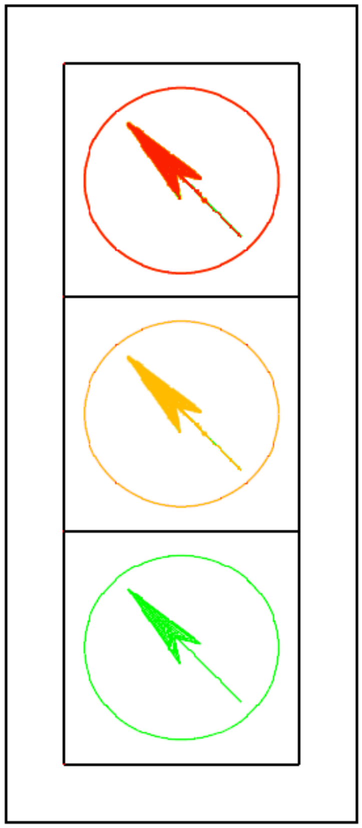


Figure 26. Illustration. Angular arrow signal display.

The geometry of the DLT intersection is different from a conventional intersection. The signal control at the main intersection typically operates as a two-phase signal with short cycle lengths conducive to good progression. Therefore, pedestrians cross the intersection in multiple crossing stages.(2) Existing literature describes alternative pedestrian signal strategies including clockwise and counterclockwise optimization of pedestrian flows at a DLT intersection.(14)

Typically, the crosswalks across the channelized right-turning roadways are installed without pedestrian push-buttons. The push-buttons for pedestrians to cross the major legs of the intersection are located on the channelizing islands which also serve as pedestrian refuges.

Figure 27 through figure 30 show various perspectives of the signal and mast arm locations at the DLT intersection in Accokeek, MD.

Figure 27. Photo. Signal pole locations at the cross junction at the intersection of MD 210 at MD 228 in Accokeek, MD.

Figure 28. Photo. Signal pole locations at the main intersection of MD 210 at MD 228 in Accokeek, MD.

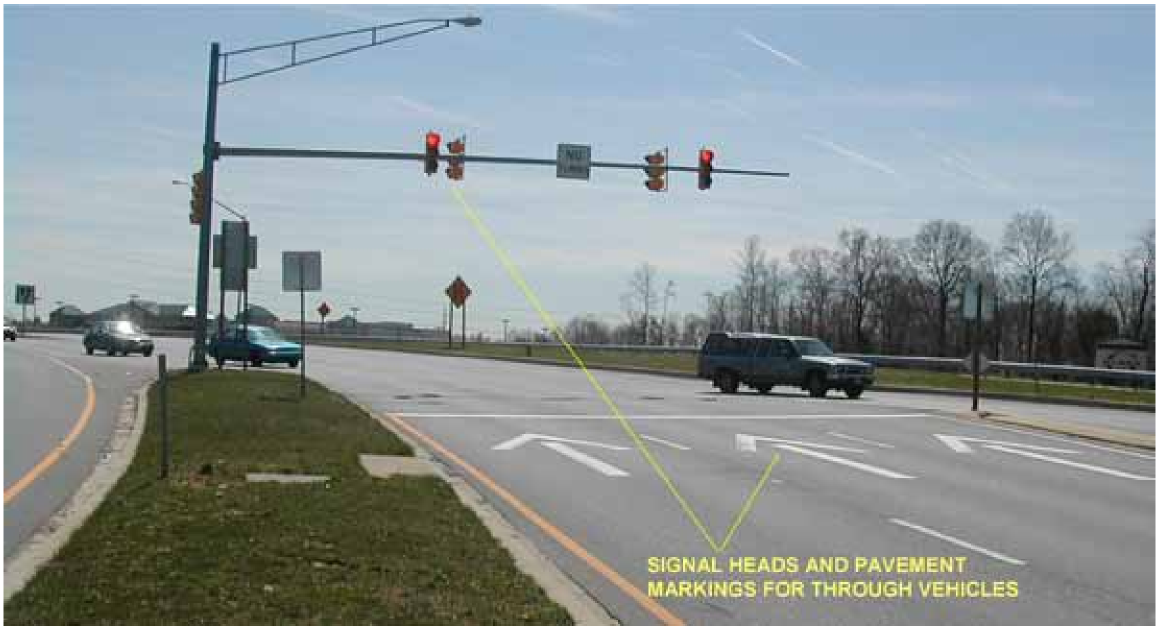


Figure 29. Photo. Signal pole locations at the intersection of MD 210 at MD 228 in Accokeek, MD.

Figure 30. Photo. Signal pole locations at the main intersection viewed from the minor street approach.

2.4.2 Signing and Marking

Signing and marking at a DLT intersection can be significantly different compared to a conventional intersection, particularly related to the midblock left-turn crossovers and the turning restrictions at the main intersection. Emphasis must be given to wrong-way pavement markings and signing to warn drivers of turn prohibitions. Overhead signing and post mounted signing are the primary methods of guidance. Pavement markings and overhead lane use signs on signal mast arms are the supplementary method of guidance.

Figure 31 shows the signing and marking plan based on MDSHA guidance for one direction of travel only on a main street and a side street approach. Figure 32 shows the existing signing and marking as it was implemented at the DLT intersection in Baton Rouge, LA, consisting of several right-in and right-out turning restrictions at driveways.

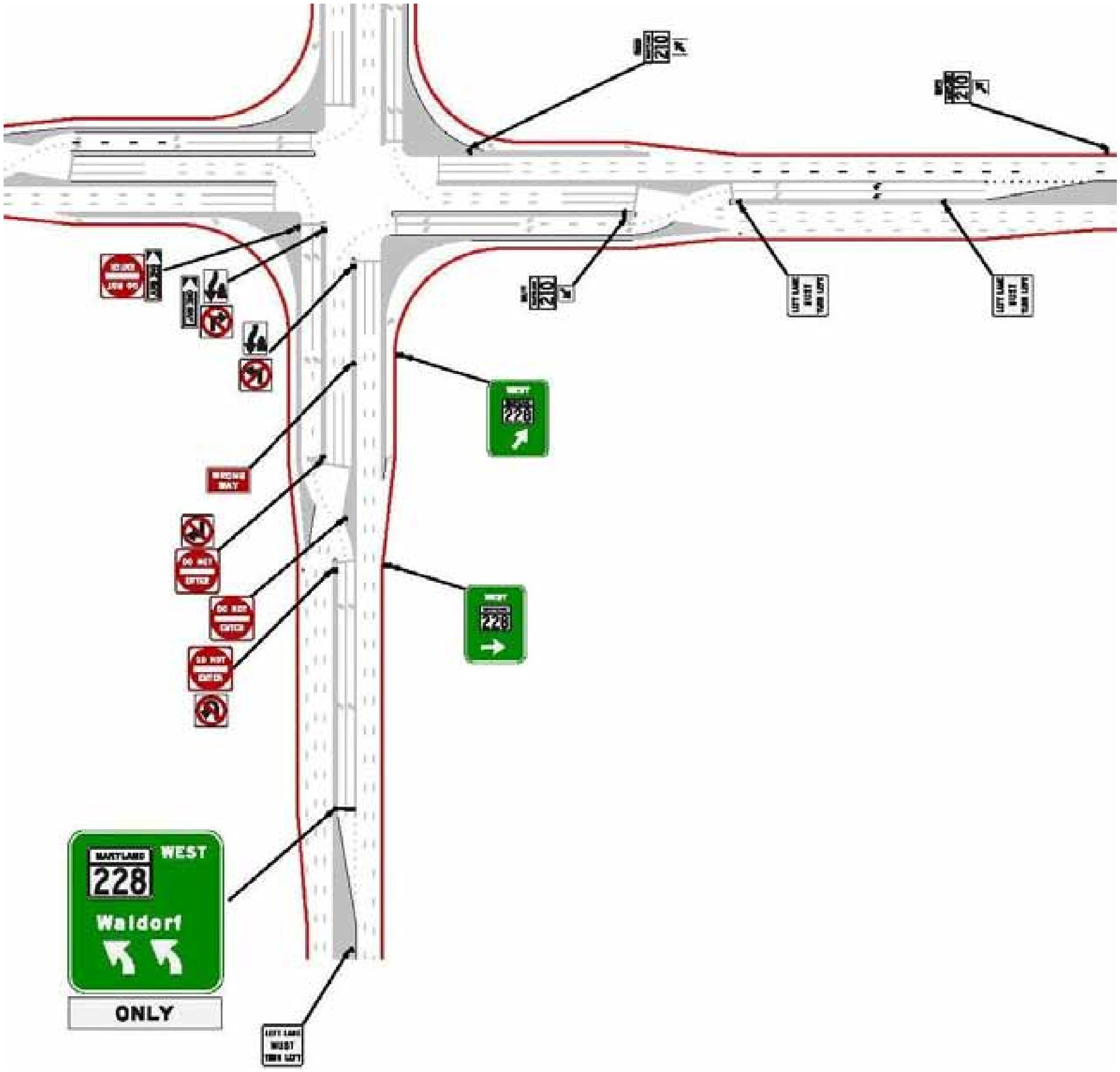


Figure 31. Illustration. DLT intersection signing and marking plan derived from Maryland practice.

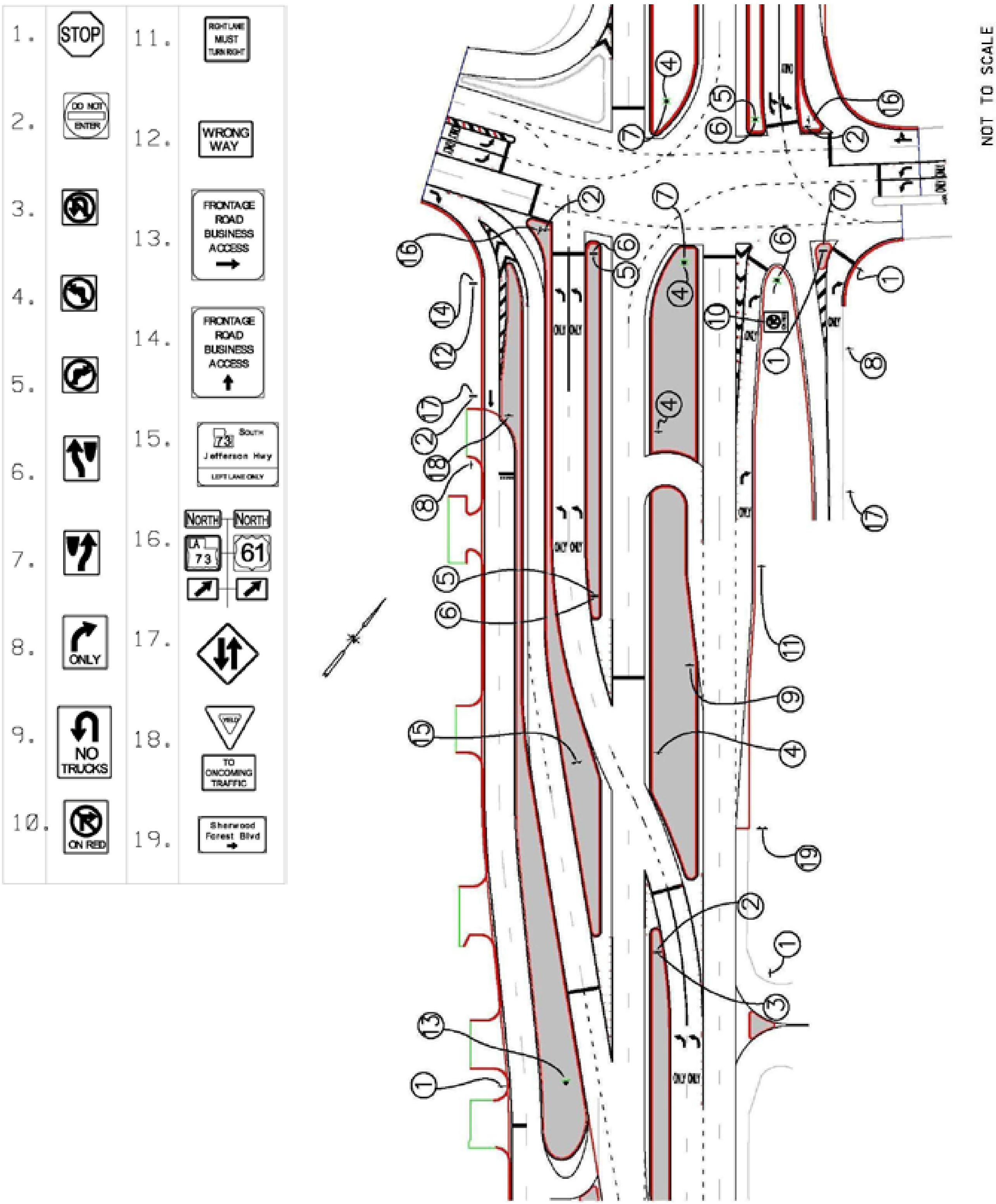


Figure 32. Illustration. Ground-mounted signing and marking as used at the DLT intersection in Baton Rouge, LA.

Photographs of overhead signing and pavement markings that are present at the DLT intersection in Baton Rouge, LA, are shown in figure 33 through figure 35.

Figure 33. Photo. Overhead signing at the DLT intersection in Baton Rouge, LA.[11]

Figure 34. Photo. DLT overhead signing at DLT intersection in Baton Rouge, LA.[11]

Figure 35. Photo. Pavement markings on the displaced left-turn lanes at DLT intersection in Baton Rouge, LA.(11)

2.5 ACCOMMODATION OF PEDESTRIANS, BICYCLISTS, AND TRANSIT USERS

Pedestrian movements at a DLT intersection are typically accommodated as shown in figure 36. The locations of pedestrian paths are depicted in figure 36 as well. At a DLT intersection, the position of the left-turn lanes between the opposing through lanes and right-turn lanes can be counterintuitive to pedestrians. In addition, the wide geometric footprint of the DLT intersection combined with short signal cycle lengths can accommodate pedestrian crossing efficiently. Median islands, if available, can provide pedestrian refuge.

Figure 36 shows the pedestrian crossing paths between the four quadrants. Crossing the street diagonally (for example, between quadrant A and D) requires pedestrians to cross two streets. The crossing procedure is as follows:

1. The pedestrian must cross a channelized right-turn roadway to a pedestrian refuge island.

2. The pedestrian then crosses the first street that offers a "Walk" signal (either the side street or main street to quadrants B or C) to the pedestrian refuge island on the opposite side. The pedestrian crosses the through lanes and left-turn lanes of the street.

3. The pedestrian crosses the second street (to A or D) by crossing the through lanes and left-turn lanes to the diagonally opposite pedestrian refuge island.

4. The pedestrian completes the crossing procedure by crossing a right-turning roadway.

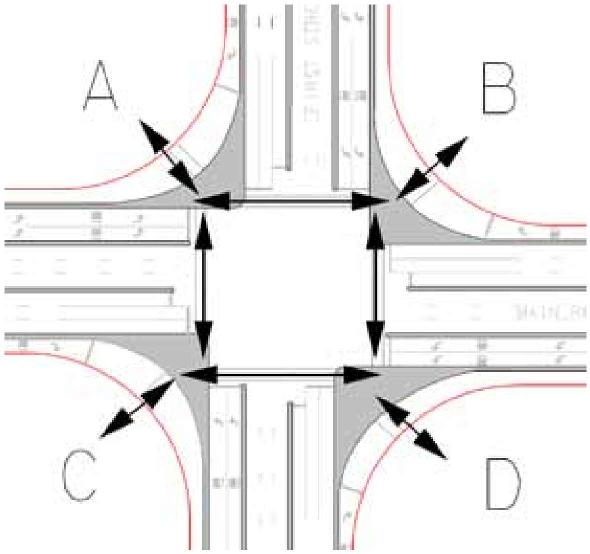


Figure 36. Illustration. Possible pedestrian movements at a DLT intersection.

The method of crossing a DLT intersection is similar to a traditional intersection design. Several measures, as described in the following paragraphs, should be considered to increase pedestrian safety.

2.5.1 Provide Pedestrian Refuges Between Opposing Through Lanes to Increase Pedestrian Safety and Minimize Vehicular Delay

Crosswalks can be installed across all four legs. If pedestrian crossing times cause long vehicular delays, multiple-stage crossings could be facilitated at a DLT intersection by providing pedestrian refuges in a median between the opposing through lanes of an approach.

2.5.2 Provide Wayfinding Signing for Pedestrians

Signing to facilitate pedestrian wayfinding can help direct pedestrians through the intersection and to desired destinations. Providing adequate wayfinding signing is important given that most pedestrians initially are unfamiliar with the designated crossing patterns of a DLT intersection design. Adequate signing helps reduce pedestrian confusion and may encourage pedestrians to use designated travel paths through the intersection.

2.5.3 Design Right-Turn Channelized Islands to Accommodate Pedestrians

Right-turn channelizing islands can enhance pedestrian safety by allowing pedestrians to cross a right-turn lane separately using the channelized island for refuge. However, this could also create potential hazards for pedestrians if the island is designed to favor the movement of vehicles as follows:

- A wide turn radius.
- A flat entry angle leaving the right turn.
- Wide lanes.

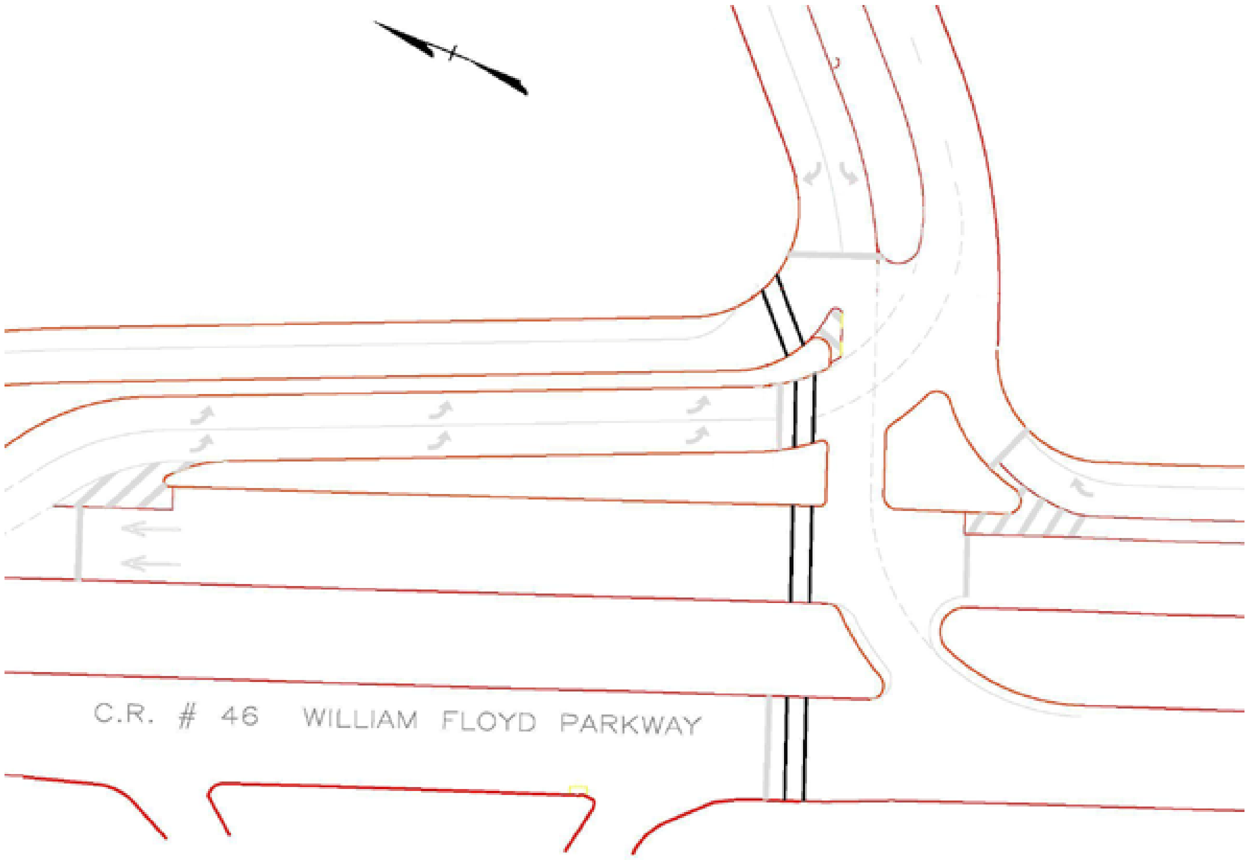
Configuring the right-turn lane with a tighter radius and narrower lanes can help reduce the speed of turning vehicles and provide better visibility for drivers of crossing pedestrians. The right-turn lane can also operate under traffic signal control. This improves the overall safety for pedestrians and reduces crossing distance.

2.5.4 Provide Accessible Devices to Assist Disabled Pedestrians

Pedestrians with vision and cognitive impairments may find crossing a DLT intersection challenging. Pedestrians with cognitive impairments may have trouble differentiating the presence of left-turn lanes from opposing through and right-turn lanes. With this in mind, locator tones can be used at the pedestrian signals, and specialized surface treatments on ramps can be located at the quadrants and median refuges to assist with differentiation. APS are recommended as well. Readers are directed to the *American with Disabilities Act Accessibility Guidelines* (specifically sections 4 and 10 on accessible elements and spaces and transportation facilities, respectively), available on the U.S. Access Board's Web site for extensive information on accommodating visually impaired pedestrians.(15)

Results of previous research indicate that overall pedestrian flow at a DLT intersection is improved greatly with shorter signal cycle lengths.(14) Pedestrian crosswalks, as implemented at the DLT intersection at the entrance of Dowling NAT Center in Shirley, NY, are shown in figure 37.

With the unusual geometry, the DLT intersection may cause several problems after its initial opening to users familiar with the conventional four-leg intersection. Public information distributed prior to opening of a DLT intersection treatment can help alleviate concerns and raise citizens' understanding and awareness of this design. Public information for pedestrians and bicyclists was disseminated with the help of flyers before the scheduled opening of the DLT intersection in Salt Lake City, UT.



Source: LKM Associates, PC

Figure 37. Illustration. Pedestrian crosswalks as implemented at DLT intersection at the entrance of Dowling NAT Center, Shirley, NY.

Bicyclists can be accommodated on the street in a DLT intersection. Off-roadway bicycle paths or shared-use paths can be accommodated if they are designed to cross at appropriate locations at the DLT intersection (e.g., at stoplines where conflicting traffic movements enter). Typical locations of a shared-use path crossing would be the same as the locations of crosswalks as previously depicted in figure 36.

Transit and school buses operating through a DLT intersection may be challenged when serving passengers in the immediate intersection area. For the most part, bus stops need to be located relatively far from the crosswalks at the intersection, either upstream of left-turn crossovers or downstream of the intersection beyond the crossover for the opposing direction. Figure 38 shows the potential location of a transit stop for one approach of a DLT intersection. More detail on bus stops follows:

- Bus stops upstream of an intersection approach that do not have a left-turn crossover are not affected.

- For existing at-grade intersections with bus stops along the route, retrofitting the intersection with a DLT intersection may result in the relocation of bus stops to locations upstream or downstream on approaches with crossovers, which affects buses making left turns at the intersection.

- For bus routes proceeding straight on the mainline, the right-turn lane upstream of the intersection can be used as the bus stop.

- For bus routes turning right on an approach, the right-turn lane or the right-turn acceleration lane can be used as the bus stop. This requires designing the right-turn lane to accommodate pedestrians (discussed earlier in this section) because passengers often proceed from the stop to the intersection to cross and would be crossing the right-turn lane. Since the bus stop has the potential to temporarily impede right-turning traffic, a pullout may be appropriate. The pullout can be located in the acceleration lane downstream of the right turn.

A disadvantage to locating transit stops further from the pedestrian crossing points at the intersection is that passengers are more likely to cross the street at the bus stop than if the stop is closer to the intersection. Crossing at a midblock, unprotected location presents hazards to pedestrians at any type of intersection. However, at a DLT intersection, it is possible that the midblock location may be through the paths of left-turning vehicles approaching the crossover (as in shown in figure 38). Pedestrians walking through vehicles queued at the crossover would not be expected by approaching through traffic, and the pedestrian’s view of approaching through traffic could be obstructed by taller vehicles in the left-turn queue. Installing a barrier in the median would discourage pedestrians from crossing midblock.

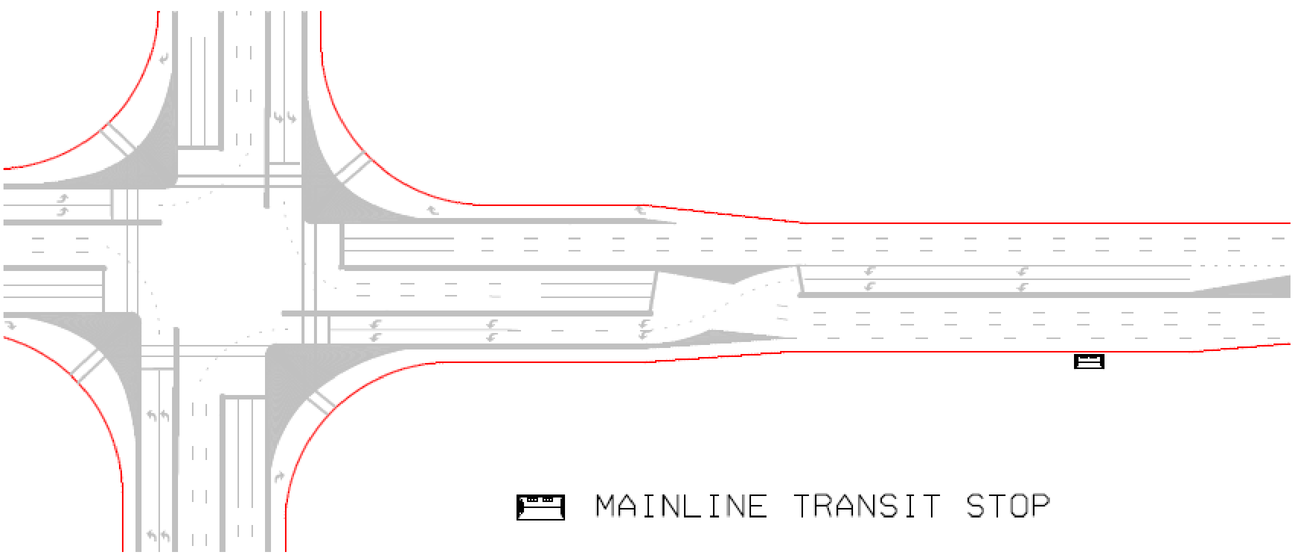


Figure 38. Illustration. Possible transit stop location in a DLT intersection.

2.6 OPERATIONAL PERFORMANCE

This section discusses the situations in which a DLT intersection can be expected to have improved performance over a conventional intersection. The discussion is based on a review of research on the DLT intersection and also on results of simulation studies of the intersection design.

2.6.1 Review of Previous Research

Several studies have examined the operational and other benefits of the DLT intersection. For highly unbalanced left-turn and through volumes on the DLT approaches or when the overall intersection volumes were low, the conventional intersection outperformed the DLT intersection. However, when the left-turn and through volumes on the DLT approaches volumes were high and balanced, the DLT intersection was found to operate better than the conventional intersection.(14) A summary of the benefits identified by the studies is presented below, grouped by category.

2.6.1.1 Capacity

Two studies published in 1994 concluded that with high volumes of conflicting movements, the DLT intersection was greatly superior to the conventional intersection, and the advantages of a DLT intersection over a conventional intersection were most pronounced when the traffic demand approached or exceeded the capacity of conventional designs and when heavy left-turn movements required protected phases.(15,3) The 1996 *Traffic Control Systems Handbook* cited a study comparing the performance of traffic operations at a DLT intersection with that of operations at a similar conventional intersection.(17) The study indicated a 60 percent increase in capacity at the DLT intersection. Another report referred to the DLT intersection as the dispersed movement intersection (DMI) and concluded that this type of intersection "can provide comparable capacity at a fraction of the cost of a grade separation."(18) The report also mentioned that the DLT intersection increased capacity without compromising safety. A 2001 report stated that the displaced right-turn junction (in Great Britain) was a multinode intersection which improved overall junction capacity through the removal of conflicts at the center of the intersection.(2)

A 1974 study in Great Britain examining right-turn capacity (equivalent to left turns in the United States) found an increase in right-turn capacity and a reduction in delay, especially at high right-turn volumes.(19) A 1994 study showed that the capacity of the upstream signalized crossover was approximately twice that of the turning volume of a conventional intersection with similar geometry and balanced traffic volumes.(15)

2.6.1.2 Travel Time, Delay, and Speed

In 1974, Hutchinson noted that "the results clearly support the claims of Al Salman and Salter, showing a great increase in capacity for right-turners (Great Britain) and a corresponding reduction in delay, particularly at high flows for right-turners."(19) The *Traffic Control Systems Handbook* reported that a study had found significant increases in average speed for the DLT intersection.(17) In 1998, Reid and Hummer compared unconventional intersections to their conventional counterparts and suggested that "the displaced left-turn intersection always had the highest move-to-total-time-ratio of all designs." (20)

Other benefits noted by the *Traffic Control Systems Handbook* were substantial reductions in auto emissions for the DLT intersection.(17) Reid and Hummer also suggested that "the displaced left-turn intersection probably needs the smallest right-of-way of all the unconventional designs (quadrant roadway intersection, median U-turn, super street median, bowtie, jug-handle, split intersection and displaced left-turn intersection)" that they examined.[20]

2.6.2 Analysis of Simulation Results

VISSIM®, a microscopic traffic simulation software, was used to gain insights into the operational performance of a DLT intersection in comparison to conventional intersections. Four intersection geometric scenarios of DLT intersections and conventional intersections were simulated. Table 2 shows the geometric design configurations of the cases simulated. The lane configurations and geometric features of the DLT intersections and conventional intersections on the approaches of the major roads and the minor roads were identical for each case. These four geometric cases with three major road directional splits were simulated under three sets of traffic volumes: low, medium, and high. The major and minor road splits were set at 50 percent each for all simulation cases. Therefore, a total of 16 unique sets of simulation conditions were developed for the DLT intersection, and an equal number of unique VISSIM® simulations were developed for comparable conventional intersections (see figure 3). The VISSIM® simulation network was 1 mi long on the major and minor road approaches for the cases simulated. The base case simulations assumed no pedestrian activity at the intersection. A discussion of the simulation results for all of the geometric design cases is provided in this section. In addition to the use of typical VISSIM® defaults, the following constants were maintained for each simulation:

- Optimum fixed signal timing determined using Synchro®.[21]
- Yellow times determined using ITE policy.
- All-red times determined using ITE policy.
- A total of 5 percent heavy vehicles on all legs.
- A total of 350-ft left-turn bay lengths upstream of the displaced crossover junction.
- A total of 325-ft left-turn bay lengths downstream of the displaced crossover junction.
- A network size of 0.5 mi in each direction from the main intersection.
- Single right-turn bays on the mainline.
- Right turn on red allowed at each signal. No left turn on red allowed.
- A signal at each displaced left-turn crossover.
- A 40-ft median width on mainline.
- Undivided side street.
- A 45 mi/h desired speed on mainline.
- A 25 mi/h desired speed on side street.

- Saturation headway of approximately 1,900 vehicles per hour per lane (veh/h/lane).
- No bus stops.
- Seeding time of 30 minutes for the simulations.
- Running period of 60 minutes for the simulations.

The four cases modeled were as follows:

1. Intersection of a six-lane major road and a six-lane minor road with four corresponding DLTs (one on each approach).
2. Intersection of a six-lane major road and a four-lane minor road with only two opposing DLTs (one on each approach of the major road).
3. Intersection of a six-lane major road and a four-lane minor T-leg with the DLTs on the major road.
4. Intersection of a four-lane major road and a four-lane minor road with only two opposing DLTs (one on each approach of the major road).

Table 2. Geometric design configuration for VISSIM® simulation.

Geometric Design Cases	Approach Configuration					
	Major Road			Minor Road		
	DLT intersection and Conventional Intersection					
	Through Lanes	Left-Turn Lanes	Right-Turn Lanes	Through Lanes	Left-Turn Lanes	Right-Turn Lanes
A	3	2	1	3	2	1
B	3	2	1	2	1	1
C	3	2	1	2	2	1
D	2	1	1	2	1	1

Table 3. Volumes for geometric design configuration for VISSIM® simulation—full DLT intersection.

Geometric Cases		Turning Movement Volume Set (veh/h)	Major Road Approach 1 Volume* (veh/h)	Major Road Approach 2 Volume* (veh/h)	Total Minor Road Volume** (veh/h)	Major Road Approach 1 Volume/Total Major Road Volume (veh/h)	Total Minor Road Volume/Total Intersection Volume (veh/h)
A	Three-lane major road, two left-turn lanes on major road, and three-lane minor road approaches	1	1,000	1,000	1,000	0.50	0.33
		2	1,750	1,750	1,500	0.50	0.30
		3	2,500	2,500	2,000	0.50	0.29
		4	3,500	3,500	7,000	0.50	0.50
		5	3,500	1,500	7,000	0.70	0.58
B	Three-lane major road, two left-turn lanes on major road, and two-lane minor road approaches	1	750	750	500	0.50	0.25
		2	1,500	1,500	1,500	0.50	0.33
		3	2,750	2,750	3,500	0.50	0.39
		4	3,000	3,000	4,000	0.50	0.40
		5	3,000	1,286	4,000	0.70	0.48
C	Three-lane major road, one left-turn lane on major road, and two-lane minor road approaches	1	1,000	1,000	500	0.50	0.20
		2	1,750	1,750	2,000	0.50	0.36
		3	2,500	2,500	3,000	0.50	0.38
		4	2,500	1,071	3,000	0.70	0.46
D	Three-lane major road, two left-turn lanes on major road, and two-lane minor road approaches	1	750	750	500	0.50	0.25
		2	1,500	1,500	1,500	0.50	0.33
		3	2,500	2,500	1,500	0.50	0.23
		4	3,000	3,000	4,000	0.50	0.40
		5	3,000	1,286	4,000	0.70	0.48

* A constant right-turn volume of 300 has been used and is excluded from the major road volumes shown.
** Both minor road approaches have the same volumes.

2.6.3 Geometric Design Case A Simulation

The DLT intersection simulated for this design case had three through lanes, two left-turn lanes, and one right-turn lane per approach for all four approaches. The DLT lane before the main intersection had a length of 325 ft, the right-turn bay had a length of 250 ft, and the left-turn bay before the separation of the DLT had a length of 350 ft. All acceleration lanes for right-turning vehicles were 300 ft long. The median separating the opposing through lanes was 10 ft wide, the median separating the through lanes from the DLT lanes was 10 ft wide, and the median separating the through lanes from the right-turn lane was 6 ft wide. The comparable conventional intersection had similar geometric features and dimensions as the DLT intersection described above on all four approaches.

The traffic flows on the approaches of the DLT intersection were randomly generated. A large number of cases modeled had directional flows to replicate peak hour directional flows at intersections. The total cycle length for all scenarios was 70 s. The ranges in traffic volumes used for each approach by movement were as follows:

- Left-turn movement: 100–750 veh/h.
- Through traffic movement: 300–2,650 veh/h.
- Right-turn movement: 50–350 veh/h.

The results for the full DLT intersection are summarized in figure 39. In addition, a partial DLT intersection was also evaluated. The results are shown in figure 40.

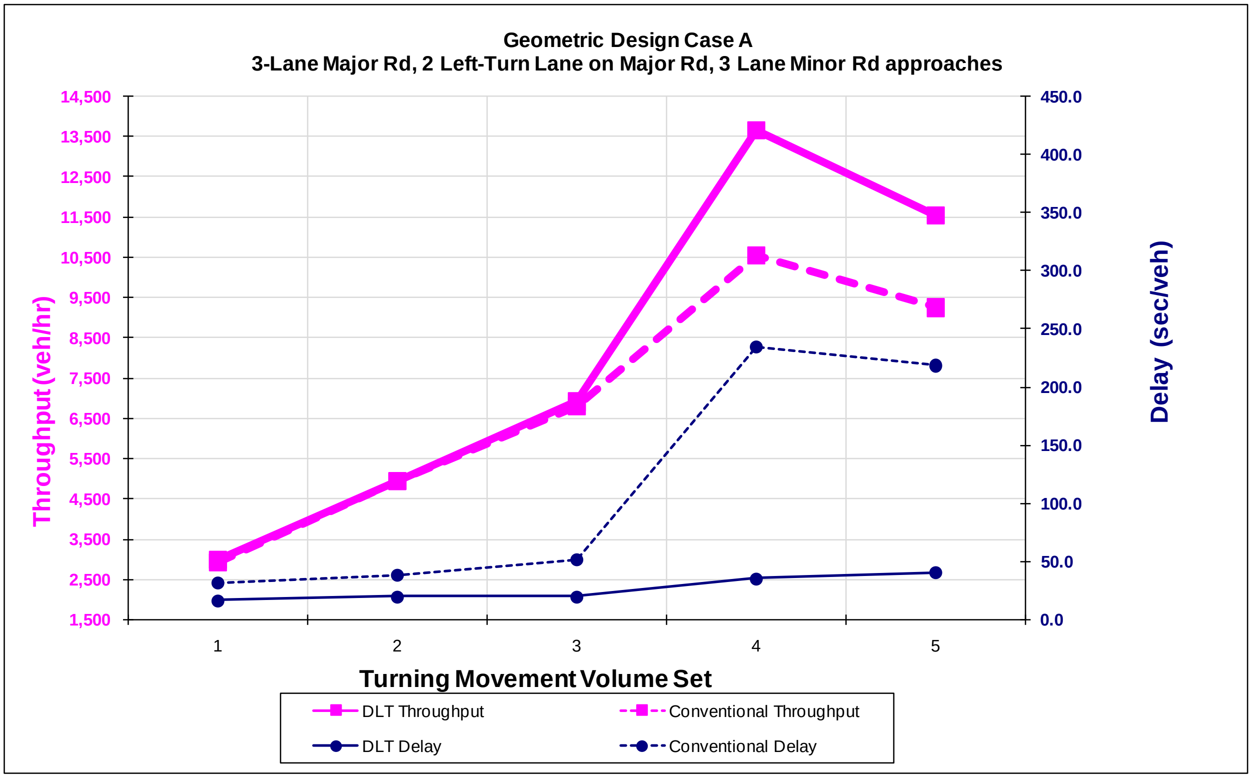


Figure 39. Graph. Throughput and delay comparisons for geometric design case A—full DLT intersection.

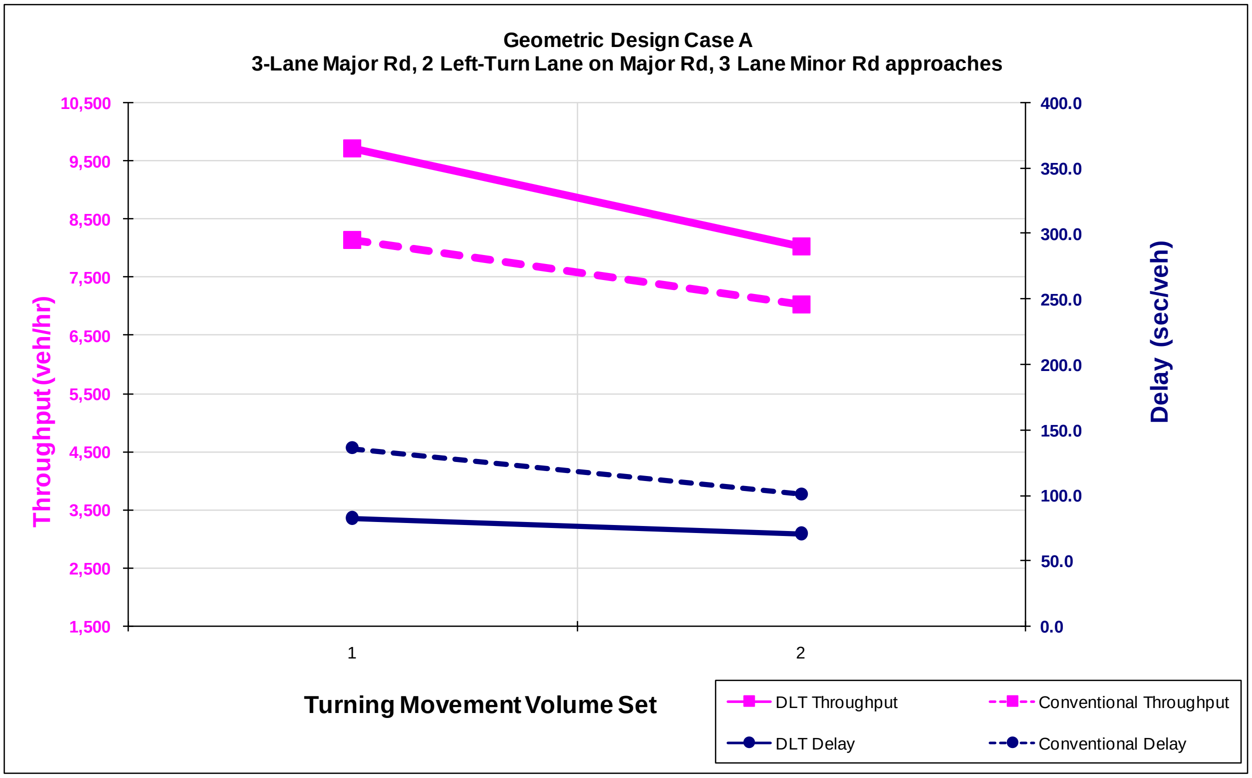


Figure 40. Graph. Throughput and delay comparisons for partial DLT intersection geometric design case A.

2.6.4 Geometric Design Case B Simulation

The intersection had three through lanes, two-left-turn lanes, and one right-turn lane per approach for the two major road approaches. The DLT lane before the main intersection had a length of 325 ft, the right-turn bay had a length of 275 ft, and the left-turn bay before the separation of the DLT had a length of 350 ft. The acceleration lanes for the right-turning vehicles were 300 ft in length. The two minor road approaches were configured as a conventional geometric design with two through lanes, one left-turn lane, and one right-turn lane. For the minor road approaches, the length of the right-turn bay was 3 ft, and the left-turn bay was 350 ft. The median separating the opposing through lanes was 10 ft wide, the median separating the through lanes from the DLT lanes was 10 ft wide, and the median separating the through lanes from the right-turn lane was 6 ft wide. The comparable conventional intersection had similar geometric features and dimensions as the DLT intersection described above on all four approaches.

The traffic flows on all the approaches were randomly generated. A large number of cases modeled had directional flows to replicate peak hour directional flows at intersections. The cycle length used for all scenarios was 80 s.

The ranges of traffic volumes used for each approach by movement were as follows:

- Major road left turns: 100–700 veh/h.
- Major road through traffic: 300–2,200 veh/h.
- Major road right turns: 50–350 veh/h.
- Minor road left turns: 50–200 veh/h.
- Minor road through traffic: 50–1,200 veh/h.
- Minor road right turns: 50–250 veh/h.

The results for a full DLT intersection for case B are shown in figure 41. The results for a partial DLT intersection for case B are shown in figure 42.

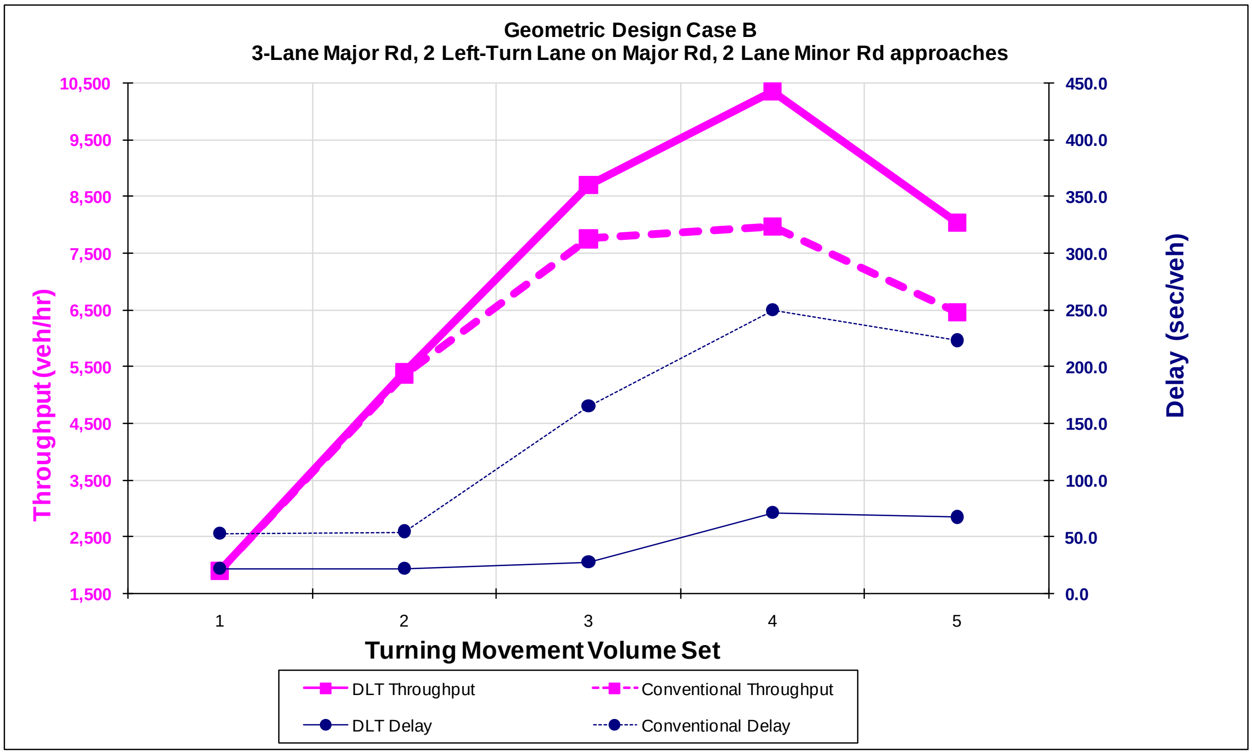


Figure 41. Graph. Throughput and delay comparisons for geometric design case B—full DLT intersection.

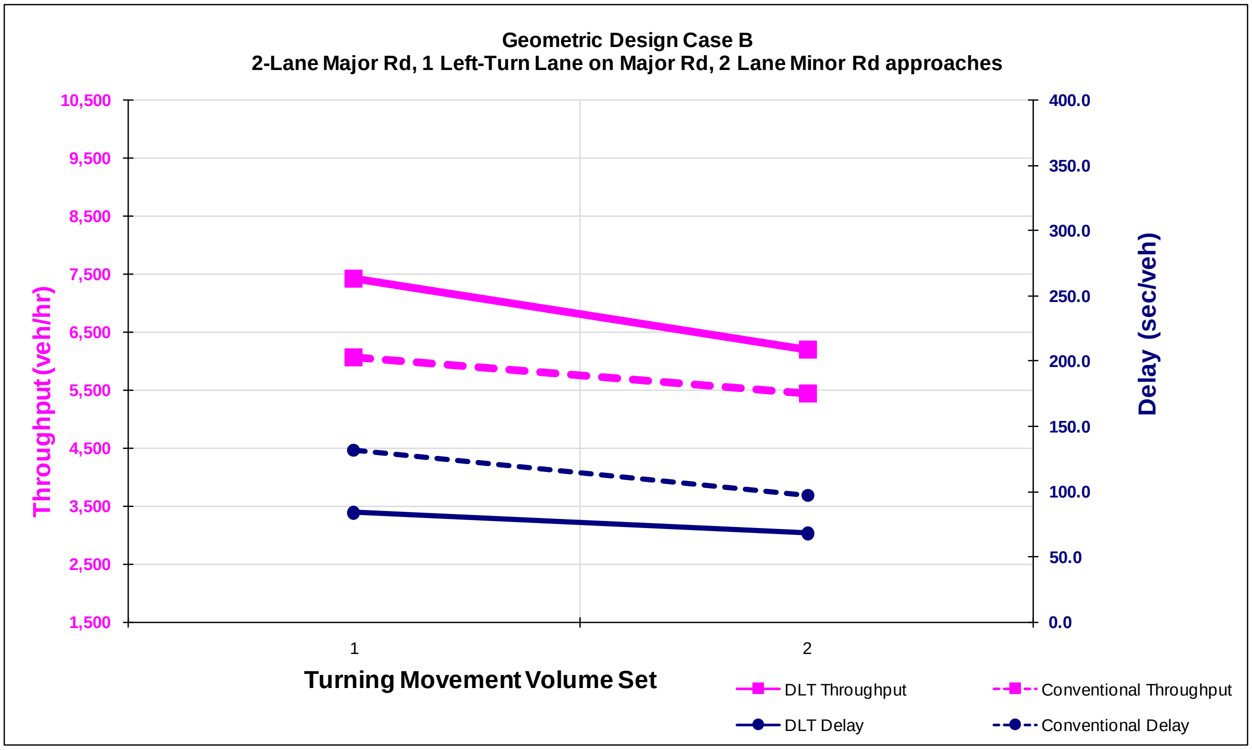


Figure 42. Graph. Throughput and delay comparisons for partial DLT intersection geometric design case B.

2.6.5 Geometric Design Case C Simulation

Case C modeled a T-intersection. There were three through lanes per direction on the major road with DLT lanes on one major road approach and one right-turn lane on the other major road approach. The minor road approach had two left-turn lanes and one right-turn lane (see figure 8). The DLT lane before the main intersection had a length of 325 ft, the right-turn bay on the major road had a length of 300 ft, and the left-turn bay before the separation of the DLT had a length of 350 ft. The acceleration lane for the right-turning vehicles was 300 ft long. The minor road approach had a conventional geometric design with two left-turn lanes and one right-turn lane. The length of the left-turn bay on the minor approach was 350 ft. The median separating the opposing through lanes was 10 ft wide, and the median separating the through lanes from the right-turn lane was 6 ft wide. The geometry could be further improved if a separate acceleration lane was provided for the right-turning vehicles from the main road. The comparable conventional intersection had similar geometric features and dimensions as the DLT intersection described above on all three approaches.

The traffic flows on all approaches were randomly generated. A large number of cases modeled had directional flows to replicate peak hour directional flows at intersections. The cycle length for all scenarios was 70 s.

The ranges of traffic volumes used for each approach by movement were as follows:

- Major road left turns: 50–750 veh/h.
- Major road through traffic: 300–2,650 veh/h.
- Major road right turns: 50–350 veh/h.
- Minor road left turns: 100–1,450 veh/h.
- Minor road right turns: 50–750 veh/h.

The results are shown in figure 43.

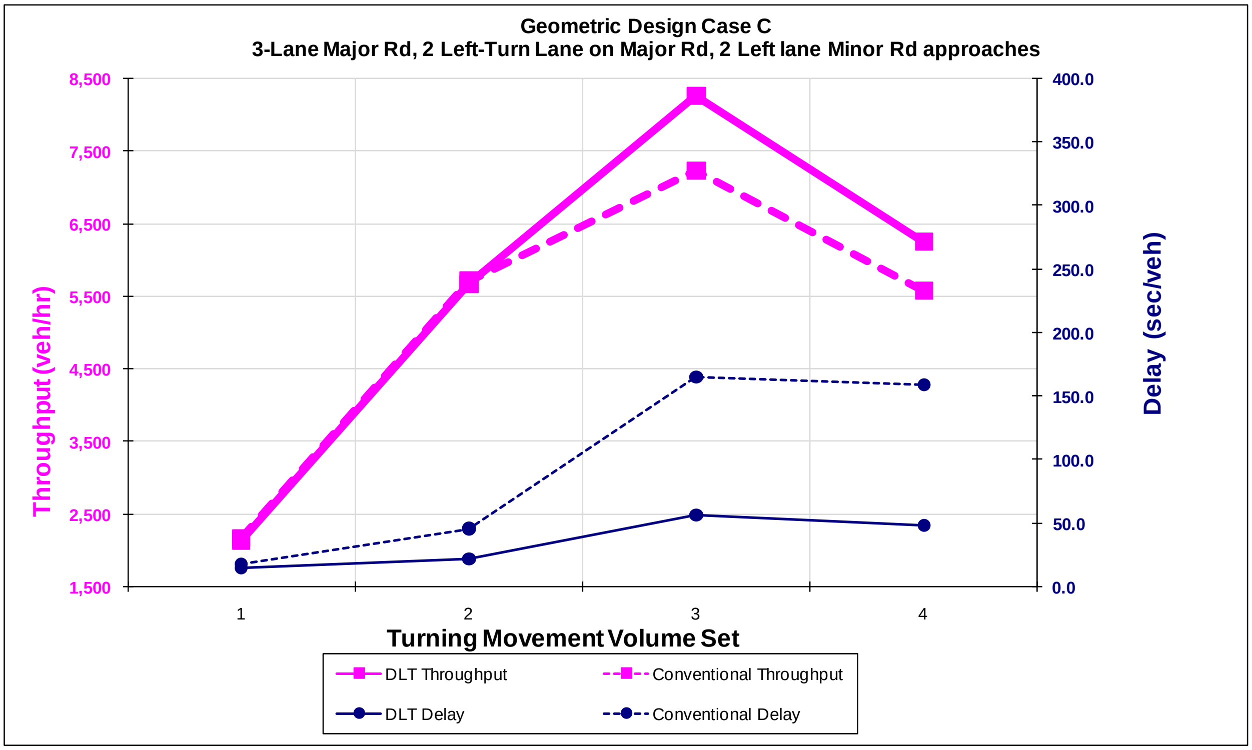


Figure 43. Graph. Throughput and delay comparisons for geometric design case C.

2.6.6 Geometric Design Case D Simulation

The intersection model had two through lanes, one left-turn lane, and one right-turn lane per approach for the two major roads. The DLT lane before the main intersection had a length of 325 ft, the right-turn bay had a length of 275 ft, and the left-turn bay before the separation of the DLT had a length of 350 ft. The acceleration lanes for the right-turning vehicles were 300 ft long. The two minor road approaches had a conventional geometric design with two through lanes, one left-turn lane, and one right-turn lane. For the minor road approaches, the length of the right-turn bay was 300 ft, and the left-turn bay was 350 ft. The median separating the opposing through lanes was 10 ft wide, the median separating the through lanes from the DLT lane was 10 ft wide, and the median separating the through lanes from the right-turn lane was 6 ft wide.

The comparable conventional intersection had similar geometric features and dimensions as the DLT intersection described above on all four approaches.

The traffic flows on all the approaches were randomly generated. A large number of cases modeled had directional flows to replicate peak hour directional flows at intersections. The cycle length used for all scenarios was 80 s.

The ranges of traffic volumes used for each approach by movement were as follows:

- Major road left turns: 100–350 veh/h.
- Major road through traffic: 300–1,500 veh/h.
- Major road right turns: 50–350 veh/h.
- Minor road left turns: 50–200 veh/h.
- Minor road through traffic: 50–1,200 veh/h.
- Minor road right turns: 50–250 veh/h.

The results are shown in figure 44.

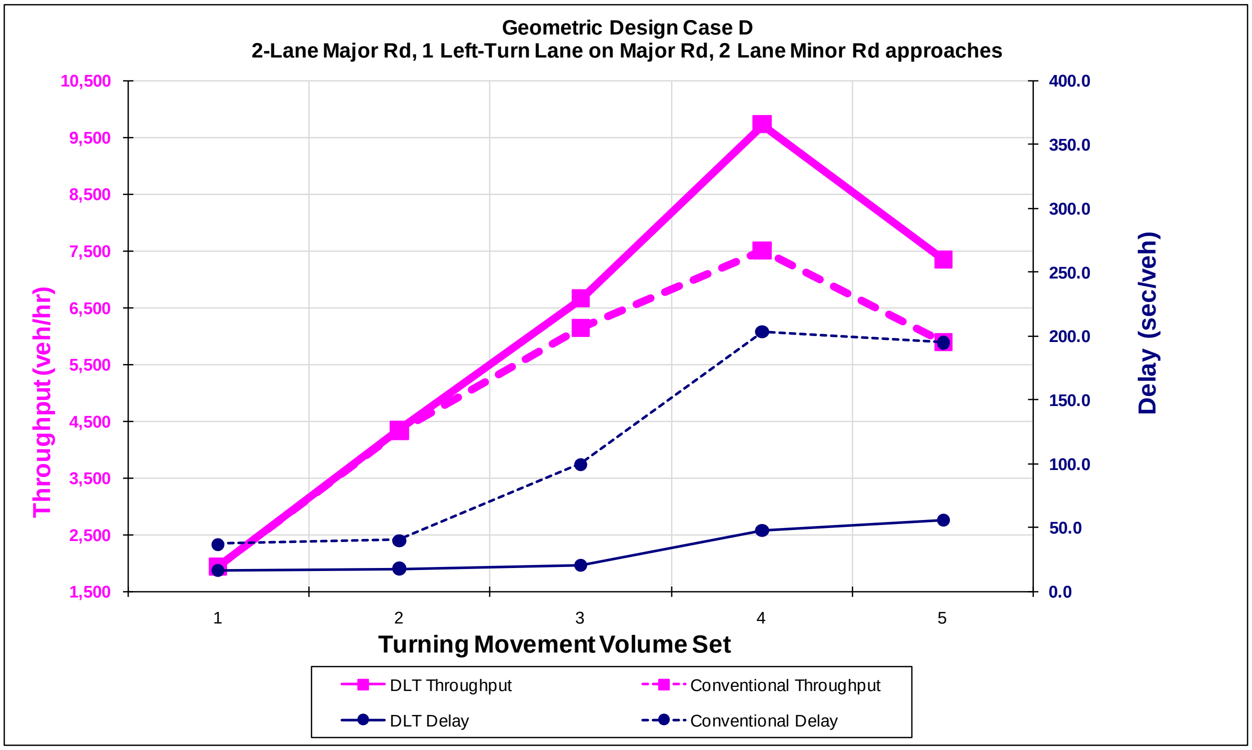


Figure 44. Graph. Throughput and delay comparisons for geometric design case D.

2.6.7 Discussion of Simulation Results

For each of the cases modeled, the DLT intersection consistently outperformed the conventional intersection with respect to vehicle throughput, vehicle delay, number of stops, and queue length. The average vehicle delay and queue estimation models can help traffic engineers and planners compare the DLT intersection with other types of intersections to measure suitability of application, especially when traffic congestion at the intersection is a serious problem. The results of the operational analysis are summarized below.

The operational improvement of the DLT intersection over the conventional intersection was notable even at relatively low traffic volumes, but greater benefits were achieved with the DLT intersection design as traffic volumes increased. The reduction in number of phases for those approaches with the DLT intersection significantly reduced vehicle delay and increased the capacity of the intersection considerably. In addition, the percent reduction in average intersection delay for a DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were balanced as follows:

- Case A: 48–85 percent.
- Case B: 58–71 percent.
- Case C: 19–90 percent.
- Case D: 54–78 percent.

The percent reduction in average intersection delay for a DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were unbalanced as follows:

- Case A: 82 percent.
- Case B: 70 percent.
- Case C: 69 percent.
- Case D: 72 percent.

The percent reduction in average intersection delay for the partial DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were balanced as follows:

- Case A: 39 percent.
- Case B: 36 percent.

The percent reduction in average intersection delay for the partial DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were unbalanced as follows:

- Case A: 30 percent.
- Case B: 30 percent.

The percent reduction in the average number of stops for the DLT intersection compared to a conventional intersection was 15–30 percent for nonsaturated traffic flows at the conventional intersection and 85–95 percent for saturated traffic flow conditions at the conventional intersection.

The percent reduction in average intersection queue length for a DLT intersection compared to a conventional intersection is shown for each simulated case as follows:

- Case A: 62–88 percent.
- Case B: 66–88 percent.
- Case C: 34–82 percent.
- Case D: 64–86 percent.

The percent increase in throughput of the intersection for a DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were balanced as follows:

- Case A: 30 percent.
- Case B: 30 percent.
- Case C: 16 percent.
- Case D: 30 percent.

The percent increase in throughput of the intersection for a DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were unbalanced as follows:

- Case A: 25 percent.
- Case B: 25 percent.
- Case C: 12 percent.
- Case D: 25 percent.

The percent increase in throughput of the intersection for the partial DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were balanced as follows:

- Case A: 20 percent.
- Case B: 20 percent.

The percent increase in throughput of the intersection for a partial DLT intersection compared to a conventional intersection is shown for each simulated case when mainline flows were unbalanced as follows:

- Case A: 14 percent.
- Case B: 10 percent.

It is important to note that all cases had signal timings adjusted for pedestrian presence. In the absence of pedestrians, cycle lengths were lowered, resulting in average intersection delay in the range of 14–19 s/veh at low and medium traffic volumes for case A.

Even with a single signal timing, the DLT intersection worked effectively for all combinations of traffic flows (low, medium, and heavy). This is unique and can be useful for intersections that cannot implement multiple signal timing plans.

2.7 SAFETY PERFORMANCE

Because relatively few DLT intersections existed when this report was developed, very limited data were available to evaluate the safety performance of DLT intersections. Based on the design and operation of the intersection, however, it is possible for a DLT intersection to offer safety advantages over a conventional intersection. Figure 45 shows the conflict points of a partial DLT intersection with left-turn crossovers present on the mainline approaches. The total number of conflict points in this case is 30 compared to the 32 conflict points at a conventional intersection. Figure 46 shows the conflict points of a full DLT intersection with left-turn crossovers present on all approaches. The total number of conflict points in this case is 28. The slightly lower number of conflict points could translate to fewer collisions.

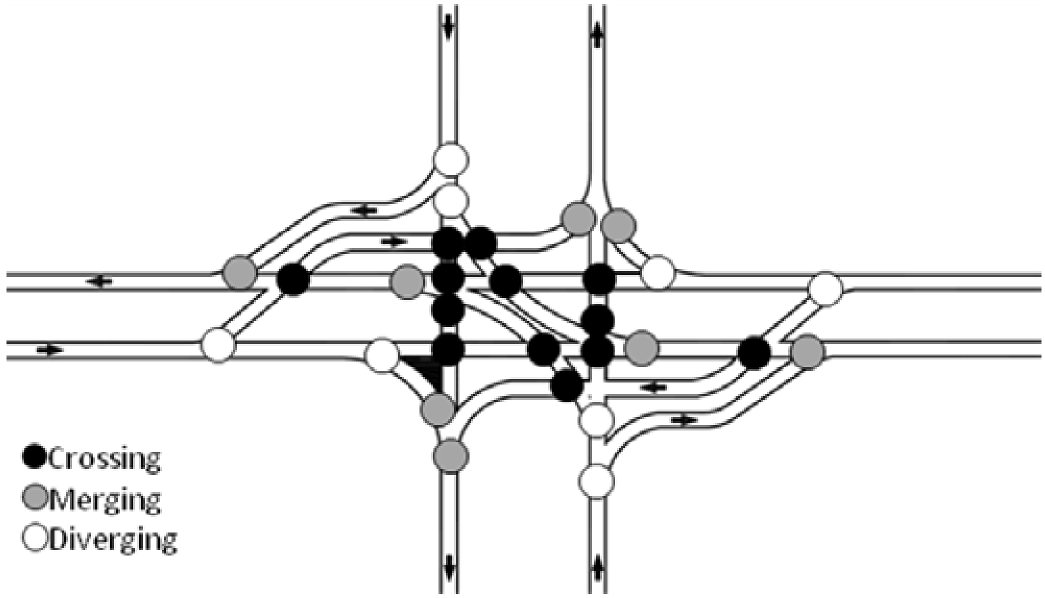


Figure 45. Illustration. Conflict point diagram for a partial DLT intersection.

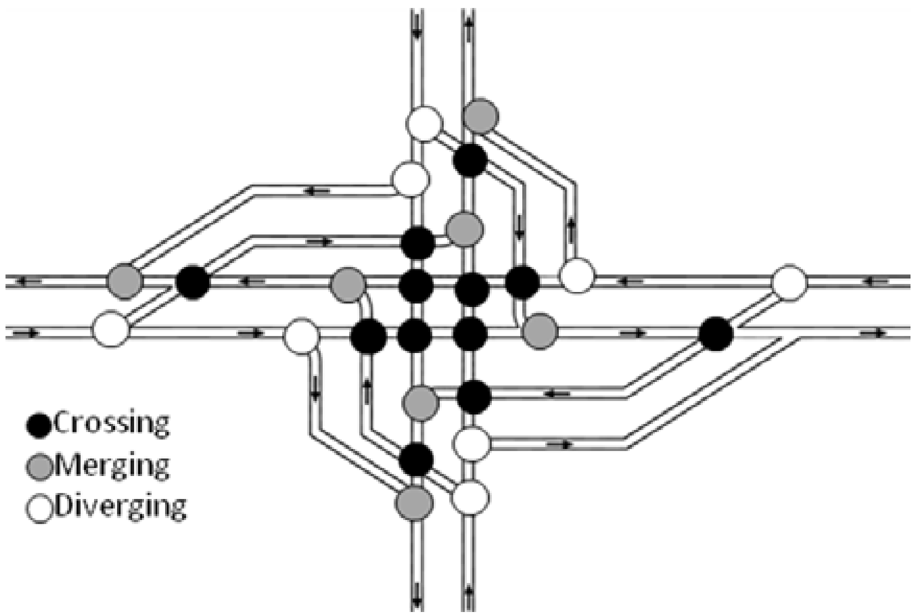


Figure 46. Illustration. Conflict point diagram for a full DLT intersection.

A possible safety disadvantage is related to unfamiliar drivers and older drivers. There are several counterintuitive design features of the DLT intersection, which were discussed previously. These features could result in driver confusion in the following ways:

- Drivers are familiar with making left-turn maneuvers at the main intersection. In the case of a DLT intersection, the indirect left turn occurs several hundred feet ahead of the main intersection. Even with adequate signage, this requires drivers to anticipate the left turn in advance of the main intersection, which may be counterintuitive.[22]

- The design features of a DLT intersection and the relocation of turn movements at the main intersection can lead to wrong-way movements. Wrong-way movements can be reduced by providing adequate signage and pavement markings.[22]

One DLT intersection was examined to determine the extent of driver discomfort with the nontraditional intersection. Dowling College sponsored a human factors study of the DLT intersection in Shirley, NY, to determine how the design affected the driving task.[23] The study found that "about 80 percent of the first time users of the DMI intersection expressed positive comments about the design." [23] According to the study, "after about a week of use, 100 percent of the daily drivers sampled expressed positive comments about the design."[23] The study concluded that "the intersection is easily negotiated by drivers who are initially unfamiliar with the design and that after a short learning period, nearly all drivers are familiar and comfortable with the DMI intersection."[23] The DLT intersection at the Dowling NAT Center was implemented with the construction of a new entrance for Dowling College. Hence, there is no before period for which intersection crash statistics can be collected for this DLT intersection.

The DLT intersection at the intersection of Airline Highway and Seigen Lane in Baton Rouge, LA, was opened for operation in March 2006. A total of 4 years of before data (2002 to 2005) and 2 years of after data (2006 to 2008) were obtained to conduct a simple before-after crash comparison. Table 4 shows a summary of the results for total crashes as well as fatal and injury crashes. Based on a simple before-after comparison, total crashes per year were reduced by 24 percent, while severe crashes (i.e., fatal and injury) were reduced by almost 19 percent after the installation of the DLT intersection. In addition, total crash rates decreased by almost 24 percent, and severe crash rates decreased by 22 percent. While the study only included 2 years of after data and did not account for changes in other factors (e.g., traffic volumes, time trends, etc.), the initial results are encouraging.

Table 4. Annual averages collision rates for DLT intersection at Airline Highway and Seigen Lane in Louisiana.

Year	Number of Reported Collisions by Severity		All Reported Crash Rate (Per Million Entering Vehicles on Major Road)	Fatal and Injury Crash Rate (Entering Vehicles on Major Road)
	Total	Fatal and Injury		
Annual average before (2002–2005)	147	37	5.09*	1.26*
Annual average after (June 2006–May 2008)	111	30	3.87**	0.98*
Difference after minus before (percent difference)	-36 (-24.4%)	-7 (-18.9%)	-1.22 (-23.9%)	-0.28 (-22.2%)

* Average annual daily traffic (AADT)s for years 2003 and 2004 were interpolated.
** AADT for year 2006 was interpolated.

2.8 CONSTRUCTION COSTS

The cost of constructing a DLT intersection is likely to be higher than that of a conventional intersection mainly due to increased footprint and possible additional right-of-way requirements. Assuming that the required right-of-way is available, the additional construction costs of a DLT intersection are relatively small compared to a conventional intersection with similar design characteristics. These costs are related to the additional grading and paving as well as additional pavement markings, signing, and signals.

The presence of left-turn crossovers for a DLT intersection requires a larger footprint compared to a similar conventional intersection (see figure 47). Assuming left-turn crossovers on all four approaches, the DLT intersection has a footprint that is almost one acre larger than a conventional intersection. The increased footprint increases the right-of-way costs if additional land needs to be acquired. The cost of right-of-way may vary substantially from $10 to $100 per square foot and may be a major factor in deciding not to install a DLT intersection.

Aside from right-of-way, the cost of additional traffic signal control is likely to be higher. The typical cost for a new signal installation is approximately $200,000. A DLT intersection has signal control at the main intersection similar to conventional intersection; however, it also requires a signal control at each left-turn crossover, which is upstream of the main intersection. For a full DLT intersection with four left-turn crossovers, the cost for traffic control can be substantially higher compared to a conventional intersection.

The cost of three completed DLT intersection projects are provided to give a perspective of the total cost for a DLT intersection project as follows:

- The recent construction of a DLT intersection in Baton Rouge, LA, involved construction of left-turn crossovers, a frontage road, widening, and channelization work. No additional right-of-way was required for this project. Construction work included grading, drainage structures, lime treatment, base course, Superpave® concrete, Portland cement concrete pavement, traffic signalization, lighting, and other related work. The total bid price was approximately $4.4 million. This cost included $1 million for frontage road development that was required to mitigate the loss of access to businesses.(6)

- The DLT intersection at the intersection of Bangerter Highway and 3500 South in Salt Lake City, UT, opened prior to the completion of this report. Preliminary press releases indicated that the total cost of the project was $7.5 million.(24)

- The DLT intersection at the intersection of U.S. Route 30 and Summit Drive in Fenton, MO, had a total construction cost of $4.5 million.

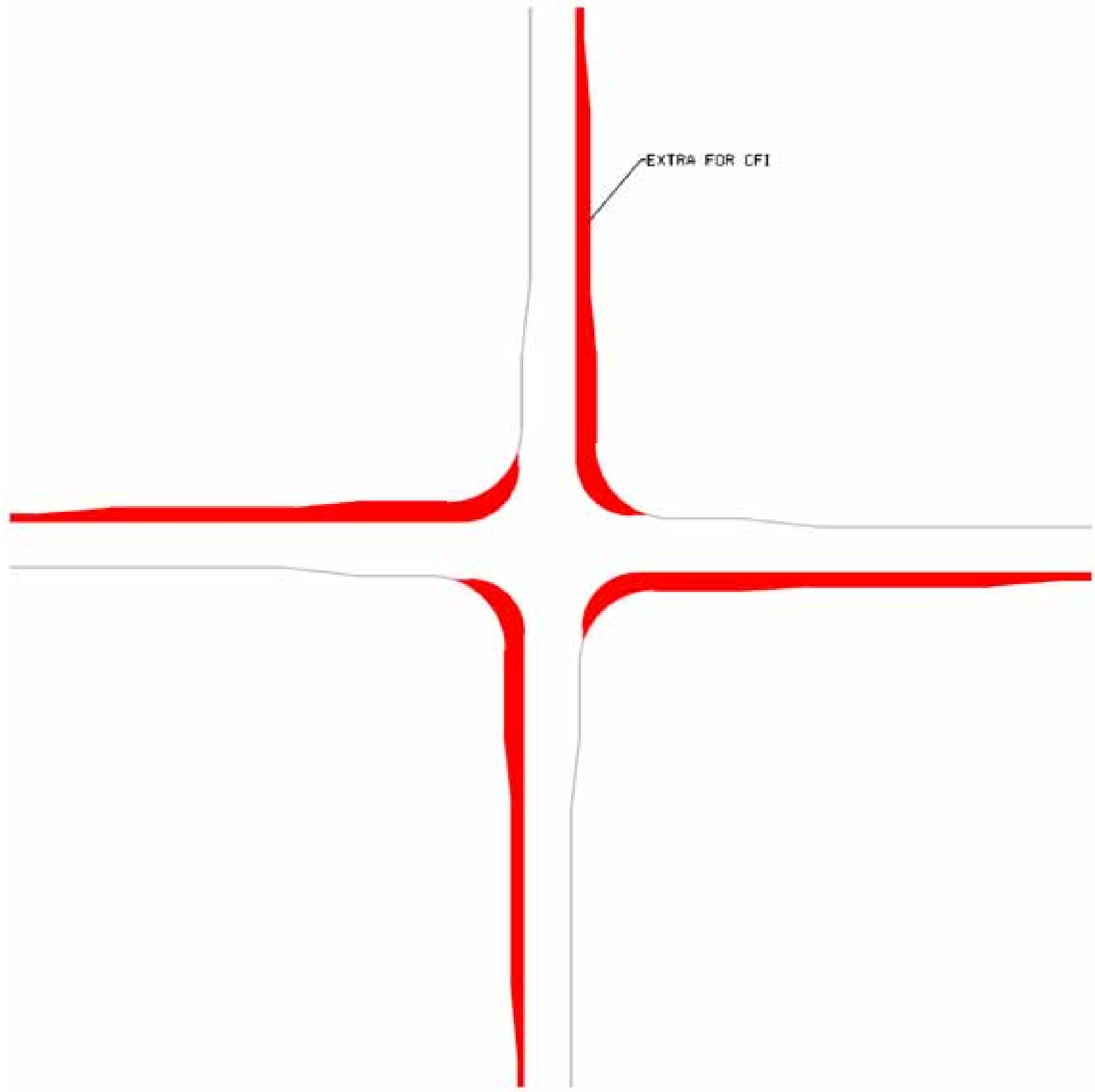


Figure 47. Illustration. Footprint comparison of a DLT intersection versus a conventional intersection.

An ideal comparison of costs and benefits consists of final construction plans for conventional intersection improvements, a DLT intersection, and other alternatives including grade-separated interchanges along with an evaluation of operational and safety performance. Operational and safety performance may be valued differently depending on the project. The potential operational and other benefits of the DLT intersection were presented in previous sections and compared to similar conventional intersection designs. The actual monetary benefits related to the operational and safety performance of a DLT intersection should be based on the individual project. This section presents a comparison of DLT intersection construction costs versus conventional intersection construction costs. Though highway agencies may be considering a DLT intersection at a location where an intersection already exists and may be weighing grade-separated options along with the DLT intersection, a comparison to conventional intersection costs is presented here since the physical construction will be most similar to a DLT intersection.

Table 5 provides a detailed construction cost comparison of a conventional intersection and a full DLT intersection. For this comparison, certain assumptions are made to simplify the process. It is assumed that additional right-of-way is available and not purchased, which is indicative of an implementation at a rural site. It is also assumed that mobilization, overhead lighting, pavement marking, and drainage costs are not significantly different between the two types of intersections. Lastly, it is assumed that no special grading or construction features, such as retaining walls, are required. Unit cost prices were obtained from the *RS Means Heavy Construction Cost Book.*[25]

Table 5. New DLT intersection construction cost estimates.

#	Item	Unit	Unit Cost ($)	DLT Intersection Quantity	DLT Intersection Total Cost ($)	Equivalent Conventional Intersection Quantity	Equivalent Conventional Intersection Total Cost ($)
1	Mobilization (assumed to be the same for all)	LS	N/A	N/A	N/A	N/A	N/A
2	Earthwork · Site prep, excavation, etc.	CY	12.47	36,880	460,000	31,720	396,000
3	Pavement						
	· Surface (2 inches).	SY	6.93	54,890	380,000	50,370	349,000
	· Base (6 inches).	SY	15.50	54,890	851,000	50,370	781,000
	· Sub-base (8 inches).	SY	10.80	54,890	593,000	50,370	544,000
3	Curb and gutter	LF	11.10	25,270	280,000	15,850	176,000
	Concrete islands/raised medians (8-inch cement concrete pavement)	SF	37.50	22,970	861,000	12,850	482,000
4	Drainage (assumed to be the same for all)	N/A	N/A	N/A	N/A	N/A	N/A
5	Traffic control devices · A new signal is assumed to be $200,000. Equipment required for a CFI is approximately two times more than that of a conventional intersection and consequently priced at $300,000.	EA	200,000	2	400,000	1	200,000
6	Utilities (assumed to be the same for all)	N/A	N/A	N/A	N/A	N/A	N/A
7	ADA requirements						
	· Ramps: 5 inches wide.	LF	450	80	36,000	20	9,000
	· Concrete sidewalk.	LF	14.42	8,240	119,000	8,420	121,000
8	Pavement markings (assumed to be the same for all)	N/A	N/A	N/A	N/A	N/A	N/A
Total					**3,980,000**		**3,058,000**

N/A = Not applicable.

Based on the assumptions for this example, the total cost of a DLT intersection in a rural area is approximately $922,000 more than a conventional intersection. The significant contributing factors to the increased costs are earthwork, materials, and additional signals. While the increase in construction costs may be substantial (nearly 30 percent), there are several conditions that may warrant the increase. For example, as Goldblatt and Mier concluded, "if the traffic conditions are severe, or if there are considerations of such techniques as grade separation, then the DLT intersection design might be the optimal solution."[(3)] In addition, one-, two-, or three-legged DLT intersection designs may be constructed as appropriate to improve safety and operations while minimizing costs.

2.9 CONSTRUCTION SEQUENCING

Constructing a DLT intersection at an existing conventional intersection presents several challenges related to the maintenance of traffic and protection of road users and workers. This section presents construction sequencing options for consideration during the construction of DLT intersections. Work zone traffic control plans were obtained for the construction of DLT intersections in Louisiana and Utah and are described below.

2.9.1 Sequence of Construction for DLT intersection in Baton Rouge, LA

The sequence of construction for the intersection of Airline Highway and Siegen Lane in Baton Rouge, LA, was obtained from the LA DOTD. An aerial photo of this intersection was shown previously in figure 8. For the purposes of this phasing sequence example, the north-south roadway is referred to as the major road where left-turn crossovers were installed. The east-west roadway is the minor road, and the approaches were constructed in a manner similar to a conventional intersection. There were three phases of construction, which are discussed below.

Phase I included the following:

- Installation of temporary signal heads, poles, and new controllers at the main intersection, the minor intersection with frontage road, and the left-turn crossovers. (During phase II, installation of fiber optic interconnect cable for new signal system was also initiated.)
- Construction of frontage roads for DLT intersection lanes, new driveways along frontage roads, and turnouts.
- Construction of right-turn lanes along major roads, left-turn lanes along major roads, right-turn lane for a frontage road in southeast quadrant, and crossovers.
- Placement of permanent striping on the southwest frontage road. Temporary traffic signals operated on a new controller.

Phase II included the following:

- Installation of new signal poles at the main intersection, the minor intersection with a frontage road, and the left-turn crossovers. New signal heads on mast arms remain covered until placed in operation.

- Installation of permanent signing, high mast pole lighting, temporary striping for right-turn lanes along major roads (northbound), and temporary striping for turnouts.

- Construction of island on the service road and its temporary striping and signal heads.

- Construction of left-turn lanes along the median edge of major roads (northbound), right-turn lanes on the minor roads (eastbound), and left-turn DLT intersection lanes on the major roads (northbound).

Phase III included the following:

- Placement of permanent signals and removal of temporary signal systems at the main intersections.

- Installation of temporary striping on DLT intersection lanes.

- Removal of left-turn lanes and the construction of islands in the median of major roads between the two left-turn crossovers.

- Completion of islands at main intersections and remaining wearing course and permanent striping.

2.9.2 Sequence of Construction for DLT intersection in Salt Lake City, UT

Work on the DLT intersection in Salt Lake City, UT, began in March 2007, and the intersection was opened to the public on September 16, 2007. A portion of the construction sequence was obtained from the Utah Department of Transportation (UDOT) Web site and is shown as follows:

2.9.2.1 Winter 2007

- Work began on the northeast and southwest corners of the intersection.

- The first noticeable traffic impact was the closure of right lanes in each direction near the intersection.

- Crews placed construction fencing, cleared two developments on adjacent sites, and removed a section of the sound barrier wall.

- Some excavation and utilities work took place.

2.9.2.2 Spring 2007

- Excavation and utility work continued.

- Crews began concrete work and paving.

2.9.2.3 Summer 2007

- Crews completed concrete work and paving.

- New signals were installed.

Construction work was completed at this intersection by closing it off completely and utilizing the existing network to detour traffic. Detour signs were placed according to typical designs and were located 350 ft ahead of the upstream intersection. Figure 48 and figure 49 illustrate the detour routes as well as detour signing used during the work.

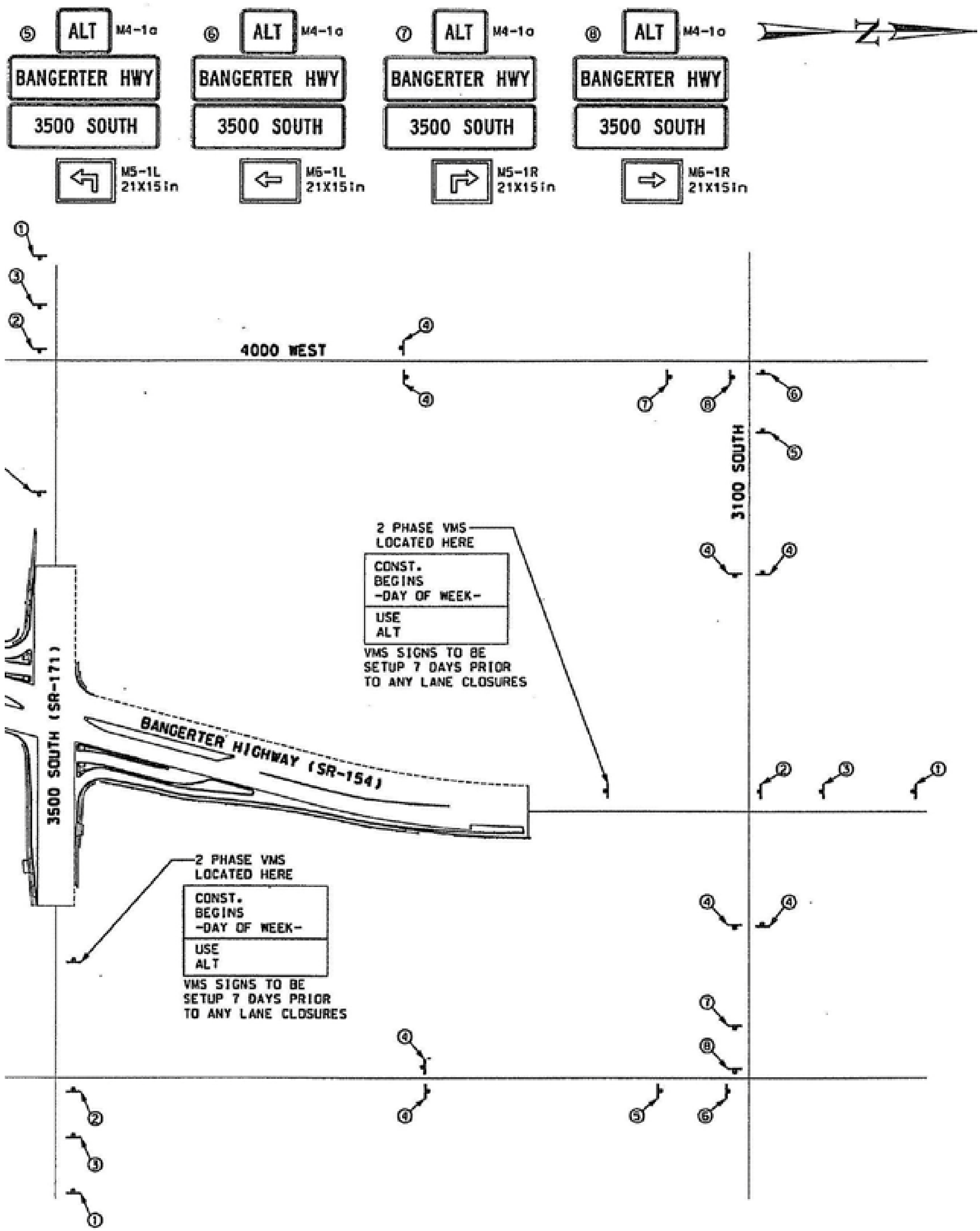


Figure 48. Illustration. Detour routes for construction of a DLT intersection in Salt Lake City, UT—north end.

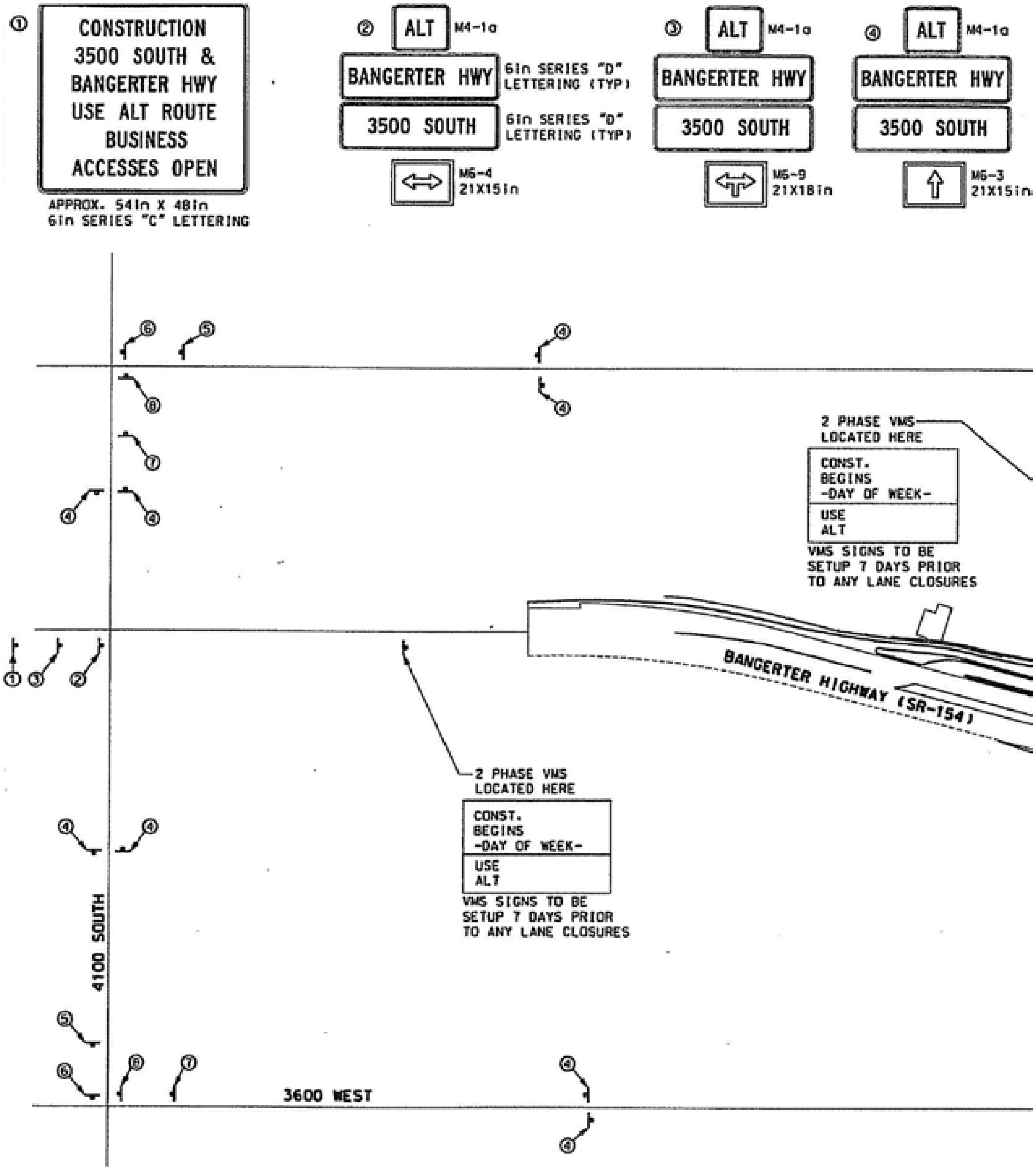


Figure 49. Illustration. Detour routes for construction of DLT intersection in Salt Lake City, UT—south end.

2.10 OTHER CONSIDERATIONS

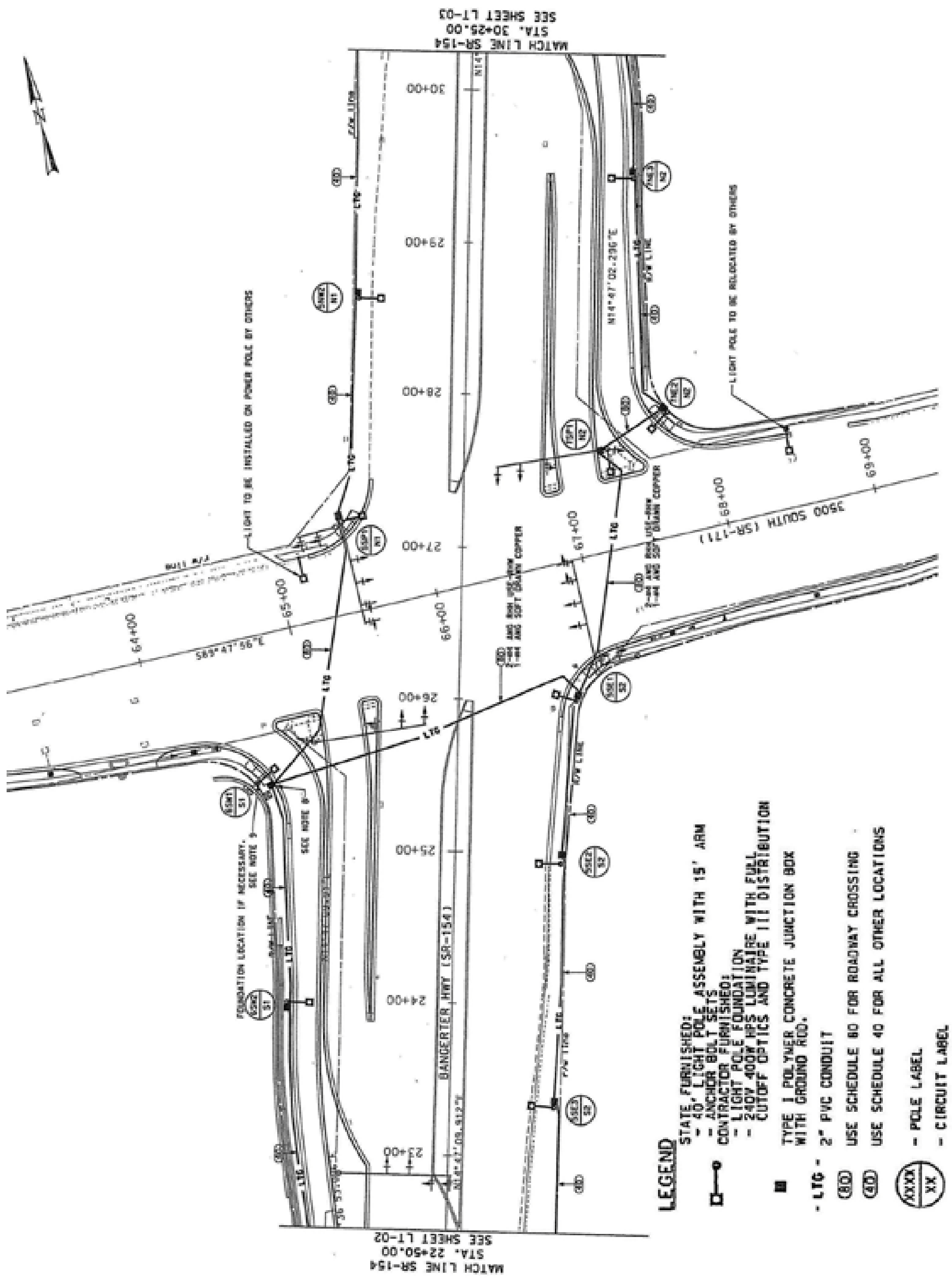
In addition to topics previously presented, there are other factors to note when considering a DLT intersection design. Possible complications that may arise after construction include possible blockage of the crossover during traffic incidents or accidents, emergency response challenges, loss of power to the traffic signals, as well as the need for taller light poles, public involvement, and traffic law enforcement.

The presence of a left-turn crossover in a DLT intersection results in conflicting internal movements. This creates a potential for the crossover to be blocked during traffic accidents or incidents where stoppage of one movement (either the left-turn crossover or the through vehicles) could block the other movement. These situations can be mitigated by construction of shoulders or a bypass roadway to move vehicles around the blockage. In addition, metering and signal coordination with upstream and downstream intersections can help control traffic flow.[22] For the DLT intersection in Louisiana, backup batteries and a natural gas generator were provided in the traffic signal system in case of power failures. In addition, six to eight law enforcement personnel were considered in the event of a failure of the backup power system.[6]

Blockage is a significant issue for emergency response; however, there are other characteristics of a DLT intersection that create issues for emergency response. With the presence of left-turn crossovers and the alternating direction of vehicle movements on an approach, the DLT intersection design creates restrictions on access for emergency vehicles. The DLT intersection design should allow for emergency vehicle access in the event of an accident or disabled vehicle. The use of mountable curbs in the crossover area could help facilitate emergency vehicle access to the crossover area. In addition, frontage roads could also provide access in an emergency. Agencies should also consider appropriate response procedures for the removal of disabled vehicles from the area, including the crossovers and the main intersection.

A full DLT intersection with left-turn crossovers on all approaches has five signalized junctions. Loss of power and signal malfunctions are causes for concern because manual traffic control using police officers is not a viable option for the safe and efficient operation of five signalized junctions. Therefore, generators and battery backup arrangements should be considered.[22]

Lighting standards and specifications outlined in AASHTO's *Roadway Lighting Design Guide*, FHWA's *Roadway Lighting Handbook*, and the Illuminating Engineering Society of North America (IESNA) publications including *Recommended Practices for Roadway Lighting*, *Recommended Practices for Tunnel Lighting*, and *Recommended Practices for Sign Lighting* can be used to determine optimal lighting for DLT intersections. (See references 26–30.) Designers at the MDSHA indicated that lighting was usually mounted higher at a DLT intersection than a conventional intersection due to the unusual nature of the left-turn crossover movements. Figure 50 shows the lighting plan, which featured high mast lighting as implemented by the UDOT at the DLT intersection in Salt Lake City, UT.



Source: Utah Department of Transportation

Figure 50. Illustration. Intersection lighting plan for a DLT intersection in Salt Lake City, UT.

Prior to the opening of any alternative design, it is important to conduct public outreach to inform and educate the public about the proper use and benefits of the new design. Media campaigns through local newspapers, television, and public meetings can be effective methods to inform the public. Figure 51 is an example of a pamphlet used by UDOT to provide information about the DLT intersection design. Once the intersection is open to the public, it is important to monitor driver behavior and utilize law enforcement as necessary to reduce illegal and unsafe actions.

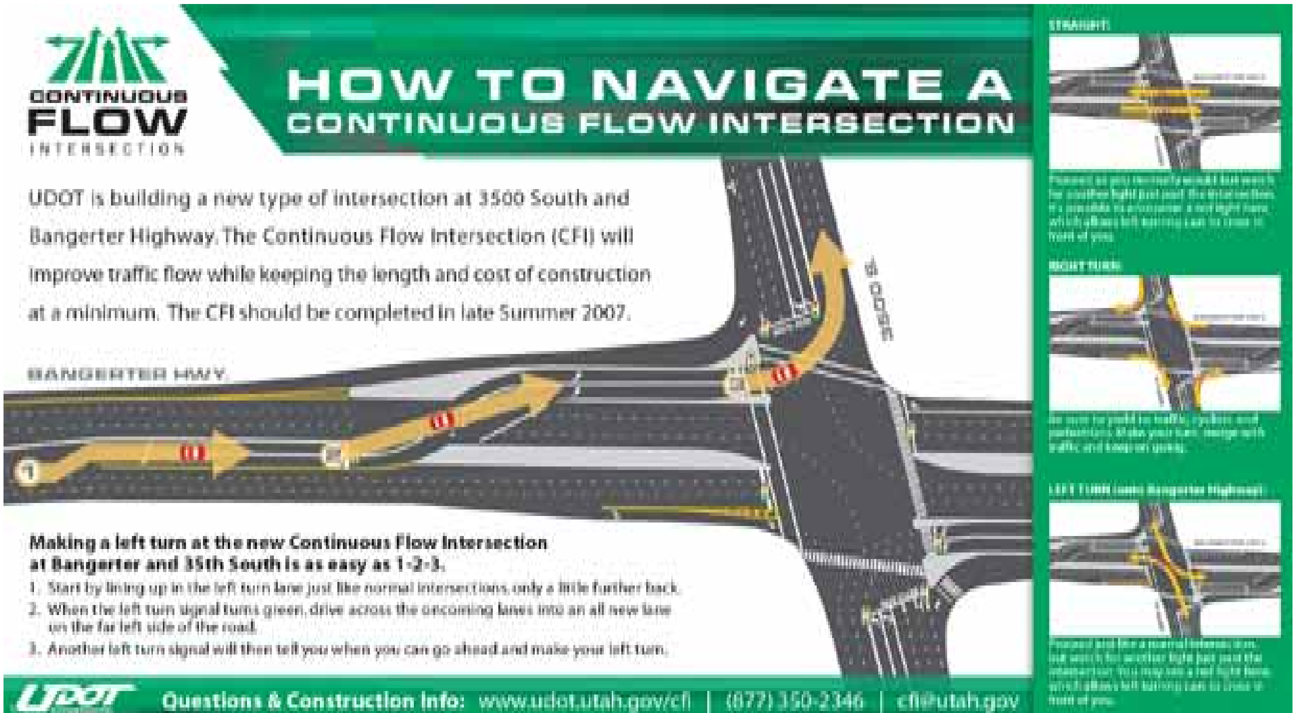


Figure 51. Illustration. DLT intersection instruction card for UDOT.(31)

2.11 APPLICABILITY

As with all the designs described in this report, the DLT intersection design is applicable under certain conditions but not appropriate for all conditions. A primary reason to choose the DLT intersection instead of a conventional design is the ability to process higher intersection volumes, especially left-turn volumes and through volumes. In a suburban or urban setting, a DLT intersection design is an attractive choice on arterials where traffic volumes are at or beyond capacity and when there is balanced traffic flow on the DLT approaches.

Replacing a conventional intersection with a full DLT intersection can produce results on the order of magnitude of a 50 to 85 percent reduction in average intersection delays and a 10 to 25 percent increase in intersection throughput. Replacing a conventional intersection approach with a partial DLT intersection can produce results on the order of magnitude of a 30 to 40 percent reduction in average intersection delays and 10 to 20 percent increase in intersection throughput. Some of the situations where a DLT intersection may be suitable are as follows:

- If the volume to capacity ratio (v/c) is greater than 0.8 on two opposing intersection approaches.
- If the cross product of left-turn and opposing through vehicles is greater than 150,000 on two opposing intersection approaches.
- If left-turning volume is greater than 250 veh/h/lane and opposing through volume is greater than 500 veh/h/lane on two opposing intersection approaches.
- If an intersection is heavily congested with many signal phase failures.
- If left-turn queues at an intersection spill beyond the left-turn storage bays.

Designers should consider the DLT intersection as an available alternative in areas with chances of significant development within the design lifetime of the project. Having the DLT intersection configuration in place before a corridor develops alleviates much of the uncertainty regarding business impacts as well as the right-of-way acquisition issues. A DLT intersection may limit access to parcels located on four quadrants of the intersection. Right-of-way availability is a factor that is a disincentive for implementing the DLT intersection.

Although there is insufficient empirical evidence of crashes experienced at DLT intersections, DLT intersections show promise in terms of safety benefits. There are theoretical reasons to expect collisions to decrease with a DLT intersection, particularly those involving left-turning and opposing through vehicles.

2.12 SUMMARY

The distinguishing feature of a DLT intersection is the relocation of the left-turn movement. The DLT intersection shifts left-turning vehicles to the left side of opposing traffic prior to the intersection, which consequently eliminates the left-turn phase for the approach at the main intersection. As such, DLT intersections offer several advantages compared to conventional signalized intersections for certain traffic conditions. Compared to a conventional intersection design, a DLT intersection design offers operational and safety benefits. Other benefits may include reductions in auto emissions and in travel time for selected movements in the DLT intersection.

DLT intersections offer improved operational performance compared to conventional intersections, particularly for relatively large left-turn and through volumes. The operational analysis conducted as part of this research and by others indicates that the operational benefits of the DLT intersection increase as traffic volume increases. Simultaneous movement of the left-turn and through traffic also improves progression of traffic platoons and increases vehicular throughput. Other operational improvements include reduced vehicle delay, reduced queue lengths, fewer stops, and increased capacity.

From a safety perspective, the DLT intersection has slightly fewer conflict points compared to a conventional intersection. Existing DLT intersections in New York, Maryland, Louisiana, and Utah are operating successfully for various periods of time with no reported safety deficiencies.

The DLT intersection also has benefits compared to a grade-separated interchange. The DLT intersection occupies a smaller right-of-way, is less costly, requires less time to construct, and offers comparable improvements in capacity and delay.

Agencies should, however, recognize the specific limitations associated with the DLT intersection design. Compared to a conventional intersection, a DLT intersection requires more right-of-way, is more expensive, presents counterintuitive movements for drivers, creates additional challenges for pedestrians, and is limited in the accommodation of U-turns and access to adjacent land parcels. Any of these issues that are significant for a specific location (such as where high pedestrian volumes are expected) may be reason enough for the highway agency to decide against a DLT intersection.

A DLT intersection has a larger footprint compared to conventional intersections, which can result in significant costs if additional right-of-way is required, particularly in urban areas. With right-of-way restrictions, it can be difficult to widen or add lanes at a DLT intersection; therefore, careful planning is required during the initial design of a DLT intersection. Other costs relate to increased materials and the additional signs and signals. Additional signals can become a significant cost, particularly for a full DLT intersection with left-turn crossovers on all four approaches. The higher construction costs associated with the DLT intersection are likely offset to some extent by safety and operational improvements; however, this should be explored on an individual basis through additional analysis.

With the unusual geometry, a DLT intersection can cause several problems during inception to users familiar with the conventional four-legged intersection. The left-turn movement prior to the intersection and pedestrian movements may be particularly confusing. Public information and educational campaigns prior to opening a DLT intersection can help mitigate some of these concerns. Additionally, signing and marking of a DLT intersection entails significant differences from a conventional intersection. Emphasis must be given to wrong-way pavement markings and signing to warn drivers of restrictions. Overhead and post-mounted signing should be placed to provide sufficient guidance, particularly for left-turn crossovers.

Another limitation of DLT intersections is that vehicle movements are more restricted compared to conventional intersections. U-turn movements are restricted at the main intersection; however, if the median is wide enough, U-turn movements on the major road can be provided at the left-turn crossover or between the left-turn crossover and the main intersection. Also, access to adjacent parcels is more restricted compared to a conventional design, which can adversely affect local businesses or residents.

Pedestrian movements are also more restricted at a DLT intersection compared to a conventional intersection design. Pedestrians experience counterintuitive traffic movements and may be forced to utilize a multiple-stage crossing, which can increase overall crossing time. Depending on the crossing scheme, pedestrians may cross “diagonally” between refuge islands adjacent to the left-turn lanes. These pedestrians walk between left-turning and through traffic. This type of movement places moving traffic on two sides of pedestrians, which can be particularly hazardous to pedestrians with visual or cognitive impairments. Wider median islands and/or wider outer separations may be needed to better accommodate pedestrians.

At the time of this report, applications of the DLT intersection were identified in Maryland, Louisiana, New York, Missouri, and Utah. There have not been any major issues with the installation of DLT intersections in these States. Based on the operational and performance to date, it appears that the DLT intersection is a viable alternative to the conventional intersection design, particularly where traffic demand approaches or exceeds the capacity of conventional designs.

CHAPTER 3. MEDIAN U-TURN INTERSECTION

3.1 INTRODUCTION

One potential treatment to balance intersection congestion and safety problems is the MUT intersection. This design has been used extensively in Michigan for many years and has been implemented successfully in Florida, Maryland, New Jersey, and Louisiana in recent years. Figure 52 shows an MUT intersection in Michigan.

Figure 52. Photo. MUT intersection in a corridor in Michigan.[32]

The MUT intersection involves the elimination of direct left turns from major and/or minor approaches (usually both). Drivers desiring to turn left from the major road onto an intersecting cross street must first travel through the at-grade main intersection and then execute a U-turn at the median opening downstream of the intersection. These drivers then turn right at the cross street. Drivers on the minor street desiring to turn left onto the major road must first turn right at the main intersection, execute a U-turn at the downstream median opening, and proceed back through the main intersection. Figure 53 provides a schematic of a typical MUT geometric design, while figure 54 shows the left-turn movements. Elimination of left-turning traffic from the main intersection simplifies the signal operations at the intersection, which accounts for most of the benefits.

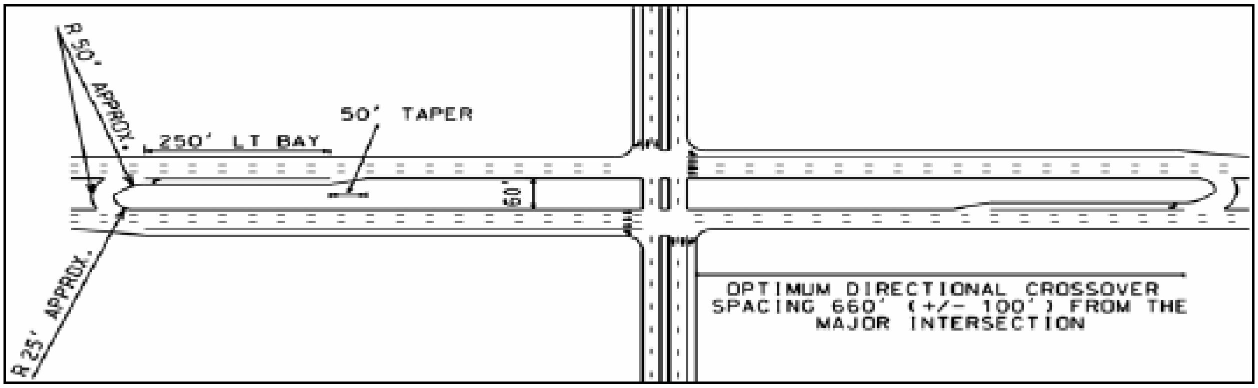


Figure 53. Illustration. Typical MUT design.

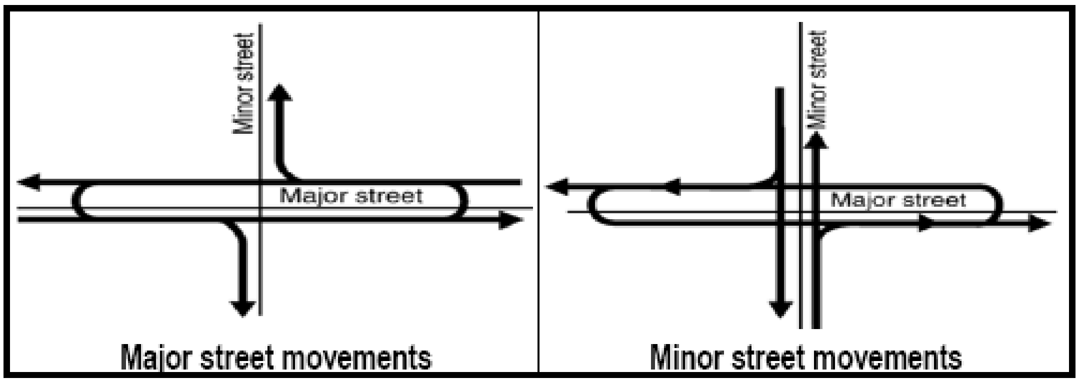


Figure 54. Illustration. MUT left-turn movements.

The MUT has been used widely in Michigan. Several highways in Michigan, particularly in the Detroit metropolitan area, were constructed with wide medians on wide rights-of-way. Many of these medians are 60 to 100 ft wide and were built decades ago in semirural areas. By the early 1960s, many of these highways had capacity problems because of interlocking left turns at conventional intersections. To address this capacity problem, the Michigan Department of Transportation (MDOT) and local highway agencies replaced the conventional intersections with MUT intersections. Today, there are more than 425 mi of boulevards, wide arterial multilane thoroughfare, with over 700 directional crossovers on MDOT highway system. Partial implementations or designs with similar concepts have appeared in Florida, Maryland, New Mexico, and Louisiana.

The MUT intersection is typically a corridor treatment applied at signalized intersections. However, the concept is also used at isolated intersections to alleviate specific traffic operational and safety problems. Levinson et al. recommended that the application of MUT intersections along the corridor should not be mixed with other indirect left-turn treatments or conventional left-turn treatments in order to meet driver expectancy.[32] This chapter concentrates on the treatment of an isolated intersection rather than on the treatment of a corridor to maintain consistency with the other chapters in this report. However, the corridor-based application of this intersection type should be kept in mind.

There are many variations of the basic MUT intersection design. Some of these variations include the following:

- Driveways or minor roads intersecting the arterial at the crossover.
- Unsignalized crossover intersections with either one or two U-turn lanes.
- Crossovers on the minor street in addition to or in lieu of the major street.
- Roundabouts instead of U-turn crossovers.
- Three-legged intersections.

Some of these variations add to the benefits provided by the basic MUT intersection design in some locations. While this chapter mentions some of these variations, the primary focus is on the most common MUT intersection design, which has four legs, a signalized main intersection, and signalized crossovers on the major road.

Another variation of the MUT intersection is the RCUT intersection. A RCUT intersection also uses U-turn crossovers to reroute some movements that would otherwise be made at the main intersection. In the case of RCUT intersections, the movements that are often rerouted are the minor street left turns, as with the MUT intersection, and minor street through movements. Because the RCUT intersection and the MUT intersection are so closely related, this chapter refers to RCUT intersections often. Chapter 4 contains a synthesis of knowledge on the RCUT intersection design and will refer back to this chapter often.

This chapter summarizes the advantages and disadvantages of the MUT intersection compared to conventional intersections where left turns are permitted from all approaches. The advantages of the MUT intersection include lower overall travel time, increased capacity at the main intersection, better progression on the major street, and enhanced safety. Pedestrians may enjoy some benefits with this design, and access management may be enhanced. Disadvantages may include higher right-of-way and construction costs and difficulties meeting driver expectations. The chapter also explores issues such as maintenance of traffic during construction and treatment of emergency vehicles. Much of the material in this chapter duplicates or is based on the FHWA TechBrief, *Synthesis of the Median U-turn Intersection Treatment, Safety, and Operational Benefits*.[33]

3.2 GEOMETRIC DESIGN CONSIDERATIONS

The MUT intersection performs well on arterials that have sufficient median width to accommodate the U-turn maneuver. This section discusses the geometry of the main intersection, U-turn crossovers, medians, and the spacing between the main intersections and crossovers. Because of Michigan experience with these intersections, MDOT typical design values are discussed throughout this section. In general, Michigan corridors with MUT intersections have median widths ranging from 60 to 100 ft. This design is used as a corridor treatment in Michigan, although it has been used successfully for isolated intersections. Figure 55 shows a design for a typical four-legged MUT intersection.

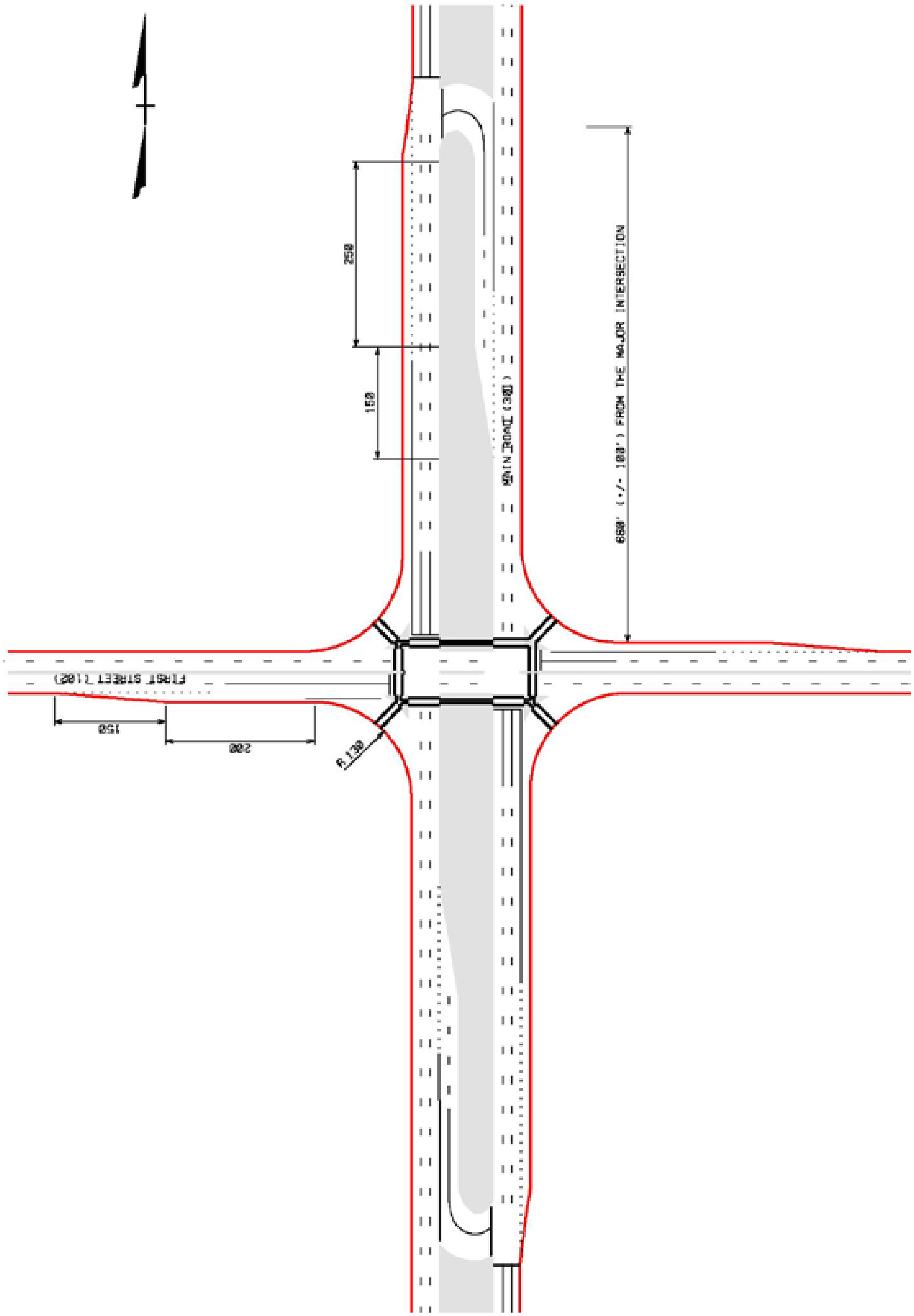


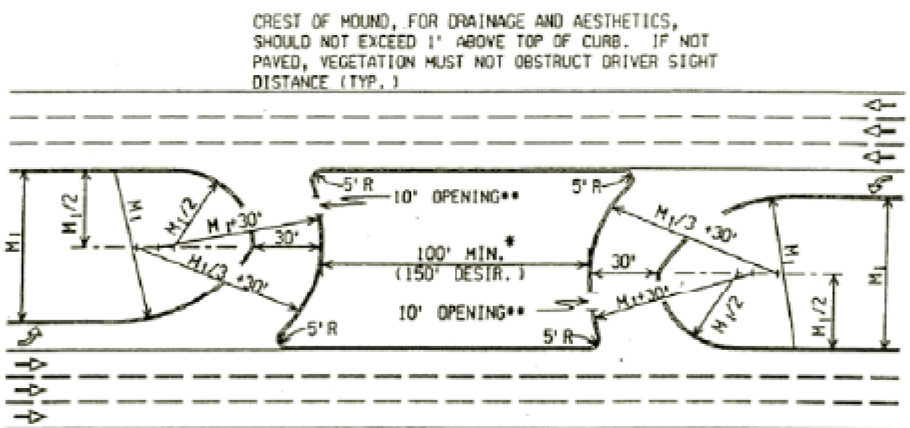
Figure 55. Illustration. Example of an MUT intersection.

At an MUT intersection, the design of the main intersection is similar to the design of a conventional intersection. The main intersection is designed for larger volumes of right-turn movements than a conventional intersection serving the same total volumes since the left-turning vehicles become right-turning vehicles. With this in mind, the intersection must be designed with right-turn bays of sufficient width and length to accommodate the volume of turning vehicles. Depending on the right-turn volume, dual right-turn lanes or an exclusive right-turn lane and an adjacent shared-use through and right-turn lane may be needed.

MDOT rarely uses channelized right turns at MUT intersections. Channelized right turns at an MUT intersection may require even more right-of-way, present a multistage pedestrian crossing, and create a more difficult driving maneuver for a driver turning right from the minor street and weaving over to use the U-turn crossover. At some MUT intersections (e.g., at partial MUT intersections), left turns from the side road are allowed as well as left-turn bays provided on the minor road approaches.

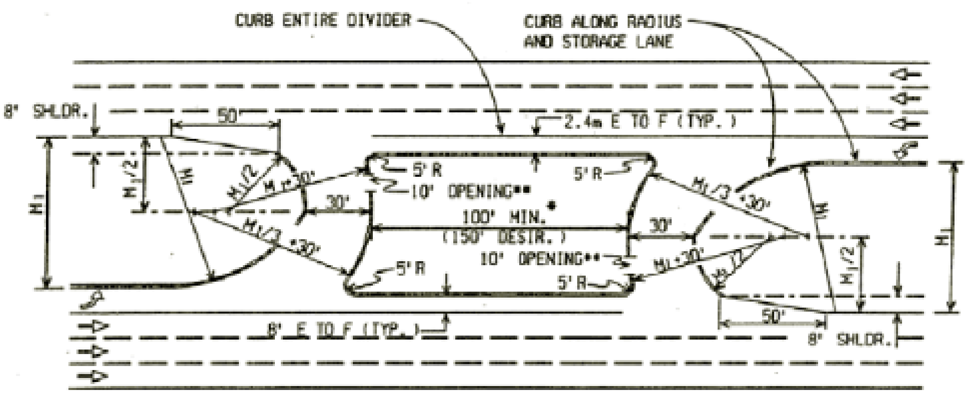
The MUT intersection has secondary intersections at each of the crossover locations. One-way crossovers with deceleration/storage lanes are highly recommended. Several studies (Scheuer and Kunde, Castronovo et al.; Taylor et al.) have found that one-way (directional) median crossovers provide better traffic operations and safety performance than two-way (bidirectional) crossovers.[34–36]

MDOT has developed design guidelines for directional median crossovers.[37] Figure 56 and figure 57 illustrate MDOT guidelines for designing directional median crossovers and show one-lane crossovers. In Michigan, it is customary for drivers of passenger vehicles to queue side-by-side in a 30-ft wide crossover and treat it as if it had two lanes. However, large trucks and other heavy vehicles typically use the entire width of the crossover. MDOT uses striped two-lane crossovers (with two lanes of storage leading up to the crossover) in some places. These crossovers are typically 36 ft wide.



Source: Michigan Department of Transportation *Geometric Design Guide 670*

Figure 56. Illustration. Directional crossover design on highway with curbs.[37]



Source: Michigan Department of Transportation *Geometric Design Guide 670*

Figure 57. Illustration. Directional crossover design on highway without curbs.[37]

The AASHTO *Green Book* provides values for minimum median width based on the needs of U-turning design vehicles.[7] The design vehicle and number of opposing lanes directly govern the required median width at the median crossover junction. Median widths between 47 and 71 ft typically result from the choice of a large design vehicle and the desire to accommodate a U-turn maneuver of that vehicle without encroaching on outside curbs or shoulders. Assuming 12-ft-wide lanes and right-of-way limits that are 10 ft wide beyond the edge of the travelway, the right-of-way for Michigan boulevards can range from 139 ft for four-lane arterials to 163 ft for eight-lane arterials.

There are several ways to accommodate these MUT intersections if sufficient right-of-way is not available to accommodate a wide median. One method of reducing the median width is to allow vehicles to turn onto the existing or widened shoulder, which could have strengthened pavement. Another method is to add pavement outside the travel lane to allow the design vehicle to complete the U-turn maneuver and merge back into the traffic stream. The additional pavement is typically referred to as loon. Sisiopiku and Aylsworth-Bonzelet define *loons* as expanded paved aprons opposite a median crossover.[38] Figure 58 shows a schematic diagram of a loon design, and figure 59 is a photograph of a loon implemented in Wilmington, NC.

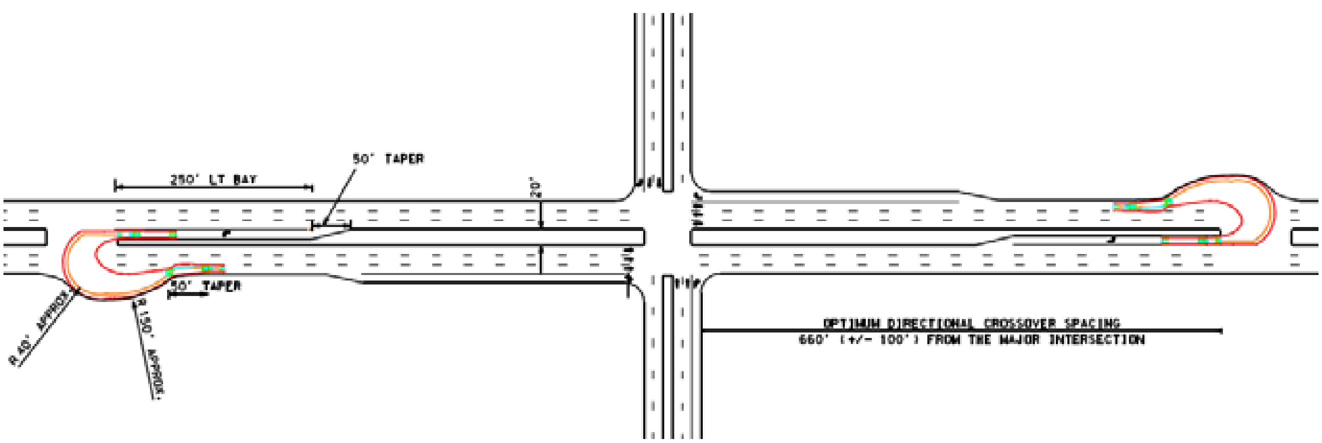


Figure 58. Illustration. Loon implementation for an MUT intersection.

Figure 59. Photo. Example of loon implementation in Wilmington, NC.

Figure 60 shows a design in which the median widens in the vicinity of the crossover to better accommodate U-turns. The reverse curves used to accomplish the widening and narrowing should be gentle enough so as to not force drivers to execute unexpected sharp maneuvers as they proceed through the curves.

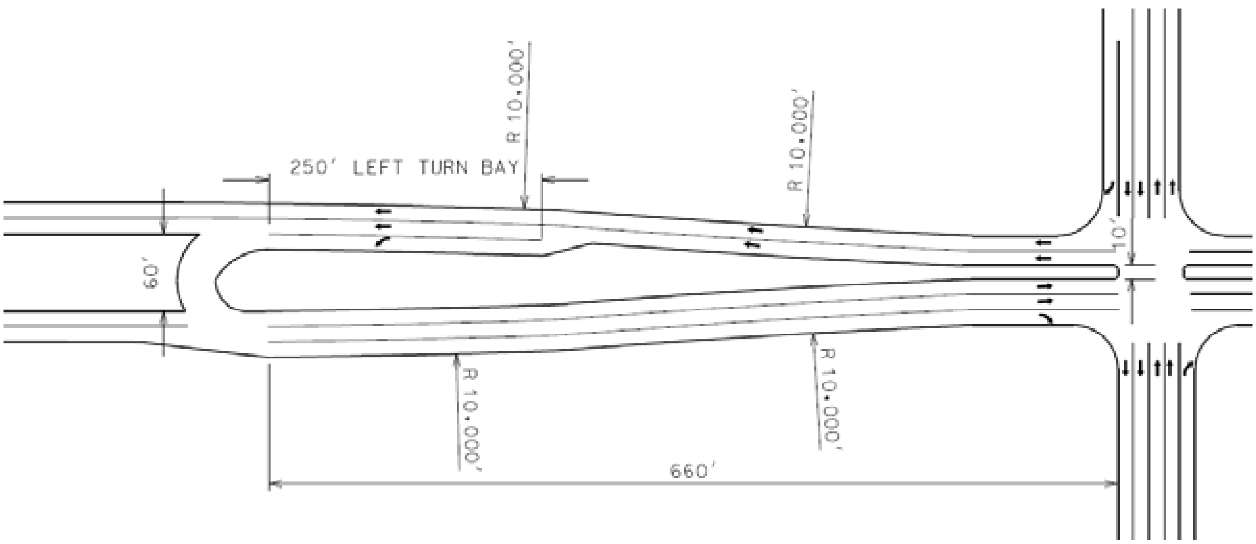


Figure 60. Illustration. Example of a transition from a wide median section to a narrow median section on MUT intersection corridors.[33]

Another way to use an MUT intersection design while keeping the main street median narrow is to place the U-turn crossovers on the minor street. Topp and Hummer showed that this variation may introduce travel time benefits compared to the common design with crossovers on the main road.[39] U-turn crossovers on the minor street mean that left turns from the main street are initiated with a right turn, which may violate driver expectations. As a result, adequate signing is critical in these cases.

The AASHTO *Green Book* recommends a distance of 400 to 600 ft for the minimum spacing between the median crossover and the main intersection.[7] MDOT recommends a distance of 660 ft ±100 ft for the median crossover from the MUT intersection.[37] The distances recommended by MDOT were established to accommodate drivers desiring to turn left from the crossroad. The longer distance facilitates the completion of the U-turn maneuver at the median crossover and subsequent right-turn maneuver at the intersection of the major road and cross street for a 45 mi/h posted speed limit on the major road. The *Access Management Manual* recommends an access spacing of 660 ft on minor arterials and 1,320 ft on principal arterials between consecutive directional median openings on divided highways.[40]

Designers should consider several issues when determining the distance from a main intersection to the median U-turn crossover. Longer distances to crossovers decrease probability of main road queues at the main intersection for the opposing direction of travel to block the crossover. They also provide more time and space for signs to be seen and read and for drivers to maneuver into the proper lane. Shorter distances to crossovers mean shorter driving distances and travel times and lower volumes at each crossover because each serve fewer driveways between the main intersection and the crossover. The selection of the spacing from the median crossover to the intersection is also a tradeoff between preventing spillback from the main intersection and the adverse impacts of additional travel for the left-turning vehicles.

Turn bays leading into U-turn crossovers are typically at least 250 ft long to provide adequate deceleration and storage. They may be longer when speeds are higher and U-turning demands are greater. In Michigan, to provide adequate storage, there are some MUT intersections where the turn bay for the crossover actually begins prior to the main intersection, at the prior crossover, or even before the prior crossover. Careful consideration of curb radii design, signing, and marking are needed at these locations so that drivers do not attempt to execute direct left turns at the main intersection.

3.3 ACCESS MANAGEMENT CONSIDERATIONS

The intent of an MUT intersection is primarily to serve through traffic on the major road. MUT intersections have the potential to provide a relatively high level of service (LOS) to through motorists on the main street over a wide range of demands. At the time of this report, no documented studies of the effects of MUT intersections on adjacent land users were identified. Inferences about the impacts on adjacent business can be drawn from *NCHRP Report 420,* which indicates that some land uses suffer economic losses with wide median installation.[12] This is particularly true for businesses such as gas stations and convenience stores that rely on pass-by traffic. The problems may be exacerbated when indirect left turns are needed to access some businesses. According to the *NCHRP Report 420*, during the planning of a project that involves creating or widening a median, the perceptions of adverse business impacts are typically worse than the ensuing reality.[12] There is no net community-wide economic impact resulting from the access changes. Nonetheless, the possibility exists that the installation of MUT intersections and concurrently much wider medians may create some business losses for some types of retail businesses.

Designers can develop MUT intersections that safely and efficiently manage access with minimum adverse impact to adjacent land users. In particular, designers have a great deal of flexibility in the placement and signalization of U-turn crossovers. On a corridor with MUT intersections, an agency may install traffic signal controls at any U-turn crossover without significantly changing the progression potential along the arterial. The signal offset for a new traffic signal at a crossover can be made to work with the existing progression band on the arterial. Signal visibility and queuing space should also be considered.

There is flexibility in locating U-turn crossovers when designing MUT intersections. Designers may generally locate a U-turn crossover within a range of distance from the main intersection without significantly reducing the efficiency of the overall intersection operation. Locating a planned crossover further from the main intersection so that it can also serve left turns into or out of an intersecting driveway or minor street may increase efficiency and safety of the whole corridor. The disadvantage of moving the crossover farther from the main intersection is that it creates longer travel distances for drivers wishing to turn left onto the crossroad at the main intersection.

Designers have a great deal of flexibility when locating driveways on an MUT intersection corridor. As with most high type intersection designs, no driveways should be allowed in close proximity to the main intersection. Driveways are also undesirable on the opposite side of the arterial from a loon. If a driveway is placed across from a loon, drivers may make wrong-way movements in the crossover.

There are mixed results for LOS and safety when driveways and side streets are located at the end of a U-turn crossover (e.g., in the loon). Such installations are common in the MUTs in Michigan and can lead to great efficiency. However, MDOT reports additional sideswipe collisions at some of these installations. MDOT has installed separate signal phases to serve the crossover and the driveway or side street in a few places, which limit the efficiency.[37] In similar circumstances, the North Carolina Department of Transportation (NCDOT) is attempting to obtain full control of access along the length of the loon on both sides of the road in its RCUT intersection applications to prevent access points at the loons.

3.4 TRAFFIC SIGNALIZATION TREATMENTS

The main intersection in an MUT design is typically signalized. Unsignalized MUT intersections exist in Michigan at low-volume cross streets on corridors with signalized MUT intersections or in developing areas where traffic volumes are expected to grow and a signal would eventually need to be installed. Agencies contemplating long-term unsignalized main intersections should strongly consider the unsignalized form of a RCUT intersection design as an alternative (see chapter 4).

A crossover at an MUT may or may not be signalized. Agencies should employ standard signal warrants in deciding whether to install traffic signal controls. In this case, the U-turn volume can be treated as the side road approach volume in the warrant criteria. A signal controller at a crossover is easy to coordinate with a signal controller at the main intersection. Therefore, agencies are able to be more aggressive in installing signals at MUT crossovers than they would at standard intersections where a new signal could have an adverse effect on the quality of progression on the major road.

Figure 61 shows the three signalized junctions at an MUT intersection, including the main intersection and the crossovers. The signals at the main intersection and the crossovers at a full MUT intersection design each have only two phases because there is no left-turning traffic (with a few exceptions as noted in section 3.2) and no exclusive pedestrian phases. Much of the efficiency gained at an MUT intersection stems from the two-phase signal operation.

Both directions of traffic on the arterial stop concurrently at an MUT intersection. This is similar to the signal at a conventional intersection. Because of the two-phase signals, the signal progression capabilities on an MUT intersection corridor are better than those of a corridor with conventional intersections. With good signal spacing and speeds, MDOT achieves sizeable two-way progression bandwidths on its MUT intersection arterials.

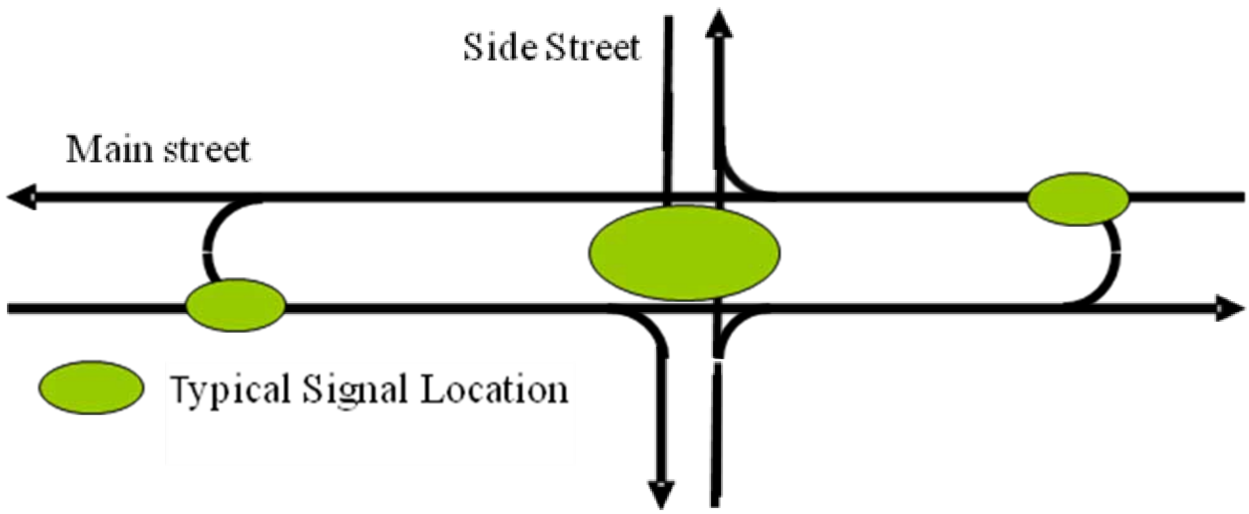


Figure 61. Illustration. Typical MUT intersection signal locations.

Figure 62 shows the signal phasing plan typically employed at an MUT intersection with signalized crossovers. Basically, the major street receives green indications during one phase, and the minor street and crossovers receive green indications during a second phase. To aid progression, MDOT starts the major street green phase approximately 7 s earlier at the crossover than at the main intersection and ends it approximately 7 s earlier. The internal offset depends on the distance to the crossover, the speed of the major street, and the expected size of the queue at the main intersection stop bar. Figure 63 shows a phasing plan with overlaps. MDOT also customarily staggers the start of the yellow and red signals for the minor street such that the yellow and red signals are displayed 1 or 2 s earlier at the near side of the major street than the far side, allowing the minor street through vehicles to clear out of the median. Figure 64 and figure 65 show the respective detector placements for the phasing scheme without and with phase overlaps, respectively. Table 6 and table 7 show the typical signal controller settings for these phasing schemes (figure 62 and figure 63).

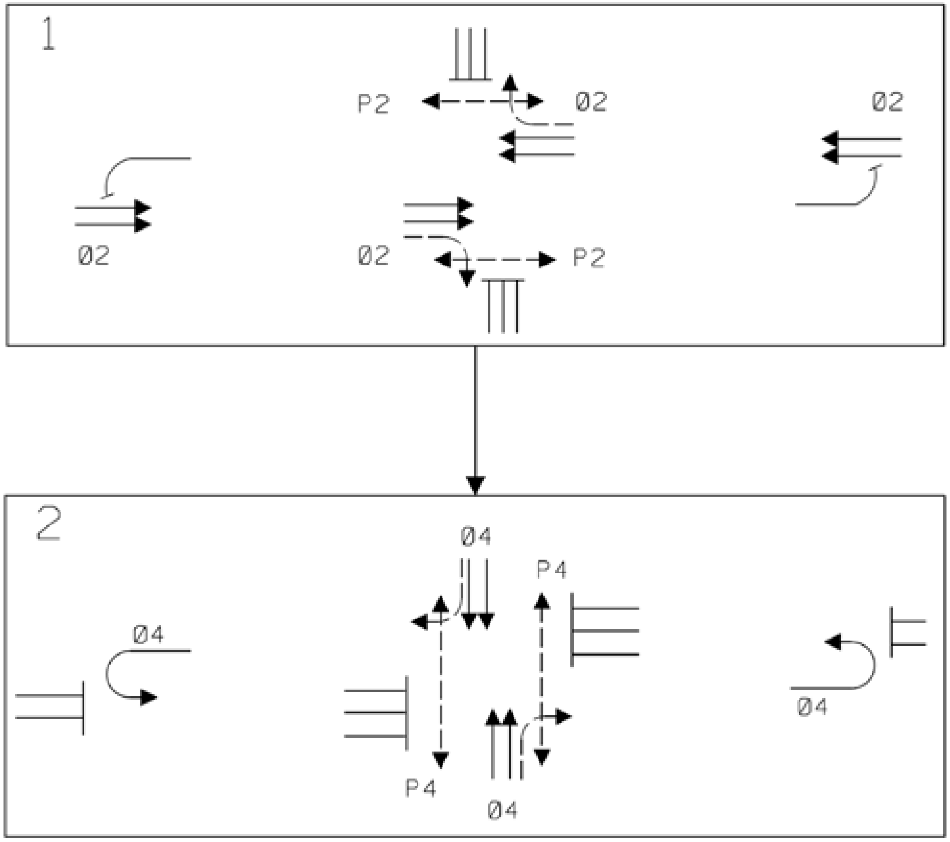


Figure 62. Illustration. Example MUT intersection phasing plan.

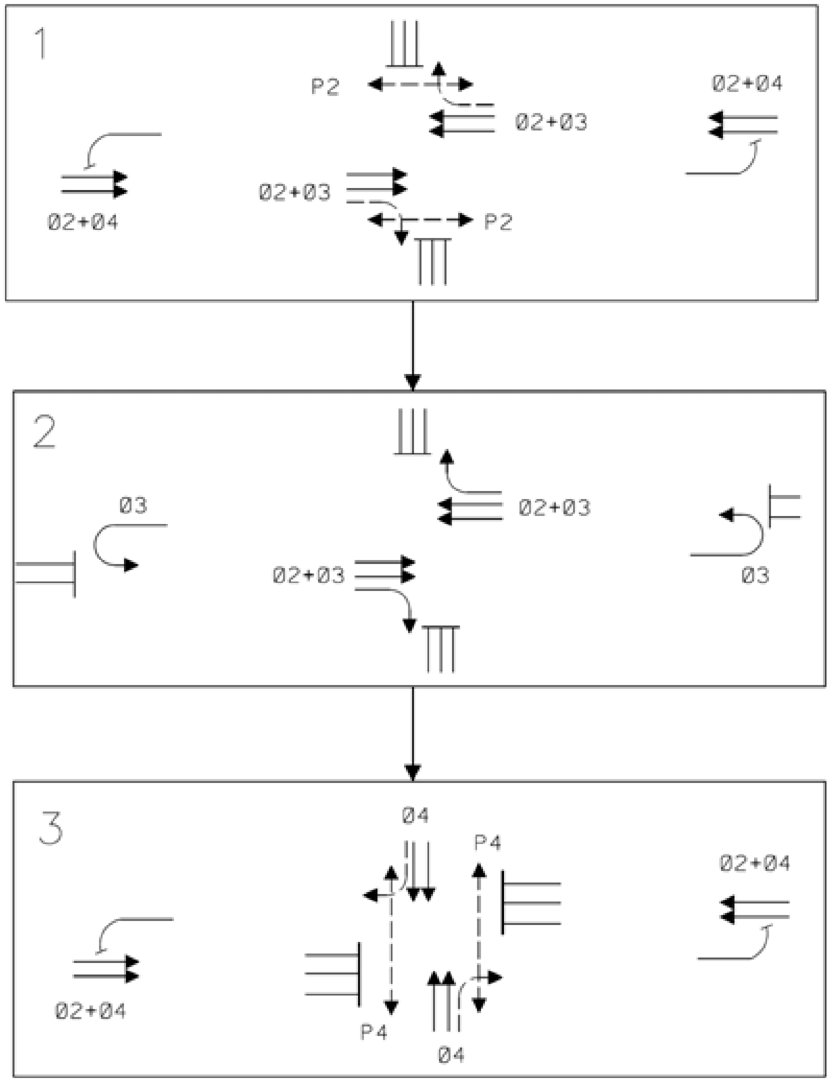


Figure 63. Illustration. Example MUT intersection phasing plan with overlaps.

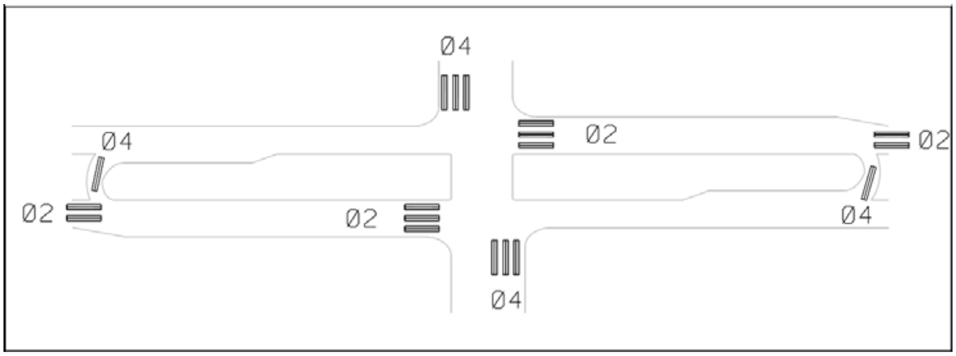


Figure 64. Illustration. MUT intersection detector placement.

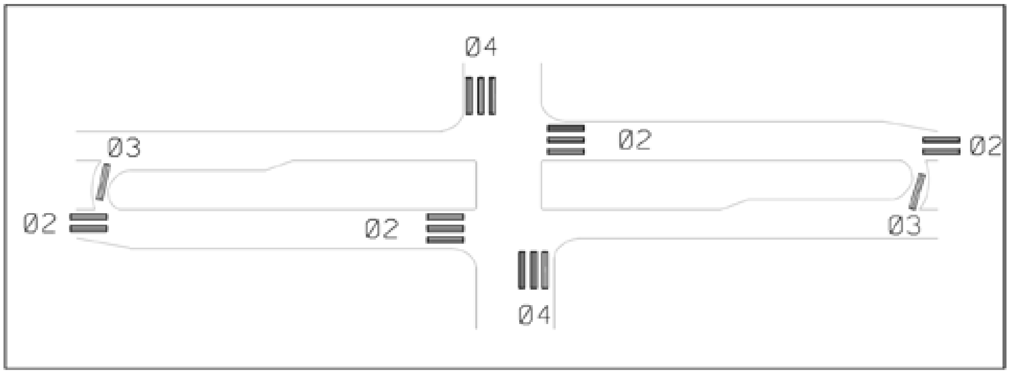


Figure 65. Illustration. MUT intersection detector placement for phasing with overlaps.

Signal timing at an MUT intersection can be straightforward. The agency chooses the cycle length and splits based on the demands at the main intersection with the signals at the crossovers merely mimicking the main intersection split. As noted in section 3.5, MDOT provides enough minimum green time to allow pedestrians to cross the major street to the median (e.g., a two-stage crossing). Actuated operation may provide the chance to start the major street green phase early at the main intersection or a crossover while preserving the background cycle for good progression.

Table 6. Typical signal controller settings for signal phasing shown in figure 62.

	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min green		15.0		5.0				
Max green		40.0		30.0				
Passage (extension)		2.0		3.0				
Amber		4.0		4.0				
All red		2.0		3.0				
Ped walk		7.0		7.0				
Ped clearance		14.0		14.0				
Recall		M in green		No				

M = Minimum.
Note: Empty cells indicate that the phases are not used.

Table 7. Typical signal controller settings for signal phasing shown in figure 63.

	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min green		15.0	4.0	5.0				
Max green		30.0	20.0	30.0				
Passage (extension)		2.0	4.0	3.0				
Amber		4.0	4.0	4.0				
All red		2.0	3.0	3.0				
Ped walk		7.0	0.0	7.0				
Ped clearance		14.0	0.0	14.0				
Recall		M in green	No	No				

M = Minimum.
Note: Empty cells indicate that the phases are not used.

Figure 66 shows possible signal locations at an MUT intersection. Note that where loons are employed, traffic signal control for the U-turn crossover must be moved back to provide room for the loon (see figure 59). MDOT does not report any problems with drivers not being able to detect and react to the signal indications in time to respond appropriately.

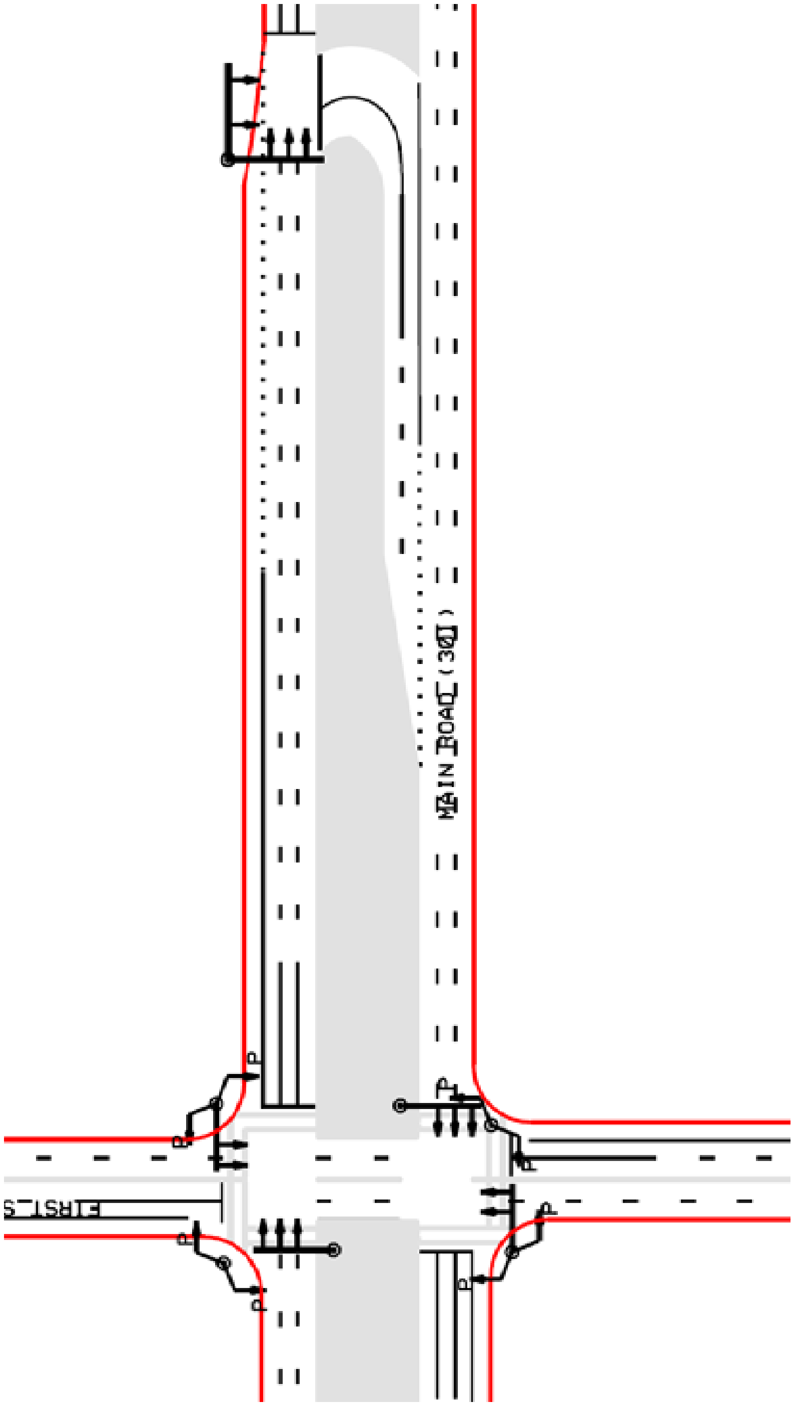


Figure 66. Illustration. Example of traffic signal locations at an MUT intersection.

3.5 SIGNING AND MARKING

Signing at an MUT intersection is critical to its success because the design may not meet the expectations of left-turning drivers unfamiliar with the intersection or intersection type. Figure 67 shows a possible signing plan for an MUT intersection. The large green guide sign for vehicles on the minor street was developed in Michigan. Prominent "No Left Turn" regulatory signs are also important at the main intersection.

Most of the signing installed by MDOT at MUT intersections are ground-mounted signs, as shown in figure 67. At many MUT and other intersections in Michigan, MDOT also provides overhead supplemental devices in the form of two backlit, four-sided case signs. These appear to unfamiliar traffic engineers as internally illuminated sign boxes with four faces displaying appropriate sign messages. A case sign is hung on span wire over the center of each of the points where the minor street intersects with a direction of the major street. The side of the case sign facing the median typically reads “No Turns.” The sides of the case sign facing the major street traffic and the minor street entering the intersection display a no left turn symbol. The side facing the wrong way traffic movement on the major street displays a wrong way symbol.

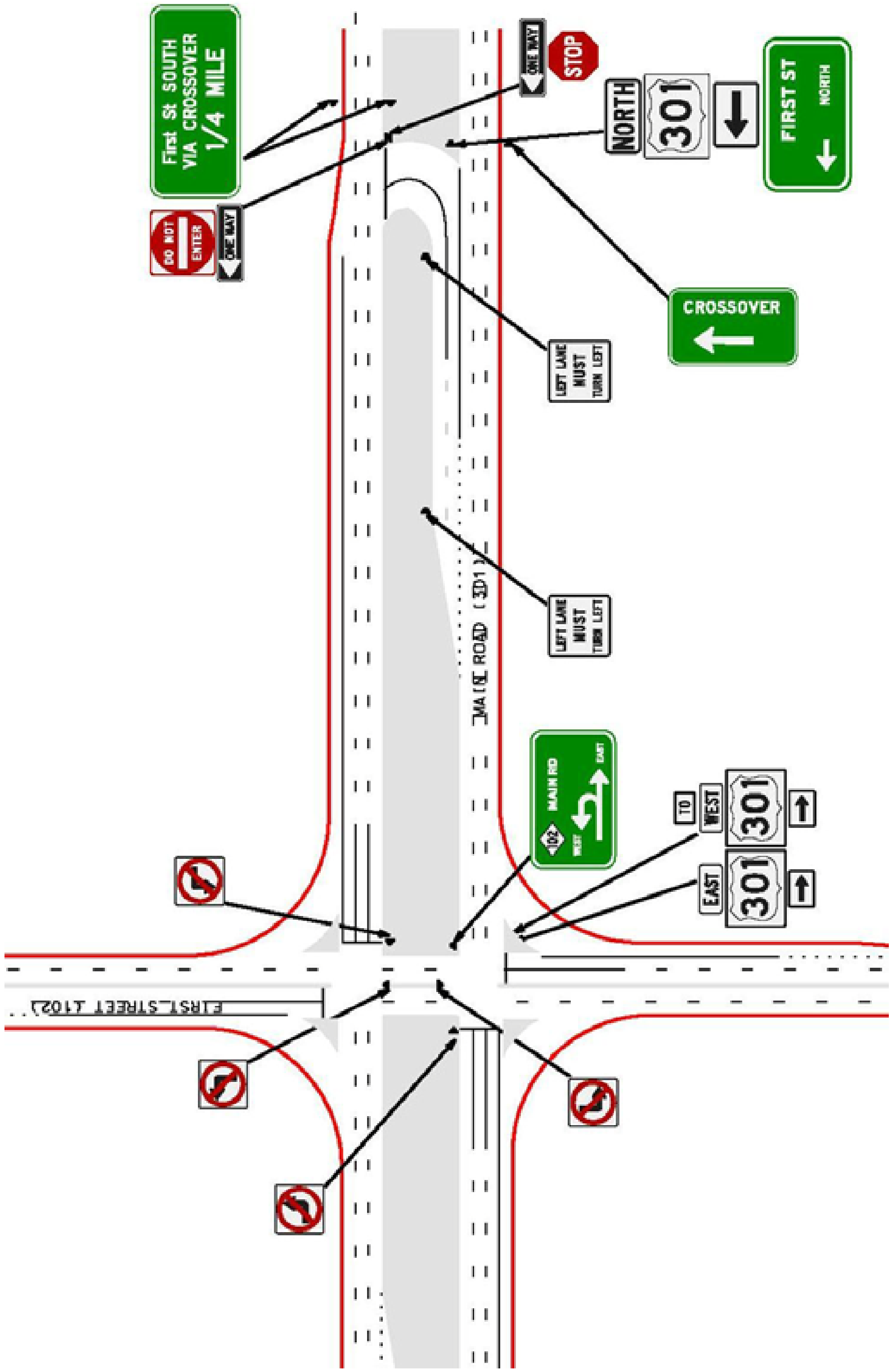


Figure 67. Illustration. Example MUT intersection signing plan.

There are guide signs other than those shown in figure 67 that can help motorists negotiate an MUT intersection. The "crossover" guide sign shown in figure 67 is rarely used by MDOT. The alternative sign shown in figure 68 is used by MDOT at the crossover when there are two U-turning traffic streams using one crossover.

Figure 68. Illustration. Alternate crossover guide sign.

The sign shown in figure 69 is frequently used as an alternative to the “Crossover ¼ Mile” guide sign shown in figure 67. The sign in figure 69 provides guidance for left-turning and right-turning motorists. Figure 70 through figure 72 show examples of signing used at MUT intersections in Michigan.

Figure 69. Illustration. Alternate major street advanced guide sign.

Figure 70. Photo. Example of minor road signing used at an MUT intersection in Michigan.

Figure 71. Photo. Example of alternative minor road signing used at an MUT intersection in Michigan.

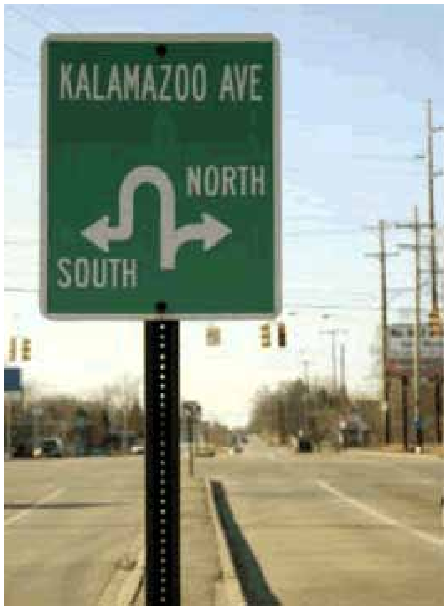
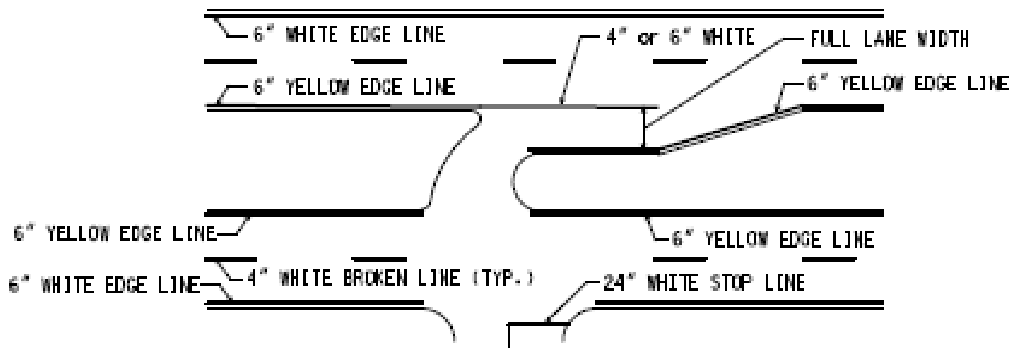


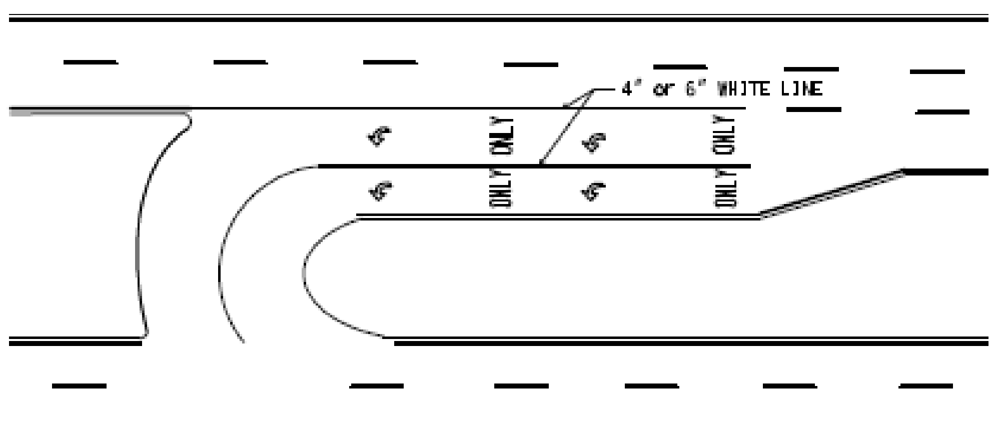
Figure 72. Photo. Example of major road signing used at an MUT intersection in Michigan.

Pavement marking standards used by MDOT provide guidance on marking the crossover area for both directional and bidirectional crossovers. Examples of the pavement marking standards used by MDOT are shown in figure 73 and figure 74.



Source: Michigan Department of Transportation *Geometric Design Guide 670*

Figure 73. Illustration. Typical pavement marking at a directional crossover.[37]



Source: Michigan Department of Transportation *Geometric Design Guide 670*

Figure 74. Illustration. Pavement markings at a directional crossover with dual lanes.[37]

3.6 ACCOMMODATION OF PEDESTRIANS, BICYCLISTS, DISABLED PEDESTRIANS, AND TRANSIT USERS

Crosswalks at an MUT intersection are at locations similar to a conventional intersection as shown in figure 75. The major street crossing can be made in one or two stages. A one-stage crossing (i.e., crossing both directions of the major street during one signal phase) is possible if the distance is not too long and if the necessary green time does not adversely impact traffic flow on the major road. At many MUT intersections in Michigan, these conditions have not been met, and a two-stage crossing of the major street is provided. In a two-stage crossing, a pedestrian crosses one direction of the major street during one signal phase and the other direction during a second signal phase often with some delay between the phases. Because there are only two signal phases and the cycle lengths are short, the amount of delay to a pedestrian due to the two-stage crossing is relatively small. If pedestrian signals and push-button controllers are provided, the devices need to be installed in the median as well as on the sides of the road.

Pedestrians with vision and cognitive impairments should find crossing an MUT intersection to be no more challenging than crossing a comparable conventional intersection. The cues that pedestrians with vision impairments rely on to cross intersections, such as the sound of traffic parallel to their crossing, are similar. Pedestrians should find the clear and direct crossing path relatively easy to use. All pedestrians should benefit from the simpler two-phase signal timing and the lower number of conflicting traffic streams than at a conventional intersection.

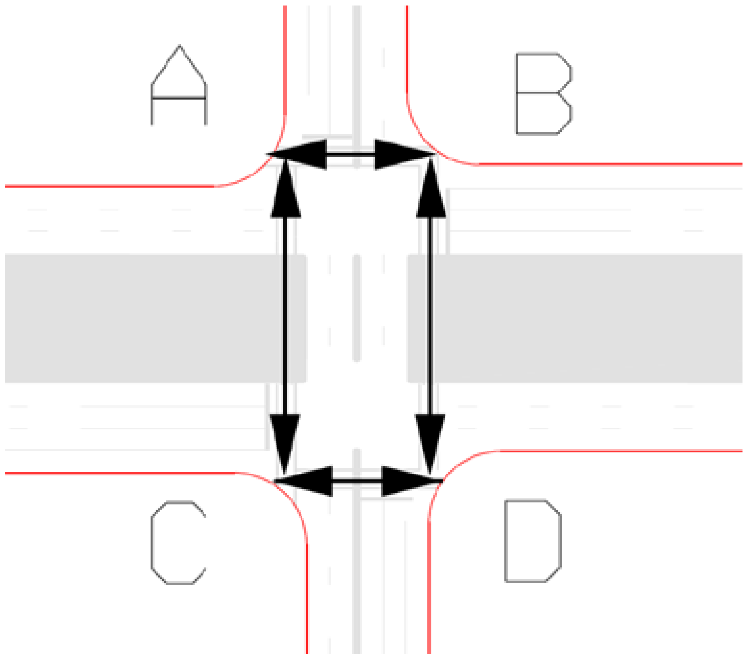


Figure 75. Illustration. Pedestrian movements at an MUT intersection.

Pedestrians crossing at an MUT intersection encounter fewer conflicting traffic streams than at a typical conventional intersection. Conflicts at conventional intersections are possible between left-turning traffic from the side road and pedestrians crossing the main street when the signal is in a phase in which the left-turn movement is permitted. Research shows that pedestrians who attempt to cross illegally during a leading protected left-turn phase can create conflicts with vehicles. By comparison, pedestrians at a full MUT intersection cross the main street during the minor street through and right-turn signal phase when the only conflicts possible are with minor street right-turning vehicles or major street right-turning vehicles making turns on red. Because of the fewer conflict points, a pedestrian crossing at a full MUT intersection may be safer than at a comparable conventional intersection. There are no empirical data available to support or reject this contention. An MUT intersection design along a corridor affords designers the flexibility to install pedestrian signals at midblock locations without adding much delay for through traffic on the major road with one condition that the pedestrian crossing is made in two stages.

Through and right-turning bicyclists encounter high green time percentages for their movements at full MUT intersections. Bicyclists desiring to make left turns from the side road face a choice of using pedestrian crosswalks to cross the major road and then the far side road or using the U-turn crossovers in a manner similar to drivers of motor vehicles. Bicyclists on the major road approaches who want to turn left onto the side road are faced with a similar decision. They can use the pedestrian crosswalks to cross the side road leg and then the far major road leg. However, the indirect left turn adds distance to the bicyclist's travel. The U-turns may also present a hazard to bicyclists as vehicles executing U-turns have more difficulty staying in lanes, and larger vehicles exhibit greater off-tracking, which may cause vehicles to encroach into bicycle paths. Therefore, agencies should design MUT intersections to accommodate most left-turning bicyclists using the crosswalks. These treatments may include upgrading the sidewalks to shared-use paths while providing signing to direct bicycles to the shared pathway or providing signing emphasizing that direct left turns in the roadway are prohibited for bicyclists and drivers.

Analogous to pedestrians, transit users are not likely to be adversely impacted by the use of an MUT intersection instead of a conventional intersection. The design of the intersection does not necessitate locating bus stops further away from the main intersection, as with the DLT intersection discussed in chapter 2. Bus stops for through and right-turning buses likely work well on the far side of the main intersection or on the side street, respectively, where they create less delay for main road vehicles than if they are located on the approach to the intersection. Bus stops for left-turning buses may be more effective on the side road so that buses stop after making the U-turn and turning right onto the minor street. If there is more than one lane departing the intersection on the side road, this maneuver allows buses to easily get into the right lane in order to stop. A bus stop after the main intersection but prior to a U-turn maneuver may create a difficult weaving maneuver across the major street from a stop in order to use the crossover. On approaches to the main intersection where there is a loon provided for opposing direction U-turns, bus stops in the loon should be strongly discouraged to keep it free for vehicles using the crossover. A typical example of desirable bus stop locations is shown in figure 76.

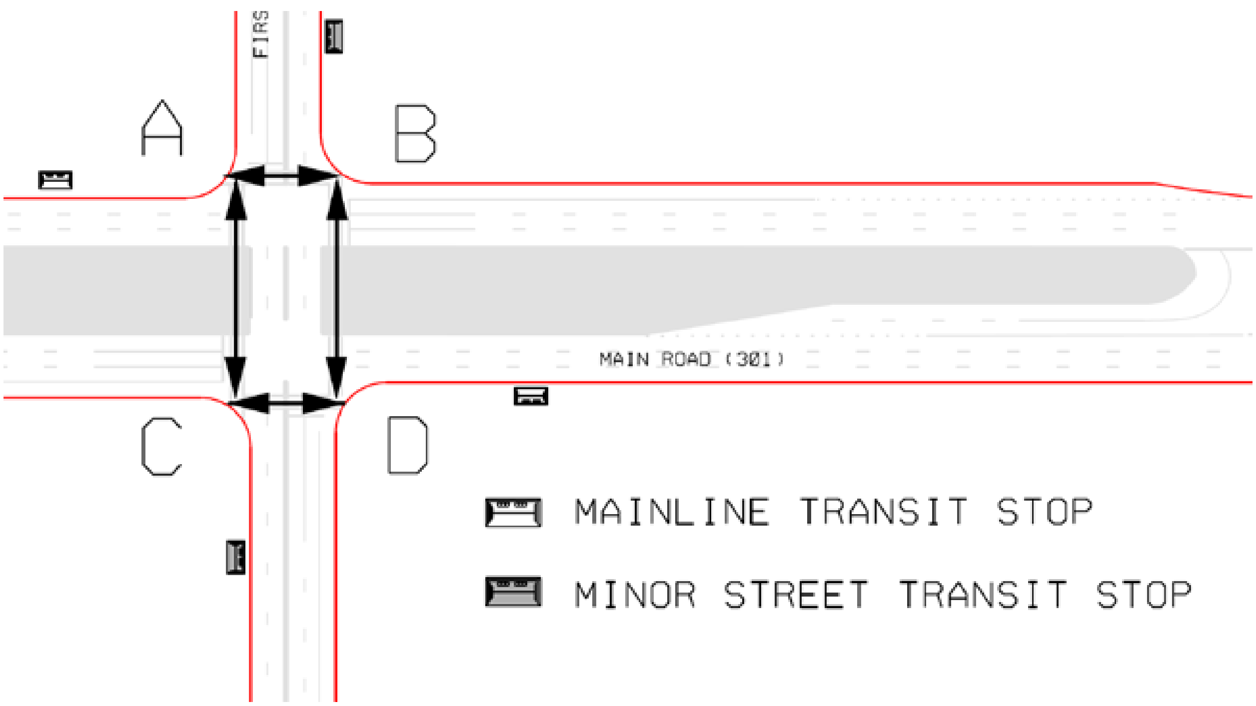


Figure 76. Illustration. Transit stop locations at an MUT intersection.

Transit users can benefit from more efficient traffic operations along an arterial in which MUT intersections are constructed to improve operations. Bus routes making left turns at an MUT intersection have to travel further and likely incur more travel time than a conventional intersection. MDOT has mitigated this in some places by allowing transit buses to make a direct left turn at the main intersection. They indicated this with a supplemental plaque that reads “Except Buses” under the “No Left Turn” sign at the main intersection. U-turn crossovers designed to accommodate large combination trucks without curb encroachments should also be able to accommodate standard transit and school buses.

3.7 OPERATIONAL PERFORMANCE

A possible advantage of MUT intersection design is the potential for improved operational performance. This section discusses situations in which the improved performance can be expected. The discussion is based on a review of research on the MUT intersection and also on results of an original simulation experiment to study the intersection design. Several studies have compared MUT intersections to conventional intersections. These studies have looked at the travel times, speeds, average number of stops, and capacity.

3.7.1 Previous Research Review

Savage studied the conversion of a five-lane roadway with a two-way left-turn lane (TWLTL) to an MUT intersection corridor in Michigan and found a 20 to 50 percent increase in the corridor capacity.(41) A study by Stover computed CLVs for the intersection of two six-lane arterial roads.(42) The effects of redirecting left turns were computed using these volumes. The provision of dual left-turn lanes on all approaches reduced CLVs by 12 percent compared to providing single left-turn lanes but still required multiphase traffic signal controls. The rerouting of left turns via directional crossovers and their prohibition at the main intersection reduced CLVs by 17 percent. Maki compared the MUT and the conventional TWLTL on four-lane and six-lane boulevards and found a 20 to 50 percent increase in capacity (throughput) for the MUT.(43) Figure 77 shows the LOS comparison between corridors with MUTs and conventional intersections.

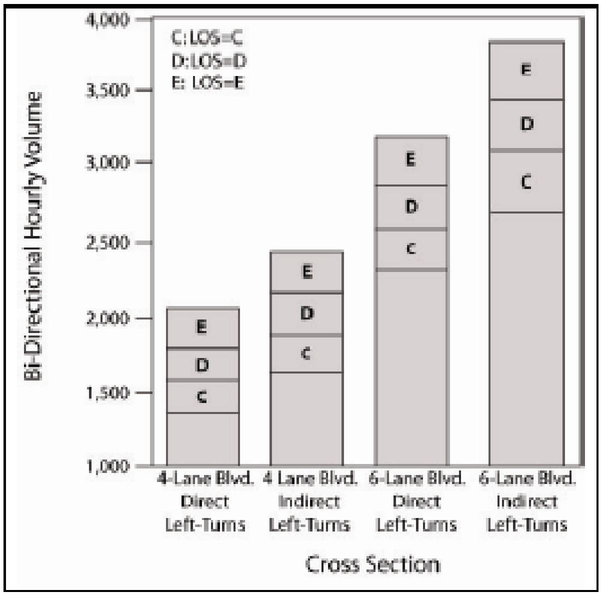


Figure 77. Graph. LOS comparison of divided highways.

Koepke et al. found that the directional crossover design provided about 14 to 18 percent more capacity than the conventional dual left-turn lane design.(44) The results of critical lane volume (CLV) analyses, after taking into account overlapping traffic movements, revealed reductions of about 7 to 17 percent in CLVs depending on the number of arterial lanes (six or eight) and the traffic mix. Lower CLVs translated into higher traffic flow capacity at the intersection.

Dorothy et al. evaluated traffic operational measures to study the differences in the performance of MUT intersections compared to the conventional TWLTLs.(45) A traffic network simulation model was used to simulate these situations for 1-hour periods. The simulated network had signals every 0.5 mi with the directional crossovers every 0.25 mi. A 60:40 split between the entering volumes on major road and cross street was assumed. When turning percentages were low, the crossovers were modeled as stop-controlled. With higher volumes, signal control was assumed in the model. The signal cycle was 80 s with a 60:40 distribution of green time for the major road phase and cross street phase, respectively. The median width varied from 40 to 100 ft. The key findings were as follows:

- When the left-turning traffic percentage was 10 percent, MUT intersections with signalized directional crossovers had lower left-turn total travel times than conventional intersections. The differences were 20, 40, and 150 s/veh at 30, 50, and 70 percent mainline saturation, respectively. Similarly, MUT intersections with signalized directional crossovers had lower left-turn total travel times than conventional intersections when the left-turning traffic percentage was 25 percent. The differences were 20, 30, and 70 s/veh at 30, 70, and 90 percent mainline saturation, respectively.

- The MUT intersections provided consistently lower network travel times compared to the five-lane TWLTL design.

- For low left-turning percentages, the directional median crossovers with stop control had approximately the same left-turn total time and network total time as the directional medians with signalized crossovers.

Reid and Hummer compared traffic operations along a typical arterial highway with MUT intersections to the arterial with conventional designs with TWLTL.(46) The analysis corridor was a 2.5-mi section of the northwestern highway corridor in Detroit, MI. The section consisted of five major signalized intersections with varied spacing from 1,600 to 3,500 ft and AADT ranging from 52,000 to 60,000 veh/day. CORSIM® was used to simulate traffic performance, and Synchro® was used to develop optimized signal timings.(21) Four time periods were considered in the analysis, including peak periods in the morning, midday, midafternoon (2–3 p.m.), and evening. Average measures of effectiveness were developed for a total of 48 CORSIM® runs. The analysis indicated that the MUT intersection had the potential to significantly improve system travel times and speeds in the corridor during the busiest hours of the day and to not compromise system travel times during off peak periods. The corridor with MUT intersections showed a 17 percent decrease in total travel time within the study area network compared to a corridor with a TWLTL. Average speeds increased by 25 percent and the average number of stops increased for the MUT intersection compared to the TWLTL.

Reid and Hummer later used CORSIM® to compare the traffic performance of seven unconventional arterial intersection designs, including the quadrant, MUT, RCUT, bowtie, jug-handle, split intersection, and DLT intersection.(20) They used turning movement volumes from existing isolated intersections in Virginia and North Carolina. Off peak, peak, and volumes corresponding to 15 percent higher than the peak volumes were examined. For each intersection type, 36 to 42 CORSIM® simulation runs of 30-minute durations were analyzed. For MUT intersections, the CORSIM® models used unsignalized U-turn crossovers for two-lane collector roads and signalized U-turn crossovers for four-lane collector roads. Entering volumes for the simulated intersections ranged from 4,500 to 7,500 veh/h. The MUT intersection produced significantly lower than average total travel times in comparison to the conventional intersection. The change in overall travel times for all movements through the intersection when compared to a conventional intersection was -21 to +6 percent during peak conditions. The overall change in the number of stops when compared to a conventional intersection was -2 to +30 percent during peak conditions.

Bared and Kaiser used CORSIM® to study the traffic operational benefits of signalized MUT on a typical four-lane road intersecting a four-lane road.(47) The cross street left-turn movement was allowed at the main intersection, resulting in a three-phase signal. An acceleration lane was provided for the vehicles turning right onto the side road from the major road. These two features used in the study were different from the typical MUT intersection implementations in Michigan. Entering volumes at the intersections used in the simulations ranged from 2,000 to 7,000 veh/h. The key findings of the study were as follows:

- Compared to conventional intersections, considerable savings of travel time were observed for the U-turn design at higher entering flows (greater than 6,000 veh/h) with 10 and 20 percent left-turning volumes.

- On average, the proportion of vehicles stopping on the network was lower for the U-turn design. For the case with 10 percent left-turning volumes, vehicles in the U-turn design experienced 20 to 40 percent fewer stops. For 20 percent of left turns, a noticeable reduction in percent stops started when volumes reached approximately 4,500 veh/h.

- Providing an acceleration lane on the crossroad was recommended to improve traffic operational efficiency.

Topp and Hummer compared median crossovers on the cross street with median crossovers on the arterial highway for MUT intersections using CORSIM®.(39) The left-turning volumes on the major road varied from 100 to 400 veh/h, the through volumes on the major road varied from 1,000 to 2,000 veh/h, the left turns on the cross street varied from 50 to 200 veh/h, and the through volumes on the cross street varied from 500 to 1,000 veh/h. The median crossovers were signalized wherever warranted. Results showed that the MUT intersection design with the U-turn movement located along the cross street reduced percent stops, total travel time, and delay for most of the volume combinations analyzed in comparison to the crossover on the arterial.

The *Traffic Control Devices (TCD) Handbook* suggests providing a left-turn phase if one of the following criteria is applicable:(48)

Based on volume, as follows:

- The number of left turns multiplied by the opposing conflicting volume in the peak hour exceeds 100,000 on a four-lane street or 50,000 on a two-lane street.

- The left-turn peak hour volume is greater than 90 veh/h or 50 veh/h on streets with through traffic speeds over 45 mi/h.

- The number of vehicles per cycle per approach at the end of green during the peak hour is greater than two at pretimed signal-controlled intersections.

Based on delay, as follows:

- The left-turn delay is greater than 2.0 veh-h in the peak hour on the critical approach, provided there are at least two left turns per cycle during the peak hour, and the average delay per left-turning vehicle exceeds 35 s.

Based on crash experience, as follows:

- For one approach, the number of left-turn crashes is equal to or greater than four crashes in 1 year or six crashes in 2 years.

- For both approaches, the number of left-turn crashes is equal to or greater than 6 crashes in 1 year or 10 crashes in 2 years.

The criteria above not only applies to the determination of the need for a separate left-turn phase at a conventional signal-controlled intersection but also to the determination of the need for signal control at median crossovers to accommodate U-turns.

Overall, the literature showed that reducing the number of signal phases and redirecting the left-turning movement at an intersection as found in the MUT intersection provided significant benefits in terms of increased roadway capacity and reductions in travel time and vehicular delay when compared to conventional intersections.

3.7.2 Research Findings

VISSIM® was used to gain further insights into the operational performance of the MUTs in comparison to conventional intersections. Two intersection geometric design cases of MUTs and conventional intersections were simulated. The two cases modeled were as follows:

- *Case A = A full MUT:* Intersection of a four-lane major road and a four-lane minor road with one lane crossover on the mainline. No left-turn movements were allowed from the minor road at the main intersection.

- *Case B = A partial MUT:* Intersection of a four-lane major road and a four-lane minor road with one lane crossover on the mainline. Left-turn movements were allowed from the minor road at the main intersection.

Table 8 shows the geometric design configurations that were simulated. The lane configurations and geometric features for the MUT and conventional intersections on both approaches of the major road were identical for each case. Similarly, the lane configurations and geometric features on both approaches of the minor road were identical for the two types of intersections. These two geometric cases were simulated under six sets of traffic volumes—low, medium, and high. The major and minor road splits were also varied for the six simulation cases. Therefore, a total of 12 unique VISSIM® simulations were developed for the MUT, and an equal number of unique VISSIM® simulations were developed for comparable conventional intersections. A U-turn volume of 10 veh/h and a right-turn volume of 300 veh/h were modeled on all approaches. The VISSIM® simulation network was 1 mi long on the major and minor road approaches for the cases simulated. The base case simulations assumed no pedestrian activity at the intersection. The following constants were assumed in VISSIM® for all simulated cases:

- Optimum fixed signal timing determined using Synchro®.[21]

- Yellow times determined using ITE policy.

- All-red times determined using ITE policy.

- A total of 5 percent heavy vehicles on all legs.

- A total of 350-ft-long left-turn bays upstream of the displaced crossover junction.

- A total of 325-ft-long left-turn bays downstream of the displaced crossover junction.

- A 0.5-mi network size in each direction from the main intersection.

- Single right-turn bays on the mainline.

- Right-turn on red allowed at each signal, no left-turn on red allowed.
- A signal at each DLT crossover.
- A 40-ft median width on mainline.
- Undivided side street.
- A 45 mi/h desired speed on mainline.
- A 25 mi/h desired speed on side streets.
- Saturation headway of approximately 1,900 veh/h/lane (alpha = 3 and beta = 2).
- No bus stops.

Table 8. Volumes for MUT intersection geometric design configurations for VISSIM® simulations of cases A and B.

Geometric Cases	Set	Major 1 Road		Major 2 Road		TotalMajor (Both Approaches)	Minor (Each Approach)		TotalMinor (Each Approach)	Major/Total Major	Total Minor/Total Intersection
		Left	Through	Left	Through		Left	Through			
2-lane major 2-lane minor 1-U turn	1	100	2,100	100	2,100	5,020	10	750	1,070	0.50	0.26
	2	110	2,090	154	1,386	4,350	10	750	1,070	0.60	0.29
	3	110	2,090	148	632	3,590	10	750	1,070	0.75	0.34
	4	150	1,800	150	1,800	4,520	90	950	1,350	0.50	0.35
	5	300	1,000	300	1,000	3,220	200	1,450	1,960	0.50	0.44
	6	100	650	100	650	2,120	450	1,750	2,510	0.50	0.26

For case A, the MUT intersection had two through lanes, one left-turn lane, and one right-turn lane per approach for the mainline approaches and two through lanes and one right-turn lane per approach for the side street approaches. The left-turn lane on the mainline upstream of the median crossover had a length of 250 ft, and the right-turn bay on the side street had a length of 200 ft. No acceleration lanes were provided for right-turning from the side street. The median separating the opposing through lanes was 10 ft wide. The comparable conventional intersection had similar geometric features and dimensions as the MUT described above on all four approaches. The VISSIM® simulations results are shown in figure 78. The MUT intersection showed an increase in throughput of 15 to 40 percent in comparison to conventional intersections. The average intersection travel time for the conventional intersections was significantly higher than the MUT intersections in saturated conditions.

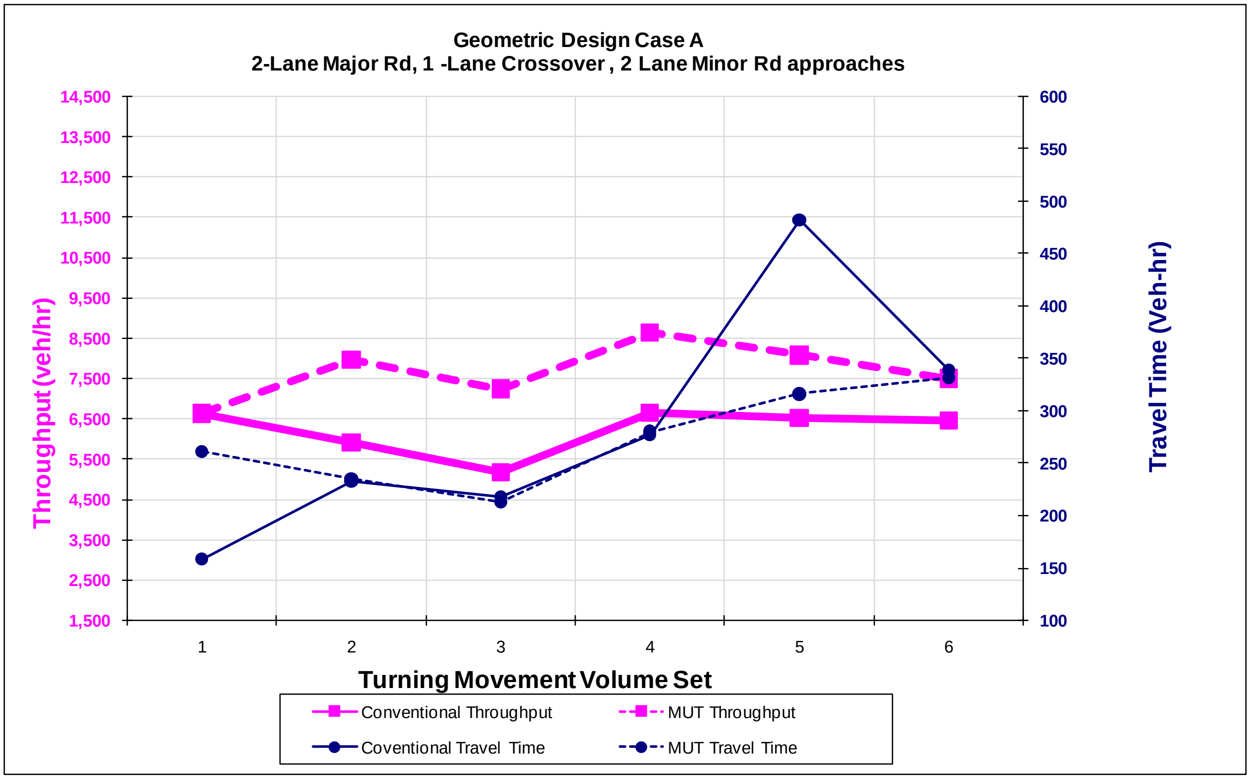


Figure 78. Graph. Throughput and travel time comparisons for geometric design case A.

For case B, the partial MUT intersection had two through lanes, one left-turn lane, and one right-turn lane per approach for the mainline approaches and two through lanes, one left-turn lane, and one right-turn lane per approach for the side street approaches. The left-turn lane on the mainline upstream of the median crossover had a length of 250 ft, and the left-turn and right-turn bays on the side street had a length of 200 ft, respectively. No acceleration lanes were provided for right-turning from the side street. The median separating the opposing through lanes was 10 ft wide. The comparable conventional intersection had similar geometric features and dimensions as the MUT described above on all four approaches. The VISSIM® simulations results are shown in figure 79. The throughput at an MUT intersection was 10 to 25 percent higher compared to conventional intersections. The average intersection travel times for the conventional intersections were significantly higher than the MUT intersections in saturated conditions.

In summary, the MUT intersections were better suited for heavy through traffic volumes on the major road and side streets with moderate balanced left turns from the major road and side streets.

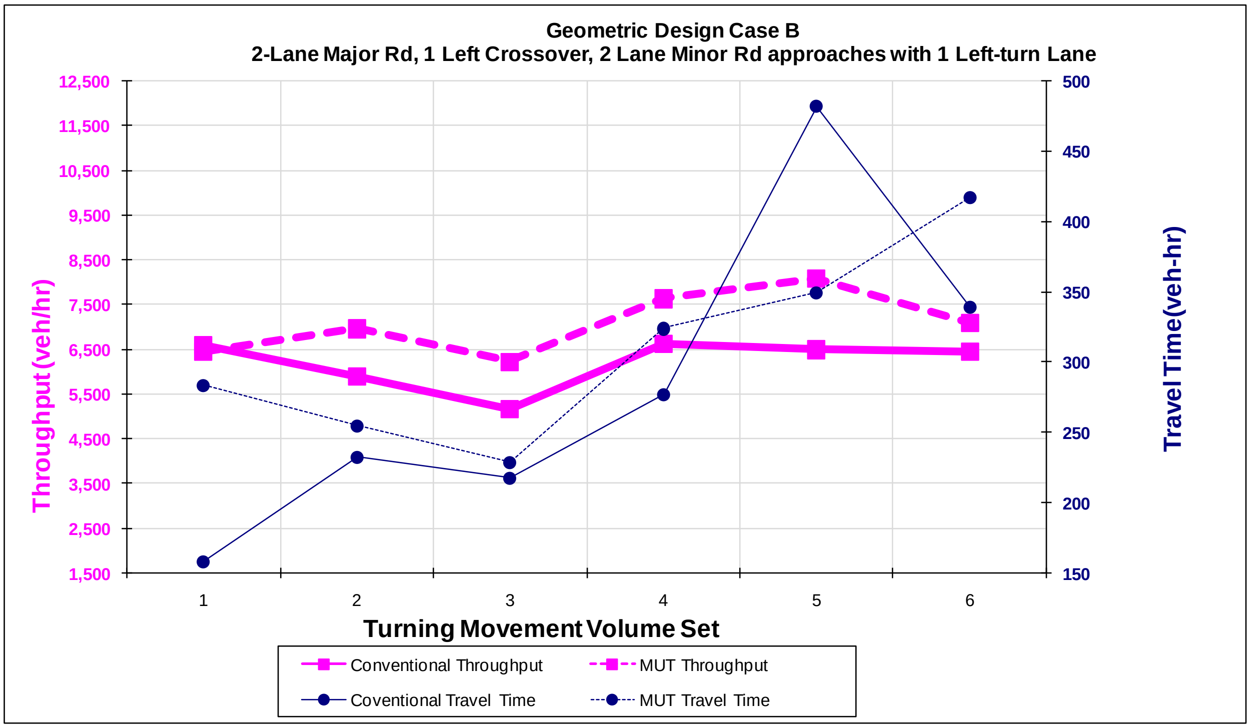


Figure 79. Graph. Throughput and travel time comparisons for geometric design case B.

3.8 SAFETY PERFORMANCE

Table 9, which is from the FHWA report entitled *Signalized Intersections: Informational Guide*, shows the number of conflict points at a four-legged signalized intersection (32 total) as compared to the MUT intersection (16 total).[(49)] The MUT intersection eliminates all crossing conflict points related to left turns and reduces the number of merge/diverge conflict points as well. Figure 80 shows the location of conflict points for an MUT intersection. Common crash types occurring at MUT crossovers are rear ends, angle, and sideswipe crashes. In the *NCHRP Report 524*, "Safety of U-Turns at Unsignalized Median Openings," collected traffic conflict data were reported. For most types of median openings, conflicts involving major road vehicles having to brake for vehicles turning from the median opening onto the major road were the most common type of conflict.[(50)] The implementation of MUT intersections resulted in overall reductions in rear-end, angle, and sideswipe crashes by 17, 96, and 61 percent, respectively.[(33)]

Table 9. Comparison of conflict points for MUT and conventional four-legged intersection.

Conflict Type	Four-Legged Signalized Intersection	MUT Intersection
Merging/diverging	16	12
Crossing (left turn)	12	0
Crossing (angle)	4	4
Total	32	16

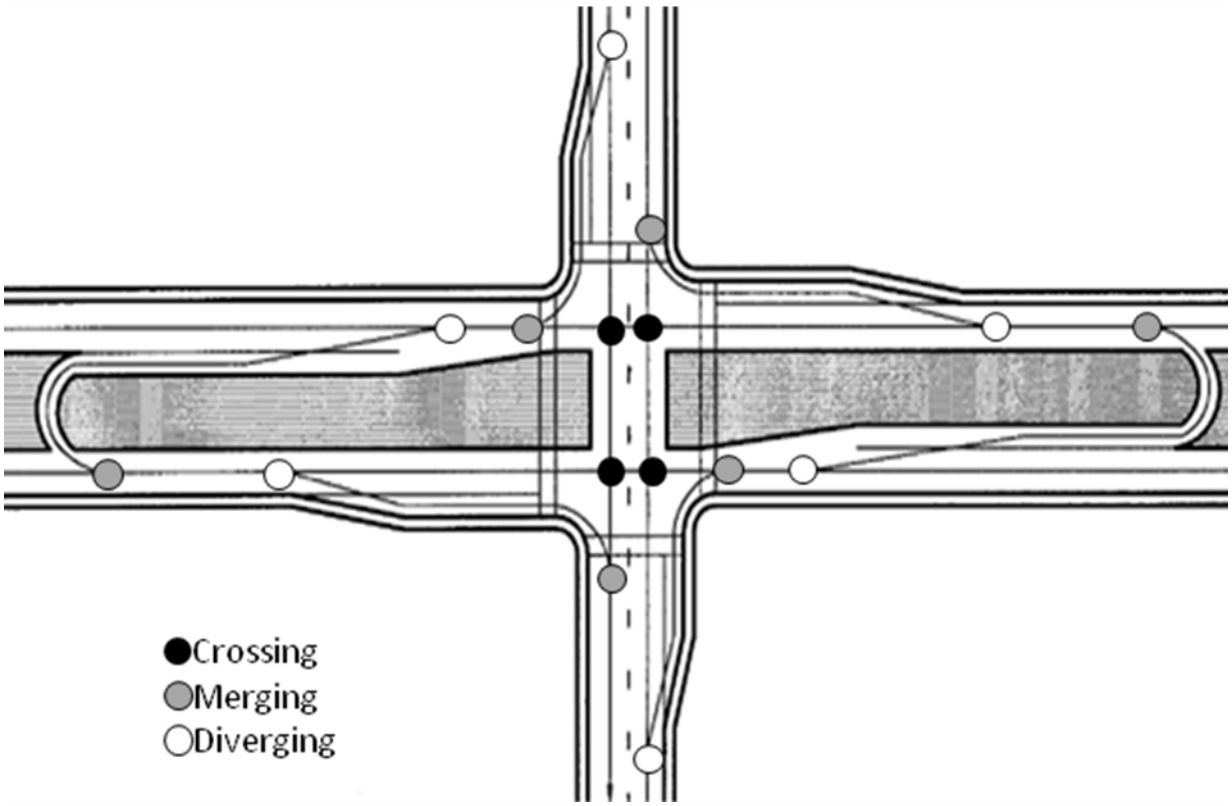


Figure 80. Illustration. Conflict point diagram for MUT intersection.

In *NCHRP Report 524,* both urban/suburban and rural median openings were analyzed.(50) Urban arterial corridors exhibited an average of 0.41 U-turn plus left-turn crashes per median opening per year. Rural arterial corridors experienced an average of 0.21. Kach compared the safety performance of conventional signalized intersections to MUT intersection locations in Michigan.(51) The study consisted of 15 MUT intersection locations and 30 conventional intersections. Analysis of crash data for the period revealed statistically significant lower crash rates for the MUT intersections for both corridor-wide and intersection-related data sets.

Castronovo analyzed the safety benefits of MUT intersections compared to conventional intersections as a function of traffic signal density.(52) Data were collected from approximately 125 boulevard segments. The analysis results indicated that as traffic signal density increased, the MUT intersection had increasingly lower crash rates than the conventional intersection.

Figure 81 shows the two types of median crossovers—bidirectional and directional. As discussed in section 3.2, a *bidirectional crossover* is an opening in the median for vehicles to make U-turns from either direction. The use of bidirectional crossovers creates additional points of conflict compared to the directional crossover shown in figure 81. In addition, an interlocking effect can be created if turning volumes are relatively large. This could create sight distance limitations and could lead to unpredictable driver behavior as drivers try to complete their U-turn maneuver when the paths are blocked.

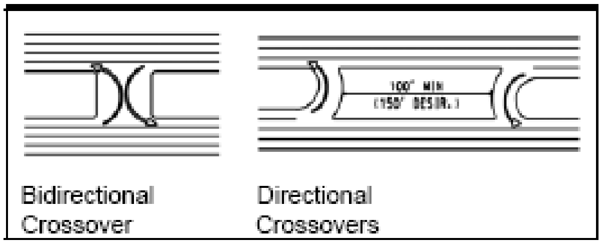


Figure 81. Illustration. Directional and bidirectional crossovers.

A directional crossover is considered to be a safer design because motorists at a properly designed directional crossover should not experience the interlocking effect found at medians with a bidirectional crossover. Several studies compared the crash experience of bidirectional, or conventional, crossovers with directional crossovers. For divided highway corridors without signals, the directional crossover had the same crash rates as bidirectional crossovers; however, for signalized corridors, the crash rate was lower when only directional crossovers are used.[(53)] Three studies showed that where existing bidirectional crossovers were replaced with directional crossovers, a reduction in crashes was typical.[(34, 36, 43)] Because replacement of a bidirectional crossover typically requires multiple directional crossovers to serve the same movements, all crossovers related to serving traffic wishing to turn left at the main intersection should be considered when estimating the impact of directional versus bidirectional crossovers or when comparing a conventional intersection design to an MUT intersection design.

Intersections with driveways or minor roads may be located at MUT crossovers. In *NCHRP Report 524*, safety at intersections on divided highways was analyzed.[(50)] The results were applicable to the situations where driveways or intersections were located at the median opening where left-turning vehicles from the main intersections were making U-turns. *NCHRP 524* concluded that for urban arterial corridors, accident rates for directional median openings at three-legged intersections were about 48 percent lower than the accident rates for the equivalent conventional (bidirectional) median openings at three-legged intersections. Average accident rates for directional median openings at four-legged intersections were about 15 percent lower than for conventional four-legged intersections.

At crossovers where U-turns are permitted at the same time as right turns from a side street or driveway, the potential for conflicts exists and should be considered. Not allowing such driveways or side streets at crossover locations is one feasible option to reduce these conflicts, but there are demonstrable efficiency benefits associated with aligning crossovers with driveways or side streets in some situations. Separate signal phases for the U-turn and the right-turn movements are another option, but those would likely add delay and could cause collisions due to added queuing. To manage the conflicts, some agencies use signs (R10-16 in the *MUTCD*) directing the U-turn movement to yield to the right-turn movement.[8]

3.9 CONSTRUCTION COSTS

In a majority of the cases, construction of an MUT intersection has greater initial costs compared to a conventional signalized intersection. The MUT intersection significantly differs from a conventional intersection with respect to the U-turn crossovers and loons, which can have significant right-of-way costs. When the existing roadway has sufficient median width for construction of a U-turn crossover without a loon, the land acquisition costs are minimized. Land acquisition costs can increase significantly if a loon is needed and additional right-of-way is required, especially at the crossover and loon locations.

Items for mobilization, overhead lighting, pavement markings, and drainage are similar for an MUT intersection as compared to a conventional intersection. Relocation of utilities varies from intersection to intersection depending on existing conditions and therefore cannot be quantified.

There is more signing at an MUT intersection than at a conventional intersection. Turn prohibitions and directional signing for the traffic using the crossover for left-turn movements is a major part of that additional cost. If the median openings for the U-turns require signal control, then additional signals and mast arms are required at each crossover. Thus, the signalization costs at an MUT intersection are higher compared to a conventional intersection. Therefore, in most cases, the MUT intersection has a higher implementation cost compared to a conventional intersection.

3.10 CONSTRUCTION SEQUENCING

This section presents ideas on how construction sequencing can be handled while constructing an MUT intersection under traffic. Because an MUT intersection may be thought of as a conventional intersection with the addition of two crossovers, maintenance of traffic during construction is generally similar to construction of a conventional intersection.

The major stages of construction and traffic shifts during construction of an MUT intersection are described for two common situations: (1) widening an existing two-lane road and (2) converting a conventional intersection on an existing divided highway to an MUT intersection. The major stages are below.

For the situation in which a two-land road is widened to a multilane divided highway, the following sequence is possible:

1. Build the lanes that will become one new direction of the arterial (e.g., eastbound) on new alignment, assuming a project on an east-west arterial.

2. Shift the exising two lanes of traffic flow to the eastbound lanes when those lanes are ready to handle traffic. The intersection will be shifted and will continue to operate conventionally.

3. Begin building the lanes that will serve the westbound direction of the arterial and the U-turn crossovers.

4. Shift westbound traffic onto the lanes serving the westbound direction of travel and the U-turn crossovers after they are completed. Allow eastbound traffic to use all of its lanes, and shift all left-turning traffic to the U-turn crossovers.

To convert an existing conventional intersection on a divided highway to an MUT intersection, the following sequence of construction can be followed:

1. Construct crossovers as this will not seriously disrupt traffic flow on the arterial.

2. Shift left-turning traffic to the crossovers.

3. Convert the conventional layout of the main intersection to an MUT intersection configuration (minor lane shifts may be needed in this stage).

The MDOT *Geometric Design Guide* suggests designing and constructing the crossovers through a separate contract prior to reconstructing the freeway in order to give the contractor as much time as possible to construct the road.(37)

3.11 OTHER CONSIDERATIONS

Enforcement at MUT intersections may be needed in the short term more than at a conventional intersection. The custom in Michigan upon opening a new MUT intersection is to allocate extra enforcement resources during the first few weeks of operation, mainly to focus on preventing left turns at the main intersection. When opening the first MUT intersection in an area, MDOT conducts a public relations campaign to try to familiarize motorists with the concept. After volumes build and driver habits form, the need for additional enforcement should subside, and normal vigilance in enforcing traffic laws should suffice. The reduced delay and shorter cycle length produced at an MUT intersection may promote less red light running.

At many signalized median crossovers in Michigan, left turns on red are permitted for drivers at the crossover making a U-turn maneuver onto the main road. This helps reduce the delay for these vehicles. Agencies and policymakers should consider the potential benefits and costs of allowing left turn on red at specific MUT crossovers where sight distance and other characteristics of the site would not be expected to contribute to an adverse impact on safety.

The MUT intersection design involves a relatively complex maneuver for left-turning vehicles. There is a need to provide some highway lighting at the median crossovers to enhance visibility for drivers. While safety benefits are associated with intersection lighting, there are significant costs associated with the installation and maintenance of lighting, especially in rural areas where a power source may not be readily available. If the MUT intersection design is applied in urban and suburban areas, the necessary utility lines often exist.

When traveling on an MUT intersection corridor to respond to incidents, emergency vehicles should not experience significant difficulties when maneuvering through MUT crossovers or experience significant delay when using crossovers to make left turns. The custom in Michigan is for left-turning emergency vehicles to use the crossovers most of the time. However, the option to make a direct left turn at the main intersection is always available if needed.

3.12 APPLICABILITY

As with all the designs described in this report, the MUT intersection design is applicable under certain conditions but not appropriate for all conditions. A primary reason to choose the MUT intersection instead of a conventional design is the ability to process higher volumes on the major road, especially through volumes. As mentioned earlier, the MUT intersection is typically a corridor treatment. Candidate corridors for this design are high-speed, median-divided highways with some two-way crossovers that have moderate major road and minor road left-turn demands. Fewer conflicting travel streams, two-phase signals, short cycles, and the chance for good progression in both directions are all possible.

Reducing signal phases at the intersection provides increased throughput in the range of 30 to 45 percent for the MUT intersections in comparison to the conventional intersections. In addition, MUT intersections have been determined to have crash rates that are 20 to 50 percent lower than conventional intersections. Head-on and angle crashes that have high probabilities of injury are significantly reduced for the MUT intersections compared to conventional intersections.

Some of the situations where an MUT intersection may be suitable include the following:

- If there are heavy through volumes and moderate left-turn volumes on all approaches.
- If the left-turn approach volume/total approach volume is less than 0.2 on all intersection approaches.
- If the left-turning volume is less than 400 veh/lane, and opposing through volume is greater than 700 veh/lane on two opposing intersection approaches.
- If the v/c is greater than 0.8 on two opposing intersection approaches.
- If the cross product of left-turn and opposing through vehicles is greater than 150,000 on two opposing intersection approaches.
- If the intersection is heavily congested with many signal phase failures for through traffic.

MUT intersections without loons designed to accommodate turns by large trucks typically need medians that are 47 to 71 ft wide as opposed to the 28-ft-wide minimum median width for a conventional intersection with dual left-turn lanes. This extra right-of-way is likely costly and may simply be unavailable at any reasonable price in a densely developed area. Loons can be used at the median crossover openings where medians widths are inadequate.

Highway agencies may also consider installation of a RCUT intersection instead of an MUT intersection. The two designs have many similarities, as discussed in chapter 4, with the key difference being that RCUT intersections allow direct left turns from the major road while rerouting minor road through movements. Although the MUT better serves an intersection with more minor road through movements than major road left turns, the RCUT intersection is more appropriate when there are more major road left turns than minor street through movements.

3.13 SUMMARY

An MUT intersection is a traditional design with the potential to provide significant operational and safety benefits to motorists under certain circumstances. The design may be employed at individual intersections or along a corridor. Left-turning vehicles are rerouted through one-way median openings located several hundred feet from the main intersection. The main intersection consequently has no left turns, which allows for two-phase signals and fewer conflict points. Michigan and other States have successfully used the MUT intersection for over four decades without major problems related to traffic operational failures or safety hazards. These agencies have developed geometric design, signal, sign, and marking guidance that agencies new to the design can use to help their drivers negotiate the design efficiently, safely, and without confusion.

The following summarizes the major conclusions from the literature on MUT intersections:

- The reduction of signal phases at the intersection provides increased capacity for the MUT intersection in comparison to the conventional intersections. The throughput increases were typically in the range of 30 to 45 percent.

- The total network travel time savings usually outweighed the additional travel time required for left-turning vehicles from the major road and cross street for corridors with the MUT intersection compared to conventional intersections.

- The safety performance of the MUT intersection was better than conventional intersections because it had fewer vehicle-vehicle conflict points. Typical total crash reductions ranged from 20 to 50 percent.

- Head-on and angle crashes that had high probabilities of injury were significantly reduced for the MUT intersection compared to conventional intersections.

Agencies employing an MUT intersection should be prepared for other impacts as well. The wider median may be viewed negatively by some adjacent land owners and business owners. Similarly, pedestrians may experience longer delays when crossing a wide median in a two-stage manner. However, pedestrians encounter fewer conflicting vehicles, and agencies may install desired midblock pedestrian signals more readily knowing that the signals should not appreciably disrupt vehicular traffic flow on the arterial. MUT intersections likely cost more to install than a comparable conventional intersection due to the wider right-of-way, but there are ways to mitigate the cost differential such as with the use of loons. Maintenance of traffic during the construction of an MUT intersection is similar to that of a conventional intersection, and other impacts such as to emergency vehicles, buses, and bicyclists are not likely to be major issues. MUT intersections primarily have safety benefits in rural areas but can provide some operational benefits in specific situations. Both safety and operational benefits are possible in urban and suburban areas. Being able to obtain sufficient right-of-way at a reasonable cost is necessary in either case.

CHAPTER 4. RESTRICTED CROSSING U-TURN INTERSECTION

4.1 INTRODUCTION

RCUT intersections, also referred to as super street intersections, are a promising solution for arterials with more dominant flows on the major road. They have the potential to move more vehicles efficiently and safely than roadways with comparable traffic volumes that have conventional at-grade intersections with minimal disruptions to adjacent development.

The RCUT intersection works by redirecting left-turn and through movements from the side street approaches. Instead of allowing those movements to be made directly through the intersection, as in a conventional design, a RCUT intersection accommodates those movements by requiring drivers to turn right onto the main road and then make a U-turn maneuver at a one-way median opening 400 to 1,000 ft downstream. Figure 82 shows a RCUT intersection at West Big Beaver Road and Lakeview Drive in Troy, MI.

Source: Google™ Earth

Figure 82. Photo. RCUT intersection in Troy, MI.

Figure 83 shows a conceptual diagram of a RCUT intersection. The RCUT intersection configuration shown is generally suited to higher volume major roads in suburban and rural areas, especially at intersections with relatively low through traffic volumes entering from the side road. At the type of intersection shown in figure 83, left turns from the main road are similar to conventional intersections. Specifically, left turns are made from left-turn lanes on the main road directly onto the side road. For this type of RCUT intersection design, pedestrians cross the main street in a diagonal fashion, going from one corner to the opposite corner.

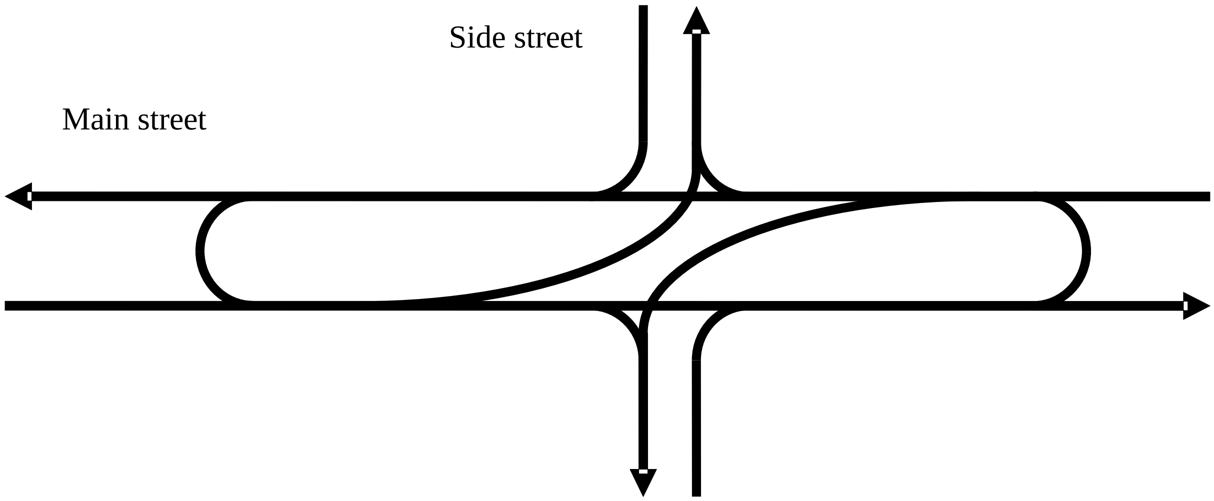


Figure 83. Illustration. Conceptual RCUT intersection configuration with direct left turns from the major road.

Figure 84 shows a more rudimentary type of RCUT intersection that is more frequently used at low-volume and rural locations. In the configuration shown in figure 84, drivers wanting to turn left from the main road to the side street make a U-turn maneuver at the median crossover and then turn right onto the side street. This maneuver is similar to the indirect left turn executed at MUT intersections discussed in chapter 3. The left turns and through movements from the minor street are again routed through the U-turn crossovers. This basic configuration shown in figure 84 can be implemented without any signal control.

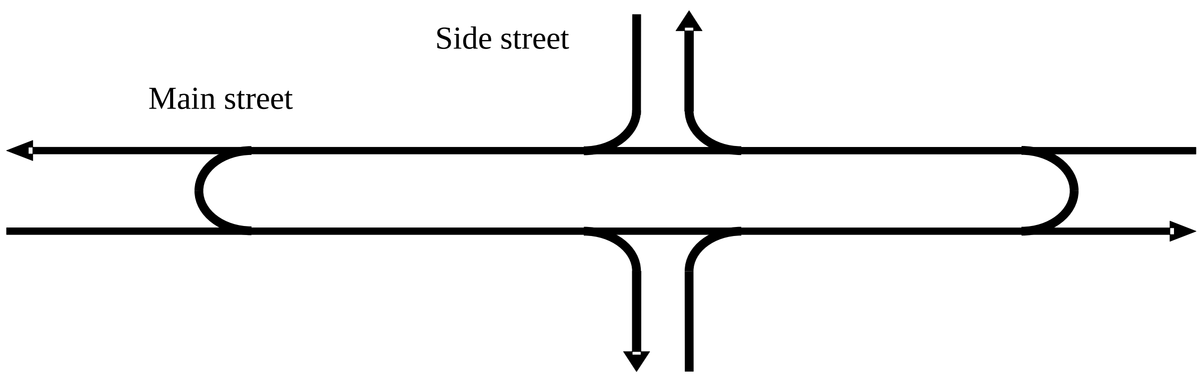


Figure 84. Illustration. Basic RCUT intersection with no direct left turns.

Traffic engineer Richard Kramer first published the RCUT concept in the early 1980s.(53) Kramer's notion was that arterials, as important routes serving large volumes of through traffic, should have a high percentage of green time at signal-controlled intersections to promote high-quality progression. His RCUT design met those objectives by functioning like a pair of one-way streets separated by only a narrow median.

4.1.1 Existing RCUT Intersections

RCUT intersections have been constructed in several locations in the United States, including the location in Michigan shown in figure 82. For this report, MDSHA and NCDOT provided information on their RCUT intersections. These RCUT intersections are the focus of examples discussed in this report.

Three rural RCUT intersections have been in existence on U.S. Route 301 on Maryland's Eastern Shore for years. In fact, Maryland has referred to its version of this treatment as a J-turn. A *J-turn* intersection is a variant of the RCUT intersection in that both the main intersection and the two crossovers are unsignalized. A J-turn looks like the concept shown in figure 83, but there is no signal control. Two J-turn intersections are shown in figure 85 and figure 86. A crossover is provided north of the northern J-turn intersection (U.S. Route 301 and Del Rhodes Avenue). The southern J-turn intersection (U.S. Route 301 with Main Street) also serves as the crossover for the vehicles that need to turn around. Another crossover is not provided south of the southern intersection shown in figure 85. Figure 86 gives a closer look at the intersection of U.S. Route 301 and Del Rhodes Avenue and the northern crossover. The offset of the MUT crossover is located about 1,400 ft from the main intersection.

Source: Google™ Earth

Figure 85. Photo. U.S. Route 301 J-turn intersections in Maryland.


Source: Google™ Earth

Figure 86. Photo. U.S. Route 301 J-turn intersection with Del Rhodes Avenue in Maryland.

J-turn intersections have been constructed at the intersections of U.S. Route 15 and College Avenue/Annandale Road and U.S. Route 15 and South Seton Avenue in Emmitsburg, MD. An aerial photograph of the intersection with Annandale Road is shown in figure 87. In addition, the intersection of U.S. Route 15 with Hayward Road in Frederick, MD, is a J-turn implementation on a T-intersection, with one set of U-turn crossovers built on the mainline for the left-turn movement from the minor road approach. Offsets of the MUT crossover from the main intersection vary from about 2,000 to 2,500 ft.

NCDOT recently adopted the RCUT intersection design as an option for its higher classes of arterials in its *Strategic Highway Corridors Plan*.[54] At the time of this report, there are three RCUT intersections completed on segments of NCDOT highways. All three are on divided four-lane roads. Two are completed in rural areas, while the third, in a suburban area, serves a large development.

The rural locations are U.S. Route 23/74 in Haywood County in the mountainous western part of North Carolina, and U.S. Route 1 in Lee and Moore Counties in the rolling central part of North Carolina. The rural RCUT intersections are both unsignalized. This segment of U.S. Route 23/74 is about 2.5 mi long and includes three sets of crossovers. This segment was implemented in 2000 as a retrofit of an existing conventional arterial. The segment of U.S. Route 1 includes five sets of crossovers spread over a 12-mi length of arterial. This section was opened on new alignment early in 2006.

Source: Google™ Earth

Figure 87. Photo. U.S. Route 15 RCUT intersection in Emmitsburg, MD.

The suburban location is U.S. Route 17 in Brunswick County, just southwest of Wilmington, NC, in the flat terrain near the Atlantic Ocean. Figure 88 shows the corridor with the RCUT intersection and crossovers on U.S. Route 17. It includes three sets of signalized crossovers over a segment less than 1-mi long. Construction was completed in mid 2006. The large retail development located at the U.S. Route 17 RCUT intersection opened in early 2007, and the development in the immediate area continues to increase.

Source: North Carolina Department of Transportation

Figure 88. Photo. U.S. Route 17 RCUT intersection corridor in Brunswick County, NC.

4.1.2 Advantages and Disadvantages

Safety benefits are anticipated from implementing RCUT intersections at appropriate locations. This is attributable to reduced vehicle-vehicle conflict points, as discussed later in this chapter. Crashes occurring at the conflict points at RCUT intersections are expected to be less severe than at conflict points at conventional intersections. Section 4.7 discusses safety issues at RCUT intersections in more detail.

When traffic signal control is needed at a RCUT intersection, it requires only two signal phases instead of the typical four or more phases that are used at a conventional four-legged intersection. Reducing the number of signal phases translates to significant time savings for all roadway users. Travel time savings consequently leads to reduced emissions and fuel consumption, increased productivity, and improved quality of life.

Another traffic operational benefit provided by a RCUT intersection is improving the progression of traffic platoons on the arterial. With a RCUT intersection, the signals that control one direction of the arterial operate independently of signals controlling the other direction. Kramer intended that a main road can operate like a pair of one-way streets and that good progression in both directions was possible at any speed with any signal spacing.(53) Conventional arterials cannot approach this efficiency without extensive control of access and signal installations. With RCUT intersections, agencies can set progression speeds as high or low as they wish (e.g., by location, direction, time, day of week, or any number of ways) without adversely increasing delay. In addition, RCUT intersections more easily accommodate the installation of new traffic signals without a significantly adverse impact on the quality of progression. However, the addition of traffic signals at the median crossovers may limit progression, depending on the volume of vehicles using the crossover.

There are several variations of the RCUT intersection design that each requires different pedestrian paths, with some being more similar to conventional intersection pedestrian paths than others. Longer paths across streets lead to increased delay or inconvenience for pedestrians and increased exposure to traffic. The nontraditional vehicle movements are counterintuitive to pedestrians with visual disabilities. However, there are potential designs and treatments that can mitigate these concerns. Therefore, installation of a RCUT intersection needs to balance pedestrian and vehicle safety and operational concerns. For example, barriers can be used to channelize pedestrians along the proper path, but the barriers would be fixed objects that could pose a hazard to motorists. A subsequent section of this chapter provides more information about accommodating pedestrians. Though pedestrians may not be expected at the intersection immediately, if development is expected to continue in the area, the RCUT intersection design should account for future increases in pedestrian traffic.

A RCUT intersection has some disadvantages for certain conditions, notably at intersections where there are heavy through and left-turn volumes from the side street approaches. Under certain volumes, the RCUT intersection becomes less efficient than a conventional intersection. At some volume levels, side street through and left-turn volumes become so heavy that the extra travel time incurred by these drivers at a RCUT intersection outweighs the time savings to drivers on the main street.

As with any new design, driver confusion is a concern. However, the experiences with RCUT intersections in North Carolina and at J-turn intersections in Maryland indicate that drivers adapt well to RCUT intersections. Another disadvantage of the RCUT intersection is the combined median and lane width needed to accommodate large vehicles making U-turns at crossovers. It is not uncommon for a large truck to have a turning radius of up to 45 ft.(7) Ideally, medians would be 42 to 66 ft wide to accommodate those vehicles making U-turns in the median, though a combination of median, lane, and shoulder width could be designed to accommodate trucks with a more narrow median. A subsequent section in this chapter addresses several treatments that enable RCUT intersections to be viable when the median width is less than the desirable width.

Like many designs that feature wide medians, RCUT intersections can be perceived to adversely affect roadside businesses, particularly businesses not at median openings that attract left-turn pass-by trips.(12) This potential negative impact should be studied to determine the possible magnitude and to evaluate any mitigation measures, as this could be a significant issue to render this design unfeasible due to real or perceived impact.

4.2 GEOMETRIC DESIGN CONSIDERATIONS

The key difference between an MUT intersection (discussed in chapter 3) and a RCUT intersection is that an MUT intersection allows through movements from the side street. A RCUT intersection has either no median openings at the intersection or has one-way directional median openings to accommodate traffic making left turns from the main street onto the side street.

4.2.1 Typical Applications of RCUT Intersection

Figure 89 through figure 91 show designs for typical four-legged RCUT intersections. This design is for the more complex version which is more suitable for arterials with higher volumes. Should pedestrians be expected at intersections, these designs need to be modified to better accommodate them. For example, if right-turn lanes and/or channelizing islands are eliminated and the tightest turn radii are used, pedestrian crossing distances are shorter.

It is worth highlighting two key variations on the typical RCUT intersection designs. Both the three-legged design, which is shown in figure 92, and the offset design, which is shown in figure 93, can be operated efficiently under specific volume conditions.(55) While offset intersections employing conventional (i.e., two-way) median openings are efficient, the RCUT intersection treatment can enhance that efficiency.(56)

4.2.2 Median Width and Crossover Spacing

Similar to the MUT intersection, the median width is a crucial design element for a RCUT intersection. The desirable right-of-way widths needed to accommodate large trucks without allowing vehicles to encroach on curbs or shoulders, assuming 12-ft-wide lanes and 10 ft of shoulder, range from approximately 140 ft for four-lane arterials to approximately 165 ft for eight-lane arterials. For this same situation, desirable minimum median widths between 47 and 71 ft are typically needed. Chapter 3 discussed this in detail and provided the table from the AASHTO *Green Book* from which designers can obtain minimum median widths based on the needs of different design vehicles executing a left turn.(7)

Chapter 3 also discussed several ways in which highway designers can use the MUT intersection concept without requiring the large right-of-ways continuously through the whole corridor. Much of the discussion of crossover spacing provided in chapter 3 for MUTs applies to RCUT intersections. The main points of the discussion included the following:

1. The first method of reducing right-of-way needs is to provide some median openings that only accommodate smaller vehicles. Proper highway signs need to be placed in appropriate locations to prohibit trucks at these crossovers.

2. A second method of reducing the amount of needed right-of-way is to allow vehicles to turn onto a shoulder, which has been strengthened with full-depth pavement.

3. A third way to reduce right-of-way is to provide bulb-outs or loons at the U-turn crossovers. A *loon* is an expanded paved apron opposite a median crossover. The purpose is to provide additional space to facilitate the larger turning path of a commercial vehicle along narrow medians.(33) Chapter 3 provided discussion on loon design.

4. A fourth method to reduce right-of-way width throughout a RCUT intersection corridor is to use reverse curves on the main street through roadways to widen the median for a short distance at a crossover and then narrow it back down beyond the crossover. Drivers may not initially expect these alignment changes but could quickly adapt to the design.

Using any of these methods means that medians do not have to be wider than 16 ft, which accommodates a minimum 4-ft-wide median and a 12-ft-wide turn bay along much of the length of a RCUT intersection design. For these cases, the overall right-of-way required for a corridor of RCUT intersections can be as narrow as 84 ft for four-lane arterials and as wide as 132 ft for eight-lane arterials.

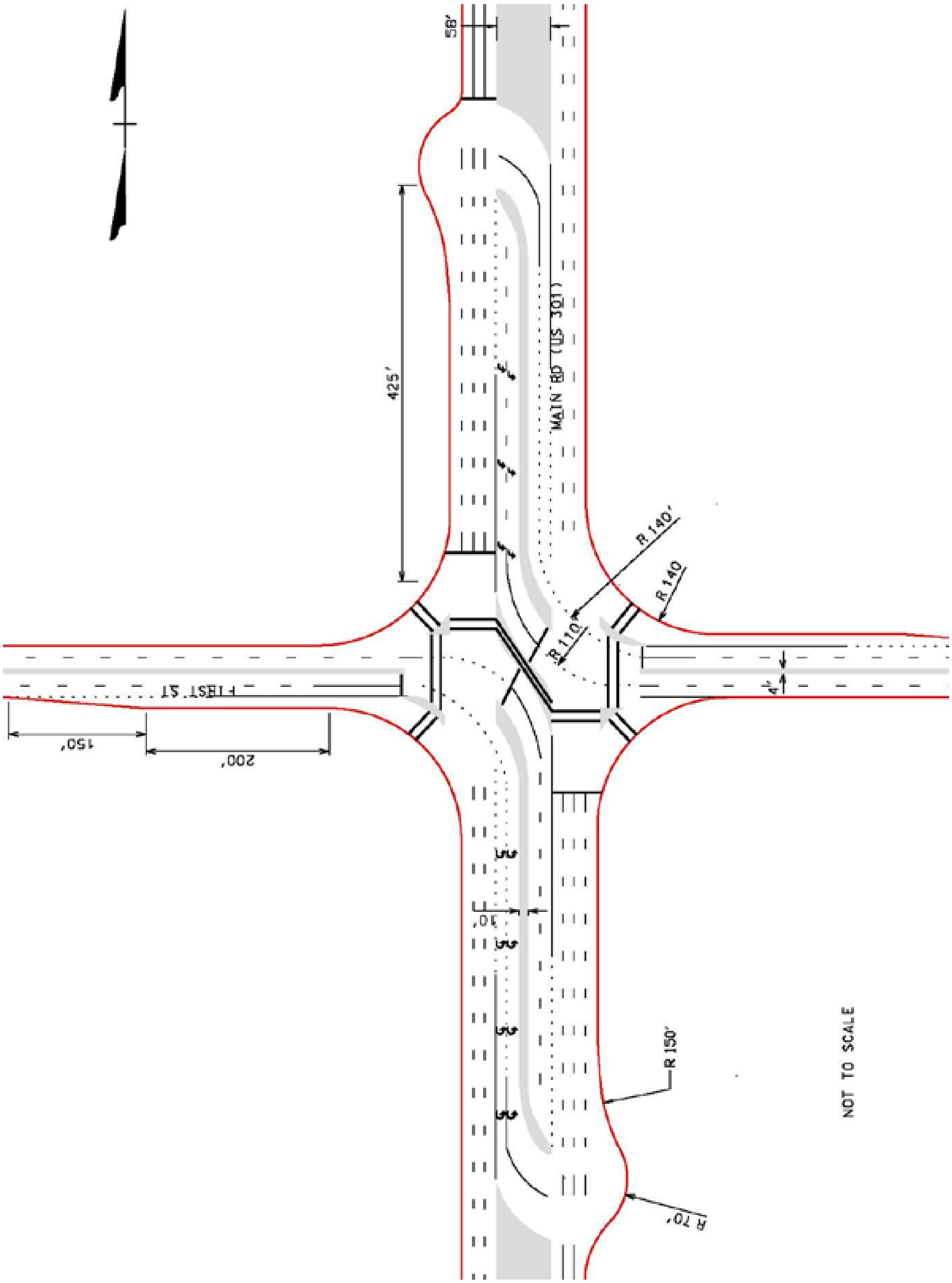


Figure 89. Illustration. Example of a RCUT intersection in which the side street has two approach lanes.

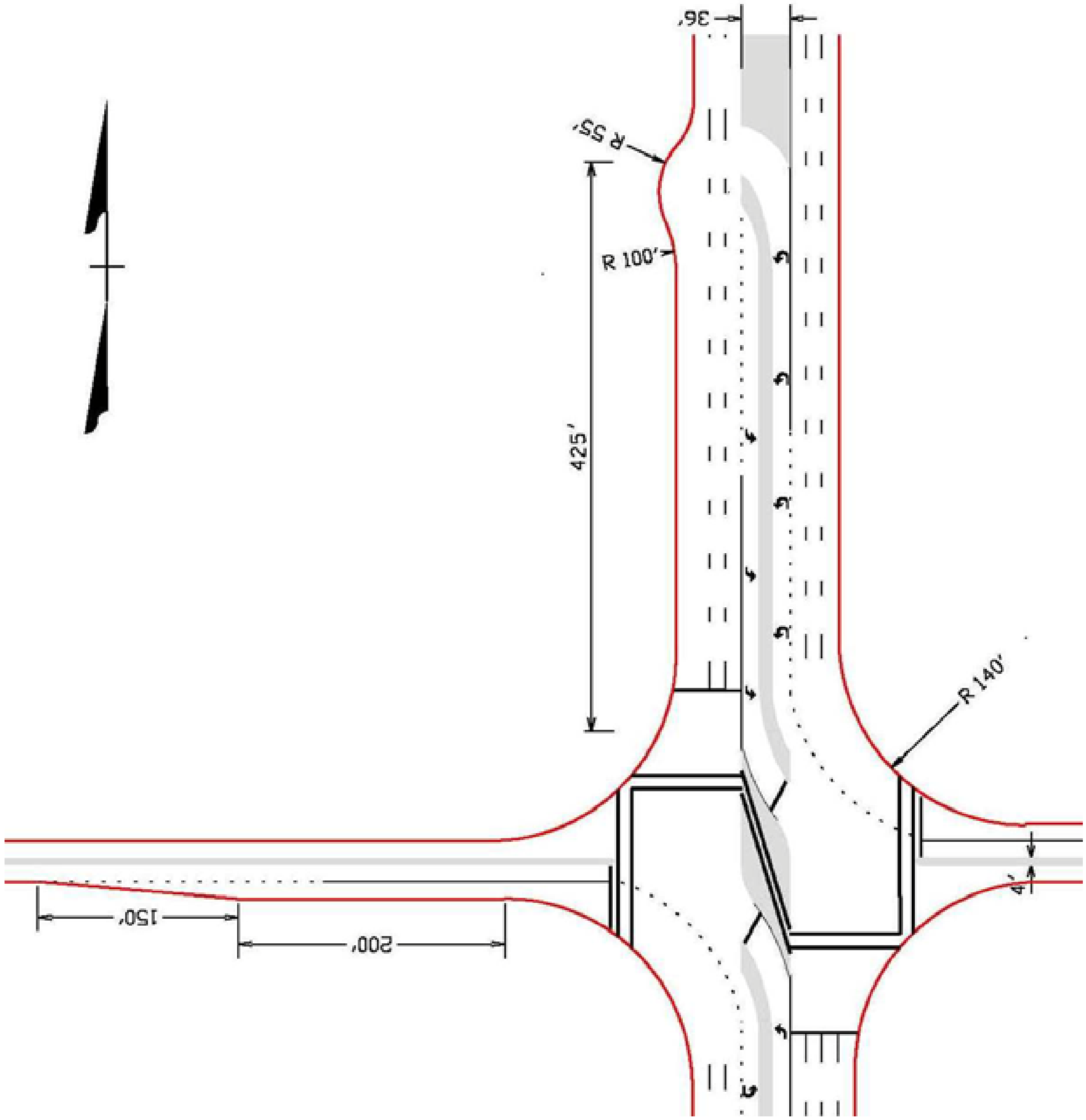


Figure 90. Illustration. Example of a RCUT intersection in which the side street has one approach lane.

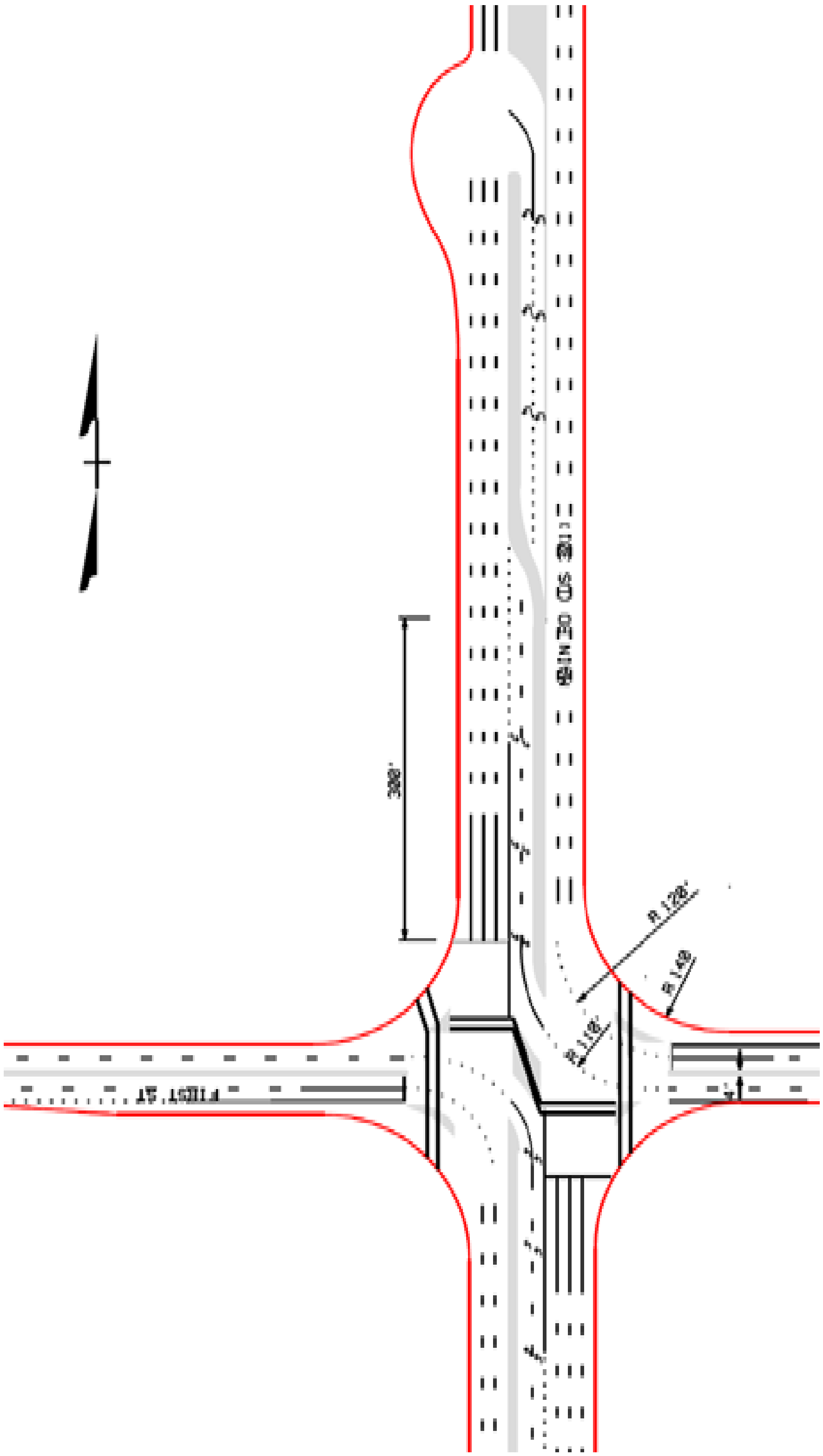


Figure 91. Illustration. Example of a RCUT intersection with dual left-turn lanes on the major road that are back-to-back with dual turn lanes for the U-turn crossover.

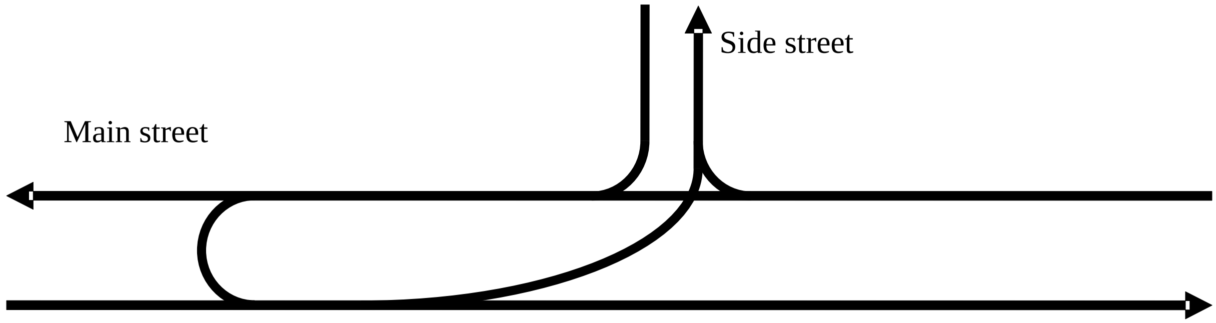


Figure 92. Illustration. Three-legged RCUT intersection design.

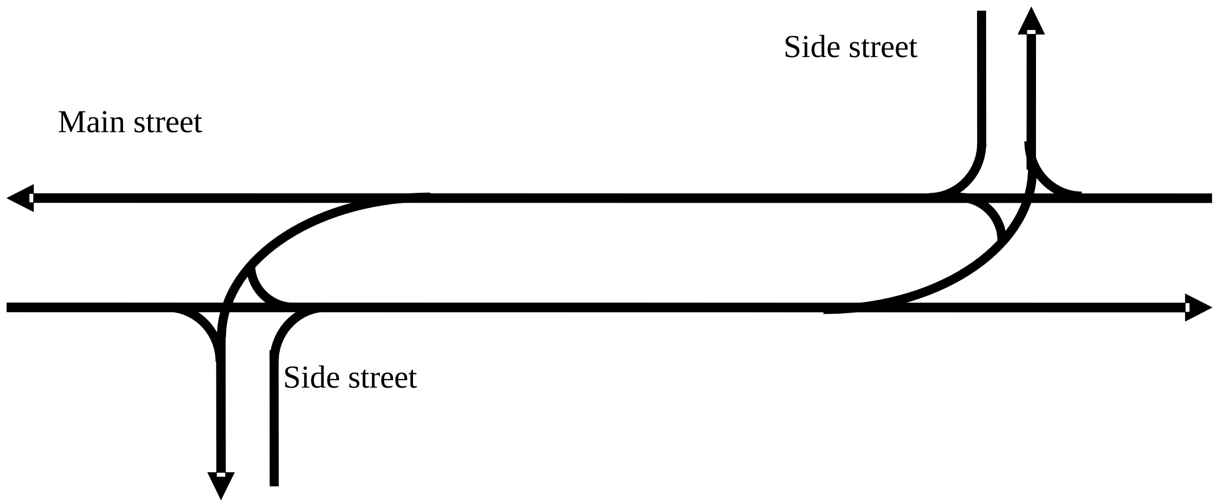


Figure 93. Illustration. Offset RCUT intersection design.

Several factors should be considered when selecting the appropriate spacing from a main intersection to a U-turn crossover. Longer spacing between the main intersection and crossovers decreases spillback probabilities, providing more time and space for drivers to maneuver into the proper lane and read and respond to highway signs. Shorter spacing between the main intersection and crossovers translates into shorter driving distances and travel times. AASHTO recommends spacing from 400 to 600 ft for MUT designs based on signal timing.(7) MDOT's experience with MUTs has led it to establish 660 ±100 ft as the standard spacing. NCDOT's standard minimum spacing between main RCUT intersections and crossovers is 800 ft.(57)

As stated in chapter 3 on MUT intersections, designers have flexibility in selecting the crossover spacing. To accommodate constraints related to drainage, sight distances, or available right-of-way, crossovers are shifted toward or away from a main intersection with relatively minimal adverse effects on traffic operations. Locating a crossover so that vehicles can make U-turns or left turns into the driveway or side street is common practice at median crossovers in Michigan. This treatment can prove beneficial at RCUT intersections where the combination of main road turning volumes and driveway volumes do not have a significant impact on the major road through traffic (by turn queues blocking through lanes, for example).

4.2.3 Crossover Design

Designers may use one-lane or two-lane crossovers for U-turns depending on traffic volume demands and the number of receiving lanes. AASHTO's *Green Book* and the MDOT *Geometric Design Guide 670* provide U-turn crossover design details for MUTs that also apply to RCUT intersections.(7,37) Figure 94 shows a typical movement of a heavy vehicle in a loon, and figure 95 shows a photograph of a heavy vehicle maneuvering a U-turn in a loon. NCDOT recommends an outside turning radius of 100 ft for the major road left-turn crossover, as seen in figure 96.

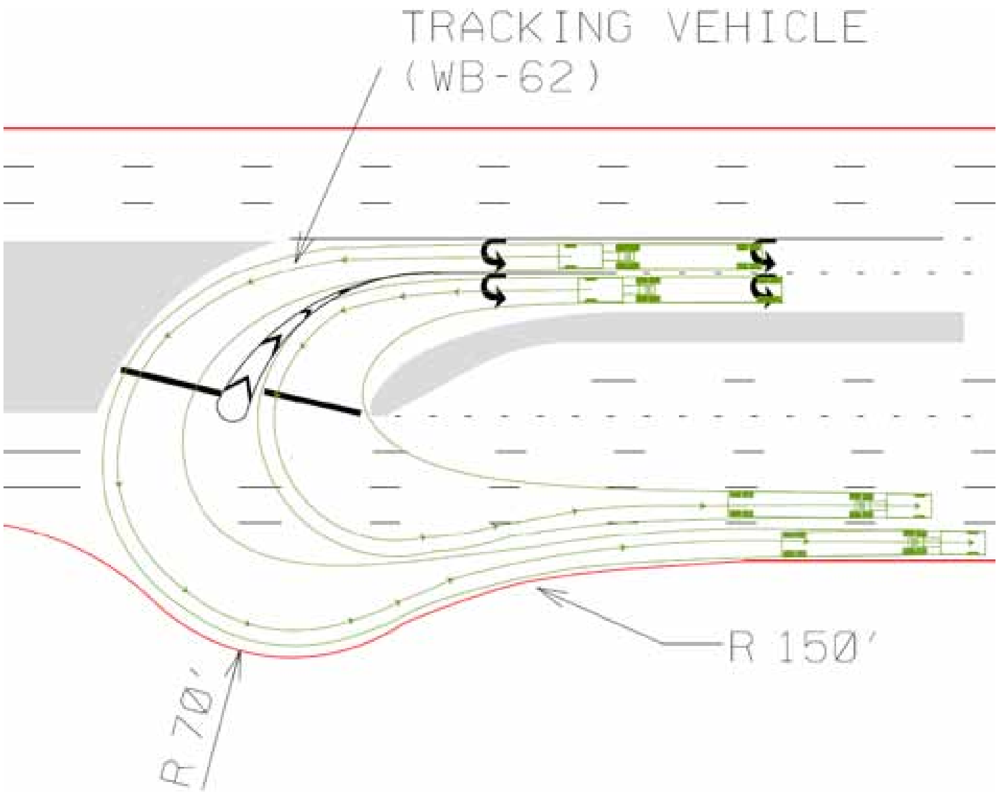
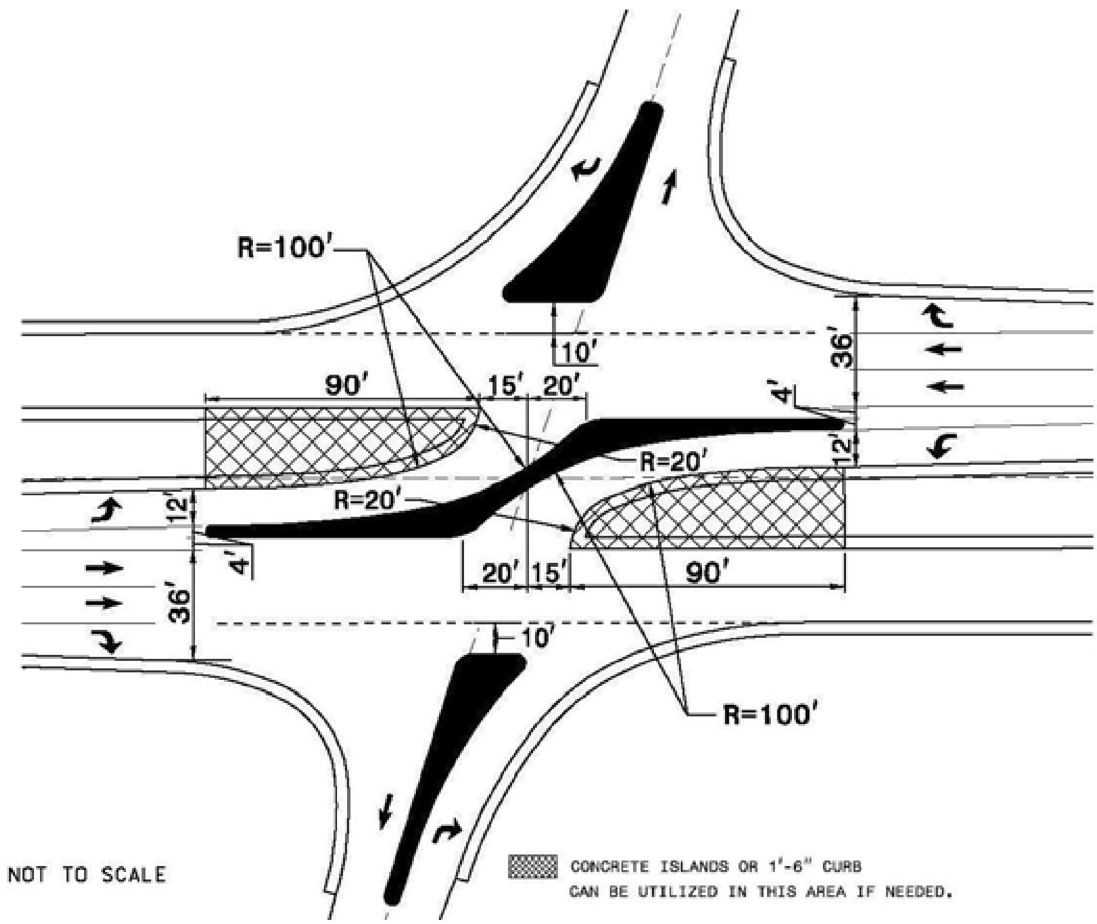


Figure 94. Illustration. Loon at crossover that features two U-turn lanes.

Figure 95. Photo. U-turn movement of a heavy vehicle at a RCUT intersection with a loon on U.S. Route 17 in North Carolina.



Source: North Carolina Department of Transportation *Roadway Design Manual*

Figure 96. Illustration. NCDOT RCUT intersection left-turn crossover design recommendation.(57)

Figure 96 shows the NCDOT design for a 46-ft median with 4-ft paved shoulders (median and outside) assuming a 55 mi/h posted speed. When other median widths, paved shoulders, and posted speeds are used, engineering judgment should be used to establish appropriate geometry.(57)

In the case of unsignalized U-turn crossovers, as in the J-turn treatments constructed in Maryland, auxiliary lanes are provided. These serve as acceleration lanes for the U-turn movements merging onto the mainline (refer to figure 97). In the Maryland treatment, the acceleration lane for U-turning drivers was constructed into the median and then continued to become the left-turn lane at the main intersection. Although this treatment involves extra paving and the disadvantage of inducing drivers into a trap lane, it works well at this intersection where sight distance is not an issue. Alternatively, the termination of the acceleration lane could be followed by the introduction of a left-turn lane upstream of the main intersection.

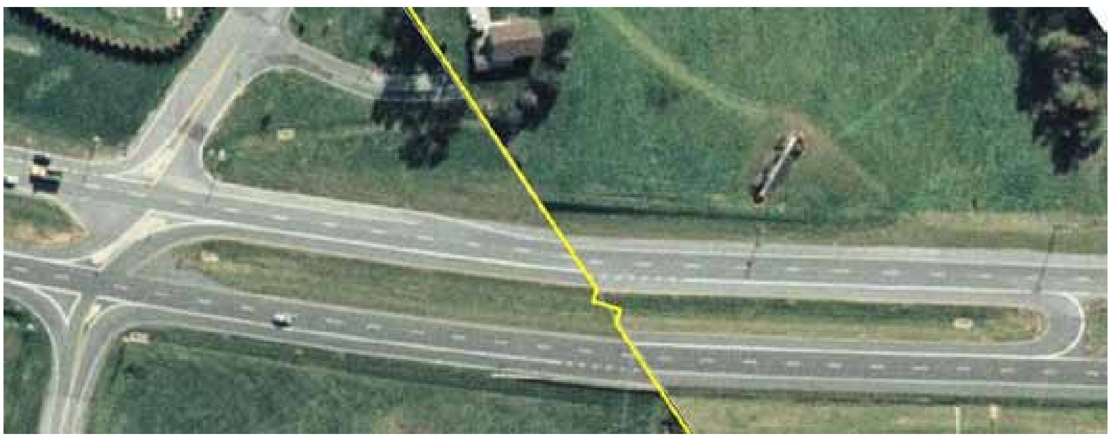


Figure 97. Photo. Auxiliary lanes at J-turn at Emmitsburg, MD.

For an unsignalized RCUT intersection, the offset of the MUT crossover from the main intersection should be located according to AASHTO's *Green Book* requirements for the selected design speed of the freeway.(7) Offset distance is based on acceleration, weaving, and deceleration lengths for the longest of either direction—from the main intersection to the U-turn or from the U-turn crossover to the main intersection. Minimum offset distance from the crossroad should include a minimum acceleration length plus the taper length, a certain weaving length for vehicles to move from the right to the left side of the freeway, and a minimum deceleration lane length (on the left side) that first includes the flare length. From the U-turn crossover, a minimum offset distance should include a minimum acceleration length (on the left side of the freeway) plus the taper length, a certain weaving length for vehicles to merge from the left to the right side (for the through turning vehicles), and a minimum deceleration lane length (on the right side) that first includes the flare length. As of yet, criteria for a minimum weaving length for this treatment does not exist. The weaving length depends on the combined maximum volumes of through volume and merging volumes from the crossroad. As a maximum, the combined volume of through plus merging volumes from the crossroad or the U-turn may not exceed 1,800 to 1,900 veh/h/lane (when lane utilization is assumed balanced). Furthermore, it would have to be verified with calibrated simulation models.

4.3 ACCESS MANAGEMENT CONSIDERATIONS

The primary intent of a RCUT intersection is to serve through traffic on the major road. RCUT intersections have the potential to provide a relatively high LOS to through motorists on the main street over a wide range of demands. No documented studies of the effects of RCUT intersections on adjacent land uses have been identified. Inferences about the effects of this intersection design on adjacent businesses can be drawn from the *NCHRP Report 420*, which indicates that some land uses suffer economic losses with wide median installation.(12) This is particularly true for businesses that rely on pass-by traffic, such as gas stations and convenience stores. The problems can be exacerbated when indirect left turns are needed to access some businesses. As stated in the *NCHRP Report 420*, during the planning of a project that involves creating or widening of a median, the perceptions of adverse business impacts are typically worse than the ensuing reality.(12) There is no net community-wide economic impact resulting from the access changes. Nonetheless, the possibility exists that RCUT intersection installations can create some business losses for some types of retail businesses.

Designers can develop RCUT intersection designs that safely and efficiently manage access with minimum adverse impacts to adjacent land users. Designers have a great deal of flexibility in designing traffic signal control layouts at RCUT intersections depending on where existing driveways and access points are located. On a RCUT intersection corridor, an agency may install traffic signal control at any intersection on the arterial without significantly changing the progression potential. The signal offset for new traffic signal control at a crossover or at a right in/right out driveway can fit within the existing progression band on the arterial. Other factors such as signal visibility and queuing space need to be considered as well.

There is flexibility in locating crossovers when designing RCUT intersections depending on the locations of existing access points. As noted previously, designers generally move a crossover without reducing the efficiency of the overall intersection operation. Moving a planned crossover location by several hundred feet so that it can also serve left turns into or out of a higher volume driveway or minor street may increase efficiency and safety of the whole corridor. Sight distance issues must be addressed when any crossover locations are considered.

As with most high-type intersection designs, no driveways should be allowed in close proximity to the main intersection. Driveways are also undesirable on the opposite side of the arterial from a loon. If a driveway is placed across from a loon, then drivers may make wrong-way movements in the crossover. There are mixed results with respect to driveways and side streets lined up with the end of a U-turn crossover (e.g., in the loon). Such installations are common in the MUTs in Michigan and can lead to great efficiency. However, NCDOT is attempting to obtain full control of access along the arterial throughout the length of the loon on both sides of the road. NCDOT has concerns about the possibility of conflicts between U-turning vehicles using the crossover and right-turning vehicles emerging from the driveway. For these reasons, NCDOT is endeavoring to not allow driveways or side roads that intersect the arterial in the loon.

4.4 TRAFFIC SIGNALIZATION TREATMENTS

If traffic volumes warrant signalization, traffic signal control on a RCUT intersection corridor requires fewer phases to accommodate a higher throughput of through vehicles. Figure 98 shows that four distinct intersections theoretically under separate traffic signal control can each operate with just two phases. Compared to conventional intersections, traffic signal control at RCUT intersections can be set to have relatively short cycles, which can reduce the amount of lost time per cycle. The major street should enjoy a high percentage of green time. Kramer suggested ⅔ to ¾ of the cycle be reserved for traffic on the main street.(53)

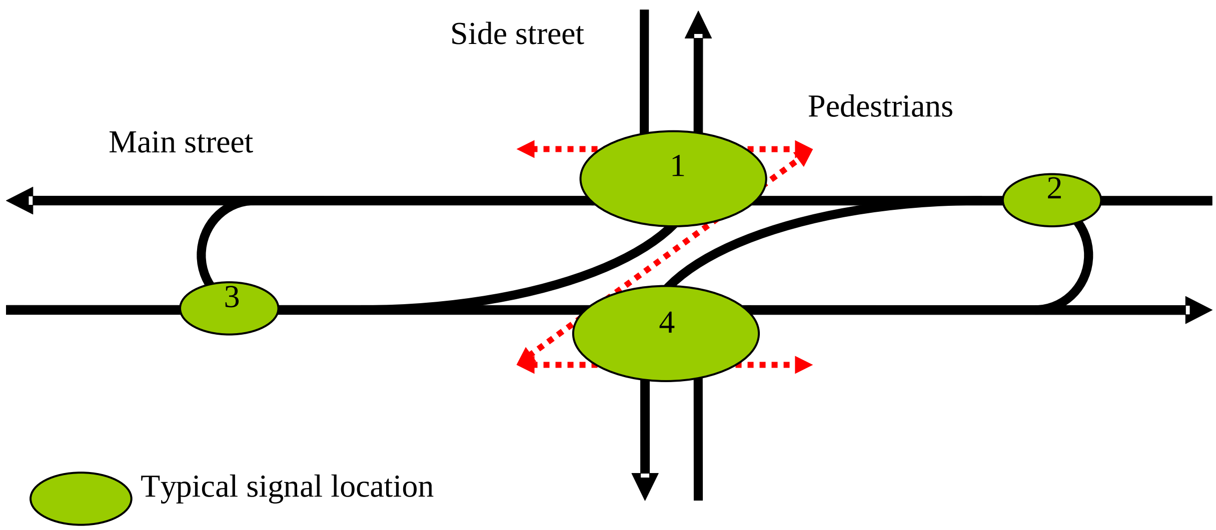


Figure 98. Illustration. Typical RCUT intersection signal locations.

4.4.1 Signal Progression

As can be seen in figure 98, signal controllers for one direction of the arterial can operate independently of the signal controllers for the opposite direction of the arterial. The only traffic stream moving through signals for opposite directions of travel on the arterial in a short distance is the pedestrian movement from signal 1 to signal 4 and from signal 4 to signal 1. Each direction of the arterial has its own cycle length. The independence of the two directions provides a much wider range of progression possibilities.

A simple procedure for establishing good progression with a RCUT intersection with independent control in both directions includes the following steps:

1. Use a standard signal-timing method to determine the optimum cycle length at each signal.
2. Select one common cycle length for each direction of the arterial, and readjust the green times at the individual signals accordingly.
3. Establish the arterial progression speed.

4. Determine signal offsets based on the distances between signal-controlled intersections and the progression speed (e.g., the end of the major street green phase at one signal-controlled intersection relative to the end of the major street green phase of the adjacent signal-controlled intersection).

5. Adjust the offsets to allow for adequate start-up times to discharge standing queues and to provide progression possibilities for left-turning and U-turning traffic.

Because of their potential to achieve outstanding progression through a series of intersections, RCUT intersections should be considered as a corridor-wide treatment in addition to a treatment for a single intersection. Consequently, there can be one intersection on the corridor that allows left turns and/or through movements from the side street (i.e., a conventional intersection) without losing much of the progression potential. One conventional intersection on the corridor restricts the operation so that both directions of the main street of the RCUT intersection must have the same signal cycle length. However, the ability of a RCUT intersection corridor to accommodate one or more conventional intersections within the signal system increases the possible range of applicability of the design.

4.4.2 Signal Design

When designing signals for a RCUT intersection, agencies must first determine where to install signals. There may be other locations along a RCUT intersection corridor where agencies might consider traffic signal control, including midblock pedestrian crossings. Signal warrants provided in the *MUTCD* provide key guidance on when and where signal control is justified.(8) Designers of RCUT intersections should realize that a corridor of these intersections can accommodate additional signal-controlled RCUT intersections locations within the major street progression band established by the surrounding signals. By contrast, additional traffic signal control on a conventional arterial is often devastating to two-way progression. Signal control at a RCUT intersection can be fully actuated to minimize delay. Detectors can be used in all of the crossovers, on the minor street approaches, and on the major street approaches. The duration of each signal phase can vary on a cycle-by-cycle basis.

Different traffic signalization practices may affect the number of signal controllers provided at a RCUT intersection. Figure 98 illustrates four typical signal locations at a four-legged RCUT intersection. NCDOT has installed a separate signal controller at each of the four signal locations implemented on RCUT intersections thus far in North Carolina, thereby preserving the independence of the signal control on either side of the arterial. This practice may increase the implementation cost of RCUT installation and may prevent the signals from working together optimally in an actuated environment. Another potential is to develop a signal design for a RCUT intersection that features three controllers. One controls the signal displays at signals 1 and 4 (with locations as depicted in figure 98), and the other two control the signal displays at signals 2 and 3 (with locations as depicted in figure 98). A third practice is to employ a signal design that features two controllers, with one controlling the signal displays at signals 1 and 2 and the other controlling signal displays at signals 3 and 4 (with locations as depicted in figure 98).

While not yet implemented, it is feasible to use a signal control plan with one controller for the four signal locations. Figure 99 and figure 100 show two signal phasing schemes. With just one controller, there is only one cycle length serving both directions of the arterial. Therefore, some loss in the quality of progression may result. The signal phasing schemes in figure 99 and figure 100 include three main movements: (1) main street through movements, (2) U-turns, and (3) left turns from the main street concurrent with right turns from the side street. These phasing schemes afford greater flexibility to accommodate junctions where there are unbalanced left-turn and/or U-turn volumes.

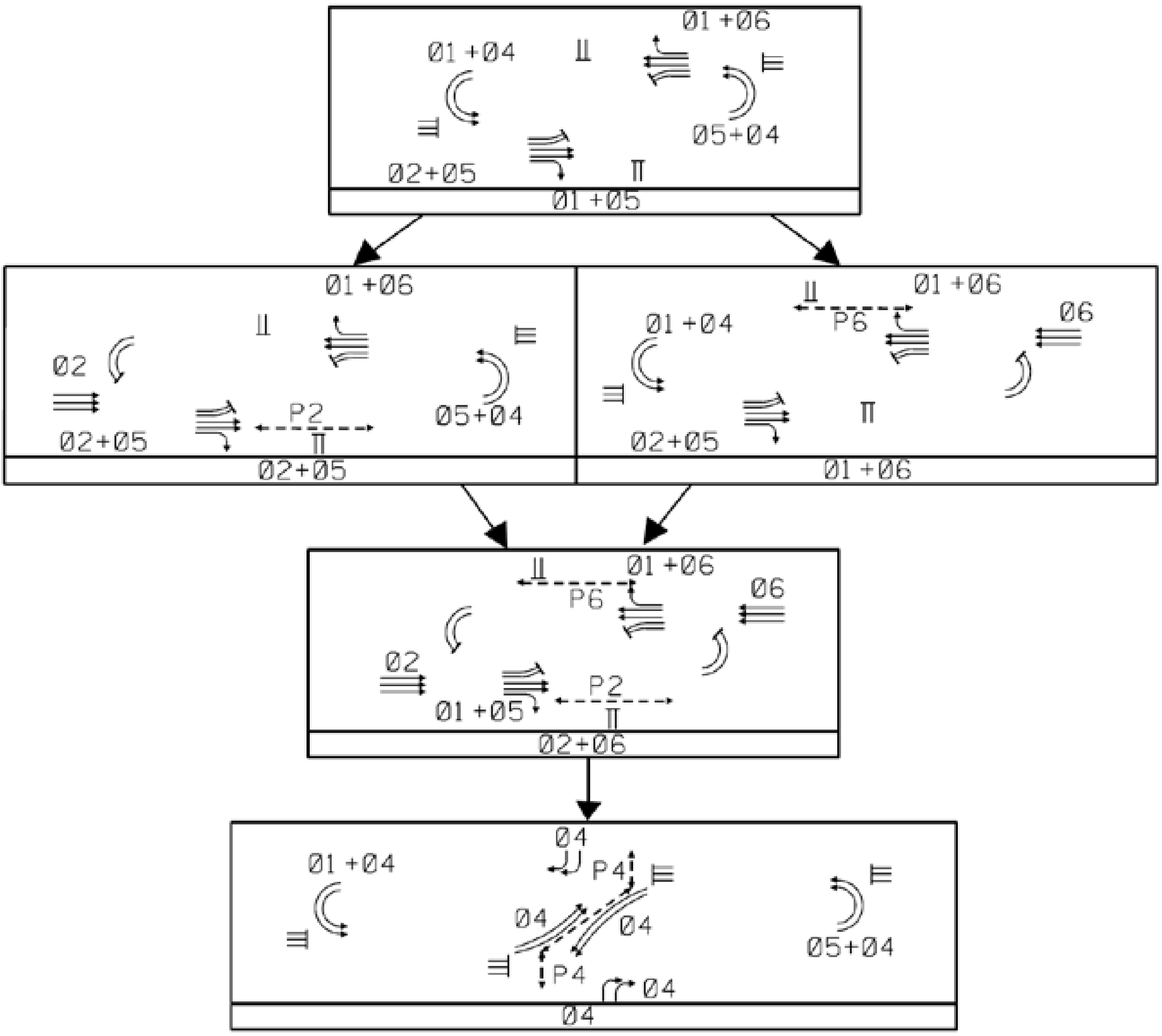


Figure 99. Chart. Signal phasing for a RCUT intersection for one controller with single concurrent pedestrian phase to allow pedestrians to cross the main street.

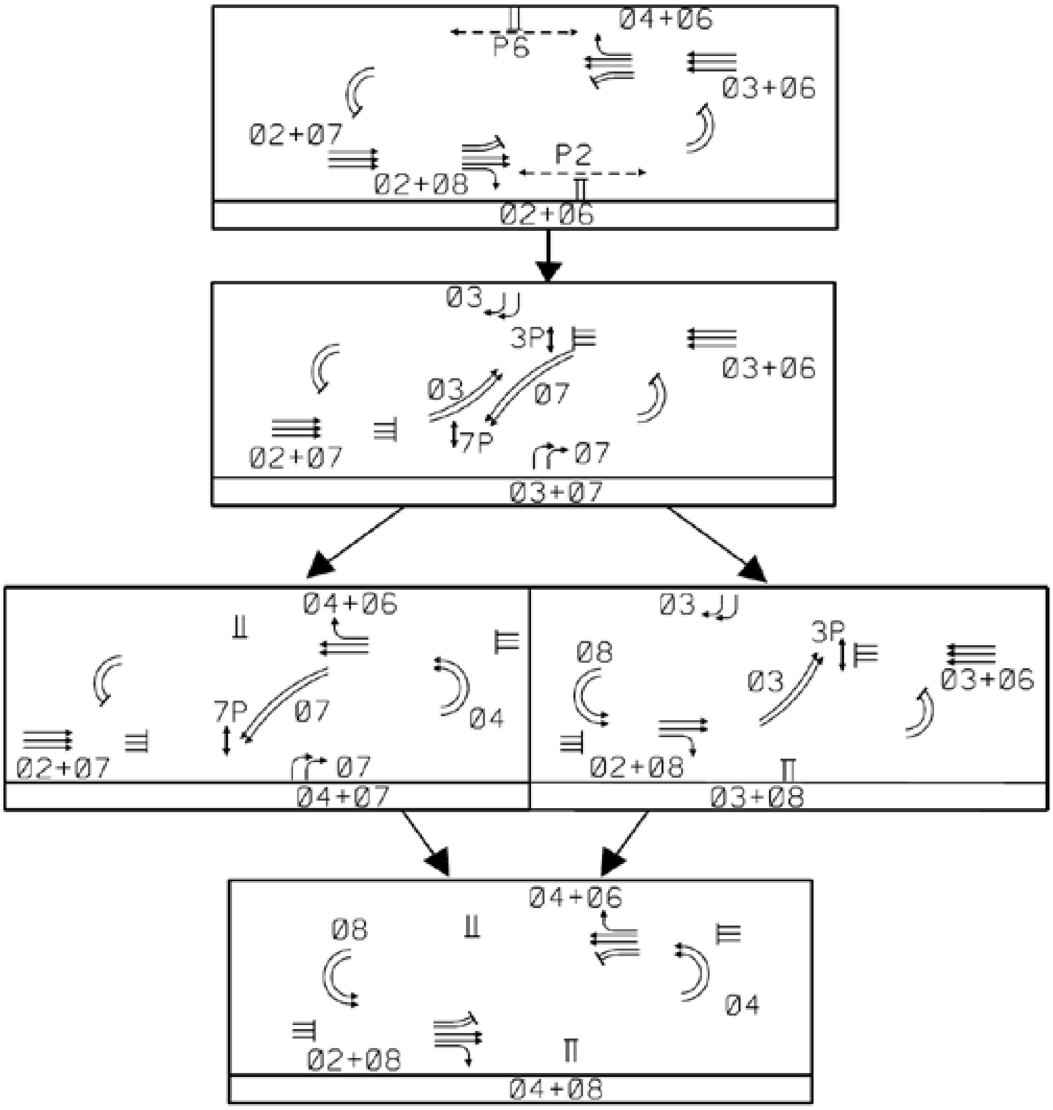


Figure 100. Chart. Signal phasing for a RCUT intersection for one controller in which pedestrians cross the main street at two separated signal-controlled crosswalks.

Figure 99 and figure 100 illustrate that pedestrians can cross the minor street approaches during the phases that serve major street through vehicles. Pedestrians can cross the major street approaches during the phases that serve left-turning vehicles. Providing a minimum green time to allow pedestrians to cross both major street legs during a single phase (i.e., a one-stage crossing) is a challenge to implement at some intersections because it can create substantial delays for through volumes. This single-stage crossing would be less likely to generate potentially dangerous crossing actions by pedestrians. A multistage crossing presents additional challenges for visually impaired pedestrians, and the pedestrian facilities need to be designed accordingly.

Table 10 and table 11 show the typical signal timing parameters for these two configurations, while figure 101 and figure 102 show the detector numbers and typical placements for these two configurations. Figure 103 shows suggested signal pole and mast arm locations for a RCUT intersection. The presence of a loon creates a challenge in locating the signal pole and mast arm.

At the U.S. Route 17 RCUT intersection in Brunswick County, NC, the signal pole was placed upstream of the loon. This means that signal heads for the major street are on the near-side of the crossover, but they likely provide better visibility to the signal for crossover traffic. Figure 104 through figure 107 show that the U.S. Route 17 RCUT intersection operates with pole-mounted signals in the median for the U-turning traffic. A potential disadvantage for signal heads mounted on ped poles in the median is that these pole-mounted signal heads may be visually blocked by queued traffic.

Table 10. Typical signal controller settings for signal phasing shown in figure 99.

	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min green	5.0	15.0		5.0	5.0	15.0		5.0
Max green	40.0	60.0		40.0	40.0	60.0		40.0
Passage (extension)	3.0	2.0		2.0	3.0	2.0		2.0
Amber	4.0	4.0		4.0	4.0	4.0		4.0
All red	2.0	2.0		2.0	2.0	2.0		2.0
Ped walk	7.0	7.0		7.0	7.0	7.0		0.0
Ped clearance	14.0	14.0		40.0	14.0	14.0		0.0
Recall	No	Min green		No	No	Min green		No

Min = Minimum.
Note: Empty cells indicate phases that are not occupied.

Table 11. Typical signal controller settings for signal phasing shown in figure 100.

	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min green		15.0	4.0	5.0		15.0	5.0	5.0
Max green		25.0	40.0	40.0		25.0	40.0	40.0
Passage (extension)		2.5	3.0	4.0		2.5	3.0	4.0
Amber		4.0	4.0	4.0		4.0	4.0	4.0
All red		2.0	3.0	3.0		2.0	3.0	3.0
Ped walk		7.0	7.0	0.0		7.0	7.0	0.0
Ped clearance		14.0	14.0	0.0		14.0	14.0	0.0
Recall		Min green	No	No		Min green	No	No

Min = Minimum.
Note: Empty cells indicate phases that are not occupied.

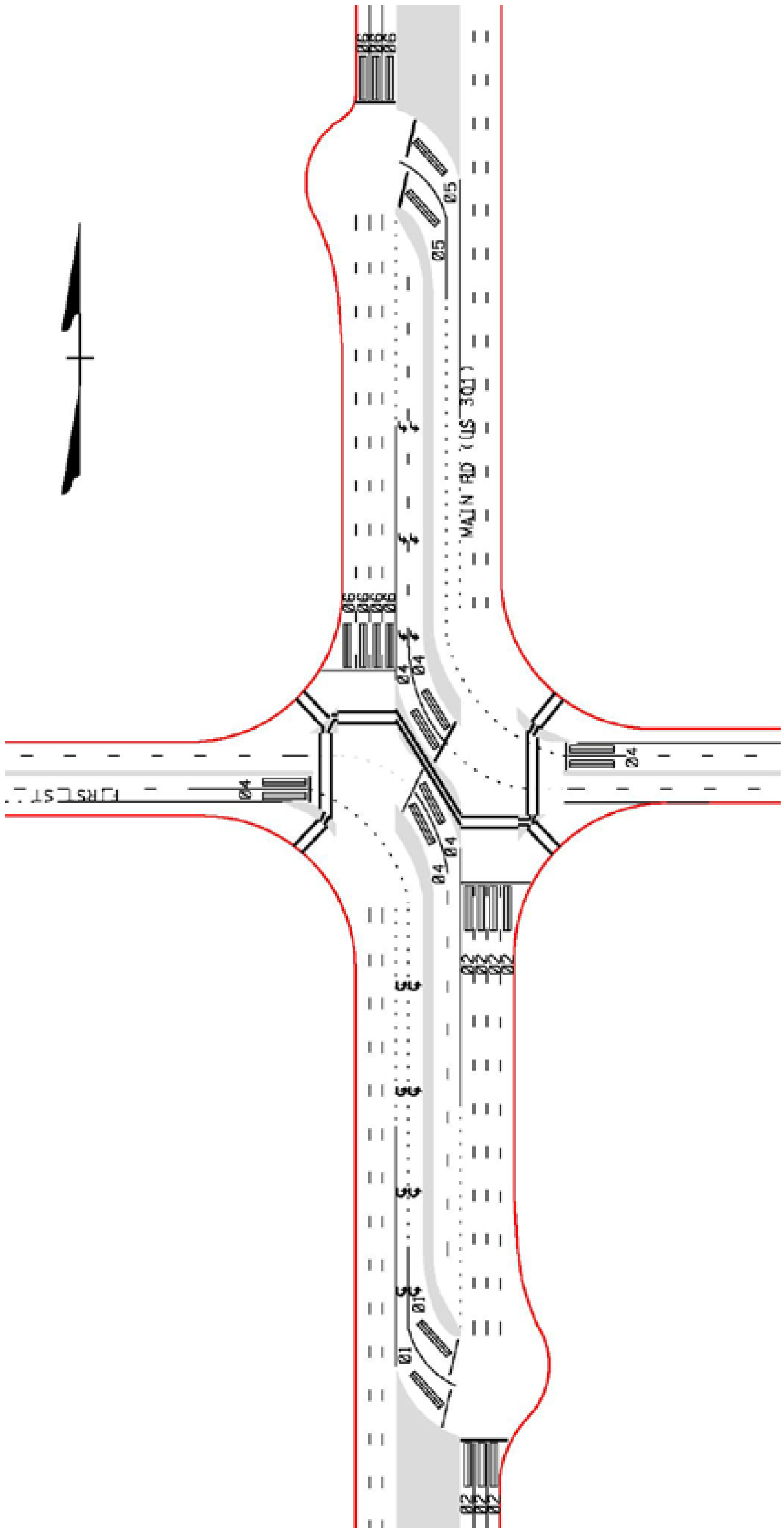


Figure 101. Illustration. Detector locations for RCUT intersection for the signal phasing in figure 99.

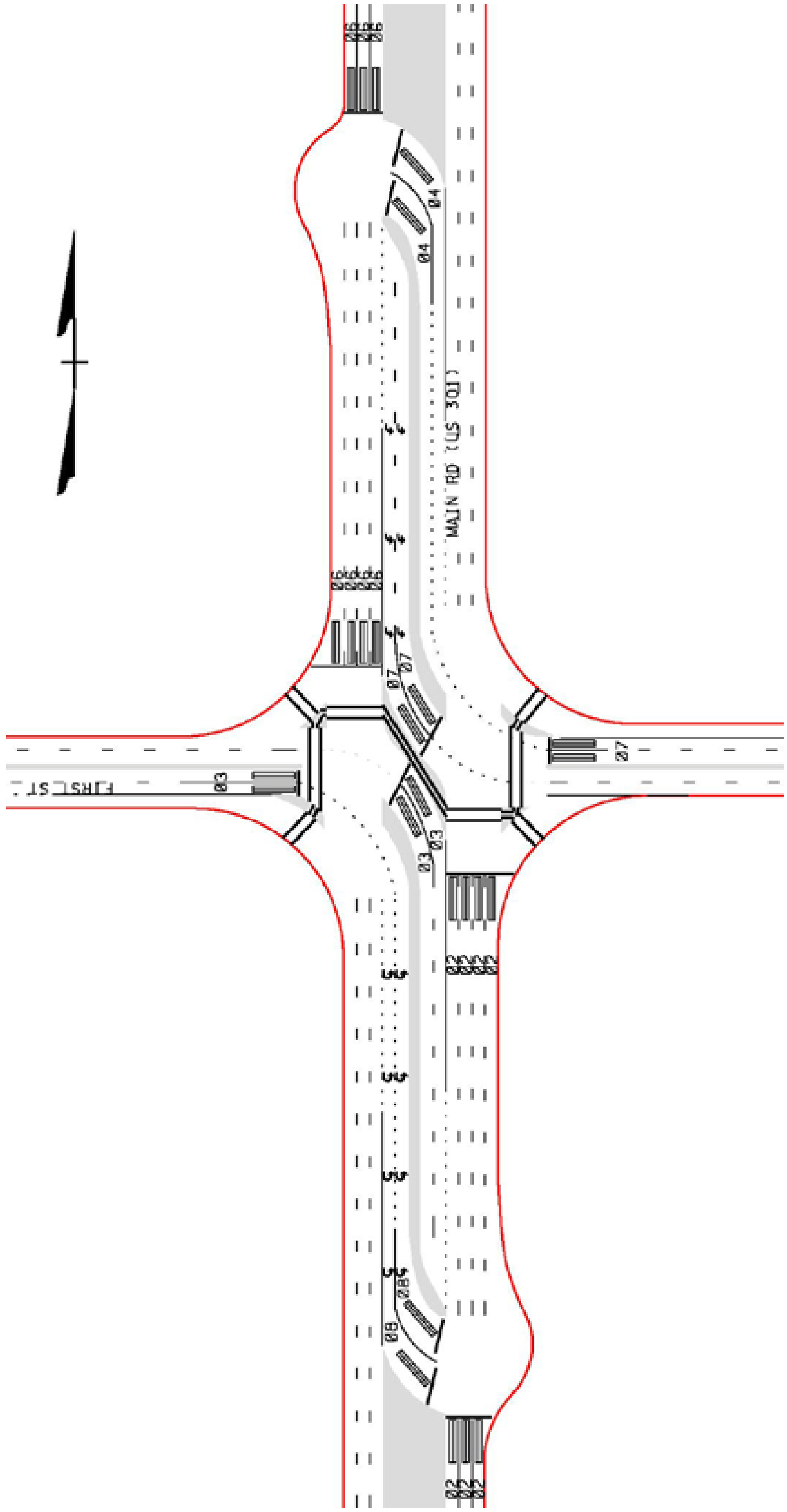


Figure 102. Illustration. Detector locations for RCUT intersection for the signal phasing in figure 100.

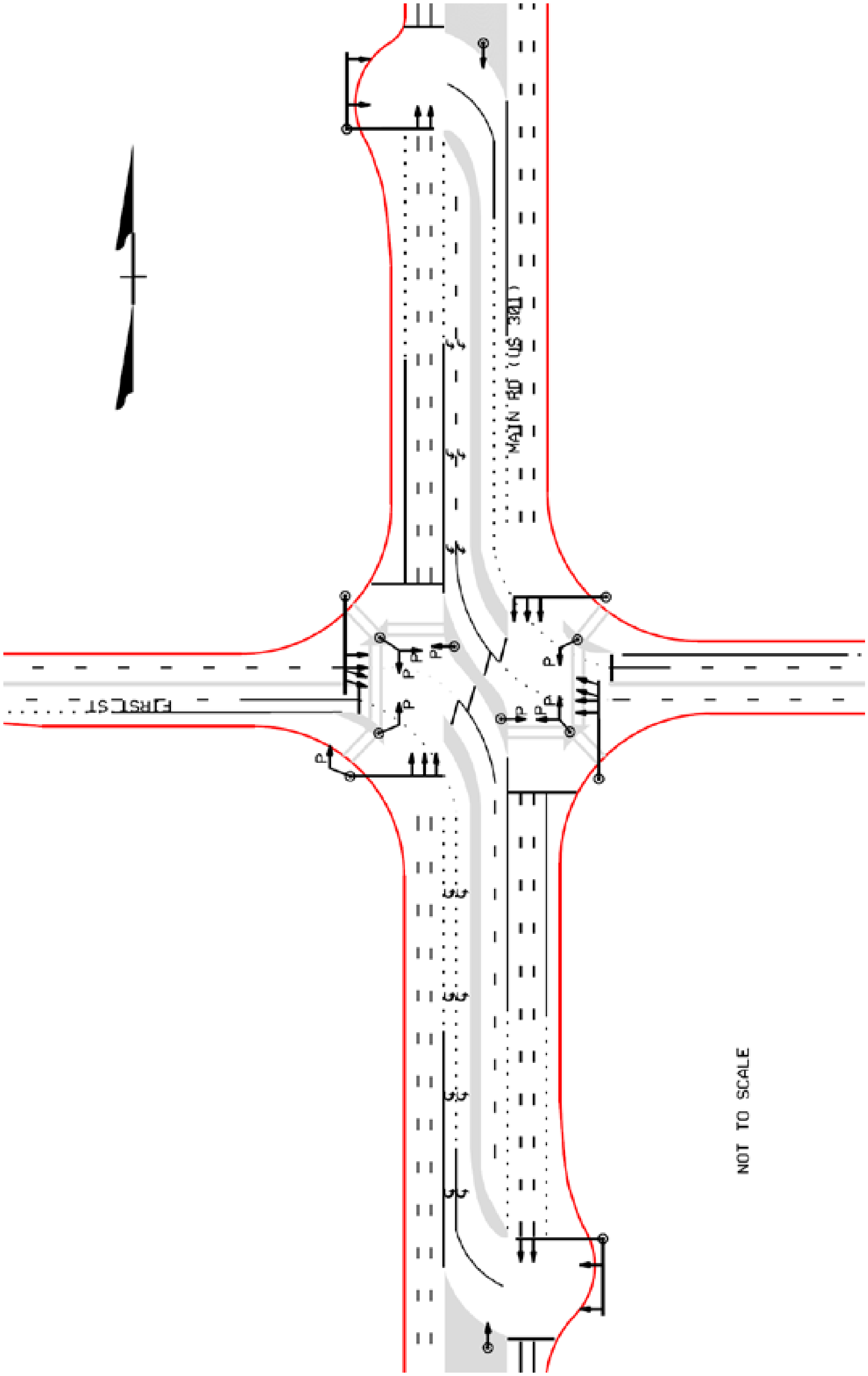


Figure 103. Illustration. Possible signal pole and mast arm locations for RCUT intersection.

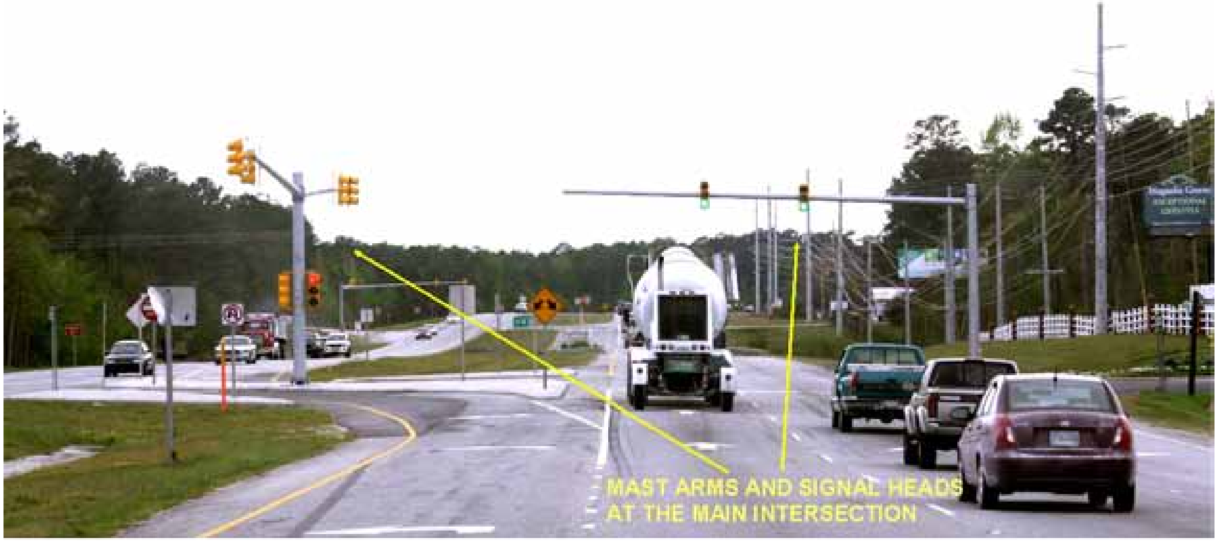


Figure 104. Photo. Signal pole locations at the main intersection of U.S. Route 17 RCUT intersection in North Carolina.

Figure 105. Photo. Signal pole locations at the main intersection of U.S. Route 17 RCUT intersection in North Carolina.

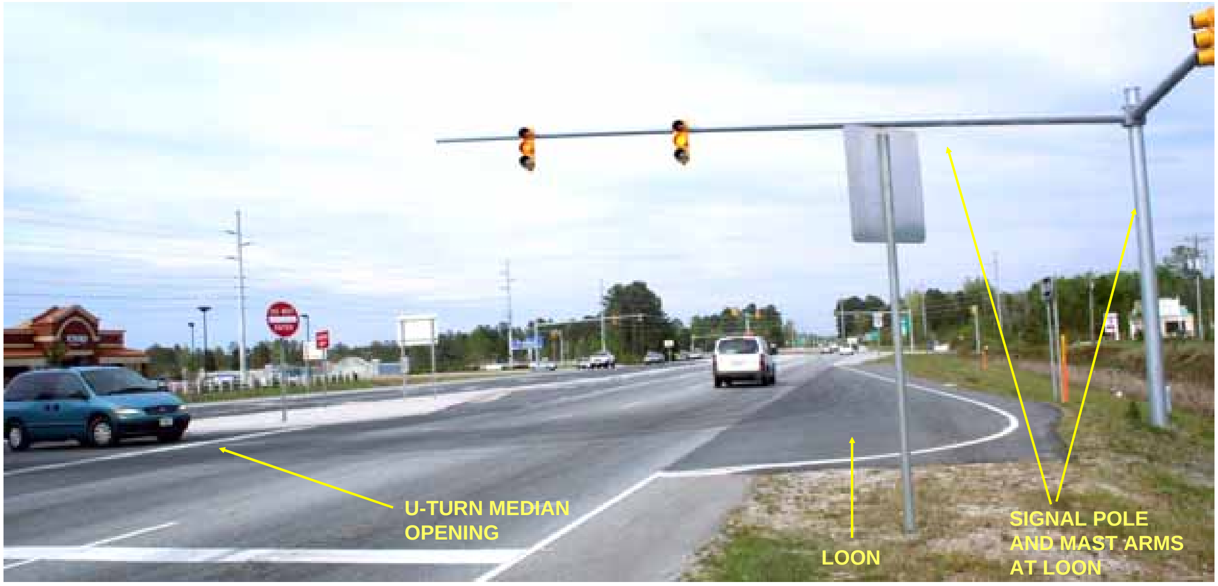


Figure 106. Photo. Signal pole locations at the crossover of U.S. Route 17 RCUT intersection in North Carolina.

Figure 107. Photo. Signal pole locations at the main intersection from the minor street approach.

4.4.3 Signing and Marking

Signing and marking a RCUT intersection is similar to signing and marking an MUT intersection, as described in chapter 3. Figure 108 shows a signing and marking plan for a RCUT intersection based largely on MDSHA guidance for one direction of travel, while figure 109 shows signing and marking guidance from NCDOT. The current MUT intersection and RCUT intersection guidance from the two States indicates there is no need for overhead signing at most RCUT intersections. Figure 110 shows the typical signing and marking used in Maryland's implementation of unsignalized J-turns.

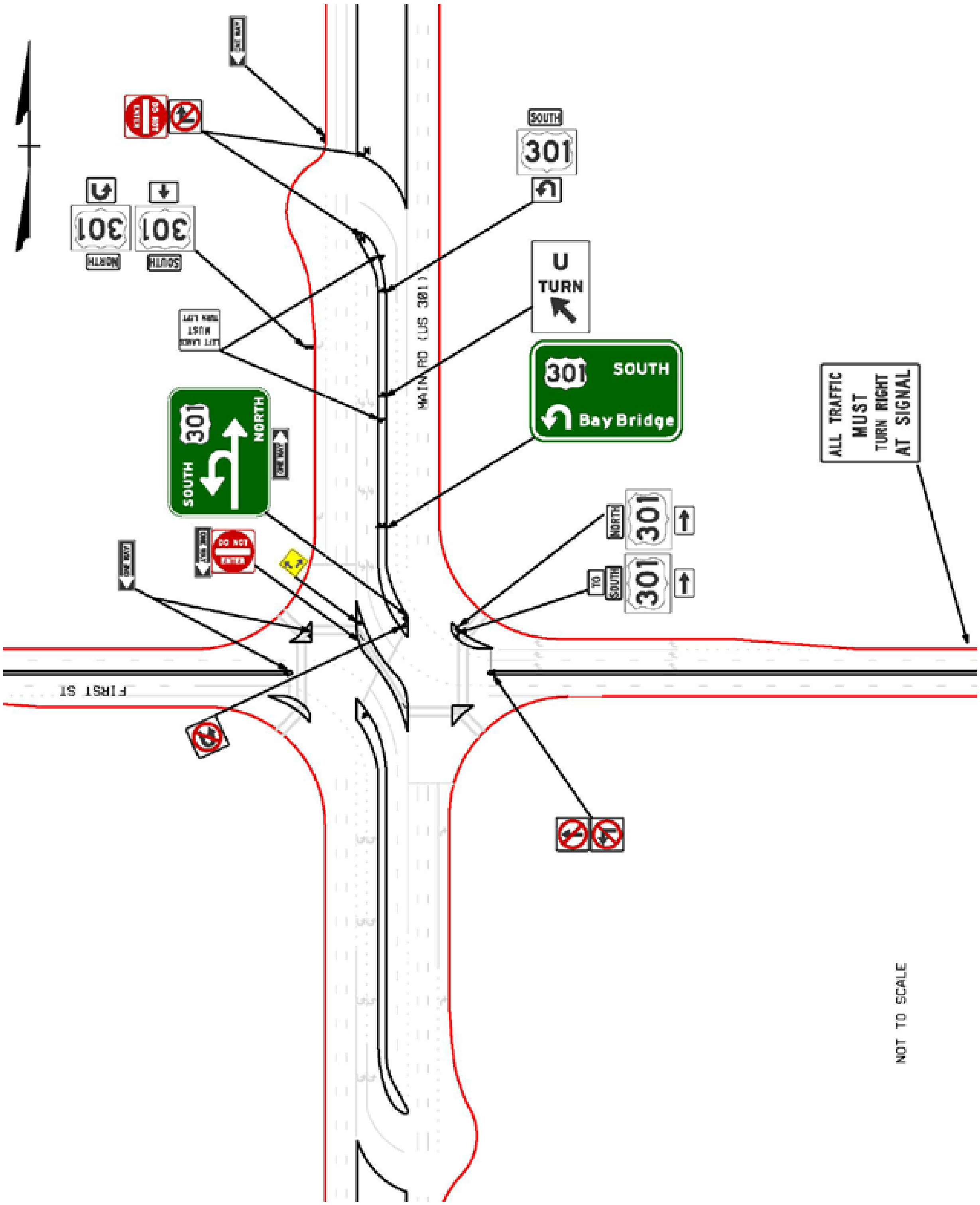
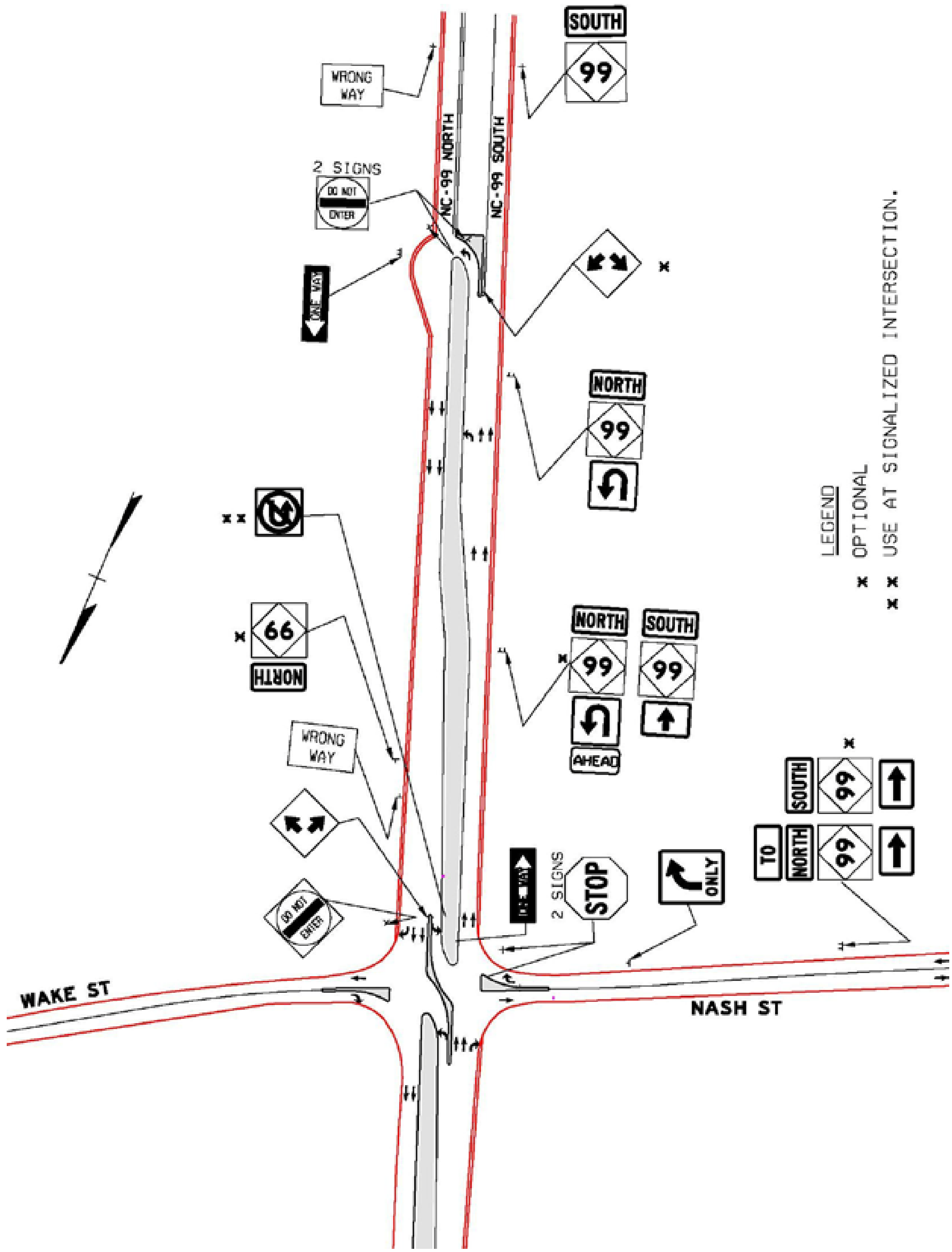


Figure 108. Illustration. RCUT intersection signing plan derived from Maryland practice.



Source: North Carolina Department of Transportation *Typical for Super Street Signing*

Figure 109. Illustration. RCUT intersection signing guidance from the NCDOT practice.[(58)]

Figure 110. Photo. Signing and marking at an unsignalized J-turn in Emmitsburg, MD.

As of this report, drivers have adjusted quickly to the three recent RCUT intersection installations in North Carolina. Few wrong way movements through crossovers have been observed at rural intersections. Few red light runners have been observed at crossovers on U.S. Route 17. Overall, traffic seems to flow smoothly. One concern expressed prior to implementation for all three areas was that these were all areas with high concentrations of tourists and retirees who might be surprised or slower to adapt to new traffic patterns. Those concerns have generally subsided.

4.5 ACCOMMODATING PEDESTRIANS, BICYCLISTS, AND TRANSIT USERS

Figure 89 through figure 91 previously showed pedestrian crosswalks for three variations of the RCUT intersection design. Figure 111 shows the typical pedestrian movements at a RCUT intersection. The major street crossing is generally on one diagonal path, which is longer than at a conventional intersection. RCUT intersections allow pedestrians to cross the main street between one but not both pairs of opposing corners. For example, figure 111 shows the crossing between the northeast and southwest quadrants (i.e., between quadrant B and C). Crossing the street diagonally from the other quadrants (i.e., between quadrant A and quadrant D) requires pedestrians to cross three streets: first across a side street (A to B or D to C), then the diagonal crossing of the major street (B to C or the reverse direction), and finally the second side street (C to D or B to A). This movement increases pedestrian exposure to vehicular traffic when compared to a traditional intersection design by requiring pedestrians to cross three legs instead of two as in a traditional intersection. As a result of the additional crossing maneuvers and subsequent crossing time, some pedestrians may attempt to directly cross the major street (i.e., C to A or B to D) or cross from the center diagonal island (E) to one of the alternate quadrants (i.e., A or D).

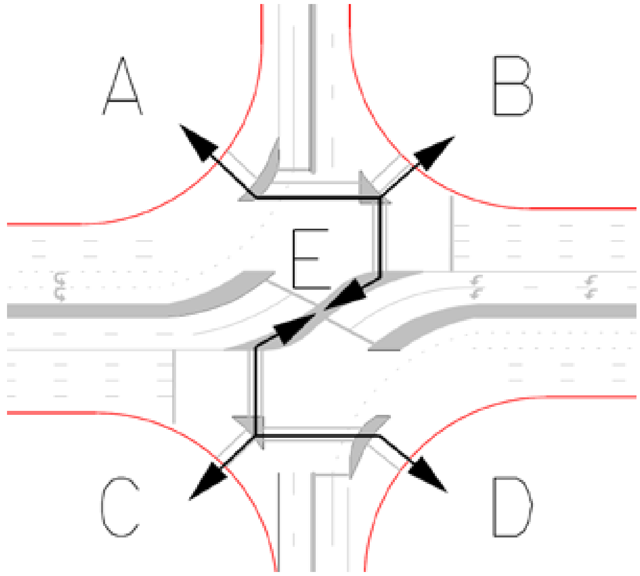


Figure 111. Illustration. Pedestrian movements in a RCUT intersection.

Several measures described in the following sections should be considered to mitigate these potentially hazardous pedestrian crossing behaviors.

4.5.1 RCUT Intersection Design in Areas that Favor Preferred Pedestrian Movements

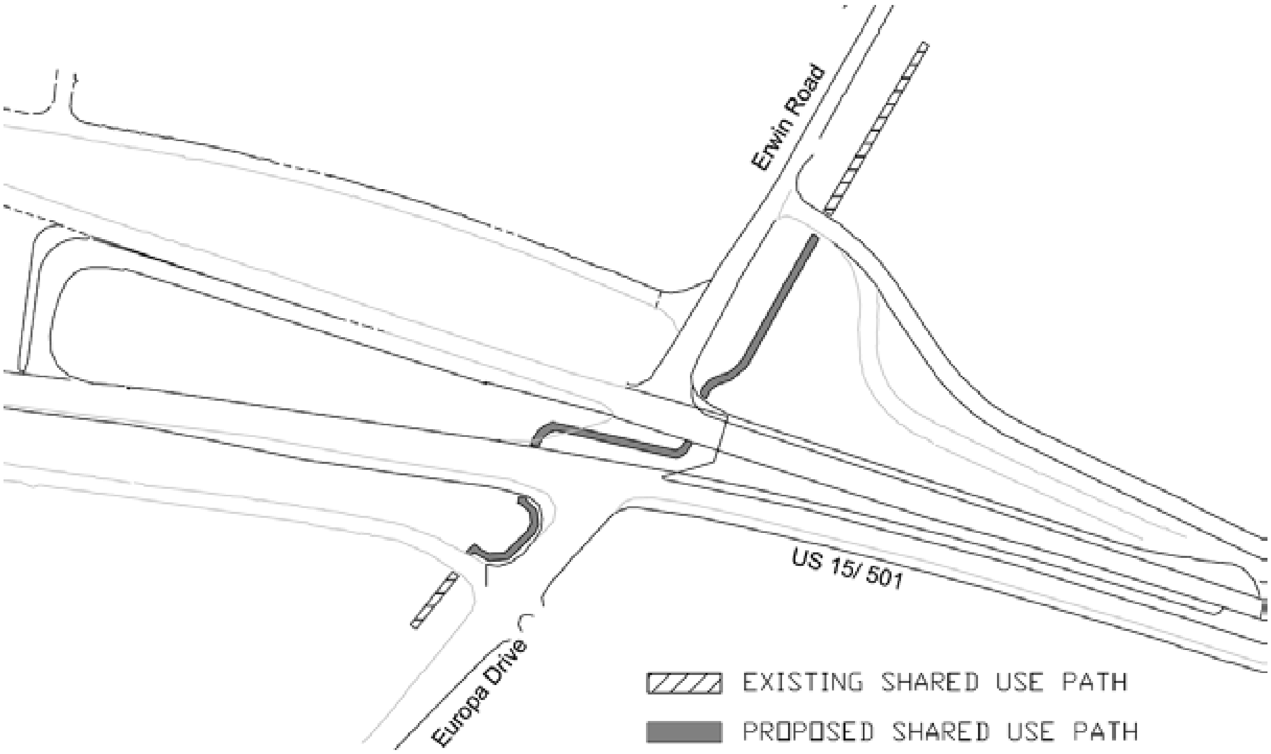
As the typical RCUT intersection design favors pedestrian movements between the northeast (B) and southwest (C) quadrants of an intersection, the best application of the RCUT intersection is in locations where this is the predominant pedestrian crossing. This application is more suited to suburban environments where land uses are separated, and pedestrian traffic is relatively low. If this is the current situation, then future development and future pedestrian traffic need to be considered. It favors predominant traffic on paths A to B and C to D. Urban commercial business district (CBD) environments may not be well suited for this type of RCUT intersection configuration, as land uses in urban areas typically result in pedestrians crossing all four legs of the intersection.

4.5.2 Wayfinding Signing for Pedestrians

Wayfinding signing can help direct pedestrians through the intersection to arrive at their desired destinations. Providing adequate wayfinding signing is important, considering most pedestrians are unfamiliar with the designated crossing patterns of a RCUT intersection design and may attempt to cross streets using traditional patterns. Adequate signing helps reduce pedestrian confusion and may encourage pedestrians to use designated travel paths through the intersection.

4.5.3 Barriers to Channelize Pedestrians

Barriers should be used to help prevent pedestrians from making undesirable crossings. Barriers should be rigid, especially at higher volume, higher capacity intersections. However, rigid barriers can present a hazard to motorists and would need appropriate end treatments. An alternative breakaway railing system or even plantings may not pose as much as a hazard to drivers (i.e., spearing hazard) and could be an alternative to channelize pedestrians. An example of pedestrian channelization at a RCUT intersection is shown in figure 112.



Source: North Carolina Department of Transportation *Typical for Super Street Signing*

Figure 112. Illustration. Median shared-use path design for the U.S. Route 15/501 RCUT intersection design in North Carolina.[59]

4.5.4 Accessible Devices to Assist Disabled Pedestrians

The nontraditional pedestrian and vehicle paths challenge pedestrians, especially those with vision or cognitive impairments who may not be able to use wayfinding signs. Some of the cues pedestrians with vision impairments rely on to cross intersections, such as the sound of traffic parallel to their crossing, will be different. To mitigate some of the potential impacts on pedestrians with impairments, locator tones on pedestrian signals and specialized surface treatments are suggested. APS are recommended as well. Readers are directed to the *American with Disabilities Act Accessibility Guidelines* (specifically sections 4 and 10 on accessible elements and spaces and transportation facilities, respectively) available on the U.S. Access Board's Web site for extensive information on accommodating visually impaired pedestrians.[15]

There are several variations to the RCUT intersection design in figure 89 through figure 91 that can enhance the ability of pedestrians to cross the main street. One option is to remove the channelized right-turn islands, as seen in figure 90. Pedestrians are able to cross in one continuous interval. Researchers should consider using common design features that minimize crossing distance (such as smaller radii) and conflicts between pedestrians and vehicles (right turn on red prohibitions) to enhance safety for all pedestrians.

Figure 113 shows another variation to the RCUT intersection design that may improve pedestrian access, in which the minor street approaches are offset. This design shortens the path to cross the arterial. The offset makes almost no difference in vehicle operations at most RCUT intersections, but pedestrian crossings would be more direct. A shorter crossing distance would make a one-stage crossing more feasible, decrease pedestrian exposure to the moving vehicles on the main street, and likely increase the percentage of pedestrians choosing to cross at the proper location. Position guidance would be needed to direct pedestrians to the crossing locations and deter them from crossing at other locations.

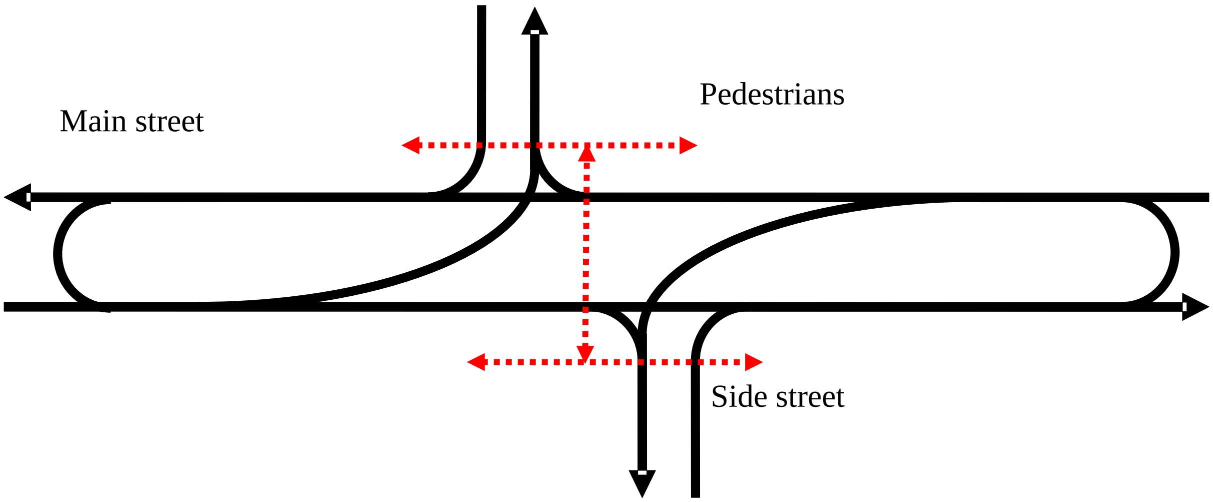


Figure 113. Illustration. RCUT intersection with minor street approaches offset to produce a shorter pedestrian crossing.

For the design shown in figure 113, the major street crossing could be made in one or two stages, depending on the signal phasing. A one-stage crossing (i.e., crossing both directions of the major street during one signal phase) is possible if the distance is not too long. Additionally, the necessary green time for that phase should not take too much green time away from the signal phase for major street through traffic signals 1 and 4 in figure 98 and can be controlled by one controller. At many RCUT intersections, these conditions may prove untenable, and a two-stage crossing of the major street should be used. In a two-stage crossing, a pedestrian crosses one direction of the major street during one signal phase and the other direction during a second signal phase, often with some delay between the phases. Because there are only two signal phases at each individual signal-controlled intersection (e.g., at locations 1 through 4 in figure 98) and the cycle lengths are short, the amount of delay to a pedestrian making a two-stage crossing should be relatively small. In the event that relatively light pedestrian crossing volumes exist, the infrequent need for a long red time on the main road to accommodate the crossing demand would suggest that a single-stage crossing may be acceptable.

Pedestrians crossing at a RCUT intersection can encounter fewer conflicting traffic streams than at a typical conventional intersection. Conflicts at conventional intersections are possible between left-turning traffic from the side road and pedestrians crossing the main street. If signal-control is present, then the conflict may still exist when there is no left-turn signal phasing for the side road or when there is protected-permitted left-turn phasing for the side road. By comparison, pedestrians at a RCUT intersection cross the main street diagonally during signal phases where there are no conflicts possible. The pedestrians crossing at a RCUT intersection may be generally slower and less direct, but fewer conflicts are expected.

As described in section 4.4, the RCUT intersection affords designers the flexibility to install traffic signal control without adversely affecting the progression capabilities (e.g., without adding much delay) for major street through traffic. This flexibility is put to use by installing pedestrian signals at U-turn crossovers or midblock locations. At U-turn crossovers, one signal is likely to be already in place, so the additional cost is for another set of traffic signals to control the second direction of the major street. Pedestrian signals at U-turn crossovers or midblock locations allow pedestrians to safely cross the major road.

RCUT intersections accommodate both bicyclists and pedestrians through the use of a shared-use path that provides refuge in the median. Figure 112 shows the plan view of the shared-use path designed by NCDOT through the median of the RCUT intersection under construction on U.S. Route 15/501 in Chapel Hill, NC. The crosswalks are perpendicular to travel lanes, which aid pedestrians with vision impairments. The shared-use path in the median has a reverse curve design.

NCDOT has designed a 10-ft-wide path with 2-ft-wide shoulders through the otherwise grassy median. Bollards are placed near the shared-use path entrances to discourage motor vehicle use. Accessible curb ramps with detectable warnings are constructed at all transitions from the sidewalk to the street. Design guidelines for shared-use paths for individual jurisdictions should be referenced for specific recommendations on geometric elements of the path.

Bicyclists along the main road appreciate the high green time percentage for the major-street through movement at RCUT intersections. Bicyclists desiring to make a left turn or through movement from the side street face a choice of using the pathway through the median designed for pedestrians or using the U-turn crossovers in a manner similar to drivers of motor vehicles. Their choice may depend on the type of bicyclist they are, as commuter bicyclists are likely to prefer to travel in the roadway while novice bicyclists may prefer the multipurpose trails. The U-turn may present a hazard to bicyclists. Vehicles executing U-turns have more difficulty staying in lanes, and larger vehicles exhibit greater off-tracking, which may cause vehicles to encroach into bicycle lanes. Therefore, RCUT intersections should offer alternate paths for bicyclists, such as the pathway through the median. This type of design is better suited for areas where separated paths for bicyclists are more prevalent than on-street bicycle lanes, reinforcing that the RCUT intersection design is better suited in suburban areas. Appropriate signing is needed to direct bicycles to the pathway through the median, and the pathway should be designed for shared use similar to the design described earlier for Chapel Hill, NC. This is similar to the bicyclist treatments at multiline roundabouts.

With respect to transit users at RCUT intersections, bus routes along the arterial are enhanced with operation that is likely more efficient and results in fewer conflicts for transit users. Bus stops work well on the far side of the minor street where they are out of the way of more turning traffic. Bus stops in the loon should be strongly discouraged to keep it free for turning vehicles. Buses making left turns or proceeding through from the minor street need to travel additional distance and incur more travel time compared to traversing a conventional intersection. U-turn crossovers designed to accommodate large combination trucks without curb encroachments should be able to accommodate standard transit and school buses.

Figure 114 shows that transit stops can be located in conjunction with the pedestrian movements discussed earlier in the section. When transit routes run along the main street, locating transit stops on the near side of the intersection is preferred so that it favors the heavy pedestrian movement (i.e., from B to C or from C to B). When transit routes run along the minor street, locating transit stops on the far side of the intersection is preferred. For a bus turning left from the main road, the stop should be located on the minor road so that buses do not have to weave from the right lane into a left lane to use the U-turn. In each case, pedestrians on the remaining quadrants have to take circuitous routes (i.e., from A to D or from D to A, as shown in figure 111).

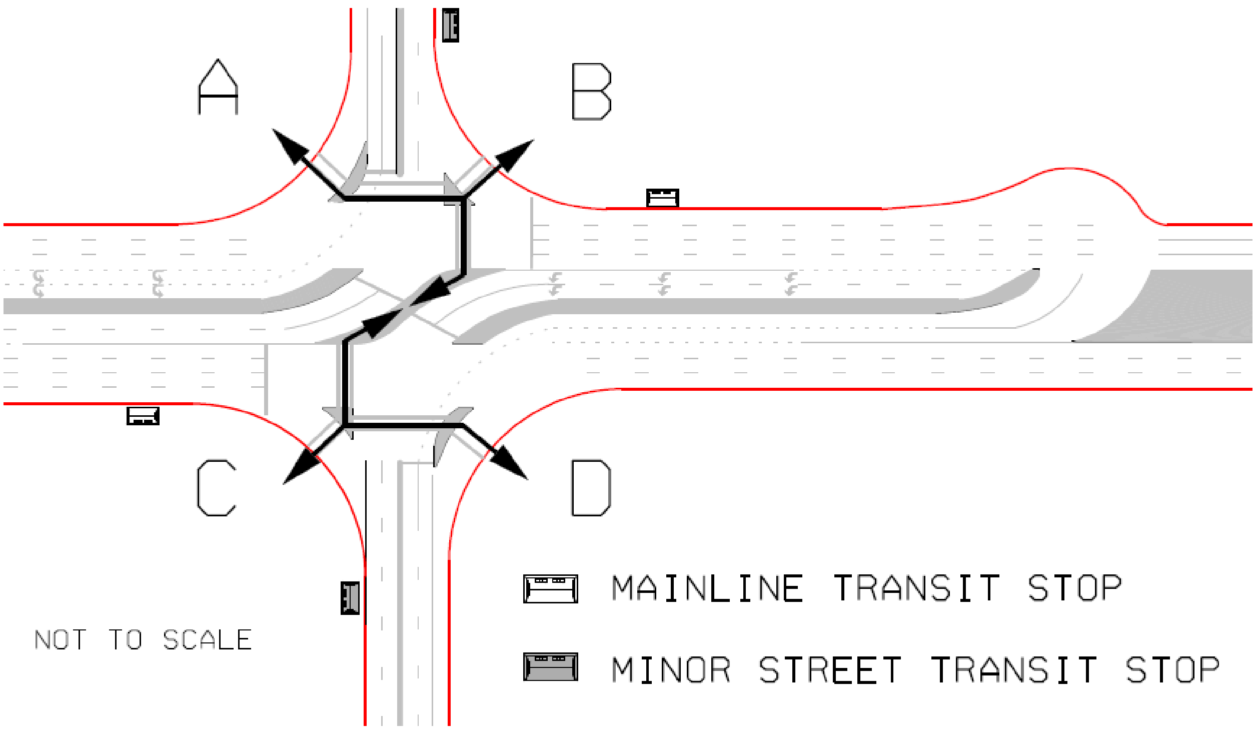


Figure 114. Illustration. Transit stop locations at a RCUT intersection.

4.6 OPERATIONAL PERFORMANCE

RCUT intersections operate better than conventional intersections under certain volume conditions. This section contains a review of previous research on RCUT intersection operations as well as the results of simulation experiments performed for this report.

4.6.1 Previous Research

Kim et al. compared three RCUT design cases to conventional intersection design.[60] Two of the RCUT design cases featured one U-turn lane. The other RCUT design case featured two U-turn lanes. For each of the three cases, several entering volume scenarios were analyzed to determine the effect on travel time and vehicle throughput. The results showed that the performance of a

RCUT design was better than that of a conventional intersection design, primarily for the one U-turn lane design and at high volumes. Travel time was reduced by 30 to 40 percent, while throughput increased 22 to 40 percent. The highest vehicle throughput for the one U-turn lane design was achieved when green time on the minor road was 20 percent of the green time on the major road. In comparison, the RCUT design with two U-turn lanes experienced a smaller increase in vehicle throughput, ranging from 9 to 12 percent.

A study of a Michigan corridor comparing TWLTLs to MUT crossovers also investigated RCUT median crossovers.(20) The comparison results are shown in table 12. During peak conditions, travel time on the corridor with RCUT crossovers decreased 10 percent. In addition, travel speed was 15 percent higher than the same conditions using TWLTL. During off peak conditions, the study revealed that RCUT crossovers produced operational differences that were similar to TWLTLs.

Table 12. RCUT intersection simulation results.

Time of Day	Major Street Geometry	Total System Time, veh-h	Mean Stops per Vehicle	Mean Speed, mi/h
Morning peak	TWLTL	302	1.95	14.5
	MUT	254	1.98	22.4
	RCUT	283	2.36	18.2
Noon	TWLTL	136	1.45	25.9
	MUT	137	1.75	28.5
	RCUT	142	1.84	27.4
Midday	TWLTL	162	1.53	24.6
	MUT	159	1.82	27.3
	RCUT	164	1.86	27
Afternoon peak	TWLTL	403	2.08	13.3
	MUT	280	2.19	19.2
	RCUT	314	2.59	17.3
Mean, all times	TWLTL	251	1.75	19.6
	MUT	208	1.94	24.4
	RCUT	226	2.16	22.5

Simulation results using a range of intersection configurations and volumes from intersections in Virginia and North Carolina suggest mixed results in overall travel time when RCUT intersections were compared to traditional intersection designs. The results ranged from -8 to +18 percent during off peak conditions and -10 to +71 percent during peak conditions. The results were also mixed with respect to overall stops when compared to traditional intersection design. The results ranged from -8 to +187 percent during off peak conditions and +16 to +146 percent during peak conditions.(61)

Hummer et al. studied the performance of several of the RCUT designs constructed in Maryland and North Carolina and discussed in this chapter. They found that the RCUTs generally performed as expected with respect to delay and safety.(20)

4.6.2 Analysis of Simulation Results

VISSIM® was used to gain further insight into the operational performance of RCUT intersections in comparison to conventional intersections. Five intersection geometric design cases of RCUT intersections and conventional intersections were simulated. Table 13 shows the geometric design configurations of the cases simulated. The lane configurations and geometric features on both approaches of the major road were identical. Similarly, the lane configurations and geometric features on both approaches of the minor road were identical.

Table 13. Geometric design configuration for VISSIM® simulations.

Geometric Design Cases	Approach Configuration				
	Major Road			Minor Road	
	RCUT and Conventional		RCUT Only		
	Through Lanes	Left-Turn Lanes	U-Turn Lanes	RCUT	Conventional
1	2	1	1	1 (R)	1 (L,TR)
2	2	1	1	2 (R, R)	2 (L,TR)
3	3	1	1	2 (R, R)	2 (L,TR)
4	3	2	1	2 (R, R)	2 (L,TR)
5	3	2	2	2 (R, R)	2 (L,TR)

R = Right-turn lane.
L = Left-turn lane.
T = Through lane.

Each of the five cases had three sets of directional splits on the major road volumes: 50:50, 60:40, and 75:25, respectively, while the minor road splits remained 50:50 for all the simulation cases. These five geometric cases with three major road directional splits were simulated under three sets of traffic volumes—low, medium and high—as shown in table 14. Additionally, turning volume sets were created where the ratio of minor road total volume/total intersection volume (MRTV/TIV) was varied from 0.12 to 0.40. A total of 90 unique VISSIM® simulations were developed for the RCUT intersection, and an equal number of unique VISSIM® simulations were developed for comparable conventional intersections. The VISSIM® simulation network was 1 mi long on the major and minor road approaches for the cases simulated. The base case simulations assumed no pedestrian activity at the intersection. The following constants were maintained for each simulation:

- Optimum fixed signal timing determined using Synchro®.[21]
- Yellow times determined using ITE policy.
- All-red times determined using ITE policy.
- A total of 5 percent heavy vehicles on all legs.
- A 450-ft-long bay.

- A total of 450-ft distances from the main intersection to U-turn crossovers.
- Study network including 0.5 mi in each direction from the main intersection.
- Single right-turn bays on the mainline.
- Right-turn on red allowed at each signal. No left-turn on red allowed.
- A signal at each left-turn or U-turn crossover.
- A 40-ft median width on mainline.
- An undivided side street.
- Loons sized as needed to accommodate a U-turning WB-50 truck.
- A 45 mi/h desired speed on mainline.
- A 25 mi/h desired speed on side street.
- Saturation headway of approx 1,900 veh/h/lane.
- No bus stops.
- Seeding time of 30 minutes for the simulations.
- Running period of 60 minutes for the simulations.

Table 14. Volumes for geometric design configurations for VISSIM® simulations.

Geometric Cases		Turning Movement Volume Set (veh/h)	Major Road Approach 1 Volume* (veh/h)	Major Road Approach 2 Volume* (veh/h)	Total Minor Road Volume** (veh/h)	Major Road Approach 1 Volume/ Total Major Road Volume (veh/h)	Total Minor Road Volume/Total Intersection Volume (veh/h)
1	Four-lane major road, one left-turn lane on major road, and one-lane minor road approaches	1	2,500	2,500	700	0.50	0.12
		2	2,500	1,667	700	0.60	0.14
		3	2,500	833	700	0.75	0.17
		4	1,550	1,550	780	0.50	0.20
		5	1,550	1,550	1,300	0.50	0.30
		6	1,250	1,250	1,700	0.50	0.40
2	Four-lane major road, one left-turn lane on major road, and two-lane minor road approaches	1	2,700	2,600	900	0.51	0.15
		2	2,700	1,733	900	0.61	0.17
		3	2,700	900	900	0.75	0.20
		4	1,810	1,810	900	0.50	0.20
		5	1,810	1,810	1,552	0.50	0.30
		6	1,520	1,520	2,026	0.50	0.40
3	Six-lane major road, one left-turn lane on major road, and two-lane minor road approaches	1	3,100	3,100	1,000	0.50	0.14
		2	3,100	2,067	1,000	0.60	0.16
		3	3,100	1,033	1,000	0.75	0.19
		4	2,710	2,710	1,356	0.50	0.20
		5	2,310	2,310	1,980	0.50	0.30
		6	1,830	1,830	2,440	0.50	0.40
4	Six-lane major road, two left-turn lanes on major road, two-lane minor road approaches, and one major road	1	3,500	3,500	800	0.50	0.10
		2	3,500	2,333	800	0.60	0.12
		3	3,500	1,167	800	0.75	0.15
		4	2,250	2,250	1,100	0.50	0.20
		5	2,000	2,000	1,700	0.50	0.30
		6	1,500	1,500	2,000	0.50	0.40

5	Six-lane major road, two left-turn lanes on major road, two-lane minor road approaches, and two major roads	1	3,500	3,500	1,000	0.50	0.13
		2	3,500	2,333	1,000	0.60	0.15
		3	3,500	1,167	1,000	0.75	0.18
		4	3,000	3,000	1,500	0.50	0.20
		5	2,860	2,860	2,450	0.50	0.30
		6	2,260	2,260	3,000	0.50	0.40

*   A constant right-turn volume of 300 has been used and is excluded from the major road volumes shown.

** Both minor road approaches have the same volumes.

Figure 115 through figure 119 show the comparison of throughput and network travel time for the five geometric design cases (see table 13) of RCUT and conventional intersections. At lower minor road volumes, simulation results showed that the RCUT intersections had the highest overall capacities for all the geometric design cases. Simulation results indicated that the throughput for RCUT intersections was 15 to 30 percent higher than comparable conventional intersections for the high-volume scenarios when the MRTV/TIV ratio was in the range of 0.1 to 0.2. The throughput of the RCUT intersection became similar to the conventional intersection when the MRTV/TIV ratio was in the range of 0.18 to 0.25. Beyond the MRTV/TIV ratio of 0.25, the conventional intersections had 5 to 17 percent higher capacities than RCUT intersections.

Simulation results indicated a 25 to 40 percent reduction in network travel time for RCUT intersections in comparison to conventional intersections for the high-volume scenarios when the MRTV/TIV ratio was in the range of 0.10 to 0.15. The network travel times for the RCUT intersections became similar to the conventional intersections when the MRTV/TIV ratio was in the range of 0.18 to 0.25. Beyond the MRTV/TIV ratio of 0.25, the network travel time for the RCUT intersections increased from 15 to 25 percent in comparison to the network travel time for conventional intersections. For the same set of simulations, VISSIM® simulation results indicated a very similar trend in the medium- and low-volume scenarios. Simulation results indicated that the difference in travel time between the RCUT and conventional intersections was a function of the MRTV/TIV ratio and was also sensitive to the relative proportion of the sum of left-turning and through vehicles on the minor road in comparison to the total minor road volume.

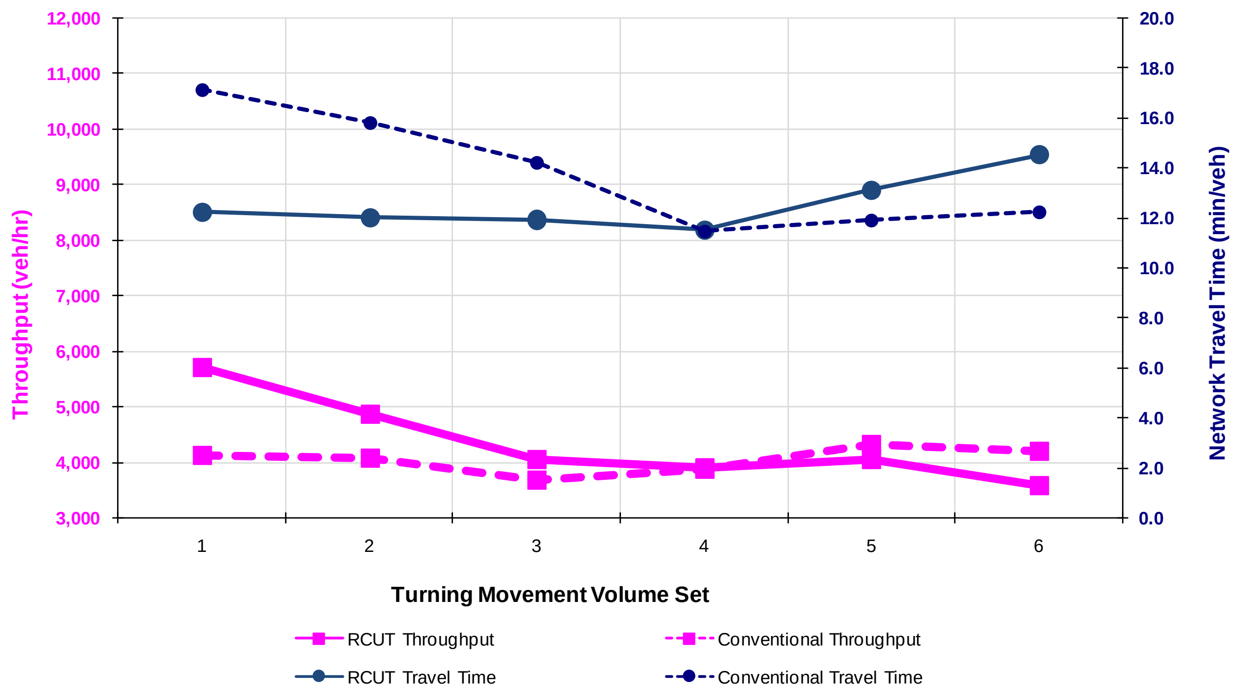


Figure 115. Graph. Throughput and travel time comparisons for geometric design case 1.

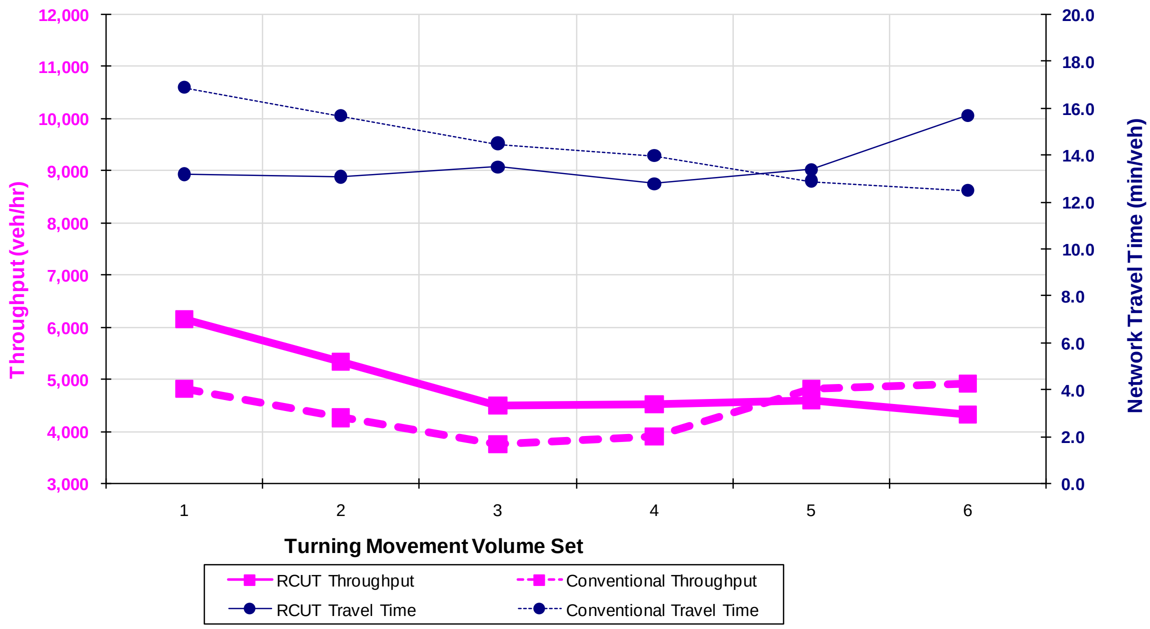


Figure 116. Graph. Throughput and travel time comparisons for geometric design case 2.

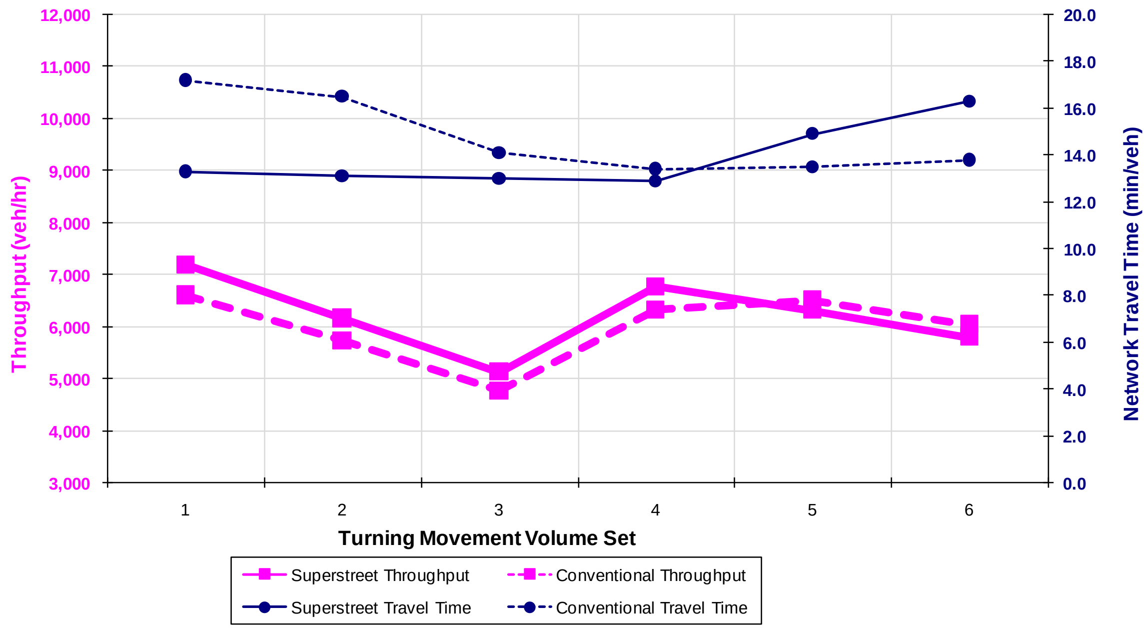


Figure 117. Graph. Throughput and travel time comparisons for geometric design case 3.

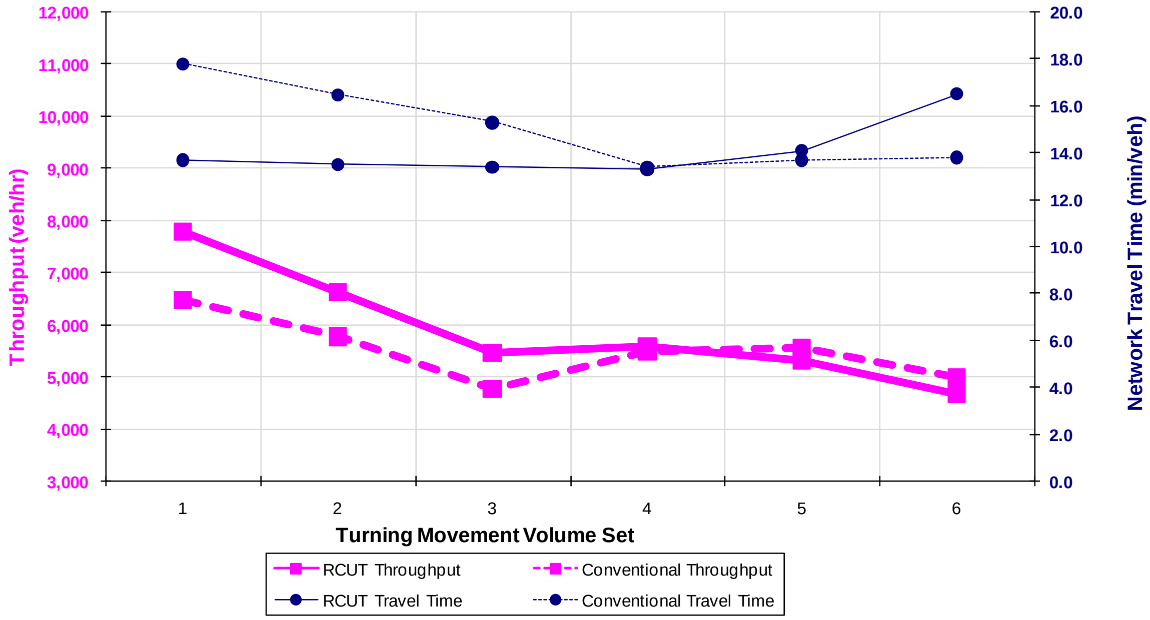


Figure 118. Graph. Throughput and travel time comparisons for geometric design case 4.

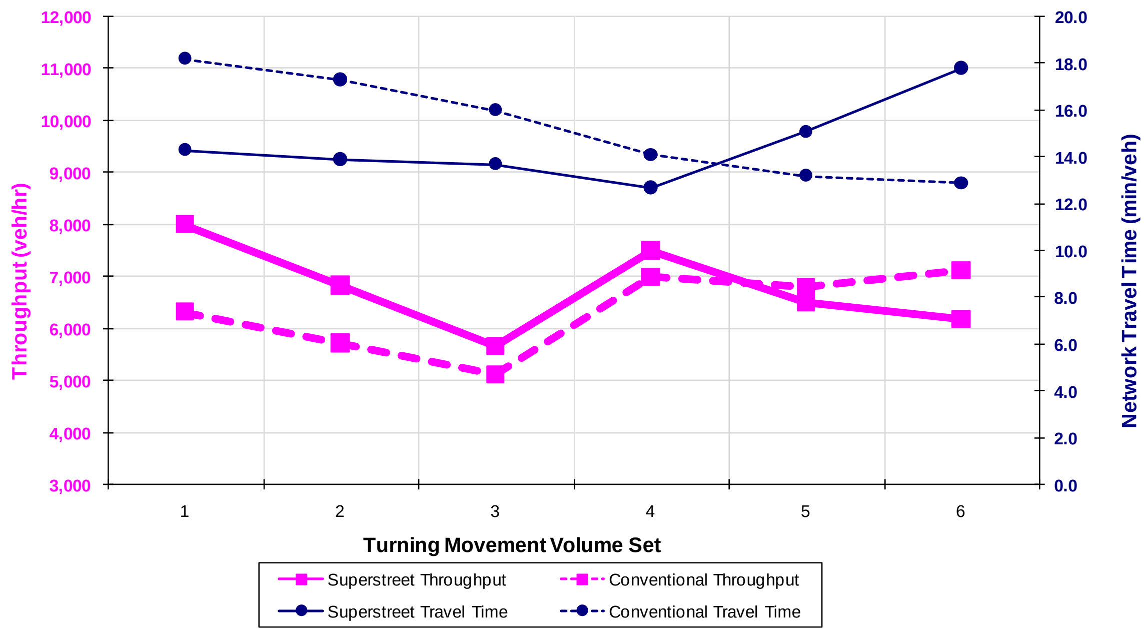


Figure 119. Graph. Throughput and travel time comparisons for geometric design case 5.

VISSIM® simulations with pedestrian presence on all legs during every signal cycle were modeled to quantify the impacts of heavy pedestrian presence at the modeled intersections. The presence of pedestrians caused no major changes in operational performance for the high-volume scenarios for RCUT and conventional intersections because the phases were long enough to accommodate the pedestrian phases. However, in the medium-volume scenarios, the presence of pedestrians resulted in an additional average intersection delay of 7 and 12 percent for RCUT and conventional intersections, respectively. In the low-volume scenarios, the presence of pedestrians caused an additional average intersection delay of 10 and 15 percent for RCUT and conventional intersections, respectively. From the simulation results, the RCUT intersections accommodated pedestrians better in the low- and medium-volume scenarios because of having just two signal phases per cycle, compared to a conventional intersection that may have three or more signal phases per cycle.

In conclusion, RCUT intersections were expected to operate better than conventional intersections in cases where the major road left turns were high, and the average major road left-turn volume per lane was close to 80 percent or more of the average minor road traffic volume per lane. The RCUT intersections typically had higher throughputs than conventional intersections when the MRTV/TIV ratio was lower than 0.25.

4.7 SAFETY PERFORMANCE

A number of documented safety studies suggest that RCUT intersections offer significant safety advantages over conventional arterials for specific situations. In addition, research in North Carolina found very few collisions caused by U-turns on main streets with medians.[62] The best evidence was from Michigan, where studies have shown lower collision rates on Michigan's signalized arterials for MUT intersections, which are similar to the U-turn treatment at RCUT intersections, as compared to conventional designs. Figure 120 shows the conflict points at a RCUT intersection.

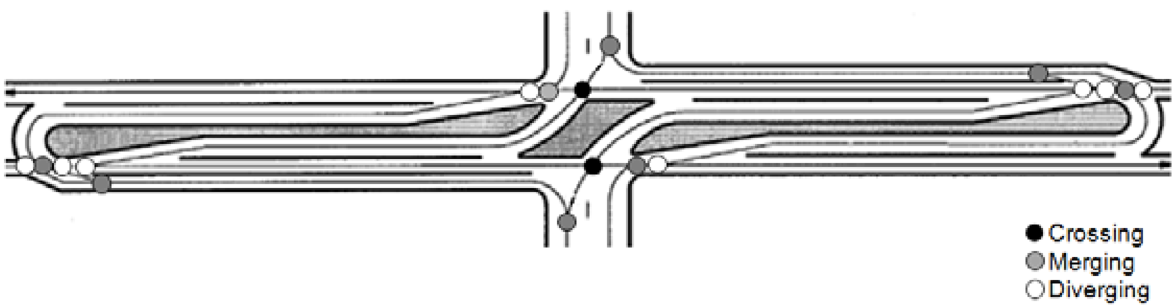


Figure 120. Illustration. Conflict diagram for RCUT intersection.

Safety data were obtained for the unsignalized U.S. Route 23/74 site in North Carolina, which was opened in 2000, but the other two North Carolina sites were too new for crash data to be available for this report.[63] Table 15 summarizes the results of an NCDOT before and after study of crash rates in the U.S. Route 23/74 corridor.[63] While the property damage only collision-reporting threshold increased during the study period, it appears that the RCUT intersection installation has likely not been harmful and has probably even been helpful.

Annual collision frequency has been consistent since the RCUT intersection completion in 2001. Table 15 shows that left-turn and angle collision frequencies, which are the crash types most susceptible to correction with a RCUT intersection, have been lower since installation. Fatal collision frequency has also been consistent across those years since 2001, and injury collision frequency has been somewhat lower. There has been a reduction in crash averages and average rates in the after period. The frequency of other collisions has risen since RCUT intersection installation, while the annual frequencies of rear-end, run-off-road, and right-turn collisions have generally remained unchanged since construction of the RCUT intersection.

Table 15. Annual average collision rates before and after 6 years at the unsignalized RCUT intersection of U.S. Route 23/74 in North Carolina.

Year	Number of Reported Collisions: By Severity: Total	Number of Reported Collisions: By Severity: Fatal + Injury	Number of Reported Collisions: By Type: Left Turn	Number of Reported Collisions: By Type: Angle	Number of Reported Collisions: By Type: Other	All Reported Crash Rate (Per Million Entering Vehicles on Major Road)	Fatal + Injury Crash Rate (Per Million Entering Vehicles on Major Road)
Annual average before (1994–1999)	16.0	10.7	4.5	3.5	8.0	1.22	0.82
Annual average after (2001–2006)	13.3	6.3	2.0	0.5	10.8	0.84	0.40
Difference after-before (percent difference)	-2.7 (-16.8%)	-4.4 (-41.1%)	-2.5 (-62.5%)	-3.0 (-85.7%)	+2.8 (+35%)	-3.8 (-31.1%)	-0.42 (-51.2%)

Three intersections on the U.S. Route 17 corridor were converted to RCUT as shown in figure 121. Each of the intersections (B, D, and F) is operated under signal control. The crossover junctions are designated by circle A, C, E, and G. Since these intersections were built as part of the redevelopment along the area, the traffic patterns changed significantly in the after conditions. Hence, a before versus after crash comparison was not conducted for these intersections. The comparison of the after crash performance at the three intersections to intersections with comparable average daily traffic in Charlotte, NC, and intersection crash performance predictions based on the AASHTO's *Highway Safety Manual (HSM)* equations (to be published later in 2010) are shown in table 16.

Figure 121. Photo. RCUT treatment at three intersections on U.S. Route 17 in Leland, NC.

Table 16. Annual average collision rates comparison based on *HSM*.

Year	All Reported Crash Rate (Per Million Entering Vehicles on Major Road)	Fatal + Injury Crash Rate (Per Million Entering Vehicles on Major Road)
Annual average after (2006–2008) for Olde Waterford	0.69	0.28
Annual average after (2006–2008) for Grandiflora	0.91	0.38
Average annual after (2006–2008) for Gregory	0.45	0.28
10-year average for 25 similar intersections in Charlotte	1.28	N/A
Crash rates from *HSM* model for intersections with similar ADTs	1.13	0.37

N/A = Not applicable.
Note: *HSM* will be published later in 2010 and will be available online: http://www.highwaysafetymanual.org.

Table 16 compares the after collision rates of the three RCUT intersection treatments on U.S. Route 17 with average collision rates obtained from 25 intersections having similar ADTs in the Charlotte area. In addition, comparison is completed with collision rates obtained from the model prescribed for four-legged signalized intersections from chapter 12 of the *HSM.* Similarly, table 17 compares the after collision frequencies of the RCUT intersections. It can be observed that the total after crash rates for all three RCUT treatments were below the crash rates predicted for a four-legged conventional intersection having similar ADTs by *HSM* and also for lower than the 10-year average crash rates obtained from 25 conventional intersections having similar ADTs in the Charlotte, NC, area. Crash rates for fatal and injury crashes for the 25 intersections in

Charlotte, NC, were not available. The crash rates for fatal and injury crashes at the intersection at Grandiflora was slightly higher than what was predicted for a conventional intersection by the *HSM.* A similar trend was observed in the collision frequencies shown in table 16.

Table 17. Annual average collision frequency comparison based on *HSM*.

Year	Frequency of All Reported Crashes	Frequency of Fatal + Injury Crashes
Annual average after (2006–2008) for Olde Waterford	10.67	3.33
Annual average after (2006–2008) for Grandiflora	8.67	3.00
Average annual after (2006–2008) for Gregory	6.00	3.67
Average for 25 similar intersections in Charlotte	12.56	N/A
Crash rates from *HSM* model for intersections with similar ADTs	11.71	3.84

N/A = Not applicable.
Note: *HSM* will be published later in 2010 and will be available online: http://www.highwaysafetymanual.org.

As of 2007, there were four RCUT intersections on U.S. Route 301. All four are at unsignalized intersections on rural sections of U.S. Route 301 on the Eastern Shore. U.S. Route 301 is a four-lane divided highway with a posted speed limit of 55 mi/h and partial access control that serves as an important through route between the Baltimore, MD, and Washington, DC, areas and Delaware. The minor streets are undivided two-lane roads with low volumes. The MDSHA installed the RCUT intersections as safety countermeasures where intersection-related collisions were occurring. Consequently, regression to the mean is a possible bias to the results shown below since the crashes may have been reduced in subsequent years even without treatment. Two of those RCUT intersections have been in place long enough for collision data to show trends related to the installation of the intersection designs.

Table 18 shows the relevant collision data for the intersection of U.S. Route 301 and MD 313 near Galena in Kent County, which was installed in 2001. The table summarizes the annual average crashes separated by severity and type and the total crashes, both in the before and after periods. The reduction in collisions was dramatic from an average of eight collisions per year from 1997 to 2000 to only two collisions from 2004 to 2006. There were 22 injury collisions from 1997 to 2000, while there were none from 2004 to 2006. There were 22 angle collisions from 1997 to 2000, whereas there have been none from 2004 to 2006. Other collision types from 1997 to 2000 included six opposite-direction collisions, two fixed-object collisions, and three other collisions. The two collisions in 2004 were a rear-end collision and another collision.

Table 18 includes only collisions reported to be within 250 ft of the main intersection. There were no reported collisions at the U-turn crossovers during the after period. The available data translates into a 90 percent reduction in total collisions and the total crash rate at the main intersection.

Table 18. Annual average collision rates before 4 years and after 5 years at unsignalized RCUT intersections on U.S. Route 301 and MD 313 in Maryland.

Year	Number of Reported Collisions: By Severity: Total	Number of Reported Collisions: By Severity: Fatal + Injury	Number of Reported Collisions: By Type: Angle	Number of Reported Collisions: By Type: Other	All Reported Crash Rate (Per Million Entering Vehicles on Major Road)	Fatal + Injury Crash Rate (Per Million Entering Vehicles on Major Road)
Annual average before (1997–2000)	8.3	5.8	5.5	2.8	2.18	1.51
Annual average after (2002–2006)	0.8	0.0	0.0	0.4	0.20	0.00
Difference after-before (percent difference)	-7.5 (-90.4%)	-5.8 (-100%)	-5.5 (-100%)	-2.4 (-85.7%)	-1.98 (-90.8%)	-1.51 (-100%)

Table 19 shows the relevant collision data for the intersection of U.S. Route 301 and MD 456 near Queenstown in Queen Anne's County, which was installed in 2005. The table summarizes the annual average crashes separated by severity and type and the total crashes, both in the before and after periods.

Table 19. Annual averages collision rates before 8 years and after 1 year at the unsignalized intersection of U.S. Route 301 and MD 456 in Maryland.

Year	Number of Reported Collisions: By Severity: Total	Number of Reported Collisions: By Severity: Fatal + Injury	Number of Reported Collisions: By Type: Angle	Number of Reported Collisions: By Type: Other	All Reported Crash Rate (Per Million Entering Vehicles on Major Road)	Fatal + Injury Crash Rate (Per Million Entering Vehicles on Major Road)
Annual average before (1997–2004)	4.0	1.5	2.9	1.1	0.52	0.32
Annual average after (2006)	0.0	0.0	0.0	0.0	0.00	0.00
Difference after-before (percent difference)	-4.0 (-100%)	-1.5 (-100%)	-2.9 (-100%)	-1.1 (-100%)	-0.52 (-100%)	-0.32 (-100%)

The reduction in collisions was also significant at this intersection, from an average of four collisions per year from 1997 to 2004 to only one collision from 2005 to 2006. There were 19 injury collisions from 1997 to 2004, while there were none from 2005 to 2006. During 1997 to 2004, there were 23 angle collisions, whereas there was 1 from 2005 to 2006. Other collision types from 1997 to 2004 included two opposite-direction collisions, four rear-end collisions, one fixed-object collision, and two other collisions.

Although sufficient after data were not available to perform an appropriate evaluation, the reduction in crash experience for the first year post-construction at MD 313 indicates an improvement in safety. With no reported collisions at the U-turn crossovers and the main intersection, there has been a reduction in crash averages and average rates in the after period.

4.8 CONSTRUCTION COSTS

Based on cost data available at the time of this report, construction costs for RCUT intersections are likely to be higher than the costs for comparable conventional intersections. To construct a RCUT intersection on U.S. Route 15/501 in Chapel Hill, NC, the total bid price was just under $5 million for a project that was 0.392 mi long. The project involved widening an existing four-lane divided highway on the outside to six lanes, adding U-turn crossovers in a configuration like that shown previously figure 82, adding four interconnected signal controllers, and relocating a frontage road away from the main intersection. The work was to be done in the midst of high-traffic loads, and some work was to be performed at night. The traffic sign costs were higher than expected, partially as a result of the design calling for two overhead sign structures totaling over $150,000 to provide guidance to motorists prior to the U-turn crossovers.

In a developing suburban area southwest of Wilmington, NC, a developer recently funded a project converting a four-lane divided arterial with several unsignalized two-way crossings into a super street corridor with RCUT intersections. The project was about 0.6 mi long and included three signalized RCUT intersections with left-turn and U-turn crossovers. The construction costs were about $2 million in 2006. While a comparable conventional intersection was not designed, engineers familiar with the site estimated that the RCUT intersection cost was about double what it would have cost to construct three conventional intersections. Even more than in the U.S. Route 15/501 case described previously, higher costs for traffic signal control were thought to be much of the reason for the higher cost in this case.

In a mostly flat, rural area near the Atlantic Ocean between Wilmington and the South Carolina border, NCDOT studied improvement alternatives for a 48-mi-long stretch of U.S. Route 17.[64] This corridor is primarily a four-lane divided arterial and includes about 50 intersections with public roads. The corridor includes the U.S. Route 17 RCUT intersection that was constructed as described previously. Substantial population and traffic growth is expected along the corridor by planning year 2030. The study examined the feasibility of three major alternatives, including the following:

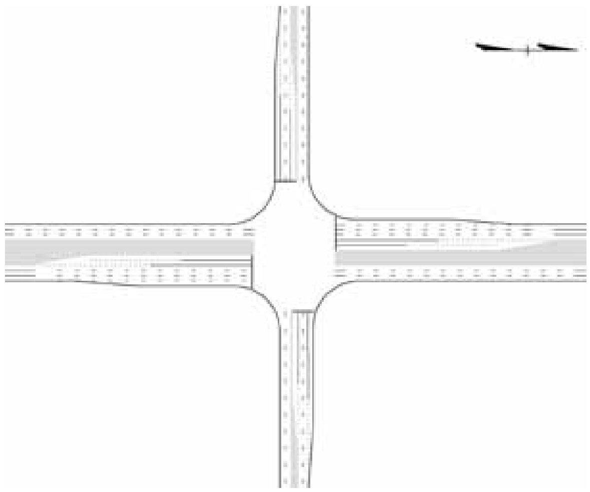
- Conventional intersection improvements using additional lanes, signals, and signal phases.
- A super street corridor with RCUT intersections.
- Conversion of the arterial into a freeway with 17 interchanges.

Conceptual designs were completed that would bring the 2030 intersection levels of service along the entire corridor to a LOS D or better, and costs were estimated for those designs using 2005 NCDOT average unit costs. The study estimated that the conventional alternative cost at $75 million, the conversion to a super street corridor with RCUT intersections cost at a projected $100 million, and the freeway alternative cost at $254 million.

The final case for which data were available in North Carolina was U.S. Route 1 in Lee and Moore Counties, a rural area in the rolling terrain of the central part of the State. The U.S. Route 1 RCUT intersection corridor included five sets of unsignalized left turn and U-turn crossovers spread over a 12-mi length of four-lane arterial. The construction on new alignment was completed early in 2006. NCDOT was late in the construction phase of a conventional arterial before converting the intersections into RCUT intersections. The reasons for the conversion were to enhance safety and to preserve mobility without signals in the corridor. NCDOT had already been receiving requests to install signals at some of the intersections.

On the Eastern Shore of Maryland, the intersection of U.S. Route 301 and MD 313 in Kent County was retrofitted to a RCUT intersection treatment, alternatively referred to as the J-turn treatment in Maryland. The predominant reason was to reduce crashes resulting from a lack of acceptable gaps in the main street that allowed vehicles to safety turn to and from the side street approaches. The total intersection improvements were completed in November 2005 at an approximate cost of $618,000.[65] Costs for modifying the intersection while keeping a conventional design were not discussed in the study.

The ideal comparison of costs and benefits would consist of final construction plans for conventional intersection improvements, RCUT intersection, and grade-separated interchanges combined with an evaluation of operational capacity and safety record. The ability to construct the improvements with the least impact on traffic would also be an important consideration in the decisionmaking process. Lacking detailed construction plans, a basic cost comparison of conventional and RCUT intersections was provided for discussion purposes. For cost-comparison, four kinds of conventional intersections were assumed as alternatives to the RCUT intersection treatment. The first was a conventional intersection with wide median and side streets having two through lanes. The second was with wide median and side streets having one through lane. The third was with a narrow median and side streets with two through lanes. The fourth was with a narrow median and side streets having one through lane. These are shown in figure 122.



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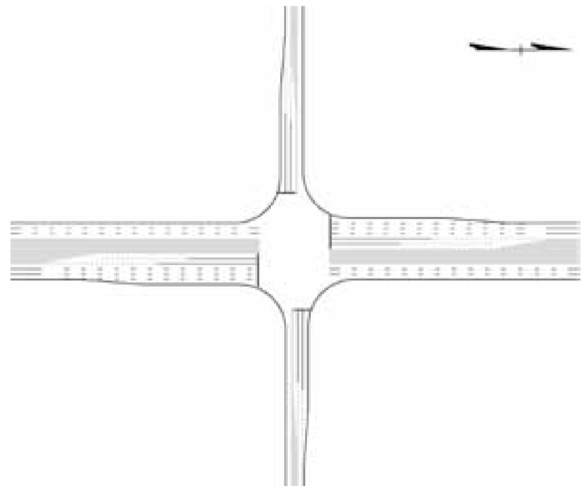

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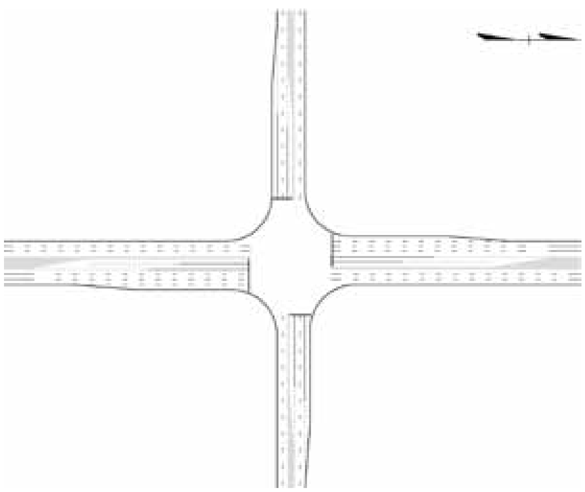

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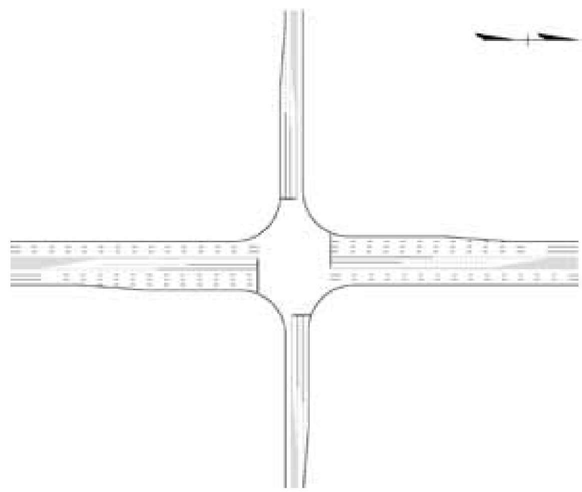

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Figure 122. Illustration. Alternatives of conventional intersections used for cost comparison.

Table 20 and table 21 provide a cost comparison of various conventional and RCUT intersection costs. For this comparison, certain assumptions were made to simplify the process. First, it was assumed that the mobilization, overhead lighting, pavement markings, and drainage costs were not significantly different between the two types of intersections. Next, relocating utilities could affect costs but were not considered in this analysis. Likewise, it was assumed that no special grading or construction features such as retaining walls were required. The cost comparison showed that the best scenario for the implementation of a RCUT intersection was when there were existing wide medians contained within a wider right of way. Unit cost prices were obtained from the *RS Means Heavy Construction Cost Book.*[25]

As shown in table 20, the cost to construct a conventional intersection with wide medians is closer to the cost to construct a RCUT intersection treatment. Table 21 shows similar construction cost estimates for RCUT intersections with mainline left-turn lanes and U-turn crossover back to back as shown previously in figure 91.

Footprint comparisons provided in figure 123 suggest that the RCUT intersection requires additional right-of-way to varying degrees. The cost of right-of-way may vary substantially from $10 to $100 per square foot and may be a major determinant. Average land prices in Virginia are $10 per square foot in the rural areas and $85 per square foot in urban areas. With such wide variation, the cost estimates do not include right-of-way acquisition.

Four signal mast arms are needed at the main intersections of RCUT intersections, similar to conventional intersections. Additionally, dual mast arms are provided at each crossover. Consequently, for the cost calculation, the RCUT intersection signal equipment is estimated to cost twice as much.

To this point, construction costs are generally higher for a RCUT intersection than a comparable conventional intersection. The differences in cost are likely to decrease over time for several reasons. First, agencies and designers can take advantage of lessons learned from earlier installations to further optimize benefits and costs. Second, agencies can learn to reduce the cost of signals, perhaps using the one controller plans, which were discussed in section 4.4. Using two controllers at an intersection seem to promise cost savings over four controllers without compromising progression capabilities. Finally, cost savings in signing are possible as drivers learn how RCUT intersections operate and therefore need less guidance.

Table 20. New intersection construction cost estimates for signalized RCUT intersection.

#	Item	Unit	Unit Cost ($)	RCUT Intersection (as shown in figure 82)		Wide Median and 2 Thru Lanes Side St.		Wide Median and 1 Thru Lane Side St.		Narrow Median and 2 Thru Lanes Side St.		Narrow Median and 1 Thru Lane Side St.	
				Quant-ity	Total Cost ($)	Quant-ity	Total Cost ($)	Quant-ity	Total Cost ($)	Quant-ity	Total Cost ($)	Quant-ity	Total Cost ($)
1	Mobilization (assumed to be the same for all)	LS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	Earthwork · Site prep, excavation, etc.	CY	12.47	20,200	252,000	17,800	222,000	16,270	203,000	17,600	219,000	14,140	176,000
3	Pavement · Surface (2 inches)	SY	6.93	29,000	201,000	32,650	226,000	29,260	203,000	27,860	193,000	24,550	170,000
	· Base (6 inches)	SY	15.50	29,000	450,000	32,650	506,000	29,260	454,000	27,860	432,000	24,550	381,000
	· Sub-base (8 inches)	SY	10.80	29,000	313,000	32,650	353,000	29,260	316,000	27,860	301,000	24,550	265,000
4	Curb and gutter	LF	11.10	10,400	115,000	9,450	105,000	9,400	104,000	9,260	103,000	9,210	102,000
5	Concrete islands/ raised medians (8-inch cement concrete pavement)	SF	37.50	6,800	255,000	1,600	60,000	1,600	60,000	4,760	179,000	4,760	179,000
6	Drainage (assumed to be the same for all)		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

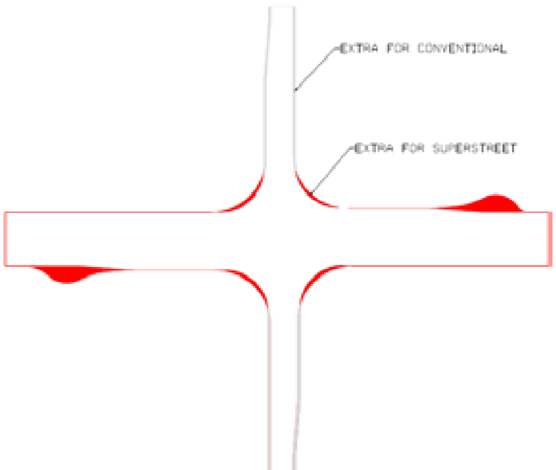
N/A = Not applicable.

Table 21. New construction cost estimates for signalized RCUT intersection with back-to-back left-turn and crossover.

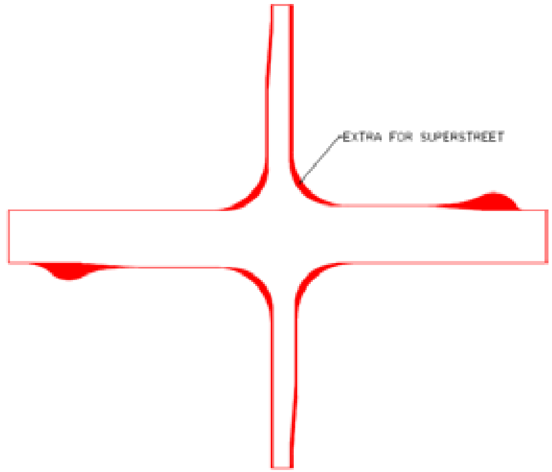
#	Item	Unit	Unit Cost ($)	RCUT Back-to-Back Crossover/ Dual LT (See figure 91)		Conventional Equiv. for Back-to-Back Super street with Dual Mainline Left-Turn		RCUT Back-to-Back X-over with Single Mainline Left-Turn		Conventional Equiv. for Back-to-Back Super street with Single Mainline Left-Turn	
				Quantity	Total Cost ($)	Quantity	Total Cost ($)	Quantity	Total Cost ($)	Quantity	Total Cost ($)
1	Mobilization (assumed to be the same for all)	LS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	Earthwork · Site prep, excavation, etc.	CY	12.47	23,940	299,000	20,080	250,000	22,580	282,000	18,800	234,000
3	Pavement · Surface (2 inches)	SY	6.93	35,200	244,000	27,200	188,000	32,800	227,000	25,800	179,000
	· Base (6 inches)	SY	15.50	35,200	546,000	27,200	422,000	32,800	508,000	25,800	400,000
	· Sub-base (8 inches)	SY	10.80	35,200	380,000	27,200	294,000	32,800	354,000	25,800	279,000
4	Curb and gutter	LF	11.10	12,230	136,000	11,700	130,000	9,165	102,000	11,650	129,000
5	Concrete islands/ raised medians (8-inch cement concrete pavement)	SF	37.50	6,400	240,000	4,750	178,000	5,500	206,000	4,750	178,000
6	Drainage (assumed to be the same for all)		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

7	Traffic control devices · New signal is assumed to be $200,000. Equip. required for a super street is double conventional	EA	200,000	2	400,000	1	200,000	2	400,000	1	200,000
8	Utilities (assumed to be the same for all)		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
9	ADA requirements										
	· Ramps: 5 inches wide	LF	450	75	34,000	40	18,000	75	34,000	40	18,000
	· Concrete sidewalk	LF	14.42	6,155	89,000	6,060	87,000	6,150	89,000	6,050	87,000
10	Pavement markings (assumed to be the same for all)		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total					**2,368,000**		**1,767,000**		**2,202,000**		**1,704,000**

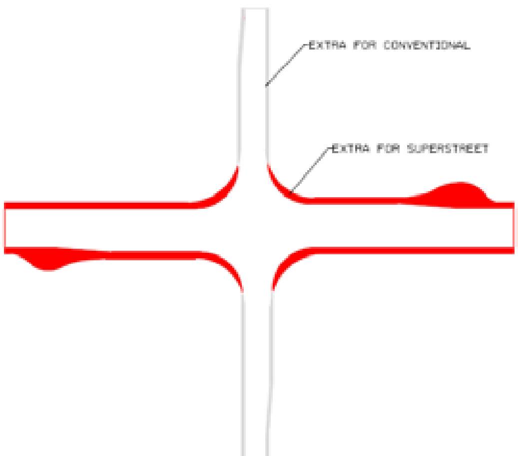
N/A = Not applicable.



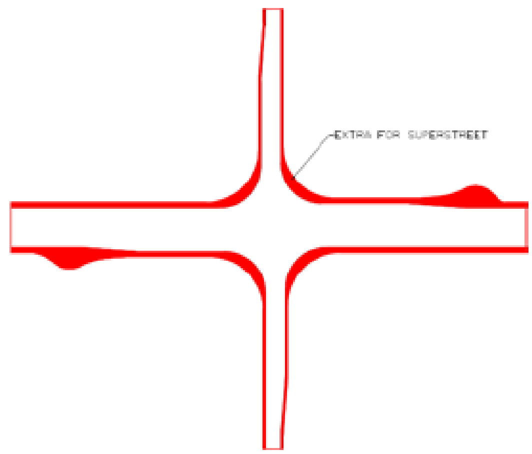
a. Footprint comparison of a RCUT versus conventional intersection with wide median and dual through side street.



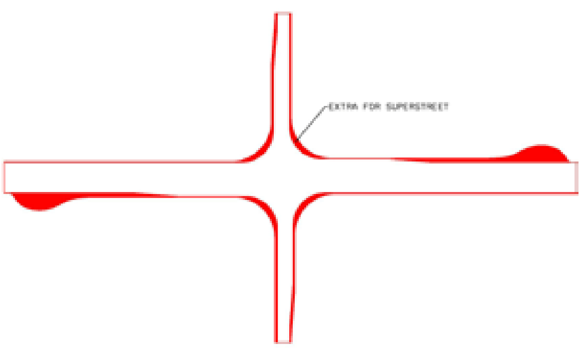
b. Footprint comparison of a RCUT versus conventional intersection with wide median and single through side street.



c. Footprint comparison of a RCUT versus a conventional intersection with narrow median and two through lanes for side street.



d. Footprint comparison of a RCUT versus conventional intersection with narrow median and single through side street.



e. Footprint comparison of a RCUT with back to back mainline left-turn and crossover versus conventional intersection.

Figure 123. Illustration. Footprint comparisons of a RCUT versus conventional intersection.

4.9 CONSTRUCTION SEQUENCING

One of the perceived challenges is retrofitting an existing at-grade conventional intersection into a RCUT intersection while maintaining traffic flow. This section presents ideas on how construction sequencing can be handled.

Maintenance of traffic during construction of a RCUT intersection is typically an issue during two types of projects. The first type is when agencies are widening a two-lane road. The major stages of construction and traffic shifts are described as follows for a project to construct an east-west arterial with an intersection:

1. Build the lanes that carry one direction of travel on the arterial on new alignment. This is illustrated in stage 1 of figure 124 with the new lanes being built for the eastbound directional travel.

2. Shift the existing two lanes of traffic flow to those new lanes when they are ready to handle traffic. The intersection is shifted as well and continues to operate conventionally. This is illustrated in stage 2 of figure 124.

3. Begin building the lanes that serve the oppositve direction of the arterial, the U-turn crossovers, and the portions of the left-turn crossovers that do not overlap the existing minor street. This step is also illustrated in stage 2 of figure 124.

4. Shift westbound traffic onto those lanes serving the opposite direction of travel and the U-turn crossovers, allow eastbound traffic to use all of their lanes, shift all minor street through traffic and turning traffic to the U-turn crossovers, and close the existing intersection to through movements from the side street when the lanes are complete.

5. Finish the left-turn crossovers with the center of the intersection vacated, as illustrated in stage 3 of figure 124.

6. Shift traffic to the permanent RCUT intersection configuration, following completion of the left-turn crossovers as illustrated in the ultimate configuration as shown in the bottom graphic of figure 124.

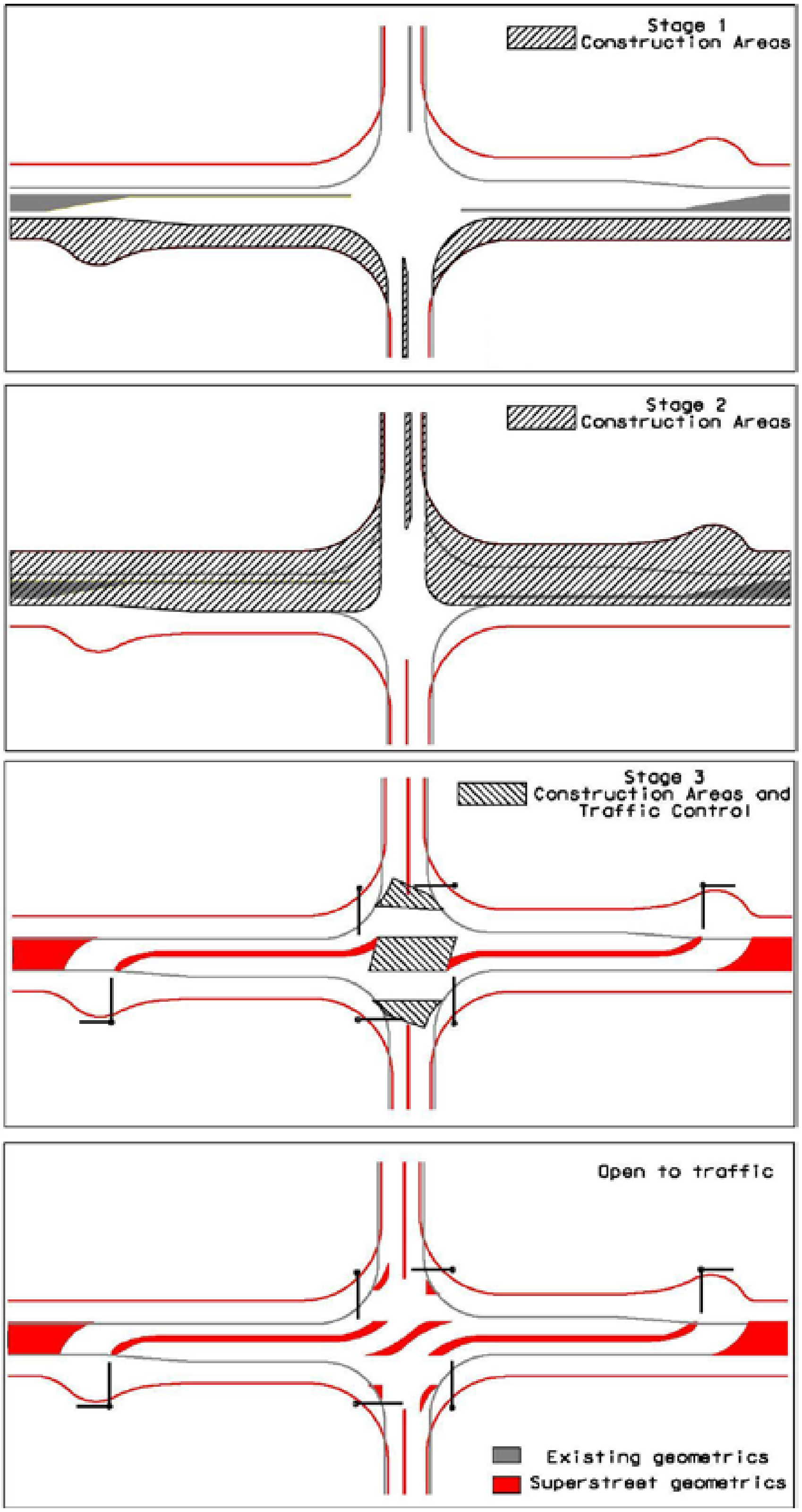


Figure 124. Illustration. Construction staging for converting two-lane road to multilane RCUT intersection.

The second type of project where maintenance of traffic typically is an issue is converting an existing conventional intersection to a RCUT intersection. This can be accomplished with two traffic shifts. The steps are as follows (see figure 125):

1. Begin constructing the U-turn crossovers and the portions of the left-turn crossovers that do not overlap the existing minor street.

2. Shift all minor street through traffic and turning traffic to the U-turn crossovers and close the conventional intersection when the U-turn crossovers are completed.

3. Complete construction of the left-turn crossovers with the center of the intersection vacated.

4. Shift traffic to the permanent RCUT intersection configuration following completion of the left-turn crossovers.

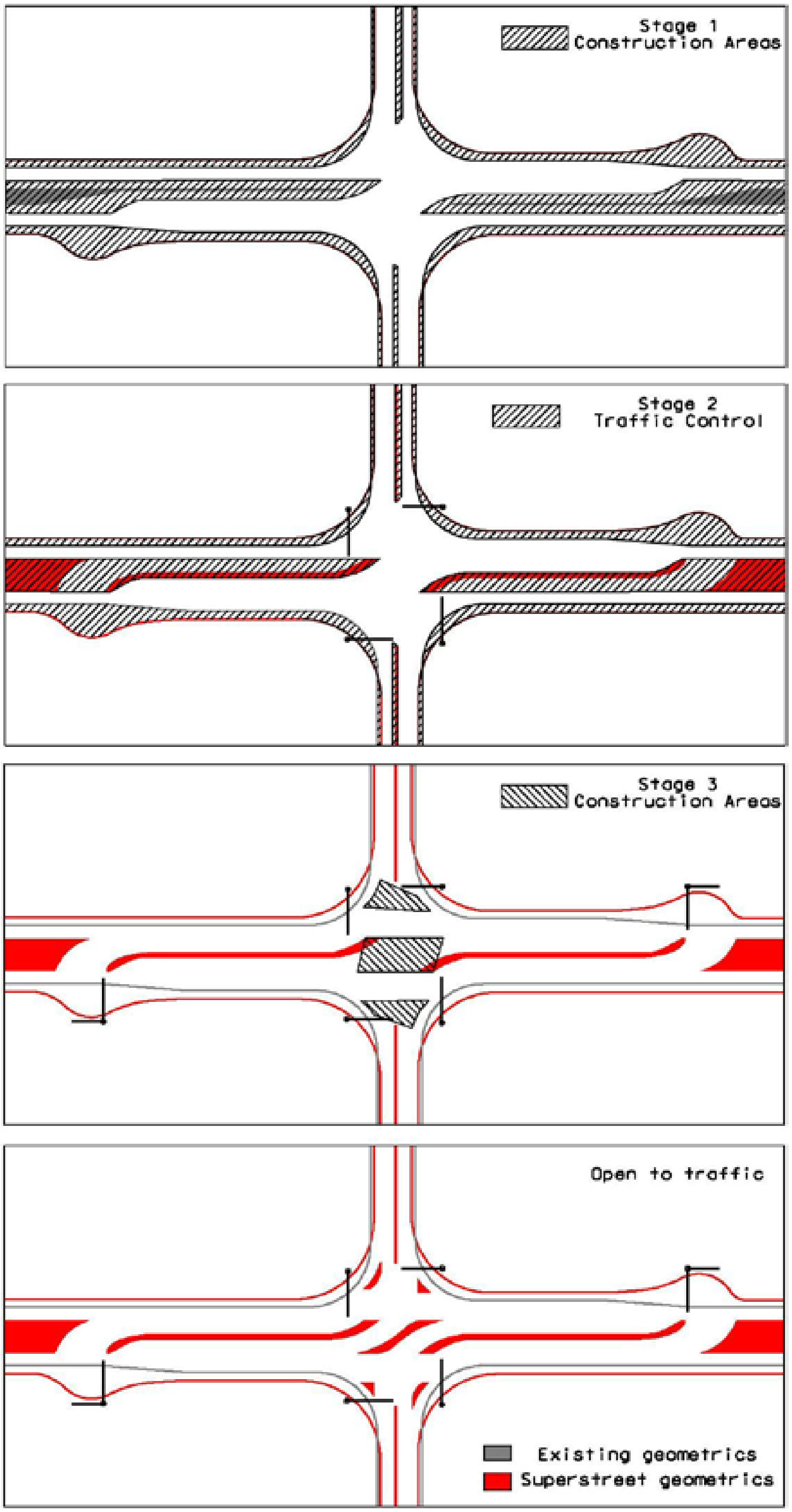


Figure 125. Illustration. Construction staging for converting a conventional intersection to a RCUT intersection.

4.10 OTHER CONSIDERATIONS

Agencies contemplating RCUT intersection installation should consider additional factors to those discussed in previous sections. These factors include maintenance costs, enforcement needs, left turn on red policies, and emergency vehicle needs.

Enforcement needs at RCUT intersections may be higher in the short term but lower in the long term. The custom in Michigan upon opening a new MUT intersection is to allocate extra enforcement resources during the first few weeks of operation. Such an enforcement program is desirable for RCUT intersections. A few wrong-way movements through crossovers and running red light events at crossovers were observed on the new RCUT installations in North Carolina. Enforcement during the periods after the RCUT intersections are initially opened to traffic help drivers become familiar and help reduce unintentional illegal maneuvers. After volumes build and habits form, the need for extra enforcement is likely to subside, and normal vigilance in enforcing traffic laws at RCUT intersections should suffice. In the long term, the ability of a RCUT intersection to allow a wide range of progression speeds and large progression bands may mean that speed is more self-enforcing on super street corridors than on conventional arterials. On a super street corridor of any length, with the good progression that designers expect, drivers quickly realize that it is in their best interest to cruise along with the platoon at the progression speed. As long as drivers comply with traffic signals in these conditions, speed limit compliance should be high. This may allow reallocation of enforcement resources from speed enforcement at RCUT intersections to other duties.

As discussed in chapter 3, motorists using U-turn crossovers on many MUT facilities in Michigan reduce their delays by making legal left turns on red. Motorists on RCUT intersections could also reduce their delays this way. Agencies and policymakers should consider the potential benefits and costs of allowing left turns on red at some portion of the U-turn crossovers at their RCUT intersections and make an appropriate decision for their locations. A flashing red arrow signal, currently in experimental status, could be used to inform drivers that left turns on red are permitted after they come to a stop. This signal is being considered for inclusion in the next edition of the *MUTCD*.[8]

As chapter 3 also described, something to consider is allowing crossovers where U-turns exist at the same time as right turns from a side street or driveway and the potential for conflict exists. Prohibiting driveways or side streets at crossover locations is one feasible option. Separate signal phases for the U-turn and the right-turn movements are another option, but that would likely add delay. To manage the conflicts, some agencies use signs (R10-16 in the *MUTCD*) to direct the U-turn movement to yield to the right-turn movement.[8] Some agencies also use a sign with a legend that reads "Right Turn on Red Must Yield to U-turn" if their laws assign the right-of-way preference to the U-turn movement in this situation.

Emergency vehicles may be affected by implementation of RCUT intersections. Emergency vehicles moving along arterials are likely be aided by the design resulting from the higher percentage of green time for the through movement, shorter queues, and fewer conflicting traffic streams. Emergency vehicles turning left from the arterial should not be affected with a design that has left turns on the mainline (see figure 82). However, emergency vehicles turning left from the arterial need to travel longer distances and likely have longer response times with the design shown in figure 83, which does not have left turns on the mainline. Emergency vehicles responding to calls should not often have to make a through movement or left-turn movement from minor streets at RCUT intersections. Should this be necessary, the emergency vehicle is rerouted and has to travel extra distance and spend extra time. Agencies could design a set of left-turn crossovers at an intersection in a rural area with negligible pedestrian crossing demand with low mountable islands to be traversal by emergency vehicles. Recognizing this design feature could tempt drivers of SUVs, pick-up trucks, and other vehicles into executing illegal crossing maneuvers. At a location where frequent left turns or through movements by emergency vehicles from a driveway or side street are expected, a RCUT intersection would not be the most appropriate solution.

4.11 APPLICABILITY

As with all the designs described in this report, the RCUT intersection design is applicable under certain conditions but not appropriate for all conditions. A primary reason to choose the RCUT intersection instead of a conventional design is the ability to process higher volumes on the major road, especially left-turn volumes and through volumes. As mentioned earlier, the RCUT intersection is typically implemented as part of a corridor treatment. Candidate corridors for this design are high-speed divided highways with intersections that have heavy major road through and left-turn demands and low to moderate minor street left-turn and through movement demands.

Second, designers can choose the RCUT intersection as a safety measure or collision countermeasure. There are good theoretical reasons to expect intersection collisions to decrease with this intersection design (e.g., fewer vehicle conflicts, particularly of the crossing type).

Some of the situations where a RCUT intersection may be suitable follow:

- If there are heavy through volumes and left-turn volumes on major road approaches.
- If the ratio of the minor road approach volume to the total intersection approach volume is less than 0.20.
- If the mainline left-turning volume/lane is greater than 80 percent of the minor road traffic/lane that would move concurrently during the same signal phase.
- If the intersection is heavily congested with many signal phase failures for through and left-turn traffic on major road.

A RCUT intersection without loons designed to accommodate turns by large trucks typically needs 40- to 70-ft-wide medians as opposed to the 28-ft-wide minimum median width for a conventional intersection with dual left-turn lanes. This extra right-of-way is likely to be costly and may be unavailable at any reasonable price in a densely developed urban area. Loons can be used at the median crossover openings where medians widths are inadequate.

4.12 SUMMARY

A RCUT intersection is a unique intersection design. It has several advantages over a conventional intersection. Applications in Maryland and North Carolina show this design is promising for improving operations and safety in certain situations. The major advantages provided by a RCUT intersection are greater vehicle efficiency for the through movement on an arterial in a signalized corridor and reduced opportunity for crashes compared to conventional designs. A RCUT intersection provides two-phase signals, short cycles, and the chance for good progression in both directions of the arterial at any speed and signal spacing. Better service to through travelers on the major arterial is the main reason to select a RCUT intersection in an urban or suburban area. Fewer conflict points mean that many RCUT intersections are safer than their conventional counterparts.

RCUT intersections reroute minor street left-turn and through movements. If the demand for those movements is high, RCUT intersections may not be the optimum design choice. The RCUT intersection requires wider right-of-ways, either in selected locations to accommodate loons or along the corridor for wider medians. RCUT intersections have initial higher construction costs than comparable conventional intersections and may have higher maintenance costs as well. RCUT intersections also create longer crossing distances that require additional pedestrian crossing time, contributing to possible safety concerns.

CHAPTER 5. QUADRANT ROADWAY INTERSECTION

5.1 INTRODUCTION

A QR intersection is a promising design for an intersection of two busy suburban or urban roadways. The primary objective of a QR intersection is to reduce delay at a severely congested intersection and to reduce overall travel time by removing left-turn movements. A QR intersection can provide other benefits as well, such as making it shorter and quicker for most pedestrians at the intersection. A QR intersection can be among the least costly of the alternative intersections to construct and maintain.

At a QR intersection, all four left-turn movements at a conventional four-legged intersection are rerouted to use a connector roadway in one quadrant. Figure 126 shows the connector road and how all four of the left-turning movements are rerouted to use it. Left turns from all approaches are prohibited at the main intersection, which consequently allows a simple two-phase signal operation at the main intersection. Each terminus of the connector road is typically signalized. These two secondary signal-controlled intersections usually require three phases.

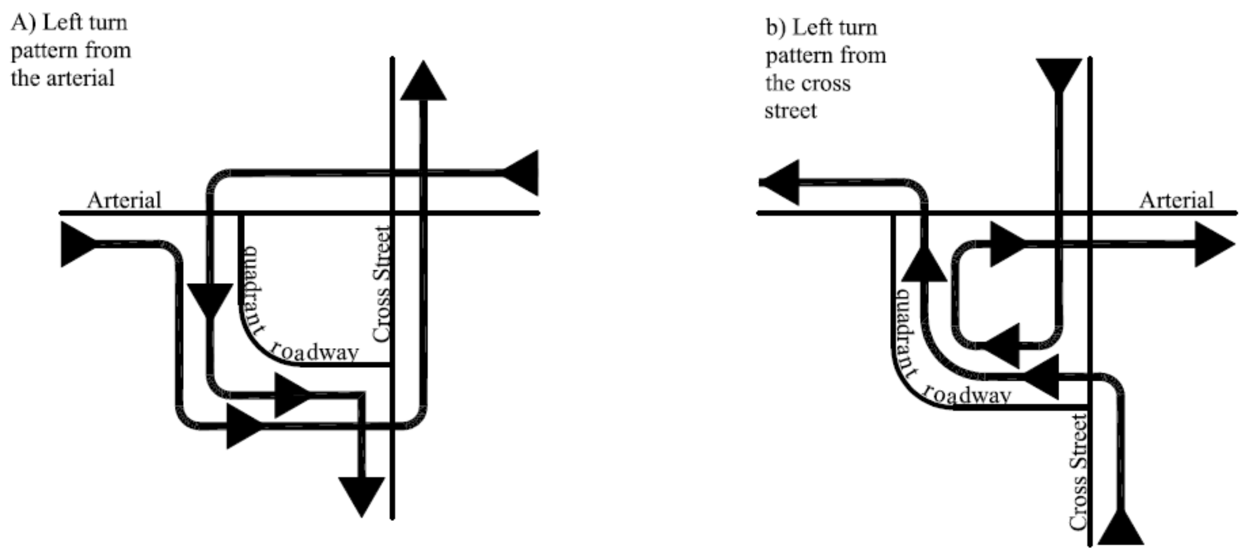


Figure 126. Illustration. Left-turn movements at a QR intersection.

Analyses have shown that a QR intersection is an efficient design at many levels of traffic demand but especially at an intersection with high through volumes and low to moderate left-turn volumes. The reason for this efficiency lies in the conversion of the signal at the main intersection from multiple to two phases. The QR intersection is also aided by the easy coordination that is possible between the main signal-controlled and the secondary signal-controlled intersections. Similar to other alternative designs covered in this report, most through drivers on the main and side roads do not have to stop at each set of traffic signals they encounter if the signals are operated in a coordinated system.

In the United States, there have been many intersections where left turns have been prohibited and redirected on connecting roads in existing signal-controlled street networks. The signs are typically installed to direct drivers who would normally turn left at the major intersection to turn left at a secondary intersection upstream from the major intersection. This form of traffic control treatment has been implemented to reduce congestion and increase capacity at the major intersection by removing at least one left-turn movement and the associated signal phase from the congested intersection. The primary difference between this type of treatment and the QR intersection in its pure form is that all left turns are removed from the major intersection of the QR intersection.

At the time that this report was prepared, the authors were unaware of any location in the United States that fully met the definition of a QR intersection with all four left turns using the connecting road, all left turns prohibited at the main intersection, and the three signals fully coordinated. The full QR intersection concept was first published by Jonathan Reid in 2000.[(66)] He explored the concept in a subsequent paper and in his paper on unconventional intersections.[(61)] Since then, the QR intersection concept has been explored by others (such as by FHWA in 2004).[(49)]

5.2 GEOMETRIC DESIGN CONSIDERATIONS

This section discusses the geometric design of the QR intersection, specifically choosing a quadrant in which to locate the connecting roadway, determining the number of connecting roadways, and designing the main intersection, the secondary intersections, horizontal alignment, and the cross section of the connecting road.

5.2.1 Quadrant Selection

QR intersection designs with one connecting roadway in one quadrant are likely the most common application, as these perform well operationally and minimize the construction and right-of-way costs compared to designs with more than one connector roadway. For one-connector designs, a critical question is which quadrant should have the connector roadway. In some cases, there is available right-of-way in just one quadrant, which makes the decision easy. In other cases, there may be an opportunity in one quadrant with the chance to integrate the connector roadway into the development, making the decision easy as well. As part of an improvement project to realign a skewed intersection, the opportunity may exist to construct connector roads in two of the quadrants.

The most difficult cases in which to make the decision on where to locate the connector road are with 90-degree intersections and with quadrants that do not have particular cost or development advantages. In these cases, the deciding factor may be the left-turn demands. One of the left-turning maneuvers (as shown in figure 126) has to make three right turns, travel through the main intersection twice, and travel the longest distance of any maneuver at the intersection. The connector roadway could be placed in these cases such that this maneuver is made by the left turn with the lowest demand. Conversely, one of the left-turning maneuvers does not have to travel through the main intersection at all and requires no greater travel distance than at a conventional intersection. The connector roadway could be placed such that the left turn with the highest demand is the one that receives the most direct path. It is important to recognize that conceptually a QR-like intersection could be created without the construction of a new roadway connector if there were existing streets to serve the function.

5.2.2 QR Intersections with Multiple Connector Roadways

Reid's idea was for a single connecting roadway in one intersection quadrant.[66] Most of this chapter is devoted to the analysis of that idea. However, an extension to Reid's idea worth noting is an intersection with connecting roadways in two or more quadrants. This subsection briefly explores those extensions.

A design with two connecting roadways could offer advantages over the single-quadrant design. The two connecting roadways would most likely be placed on diagonal quadrants as seen in figure 127 to avoid the need for a fourth signal phase at any of the secondary signal-controlled intersections. Two connecting roadways offer the chance for every left-turn maneuver to be initiated from the left side of the street. This avoids the violation of driver expectations inherent in the single-quadrant design wherein two of the left turns are initiated from the right side of the roadway. With the two-quadrant design, two of the left turns have to travel through the main intersection before turning, which could also violate some driver expectations. Two-quadrant designs should perform better operationally than single-quadrant designs carrying the same demands, assuming that good signal progression can be arranged through all five signals. Other drawbacks of the two-quadrant designs are the potential additional right-of-way required, the additional construction costs and maintenance costs, and the additional street crossings that pedestrians have to negotiate.

As noted earlier, the selection of multiple connector designs may be facilitated by the existence of streets in the network that could serve the function. In many urban street networks, connectors may exist in two or more quadrants. In these cases, it will be necessary to determine if the connecting streets have the capacity and sufficient design standards to accommodate the rerouted traffic.

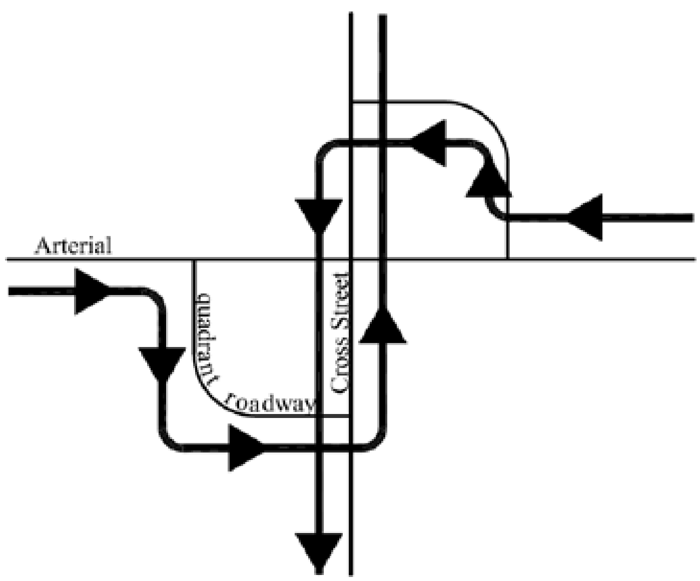


Figure 127. Illustration. Intersection with connector roadways in two quadrants.

Intersection designs with connecting roadways in three or four quadrants are also possible. The success of any three- or four-quadrant design would depend heavily upon the efficiency of the secondary signal operations. If the secondary signals require four phases or long signal phases, then the design's advantages of minimizing the time and number of phases at the main intersection would be lost. Three-quadrant and four-quadrant designs require more right-of-way and have higher construction and maintenance costs than single-quadrant designs.

5.2.3 Main Intersection

At a QR intersection, the design of the main intersection would be similar to that of a conventional intersection with turn prohibitions. Appropriate pavement markings or median designs should be employed to convey the message to drivers that no left turns or U-turns are allowed. Right-turn lane criteria are the same for a QR intersection as a conventional intersection except for the right turns in the quadrant with the connecting roadway. Right-turn demands do not change at the main intersection in the other three quadrants. Through volumes at the main intersection are higher in all four directions than at a conventional intersection because of rerouted left-turning traffic. Pedestrian crosswalks would normally be provided across all four approaches at the main intersection.

5.2.4 Secondary Intersections

The distance from the main to the secondary intersections is critical to the success of a QR intersection design. The considerations and trade-offs are similar to those between the main intersection and U-turn crossovers for an MUT intersection (chapter 3) or a RCUT intersection (chapter 4). The distance needs to be sufficient to provide adequate vehicle storage and prevent spillback from one signal-controlled intersection to the next. There also needs to be enough spacing to provide room for adequate signing and to ensure that each set of signal control is visible. Longer distances mean higher costs for right-of-way, construction, and maintenance of the connecting road. Longer distances may restrict progression from one signal to the next on the main streets. More importantly, longer distances can translate into more vehicle-hours of travel.

There are additional factors to consider when deciding on the distance from the main to the secondary intersections. One factor is the economic viability of the parcel contained within the connecting roadway. If the parcel is small, then it may be too small for many commercial uses. Another factor to consider is the design speed of the connecting road. If the size of the parcel is too small, there may not be enough area to fit a horizontal curve with an adequate radius, and transitions for the speed that motorists would likely expect to travel on the connecting roadway.

Considering all of the above, a spacing of 500 ft from the center of the main intersection to the center of the secondary intersections appears adequate as a minimum for many situations. This spacing is in line with Reid's recommendation and with the main intersection to crossover spacing recommended in chapters 3 and 4 for MUT intersections and RCUT intersections.[(66)] The chances of spillback should be minimal for that distance between signals and moderate cycle lengths. At 40 mi/h on the main street, the offset between signals spaced 500 ft apart is under 9 s, which should not adversely impact progression. With 500-ft spacing between the main and secondary intersections and 90-degree intersection angles, there is sufficient area to fit a curve radius to meet a reasonable 30 mi/h design speed on the connecting road. Assuming typical cross sections, the size of the parcel inside the connecting roadway would be about 3.5 to 4.0 acres, which is viable for a small commercial enterprise.

One critical point about the design of the secondary intersections is that the signal phase duration required by the connecting road should be minimized to allow more green time for the main street approaches. In practice, this would likely mean not allowing a fourth leg at the secondary intersections. Driveways and side streets should not be installed directly opposite the connecting roadway.

The design of the secondary intersections should include appropriate pavement markings. Median designs should be employed to convey the message to drivers that U-turns are not allowed and that left turns are not allowed for one approach. Right-turn lanes should be strongly considered, as the demands would be boosted by the presence of rerouted left-turning vehicles. Reid showed a connecting roadway with three lanes, allowing dual left-turn lanes from the connecting roadway to the main streets at both ends to help keep those phases short.[(66)] Pedestrian crosswalks would normally be provided across all three approaches at the secondary intersections.

5.2.5 Horizontal Alignment

Alignment design for the connecting roadway may present a challenge. The designer will want to provide as gentle a curve as possible, while ending the curve and its transitions before the intersections at both ends. The designer will also want to provide good opportunities for driveway connections to the parcel inside the connecting roadway.

As mentioned above, a 500-ft spacing between the main and secondary intersections is associated positively to a design speed of 30 mi/h on the connecting roadway at a 90-degree intersection. Table 22 provides the relevant geometric design data from the AASHTO *Green Book* for a design speed of 30 mi/h.[(7)] The radii and runoff lengths are minimum values, and the radius should be applied to the inside edge of the roadway as recommended by AASHTO.

Table 22. Connecting roadway geometric data for 30 mi/h design speed.

Superelevation (percent)	Radius (ft)	Runoff Length (ft)
-2	333	0
0	300	0
2	273	45
4	250	91

A 30 mi/h design speed on the connecting road should be appropriate in many circumstances. Higher design speeds may lead to more difficulties with sight distances to the intersections and the back of the queues.

5.2.6 Connecting Road Cross Section

As mentioned previously, Reid originally presented the QR intersection connecting road with a three-lane cross section.[(66)] This allowed dual left-turn lanes at each end and a two-way left-turn lane serving driveways in the middle. Three 12-ft-wide lanes with curbs, gutters, and sidewalks on both sides likely require approximately a 60-ft-wide right-of-way and leave an economically viable parcel inside the connecting roadway. This cross section allows only single left-turn lanes from each main street onto the connecting roadway. To further increase that capacity, designers could use a four-lane or five-lane cross section for the connecting roadway. Figure 128 shows a QR intersection with a four-lane connecting roadway. The right-of-way widths and costs grow proportionally for the wider connecting roadways, but the delay savings and other benefits may be worthwhile in some cases.

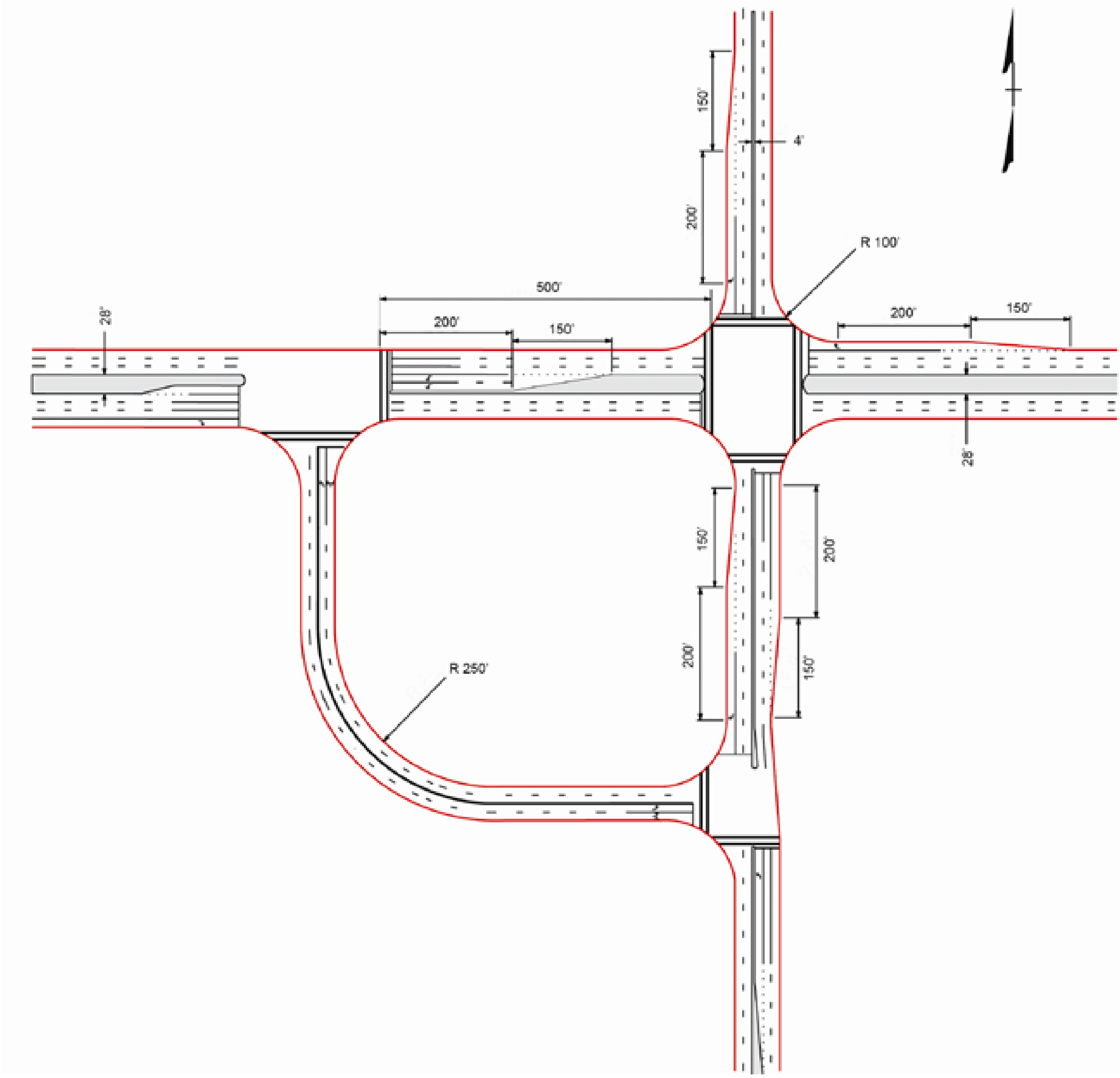


Figure 128. Illustration. QR intersection with four-lane connecting roadway.

5.3 ACCESS MANAGEMENT CONSIDERATIONS

Designers who are considering QR intersections have to be conscious of the impacts on access. As with conventional intersections, limiting access in the vicinity of the main intersection has positive benefits on capacity, quality of flow, and safety. If there are medians or raised median islands on the major road and crossroads at the major intersection, they should be retained when a QR intersection is implemented. If none exist before implementation, then they should be considered for installation as part of the design of the QR intersection.

The removal of the left-turn lanes at the major intersections allows for wider medians to be created within the immediate vicinity of the major intersection. Driveways that allow only right turns in and right turns out offer operational and safety benefits compared to full access driveways.

Access to local parcels is affected by the location and design of the connector, the spacing from the main intersection to the secondary intersections, and the size of the parcel created in the quadrant by the connector road, assuming the connector road is constructed as part of the QR intersection as opposed to utilizing existing streets. Conceivably, access to the parcel in the quadrant could be provided via driveways on the main road, the crossroad, and the connector road. All the driveways could be designed to be right in and right out. However, this may limit accessibility of the parcel from some directions. For example, consider a connector roadway in the southwest quadrant. If the connector roadway is designed with a raised median, then drivers approaching from the east will not have direct access to the site. Consequently, a break in the median on the connector road may be desirable to provide full access to parcel.

At a QR intersection, U-turns are not permitted at the main intersection. U-turn movements are possible from every direction at a QR intersection using the connecting roadway; however, the movements are not straightforward. Drivers would likely need signing or public information programs to learn the path for the U-turn. Thus, a QR intersection may be more applicable to intersections that experience low U-turning volumes.

5.4 TRAFFIC SIGNALIZATION TREATMENTS

A QR intersection has three signal-controlled intersections, including a two-phase signal-controlled main intersection and three-phase signalized intersections at the ends of the connecting road. These are shown in figure 129. While the design of the individual signals is straightforward, the main challenge in the signal design for a QR intersection is how traffic can be progressed through the signals most efficiently.

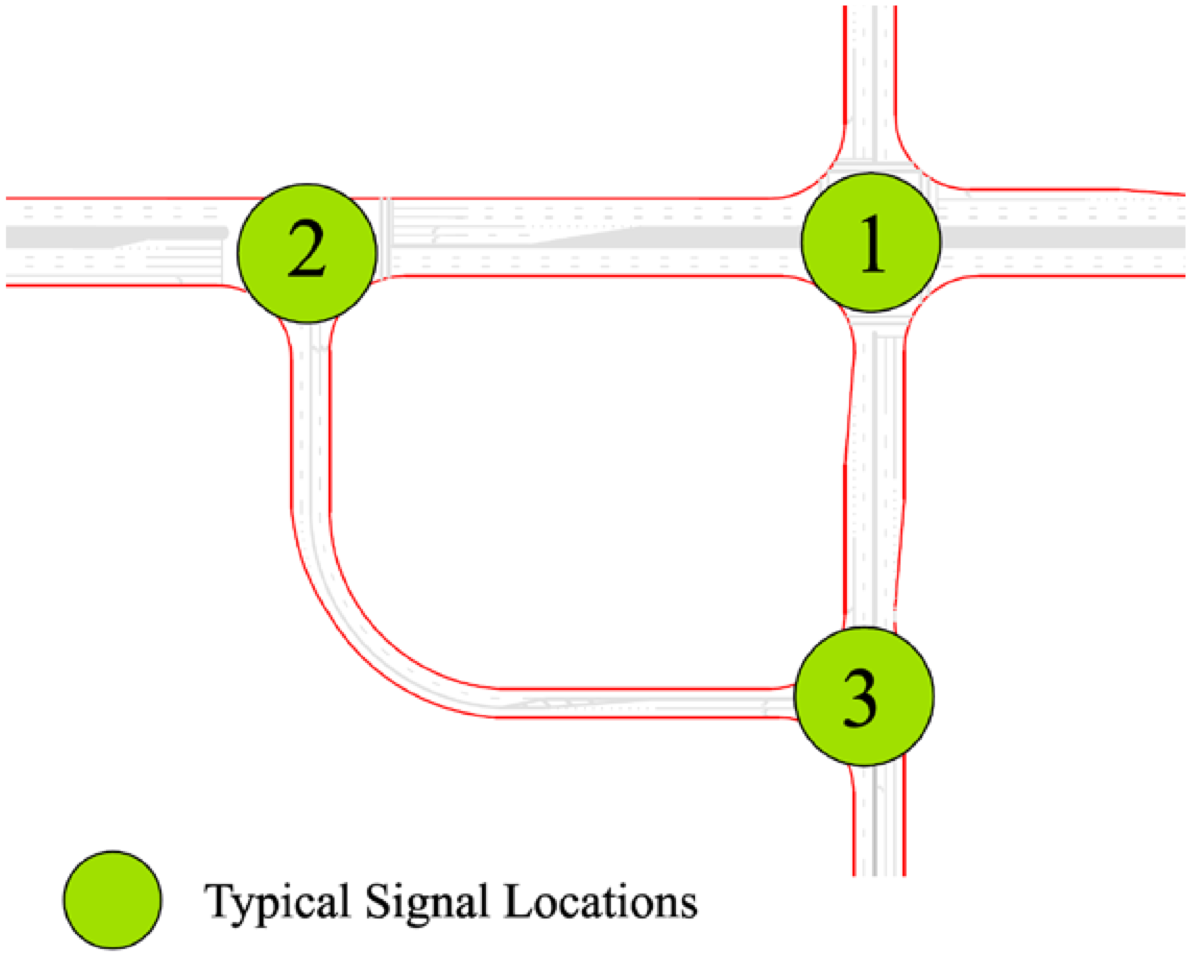


Figure 129. Illustration. Typical QR intersection signal locations.

5.4.1 Signal Design

Figure 130 shows the signal phasing scheme that Reid suggested to optimize progression.(66) In the three-phase scheme, the green phase for the main street (the east-west street in figure 129) at the main intersection extends through the first two phases. Reid's scheme allows three of the four major street movements past the first signal that drivers encounter during one phase and past the second signal that they encounter during the next phase. Only the southbound movement in Reid's scheme move through both signals in only one phase. Reid's scheme produced positive operational results based on simulations comparing QR intersections to other designs.(66)

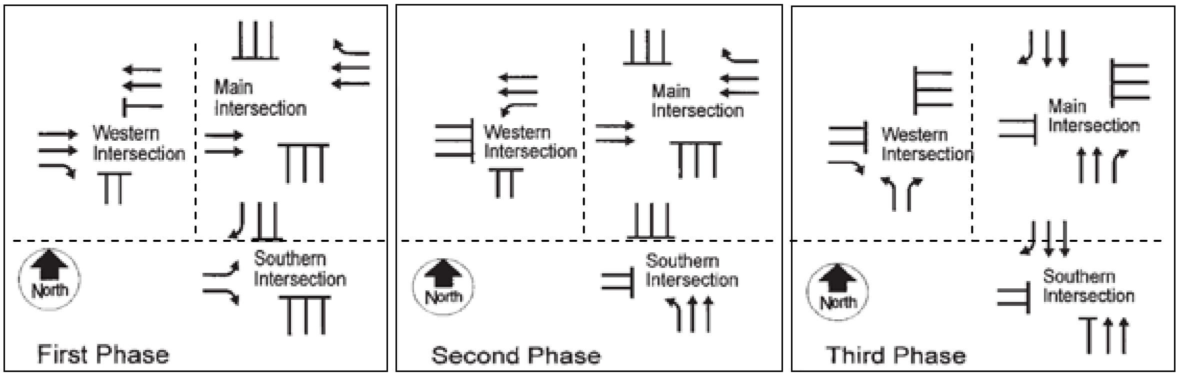


Figure 130. Illustration. Reid's suggested QR intersection signal phasing scheme.(66)

Reid's signal phasing scheme assumes that one of the intersecting streets has a higher demand and deserves more green time at the main intersection than the other intersecting street. If this is not the case such that the two major streets carry relatively equal travel volumes, then a slight modification to Reid's scheme may be beneficial for signal phasing.

When geometry of the intersection is such that the quadrant intersections are so far away from the main intersection that using the same controller to operate signals at all three intersection is not practical or feasible, then the three signalized junctions could be operated by separate controllers. In such a situation, the phasing scheme would be as depicted in figure 131. Figure 132 shows the detector placements for this phasing scheme.

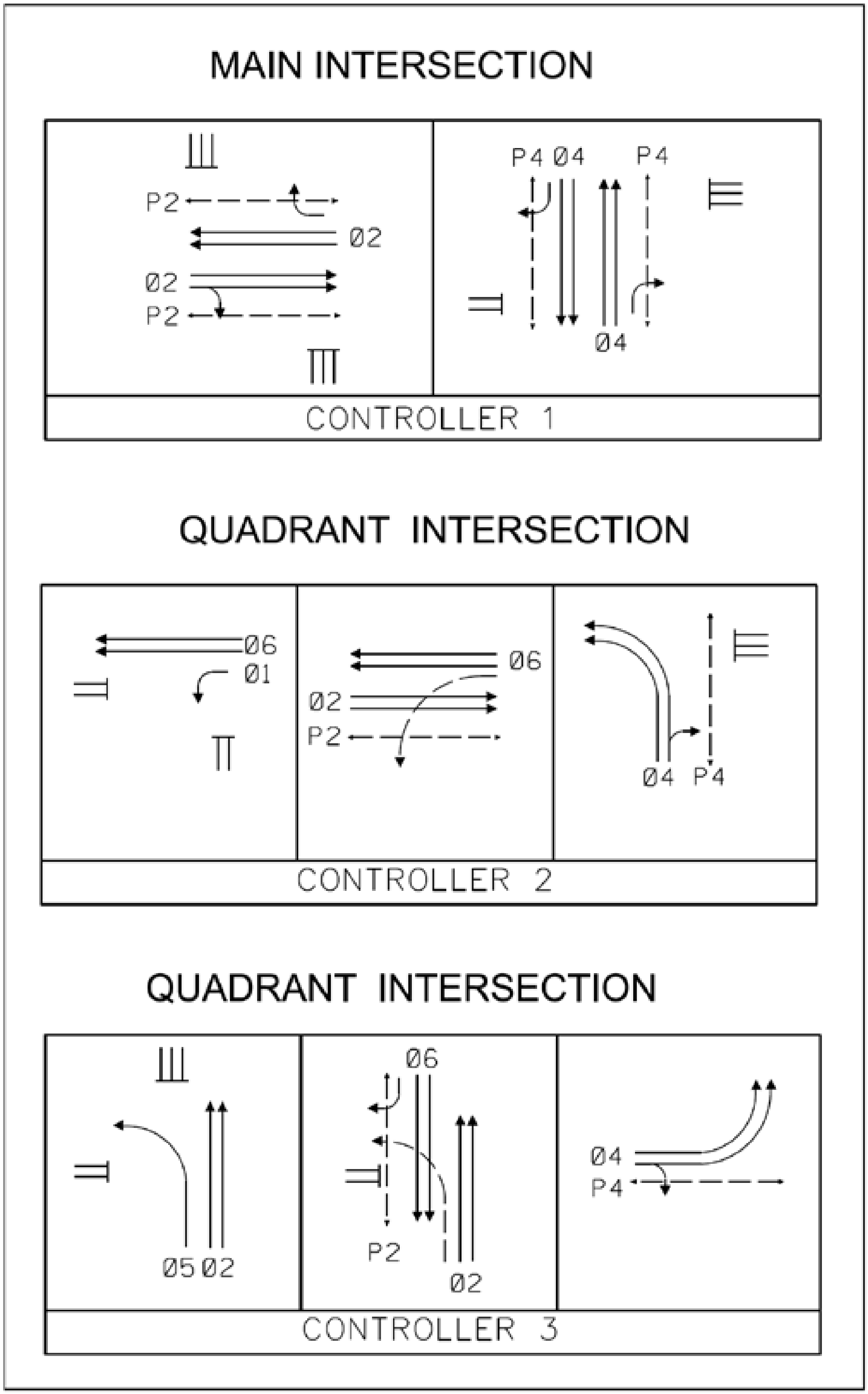


Figure 131. Illustration. QR intersection signal phasing scheme for separate controllers.

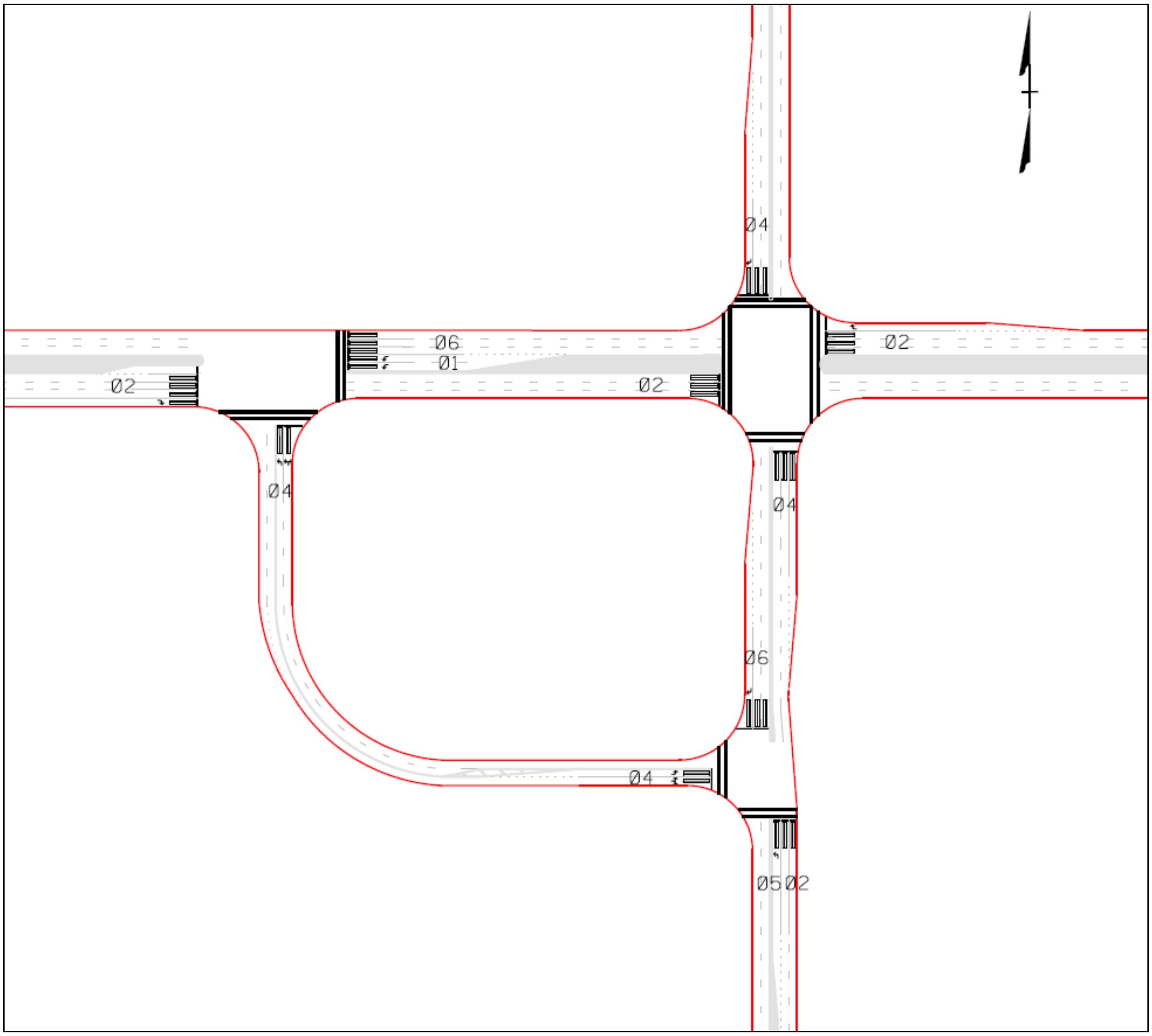


Figure 132. Illustration. Detector locations for QR intersection for signal phasing in figure 131.

A QR intersection gains its relatively good efficiency in large part from the ability to use shorter cycles than a conventional intersection. If analysis begins to suggest that longer cycles are needed for a QR intersection, designers should question whether a different intersection design might better serve the location. The three signalized junctions would require signal equipment including signal poles, mast arms, or span wire. Figure 133 shows one possible set of locations for mast arm signal poles and signal heads. In addition, locations with significant pedestrian volumes would require pedestrian signal heads and actuation.

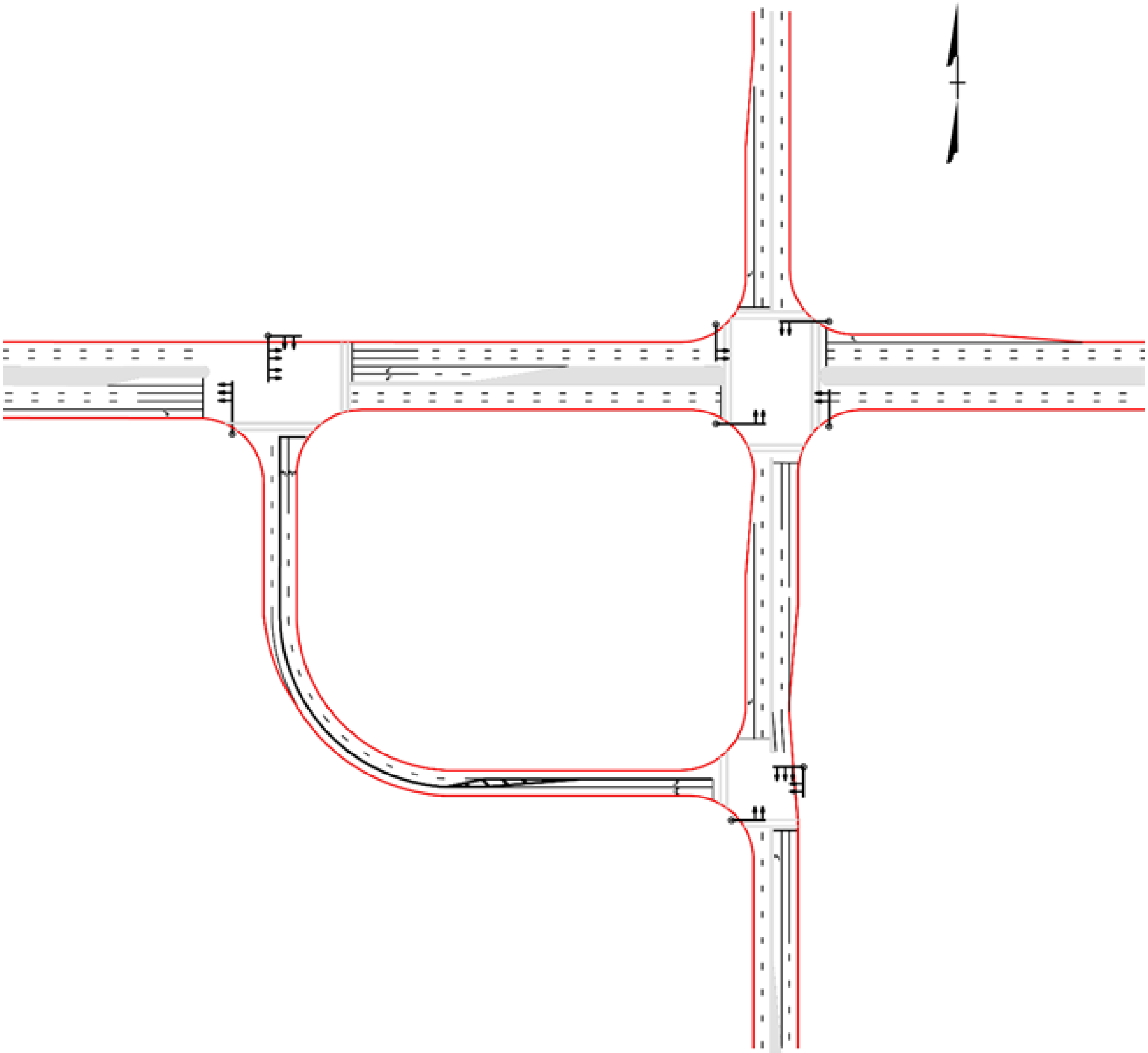


Figure 133. Illustration. Possible signal pole and mast arm locations for QR intersection.

5.4.2 Signing and Marking

The key signing issue at a QR intersection is to convey to drivers where they need to execute left-turning maneuvers. All four left turns are made in different locations compared to where they are made at traditional intersections. As figure 126 shows, two of the left turns at a QR intersection require a driver to first turn right. Advanced guide signing and guide signing at the secondary intersections are needed to lead unfamiliar motorists through a QR intersection.

Figure 134 shows a possible signing plan for a QR intersection. The plan combines features from the standard signing plans that the New Jersey Department of Transportation (NJDOT) uses for jughandle intersections where left turns are initiated from the right side of the road and from signing plans that MDOT uses for MUT intersections where left turns are initiated beyond the main intersection.

At QR intersections with high volumes, high speeds, cluttered roadsides, or other unusual conditions, designers should consider the need for overhead guide signing. Agencies employ overhead signs in some cases to reinforce the messages from standard ground-mounted signs. However, overhead signs add to project costs. The NJDOT and MDOT have found that they can provide adequate information to motorists via ground-mounted signs in a majority of their alternative intersections.

Additional traffic control devices needed at QR intersections include pavement markings, regulatory signs, and warning signs. Adequate pavement markings and regulatory signs complement median nose design and occasional enforcement to ensure that no left turns or U-turns are made at the main intersection. As mentioned previously, speed limit signs, curve warning signs with advisory speeds, and chevron signs can be deployed to convey messages about appropriate speeds. The “Signal Ahead” (W3-3) signs may also be appropriate on the connecting roadway since there may be limited visibility of the signal heads or the back of the queue.(8)

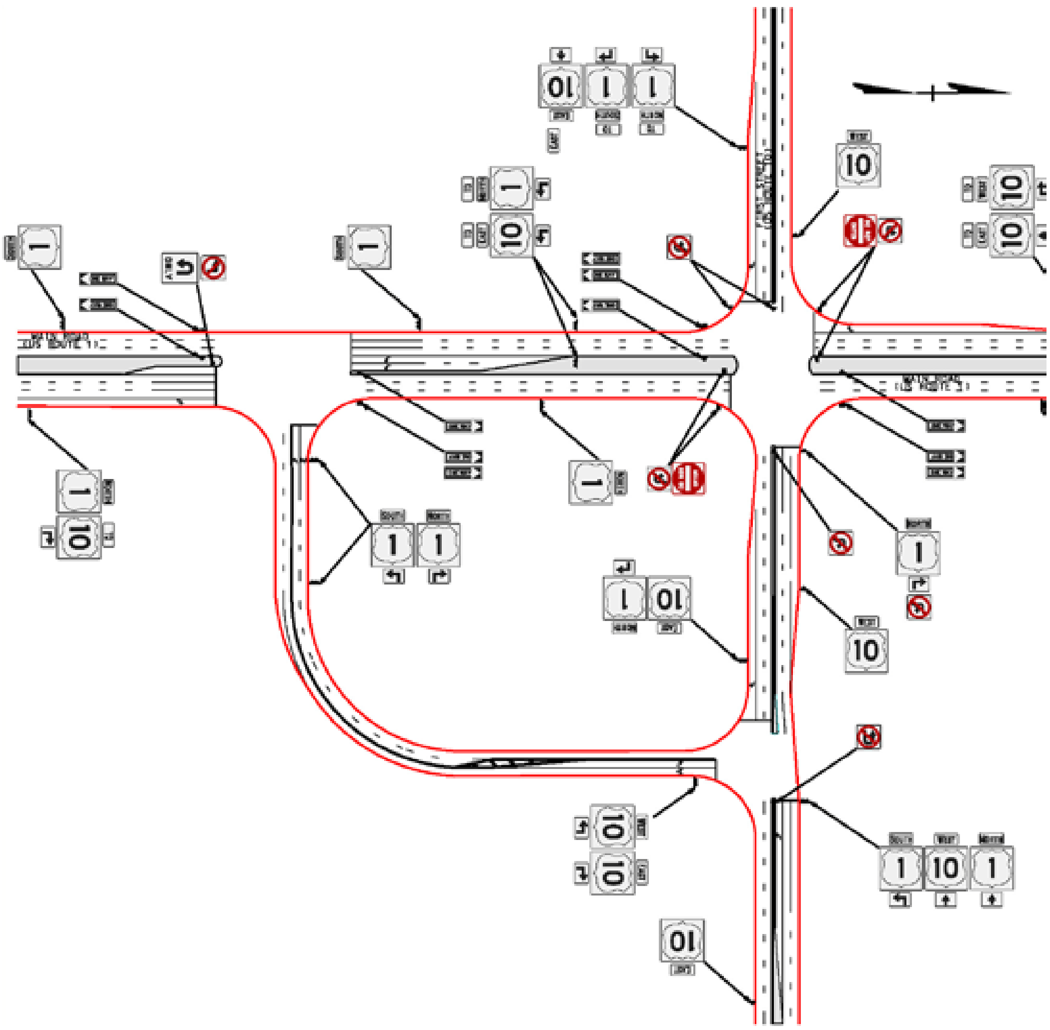


Figure 134. Illustration. Possible signing plan for QR intersection.

5.5 ACCOMMODATION OF PEDESTRIANS, BICYCLISTS, AND TRANSIT USERS

This section presents information on QR intersections with respect to pedestrians, bicyclists, and buses.

5.5.1 Pedestrians

At a QR intersection, some pedestrians have to cross an extra street to make a desired movement compared to a conventional intersection. At a QR intersection, only four movements have to cross an extra street (as compared to a conventional intersection) to reach their outbound sidewalk. As shown in figure 135, the extra crossings are for eastbound and westbound pedestrians at crossing F and for northbound and southbound pedestrians at crossing I.

Pedestrians may find it easier to cross a QR intersection than a comparable conventional intersection because a QR intersection has only two or three signal phases at the intersections. Shorter cycle lengths at QR intersections reduce pedestrian delay. Some pedestrians may have shorter walking distances due to the curved connecting roadway. The paths of pedestrians conflict with right-turning vehicle paths similar to the conflicts at a conventional intersection. Crosswalk lengths may be shorter than at comparable conventional intersections since there are no left-turn lanes at the main intersection.

Designers should be aware of a potential issue at QR intersections with timing signals for pedestrians crossing the main streets at the secondary intersections. Accommodation of pedestrian movements is desirable across all legs to encourage pedestrian mobility. The potential issue at QR intersections relates to the conflict between pedestrians crossing paths H and G and traffic turning left from the connector roadway as shown in figure 135. Signal designers should be concerned about providing appropriate signal displays that are in compliance with the *MUTCD*.(8) This conflict may reduce the saturation flow rate of the left-turn lane group from the connecting roadway. To accommodate concurrent pedestrian movement during the signal phase serving that left turn, a large portion of the cycle may be needed. Designers concerned with this potential should estimate the pedestrian crossing volume at the points shown in figure 135, perform highway capacity calculations to estimate the effects on LOS and signal timing, and decide whether to remove the pedestrian crosswalk at locations G and H or provide an exclusive pedestrian phase. It would likely take a crossing pedestrian volume of several hundred people per hour to justify an exclusive pedestrian phase.

The secondary signal-controlled intersections in a QR intersection are conventional. Consequently, the treatments are similar to conventional intersections for pedestrians with disabilities. The QR intersection characteristics that contribute to an easier crossing described previously will also assist pedestrians with visual or cognitive disabilities.

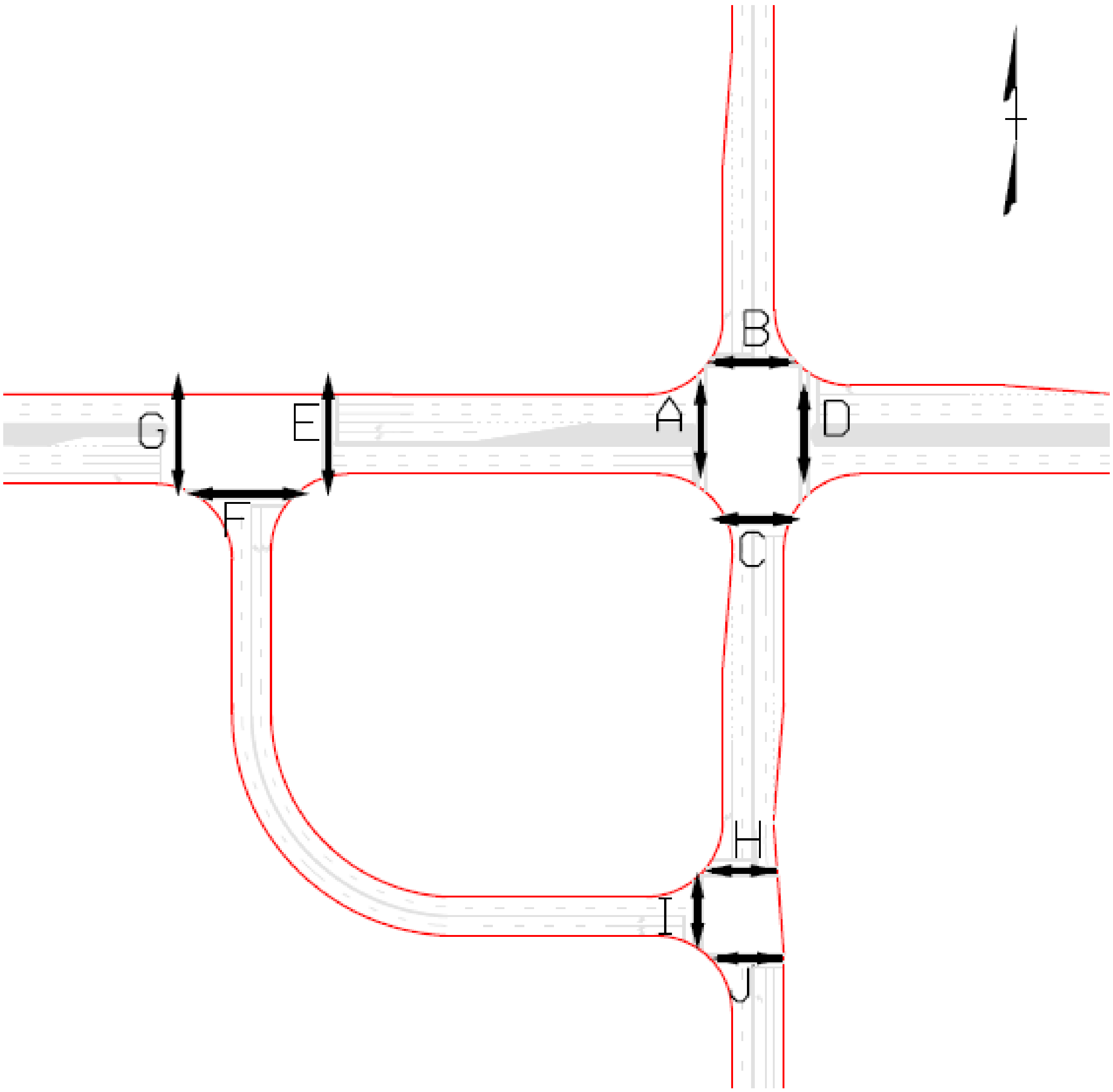


Figure 135. Illustration. Crosswalks at a QR intersection.

5.5.2 Bicyclists

Most bicyclists should find a QR intersection easier to negotiate than a conventional intersection. Through bicyclists on both intersecting streets should experience relatively longer green times and favorable progression. Three of the right-turning movements are unaffected as compared to a conventional intersection, while the fourth has a shorter travel distance using the curved connector roadway. Left-turning bicyclists have a choice of following the vehicular paths and making trips (for three of the four left turns) or following the crossing paths of pedestrians at the main intersection with no extra distance to travel.

5.5.3 Buses

Through and right-turning buses negotiating a QR intersection should experience some operational benefits. Left-turning buses have to travel longer distances and make extra turns, as compared to a conventional intersection, so their operations may suffer. A QR intersection should not affect bus stop placement except in the case of left-turning buses. Spacing the main and secondary intersections 500 ft apart would provide adequate room for a midblock bus stop between those two intersections. The preferred locations of bus stops on the connecting roadway would be on the tangent sections.

5.6 OPERATIONAL PERFORMANCE

The main reason to choose a QR intersection design is to gain operational performance that is better than other intersection designs. This section summarizes two simulation experiments reported in the literature that demonstrate the promise of the QR intersection. The section then presents the results related to QR intersection performance conducted for this study.

5.6.1 Review of Previous Research

Reid introduced the QR intersection concept in 2000 with a paper in the *ITE Journal*.(66) In the paper, he reported the results of an experiment carried out using the CORSIM® microscopic simulation package to compare operations between a QR intersection and a conventional intersection. Key features of the QR intersection network used in the experiment were four-lane main streets, a three-lane connector roadway, and a 500-ft spacing between the main intersection and the secondary intersections. The conventional intersection network had dual left-turn lanes on the main street and single left-turn lanes on the cross street. All left turns had protected left-turn phases. Fixed signal timing for the QR intersection was optimized using Synchro®, while the conventional intersection had a fully actuated signal.(21) Variables examined during the experiment at two levels included intersection type, total volume level, volume split between main and side streets, volume directional split on the arterial, and turn percentage.

Table 23 shows a summary of Reid's results.(66) The results are averages over all the simulation runs. The most important result is the 15 percent reduction in overall system travel time for the QR intersection. Delays and maximum queue lengths were reduced markedly with the QR intersection, and left-turn travel times only increased marginally for the QR intersection. Analysis of the variable interactions showed that the QR intersection had larger reductions n travel time when the overall demands were highest at about LOS E for the conventional intersection and surprisingly when the left-turn volumes were higher.

Table 23. Simulation experiment results.

Measure	Conventional	QR Intersection	Percent Difference
Cycle length (s)	142	90	-58
System delay (veh-h)	35.8	24.4	-46
System travel time (veh-h)	66.9	58.2	-15
Stops/vehicle	0.71	0.78	+9
Speed (mi/h)	23.4	27.2	+14
Maximum queue (veh)	23.4	12.4	-88
Westbound left-turn travel time, (s/veh)	120.9	125.6	+4
Eastbound through travel time (s/veh)	86.6	66.5	-30
Main intersection delay (s/veh)	41.2	13.5	-215
Main intersection LOS	E	B	Not relevant

Reid and Hummer performed another CORSIM® experiment examining the QR intersection and other designs.(61) They simulated seven actual intersections ranging from a four-lane street intersecting a two-lane street to an eight-lane street intersecting a four-lane street. For each intersection, they simulated three demand levels: off peak, peak, and peak plus 15 percent. The researchers optimized the fixed-time signal timings for each design. The results showed that in all cases but one (i.e., in 20 of the 21 cases simulated), the QR intersection produced lower system travel times than the conventional design. In the one case where the conventional was better (i.e., the off peak at the intersection of a six-lane highway and a four-lane highway), the difference was 1 veh-h (74 to 73 veh-h). In the 20 cases in which the QR intersection was superior, the difference was estimated to be as high as 50 veh-h. Reid and Hummer also reported percent stop results from their simulations.(61) The conventional intersection produced a lower percent stop than the QR intersection in 15 of the 21 cases simulated. The QR intersection had lower percent stops in five cases.

5.6.2 Analysis of Simulation Results

New analyses were conducted to demonstrate how the design of the QR intersection affects capacity. In this analysis, a CLV spreadsheet was used to compare the capacity of major and minor approaches for different configurations of a QR intersection.

Key features of the QR intersection used in the experiment were the number of through and left-turn lanes on the major and minor approaches, as well as the number of left- and right-turn lanes on the connector road. The distribution of the volume on the major road was varied between 50:50 and 75:25 for each of the scenarios. For all scenarios, it was assumed that a constant right-turn volume of 300 veh/h and a constant U-turn volume of 10 veh/h were used. A discussion of the simulation results for all of the geometric design cases is provided as follows. Besides all of the usual VISSIM® defaults, the following constants were maintained throughout each experiment:

- Optimum fixed signal timing determined using Synchro®.[21]
- Yellow times determined using ITE policy.
- All-red times determined using ITE policy.
- A total of 2 percent heavy vehicles on all legs.
- A total of 300-ft left-turn and right-turn bay lengths in the entire network.
- A 0.5-mi network size in each direction from the main intersection.
- Single right-turn bays on the mainline.
- Right-turn on red allowed at each signal, no left-turn on red allowed.
- A signal at each displaced left-turn crossover.
- A 40-ft median width on mainline.
- Undivided side street.
- A 45 mi/h desired speed on mainline.
- A 25 mi/h desired speed on side street.
- A 30 mi/h desired speed on connector roadway.
- No bus stops.

The four cases modeled included the following:

1. Intersection of four-lane, two-way major road, two-lane, two-way minor road with one left-turn lane on the mainline, and a two-lane, two-way connector roadway.

2. Intersection of four-lane major road, four-lane minor road with one left-turn lane on the mainline, and two-lane connector roadway.

3. Intersection ofsix-lane major road, four-lane minor road with one left-turn lane on the mainline, and two-lane, two-way connector roadway.

4. Intersection of six-lane major road, four-lane, two-way minor road with two left-turn lanes on the mainline, and four-lane, two way connector roadway.

These four cases are summarized below in table 24.

Table 24. Geometric design cases of quadrant intersection.

Case	Major Road Approaches		Minor Road Approaches		Connector Road Approaches	
	Through Lanes	Left-Turn Lanes	Through Lanes	Left-Turn Lanes	Left-Turn Lanes	Right-Turn Lanes
A	2	1	1	1	1	1
B	2	1	2	1	1	1
C	3	1	2	1	1	1
D	3	2	2	2	2	1

Figure 136 through figure 139 show the comparison of throughput and average intersection delay for the four geometric design cases (see table 24) of QR and conventional intersections.

For case A with two through lanes on the major road approach and a single through lane on the minor road approach, the conventional intersection performs slightly better compared to the QR intersection. For case B with two through lanes on the major and minor road approaches, the conventional intersection was similar in operational performance compared to the QR intersection. For case C with three through lanes on the major approaches, two through lanes on the minor road approach, and a single lane connector roadway approach, the QR intersection was similar in operational performance compared to the conventional intersection. For case D with three through lanes on the major approaches, two through lanes on the minor road approaches, and a two-lane connector roadway approach, the QR intersection was significantly better than the conventional intersection in operational performance.

Simulation results showed that the QR intersections performed comparably to the conventional intersections for moderate and balanced through volumes on the major road. However, the QR intersections had higher throughput and lower travel times compared to the conventional intersections for scenarios with heavy through and moderate left-turn volumes on the major road and heavy through and left-turn volumes on the minor road. For such scenarios, the increase in throughput ranged from 5 to 20 percent with a 50 to 200 percent savings in travel times.

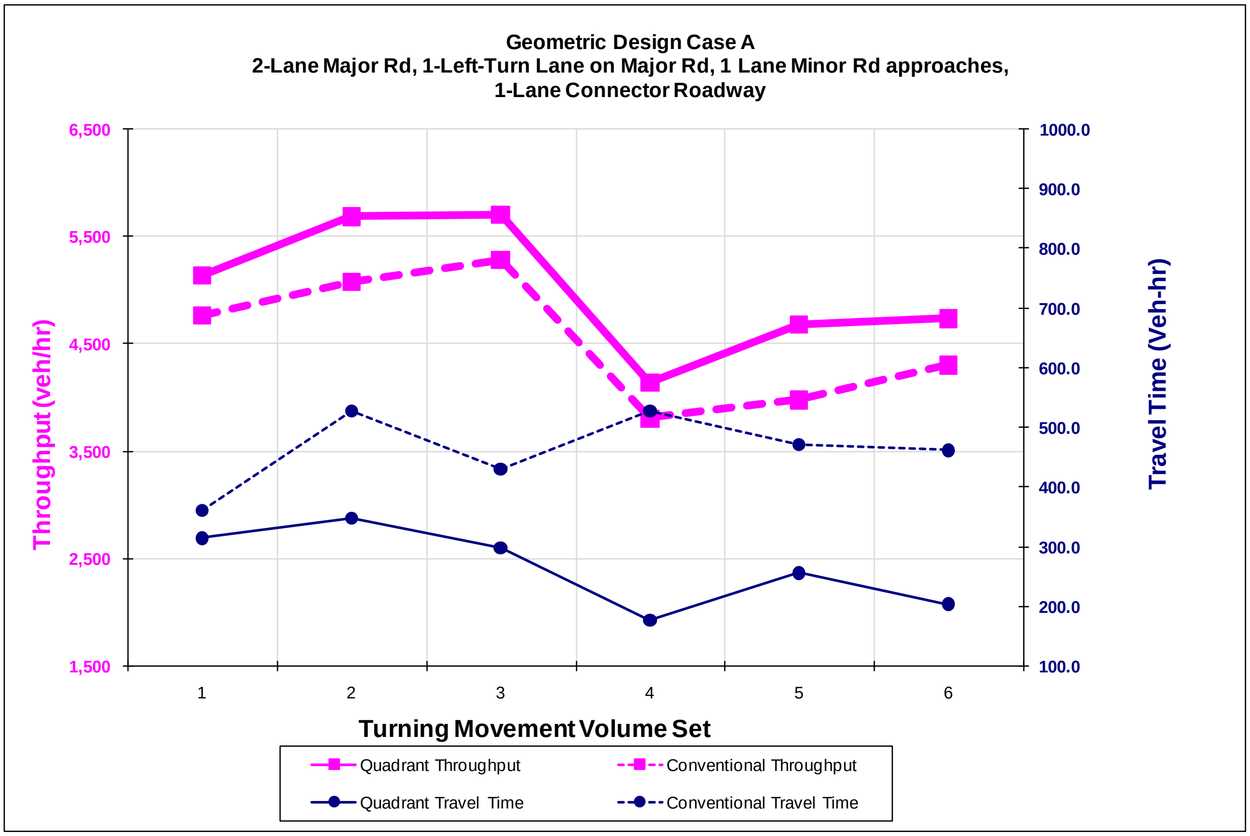


Figure 136. Graph. Throughput and travel time comparisons for geometric design case A.

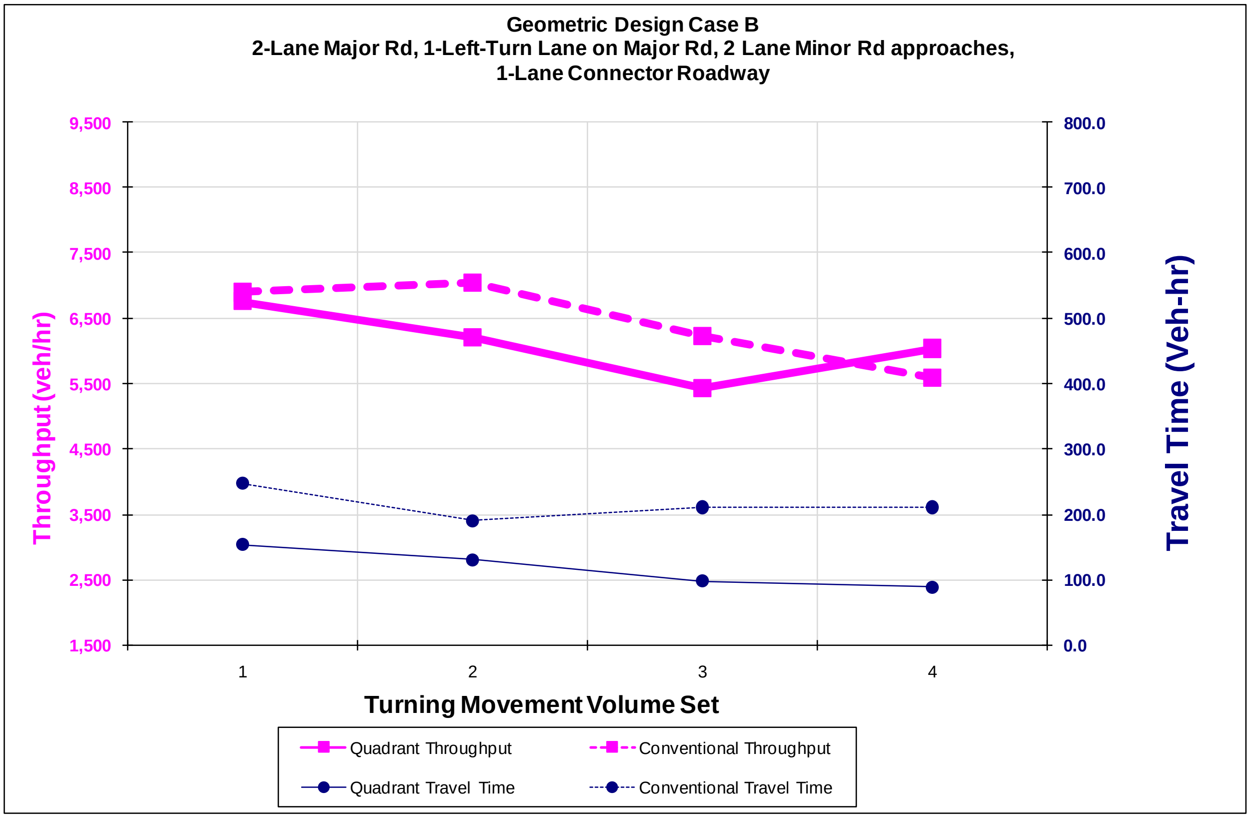


Figure 137. Graph. Throughput and travel time comparisons for geometric design case B.

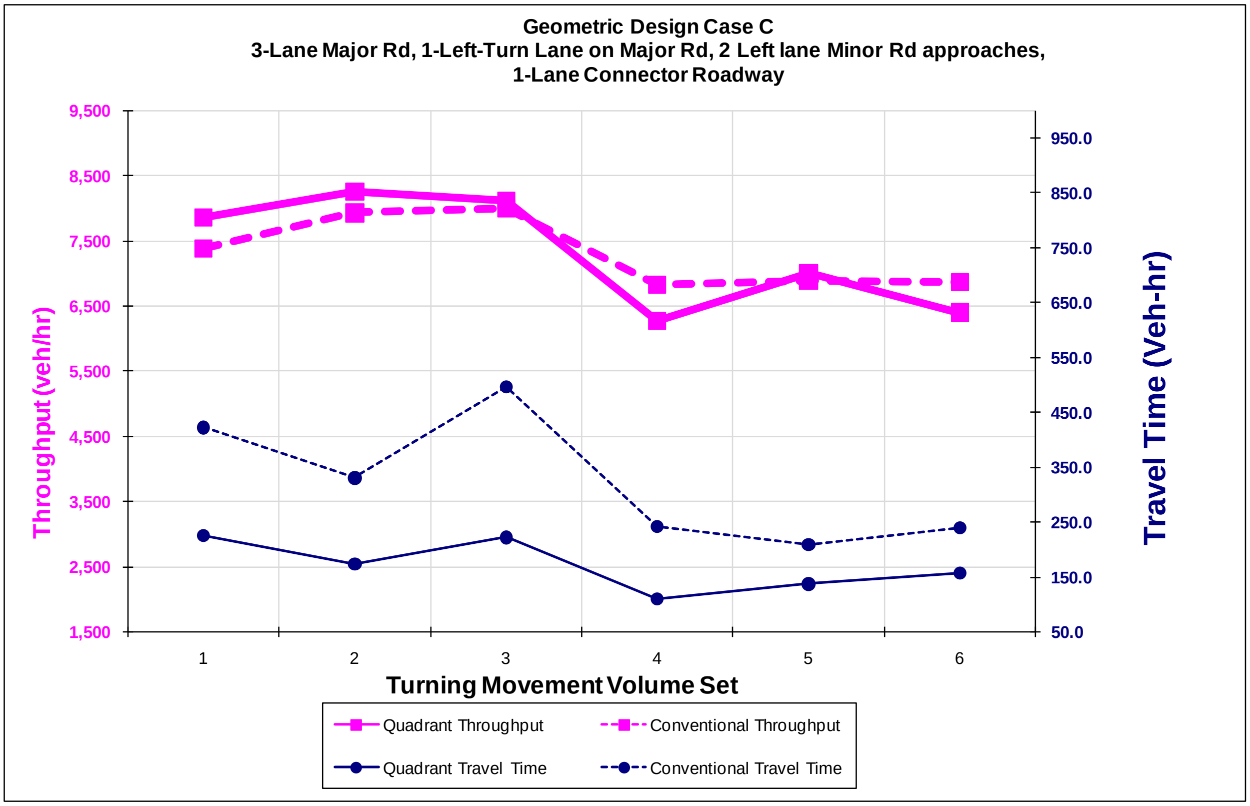


Figure 138. Graph. Throughput and travel time comparisons for geometric design case C.

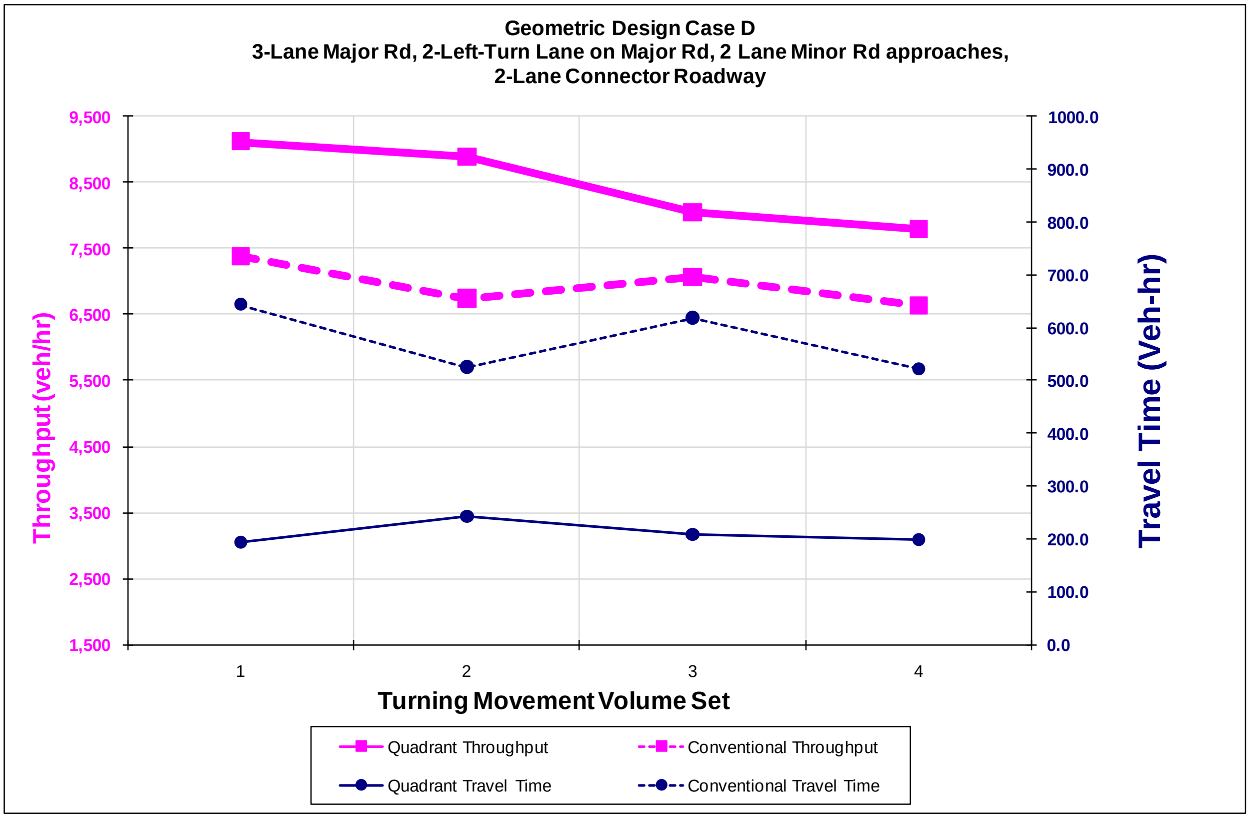


Figure 139. Graph. Throughput and travel time comparisons for geometric design case D.

Table 25 shows the geometric design cases with the turning volumes sets that were simulated in VISSIM® for the high-volume scenarios.

Table 25. Volumes and QR intersection configurations for VISSIM® simulations.

Geometric Cases			Split	Input Volumes						
				Major Road			Minor Road			Total Input
				Left	Thru	Right	Left	Thru	Right	
A	Quadrant	Two thru and one left on major road, one thru on minor road, and one-lane connector roadway	50:50	210	1,200	300	260	350	250	5,140
				210	1,600	300	260	350	250	5,940
				310	1,600	300	260	350	250	6,140
			30:70	210 (90)	1,200 (514)	300 (129)	260	350	250	4,163
				210 (90)	1,600 (685)	300 (129)	260	350	250	4,734
				310 (133)	1,600 (685)	300 (129)	260	350	250	4,877
A	Conventional		50:50	210	1,200	300	260	350	250	5,140
				210	1,600	300	260	350	250	5,940
				310	1,600	300	260	350	250	6,140
			30:70	210	1,200	300	260	350	250	4,163
				210	1,600	300	260	350	250	4,734
				310	160	300	260	350	250	4,877
B	Quadrant	Two thru and one left on major road, two thru on minor road, and one-lane connector roadway	50:50	310	1,600	300	210	1,100	300	7,640
				160	1,600	300	210	1,100	300	7,340
			30:70	310	1,600	300	210	1,100	300	6,377
				160	1,600	300	210	1,100	300	6,163
B	Conventional		50:50	310	1,600	300	210	1,100	300	7,640
				160	1,600	300	210	1,100	300	7,340
			30:70	310	1,600	300	210	1,100	300	6,377
				160	1,600	300	210	1,100	300	6,163

C	Quadrant	Three thru and one left on major road, two thru on minor road, and one-lane connector roadway	50:50	310	2,200	300	210	1,100	300	8,840
				210	2,200	300	210	1,100	300	8,640
				210	2,400	300	210	1,100	300	9,040
			30:70	310	2,200	300	210	1,100	300	7,234
				210	2,200	300	210	1,100	300	7,091
				210	2,400	300	210	1,100	300	7,377
C	Conventional		50:50	310	2,200	300	210	1,100	300	8,840
				210	2,200	300	210	1,100	300	8,640
				210	2,400	300	210	1,100	300	9,040
			30:70	310	2,200	300	210	1,100	300	7,234
				210	2,200	300	210	1,100	300	7,091
				210	2,400	300	210	1,100	300	7,377
D	Quadrant	Three thru and two left on major road, two thru on minor road, and two lane connector roadway	50:50	510 (210)	2,400	300	510	1,100	300	9,940
				510 (210)	2,200	300	510	1,100	300	9,340
			30:70	510 (219)	2,400 (1,029)	300 (128)	510	1,100	300	8,406
				510 (219)	2,400 (1,029)	300 (128)	510	1,100	300	8,006
D	Conventional		50:50	510 (210)	2,400	300	510	1,100	300	9,940
				510 (210)	2,200	300	510	1,100	300	9,340
			30:70	510 (219)	2,400 (1029)	300 (128)	510	1,100	300	8,406
				510 (219)	2,400 (1,029)	300 (128)	510	1,100	300	8,006

Note: The figures in parentheses indicate the directional splits for the major road volumes.

5.7 SAFETY PERFORMANCE

Since a complete QR intersection has not been built as of the preparation of this report, there is no empirical basis on which to draw when making estimates on the expected safety of a QR intersection. Nonetheless, clues about conflicts and from collision models are helpful to make some inferences about QR intersection safety. The number of vehicle-vehicle conflict points is lower at a QR intersection than at a conventional intersection. As described previously in this report, there are 32 vehicle-vehicle conflict points at a conventional intersection, not including U-turns. Figure 140 shows that there are 28 vehicle-vehicle conflict points at a QR intersection. This reduction in conflict points may serve as an indicator of improved safety although research shows no definitive relationship to crash experience.

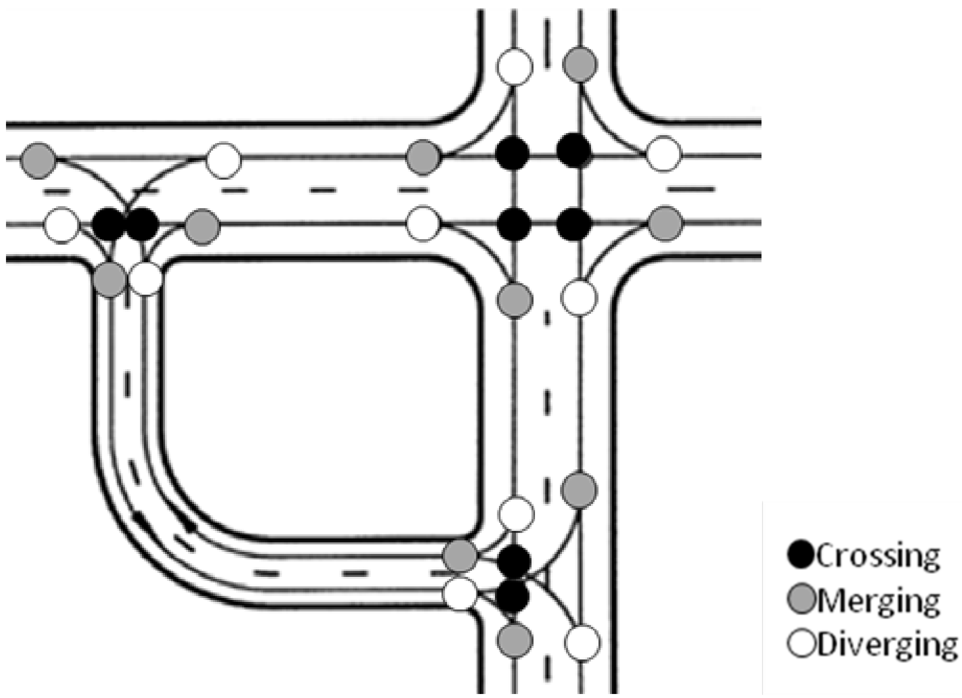


Figure 140. Illustration. Vehicle-vehicle conflict points at a QR intersection.[(49)]

5.8 CONSTRUCTION COSTS

This section presents a discussion of construction costs for a retrofit of a conventional intersection into a QR intersection with a new connector roadway. Due to the wide-ranging scale, meaningful costs for a QR intersection were not developed for the scenario where a new intersection would be constructed.

Construction costs are likely higher for a QR intersection than a conventional intersection due to the new connector roadway and additional traffic control. The cost of the connector roadway is the largest additional cost compared to a conventional intersection. The connector roadway is about 880 ft (centerline to centerline), or 0.167-mi long, with a 500-ft spacing between the main and secondary intersections. For a three-lane connector road with sidewalks on both sides, the required right-of-way is about 1.1 acres. On a corner in a developing area, that right-of-way could cost from several thousand dollars to over $1 million. The cost to construct the connector roadway varies widely with time, place, and circumstances such as the amount of grading and utilities needed to relocate. Using an order of magnitude cost of $3 million per 1 mi to construct a typical three-lane urban street, it is estimated that the construction cost would be about $500,000 for the connector roadway.

The smaller footprints of the main roads through a QR intersection would provide some construction cost savings relative to a conventional intersection. The smaller footprint would occur primarily because the main streets at a QR intersection need a left-turn lane on only one approach each. The savings from this reduced main street width is likely to be less than $100,000 altogether.

Signal costs are higher at a QR intersection than at a conventional intersection because there are three interconnected signals instead of one. Based on signal costs experienced in North Carolina at recent super street installations (which also may have volumes that warrant three interconnected signals at similar spacing), the additional signal costs at a QR intersection could be over $300,000.

To summarize, the construction costs are likely higher for a QR intersection than a conventional intersection. From the main components adding to the cost (i.e., connector roadway, extra signals, and extra overhead signs), the cost of the connector roadway is the greatest cost and could have a significant impact on the total project cost depending on availability and cost of additional right-of-way. While these higher costs are offset slightly by reduced widths on the main streets, there is an overall increase in project costs for the QR intersection design. The presence of an existing connector roadway on one of the quadrants of the main intersection could be used as the QR intersection connector roadway, resulting in substantial savings in land acquisition costs and complete signalization of the junctions.

5.9 SEQUENCING OF CONSTRUCTION

The complexity of maintenance of traffic during the construction of a QR intersection varies with the situation. An agency can construct the connecting roadway without affecting vehicular traffic on the major streets and can keep operating the main intersection in conventional style. Only the sidewalks crossing the connecting roadway would be affected during its construction, and pedestrian traffic on the sidewalks may have to be rerouted for brief periods. After the connecting roadways open, an agency can close the left-turn lanes at the main intersection and proceed with repaving, median reconstruction, and restriping of the main streets. Agencies need to ensure that all new signs and signals for the QR intersection are covered until the facility is opened so as not to distract or misdirect motorists.

5.10 OTHER CONSIDERATIONS

Agencies considering QR intersection installation should consider issues such as lighting, maintenance costs, enforcement needs, public relations, emergency vehicles, and school bus routing. Lighting is often associated with signalized intersections, particularly in urban and suburban areas. Given that the QR intersection design includes three signalized intersections compared to the single signalized intersection of a conventional design, there is the potential for increased lighting needs. There has been an added safety benefit associated with intersection lighting. These costs for lighting are higher for a QR intersection design compared to the conventional design because the overall junction is larger and made of three intersections. A common drawback to lighting is the expense of running electricity to the luminaries and control box. However, the QR intersection design is applicable mainly in urban and suburban areas where it is likely that the necessary utility lines already exist.

The maintenance costs for a QR intersection are likely higher than for a comparable conventional intersection. Higher costs are due in part to the two extra signals that must be powered and maintained. The connecting roadway also requires extra maintenance.

Enforcement needs at QR intersections may be higher shortly after their opening than at conventional intersections. In Michigan, the approach for opening a new MUT intersection is to allocate additional enforcement resources during the first few weeks of operation to reduce the number of illegal left turns at the main intersection. This may also be appropriate at new QR intersections. Once drivers become familiar with the operation of the intersection, the need for additional enforcement will likely subside, and normal vigilance in enforcing traffic laws on QR intersections should suffice.

To help drivers learn how to use the design, agencies should consider a public information campaign to coincide with the opening of a QR intersection. Press releases, flyers distributed to nearby businesses and residents, and material posted on the agency Web site could help. The information should discuss the need for left-turning motorists to follow the signs. It should also indicate that motorists will experience better intersection operations with the new design. Public information should also instruct pedestrians using the intersection, including discussing transit stop locations, especially if they are being relocated.

Emergency vehicles trying to make left turns at a QR intersection have longer travel times and possibly increased delays than at a conventional intersection. Agencies should therefore consider allowing direct left turns by emergency vehicles at the main intersection. Other than possibly a sharp median nose, there are no physical obstacles to prevent making a direct left turn. Another issue related to emergency vehicles is whether to give the connecting roadway its own street name and address numbers. This is necessary for efficient emergency vehicle response. However, a named connecting roadway complicates signing. It may be prudent to name the connecting roadway only if there are land parcels that are only accessible directly from the connector road.

Like all other intersection users, school buses should generally benefit from reduced travel times through a QR intersection. However, school bus routes that turn left at a QR intersection can generally be lengthened. As mentioned earlier in the report for transit bus stops, school bus stops on the curved portion of the connecting roadway may not be optimum due to driver sight lines to the bus and the back of the queue.

5.11 APPLICABILITY

The QR intersection is intended to reduce travel time through congested intersections in urban or suburban areas. It is a spot treatment at a particular intersection, like the DLT intersection, rather than a treatment that lends itself to application along a corridor, like the MUT and RCUT intersections. Particular conditions that planners and designers should associate with the possibility of a successful QR intersection installation include the following:

- *Heavy through volumes:* QR intersections are appropriate for intersections with heavy through volumes and low to moderate major road left-turn volumes. However, they have an additional signal for through traffic to pass through. Therefore, if conventional traffic management can provide an adequate peak period LOS, then there is little to be gained from making the extra investment in the QR intersection.

- *One high left-turn volume:* If only one of the four left-turn movements at the main intersection is heavy and if the connector can be constructed in the quadrant that allows direct left turns onto that connector, then the QR intersection has great promise.

- *Moderate or low left-turn volume:* A QR intersection is most appropriate for lower left-turn volumes since the intersection design increases travel distances for left-turning vehicles and increases the number of signals to pass through. At some point, the left-turn demands become too high, and the extra travel time for left-turning vehicles exceeds the savings for through vehicles.

- *Empty or redeveloping quadrant:* The ideal case for a QR intersection exists when a developer is willing to donate right-of-way and build the connector roadway in exchange for the favorable access that the connector roadway provides to adjacent parcels. The right-of-way costs for the connector roadway could be substantial and at some point could be cost prohibitive, forcing planners and designers to choose other intersection options.

- *Nearby signals:* A QR intersection works well by reducing the cycle length at the main intersection and providing an adequate amount of green time for the main streets. If there are nearby signals along the arterials, then the QR intersection signals should be fairly easy to integrate into a signal system. A single large intersection in the middle of a corridor with otherwise good progression potential might be a candidate for a QR intersection when compared to a conventional, multiphase signal-controlled intersection with a long cycle.

- *Future plans for grade separation:* QR intersections work well as an intermediate stage between a conventional intersection and interchange. Early in the development of an intersection, a highway agency could operate it as a conventional design while reserving right-of-way in a quadrant for a connector roadway. When demands are high enough to justify it, the agency could build the connector roadway and operate the intersection as a QR intersection. When demands begin to overwhelm the QR intersection, the agency can build a grade separation and either continue to use the connector roadway or integrate the connector roadway into a quadrant interchange, a partial cloverleaf interchange, or some other interchange form. In the intermediate stage, a QR intersection could provide the benefit of efficient operations without the expense of the bridge for the interchange.

- *Skewed intersection:* A skewed intersection lends itself to a QR intersection in several respects, as it allows a shorter connecting roadway, provides a gentler curve on the connector, and eliminates the need for any drivers to make turns over 90 degrees.

Agencies should not consider a QR intersection unless the through and left-turn demands justify it operationally and unless there is a chance for right-of-way for the connector road to be available at a reasonable cost. The other listed conditions would enhance the positive response to a QR intersection but are not absolutely necessary to its success. In other words, a QR intersection would likely work better relative to other designs in an area with moderate pedestrian demands, but it does not need moderate pedestrian demands to be justified.

In this report, there is an absence of crash experience because safety performance of a complete QR intersection is not known. A well-designed QR intersection may improve intersection safety because of lower conflict points that are more spatially separated in comparison to a conventional intersection.

5.12 SUMMARY

The main objective in employing a QR intersection is to increase operational efficiency through a heavily congested intersection. By moving the left turns away from the main intersection and allowing a two-phase signal, a QR intersection is one of the most efficient at-grade intersection designs discussed in this report. The QR intersection also accommodates pedestrians, allowing an easier crossing and penalizing only 4 of the possible 48 pedestrian movements with an extra street crossing.

The main drawbacks to the QR intersection design are the potential expectancy violations of left-turning drivers, the additional right-of-way needed in one quadrant, and the extra cost to build the connecting roadway. Good signing can help mitigate the violated expectancies of left-turning drivers, but no signing system will reach all drivers at all times. Other designs that require similar maneuvers of left-turning drivers, such as jughandles in New Jersey, function well. The extra right-of-way needed means that the QR intersection would likely be applied more often in developing areas. It is possible that developers would see the advantage of having the connecting roadway integrated into their developments and cooperate with highway agencies in building the connecting roadway. Moreover, the existing roadway network may lend itself to a QR intersection if an existing roadway can be converted to serve the role of a QR intersection’s new connector roadway. The added construction and maintenance costs of the QR intersection are in line with other nonconventional intersections and should always be considered in conjunction with all of the savings in time, energy, and emissions that they provide.

To summarize, the QR intersection can reduce traffic congestion at an intersection in a developing area. It could serve as a temporary solution until a grade-separated solution is funded and built. As QR intersections are built, a safety record can be established, and the questions regarding motorist understanding can be answered more definitively.

CHAPTER 6. OTHER INTERSECTION CONFIGURATIONS

6.1 ATERNATIVE INTERSECTION CONFIGURATIONS

This chapter briefly identifies alternative intersections (without the same level of detail that has been provided in the previous chapters). Roundabouts are included, although they are becoming more widespread in application throughout the United States. Roundabouts are not covered in detail in this report because they have been covered extensively in other publications.[67, 68]

6.2 ROUNDABOUTS

Roundabouts are a form of intersection control in which the turning movements of the intersection are separated physically by a central island, and the traffic moves along the travel lanes surrounding the central island. Traffic leaves the intersection by executing a right-turn maneuver at the appropriate leg. Roundabouts are popular in many parts of the world. In the United States, there are limited applications, but they are increasing in number as drivers become more familiar with them. Although similar in concept to rotaries and traffic circles, roundabouts are different in geometry and operation. Their differences are highlighted in the FHWA publication, *Roundabouts: An Informational Guide*.[67] Figure 141 shows the geometry of a typical roundabout, and figure 142 shows a roundabout.

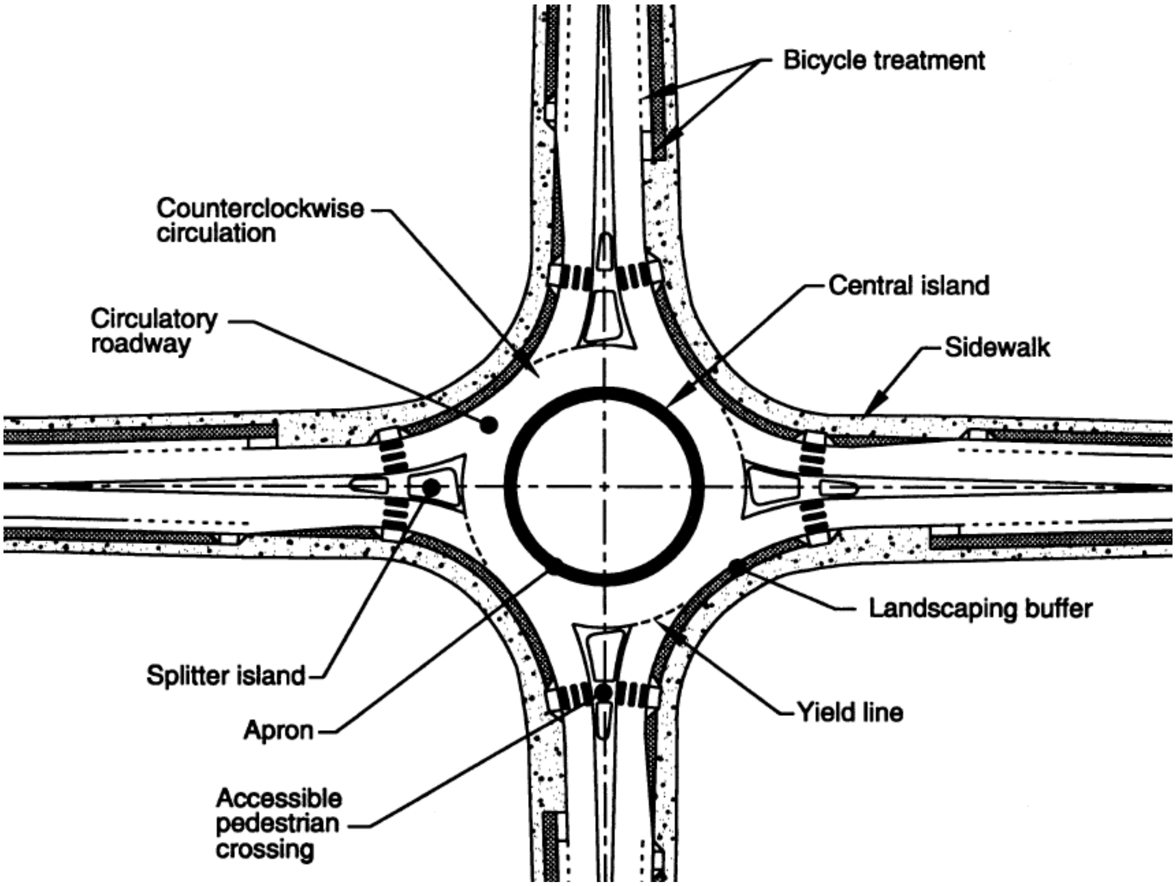


Figure 141. Illustration. Typical geometry of a roundabout.[(67)]

Figure 142. Photo. Typical roundabout.

Methods to determine capacities of single-lane and double-lane roundabouts are outlined in FHWA's *Roundabouts: An Informational Guide*, and the latest operational findings are documented in *NCHRP Report 572*.[67,68] Proper signing and marking to provide regulatory and supplemental warning are designed in accordance with *MUTCD*.[8]

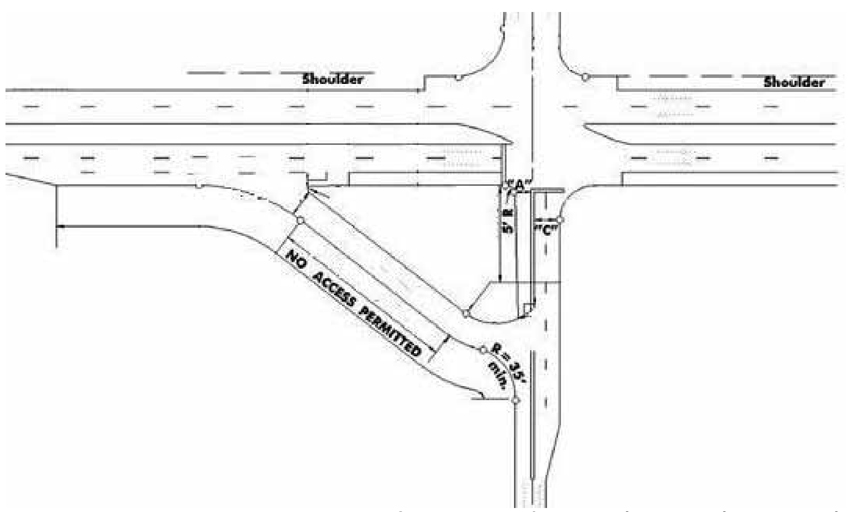
The roundabout informational guide provides detailed recommendations on the design of splitter islands, sight distance, and vertical alignment issues.[67] The *NCHRP Synthesis 264*, "Modern Roundabout Practice in the United States," details design-related information from several existing sources and design guidelines from Great Britain, France, and Germany.[69] It also includes discussions on roundabout costs and public acceptance. In addition, several States including Florida, Maryland, Oregon, New York, and North Carolina have their own roundabout policies. (See references 70–73.)

6.3 OTHER ALTERNATIVE INTERSECTION CONFIGURATIONS

This section briefly identifies other alternative intersection configurations including the jughandle intersection, the continuous green T-intersection, and the offset T-intersection, among others.

6.3.1 Jughandle Intersection

A *jughandle intersection* is defined by the NJDOT *Roadway Design Manual* as an at-grade ramp provided at or between intersections to permit motorists to make indirect left turns and/or U-turns.[74] The typical design of a jughandle intersection is shown in figure 143. An illustration of a typical forward jughandle with the at-grade ramp located prior to the main intersection is shown in figure 144. There are several variants of the jughandle, including the reverse jughandle and the U-turn ramp jughandle.



Source: New Jersey Department of Transportation *Roadway Design Manual*

Figure 143. Illustration. Typical geometry of a jughandle intersection.[74]

Source: Google[TM] Earth

Figure 144. Photo. Typical jughandle intersection in New Jersey.

6.3.2 Hamburger or Through-About Intersection

The hamburger or through-about intersection design is a variant of the signalized roundabout. The primary difference is that the mainline through movements are allowed in the intersection. The through and left-turn movements from the minor street are executed by following the circulatory movement around the semicircular islands at the main intersection. This kind of a configuration allows the main intersection to operate on a two-phase signal. The typical configuration is shown in figure 145, and a photograph of a hamburger intersection in Virginia is shown in figure 146.

Figure 145. Photo. Typical hamburger intersection movements.[75]

Source: Google™ Earth

Figure 146. Photo. Hamburger intersection in Fairfax, VA.

6.3.3 Synchronized Split-Phasing Intersection

Figure 147 shows vehicular movements in a synchronized split-phasing intersection, which is also known as the double crossover intersection. In this design, which was not found to exist during the preparation of this report, the through and left-turn movements on the mainline cross over before the main intersection. This helps disperse the turning traffic before the main intersection. At the main intersection, the through and the opposing lefts can move concurrently during the same signal phase. This intersection can then operate with two phases. As opposed to the DLT intersection (see chapter 2) where only the left-turning traffic is crossed over, both the through and the left-turn movements are crossed over at the synchronized split-phase intersection.

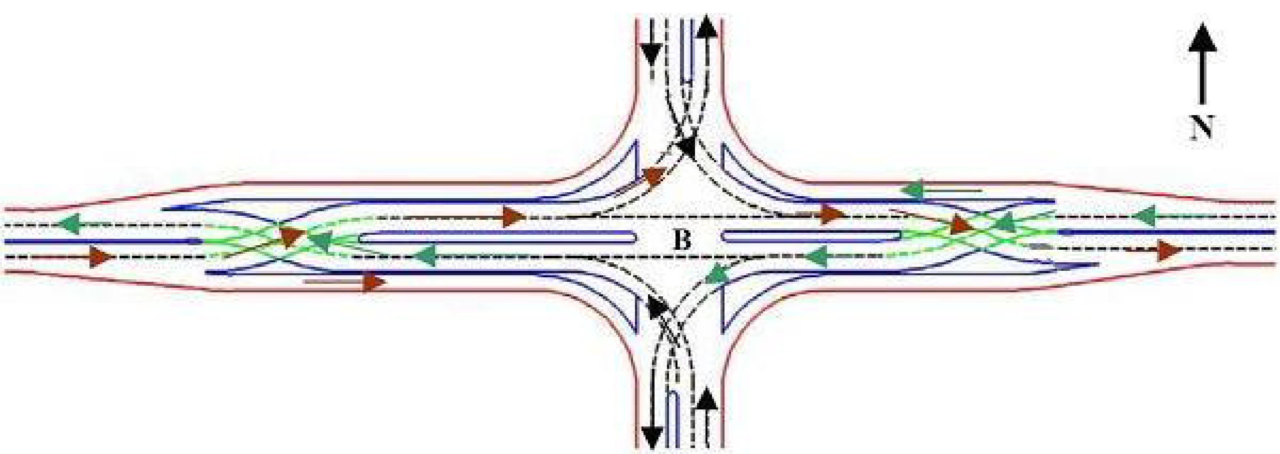


Figure 147. Illustration. Typical synchronized split-phase intersection movements.[76]

6.3.4 Offset T-Intersection

The offset T-intersection is shown in figure 148. It is a variation of the conventional intersection, with the minor street approaches offset by a distance. This lateral separation causes through movements from the minor streets to be diverted to right-turn movements followed by left-turn movements to the other offset minor leg.

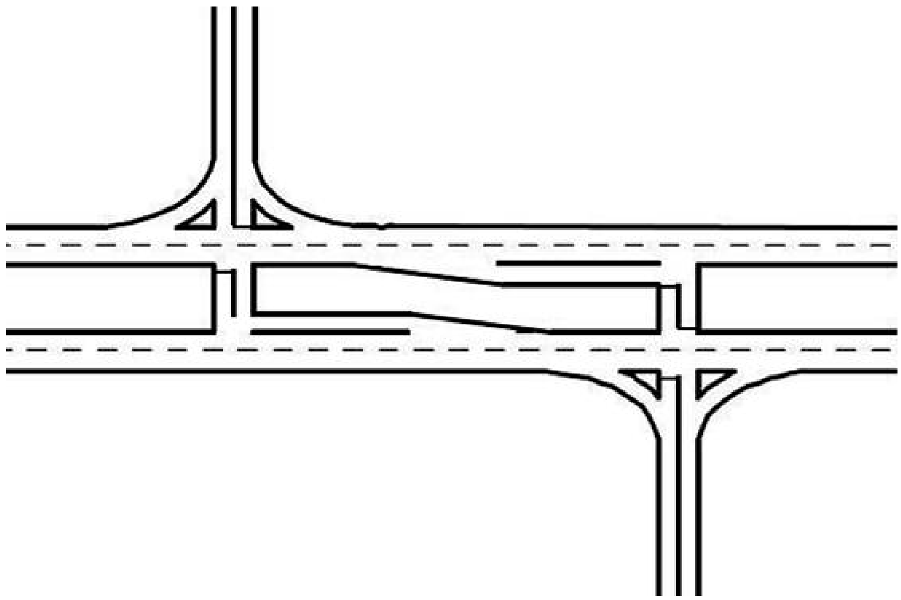
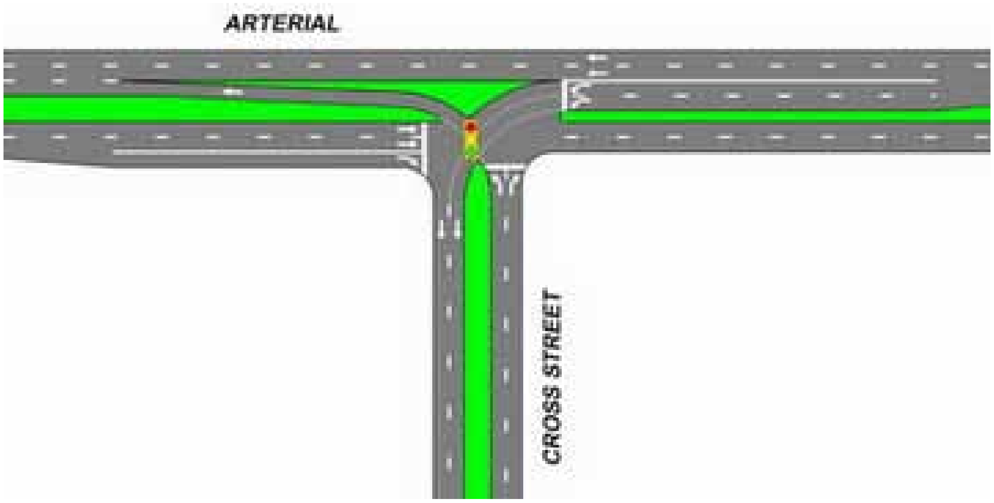


Figure 148. Illustration. Typical geometry of an offset T-intersection.[75]

An offset T-intersection has a total of 22 conflict points, compared to 32 conflict points at a conventional intersection, and can potentially reduce angle collisions. This kind of an intersection is particularly useful in situations where both the major and minor road through volumes are low. Another situation where the offset-T intersection can be appropriate is a retrofit of a skewed intersection with heavy turn volumes and limited through volumes. The design of the offset between the legs of the minor street is dictated by the through and left-turn volumes present at the intersection and sight distance considerations.[75]

6.3.5 Continuous Green T-Intersection

The continuous green T-intersection is shown in figure 149. The basic differences between a continuous green T-intersection and a normal signalized T-intersection is the channelized left-turn movement from the stem of the minor street to the mainline which enables the mainline through movement to be executed at the same time. The signal control at a continuous green T-intersection operates with three signal phases. The through movement in one direction can flow continuously.



Source: ATTAP, Maryland State Highway Administration

Figure 149. Illustration. Typical geometry of a continuous green T-intersection.[4]

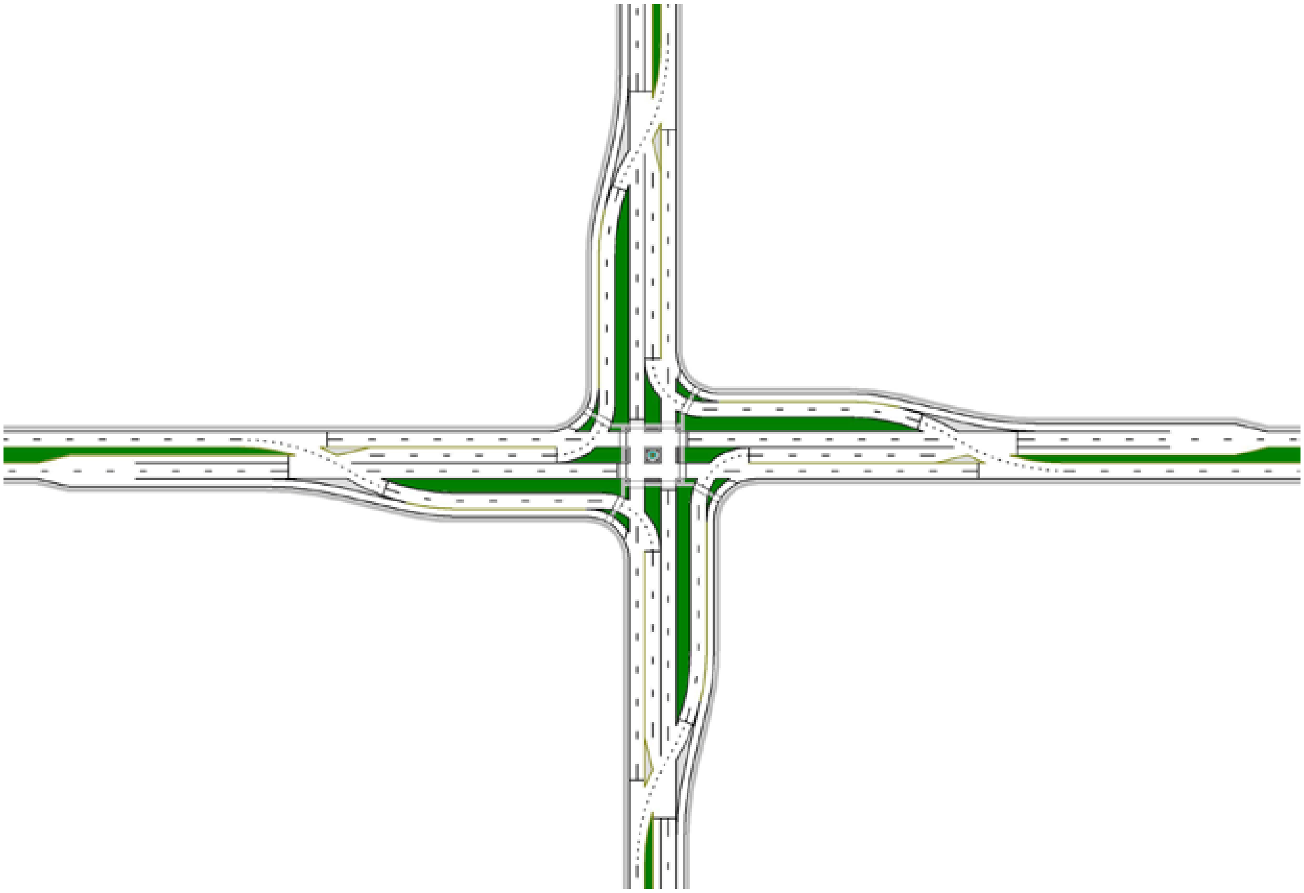
Continuous green T-intersections have been implemented in Florida, Maryland, Virginia, and Michigan. Figure 150 presents an aerial illustration of one in Arlington, VA.

Source: Google™ Earth

Figure 150. Example of a continuous green T-intersection in Arlington, VA.

6.3.6 Parallel Flow Intersection

Several DLT intersections have been constructed in the past decade in the United States, as documented in chapter 2. A variant of the DLT intersection is the parallel flow intersection or paraflow that is illustrated in figure 151. This design has been patented (U.S. Patent No. 7,135,989) by Quadrant Engineering, LLC.[77]



Source: Quadrant Engineering, LLC

Figure 151. Illustration. Typical geometry of a parallel flow intersection.

As in a DLT intersection, the left-turning traffic crosses over opposing through lanes and travel on bypass lanes. The bypass roadway is located parallel to the cross street and merges to the main road at the crossover or bypass. After the left-turn traffic accomplishes the left-turn movement at the main intersection, it merges to the main traffic on the receiving lanes with the help of bypass lanes and the crossover on the receiving approach.[78]

In this design, left-turning traffic faces opposing traffic and signal control at two junctions—the crossover and the main intersection. The main intersection operates under signal control with two phases, and the crossover junctions have coordinated signal control with the main intersection. Figure 152 shows the aerial view of a parallel flow intersection in Oaklyn, NJ. The intersection functions as a partial parallel flow with left-turn crossovers (highlighted in the box) on the mainline approaches.

Source: Google™ Earth

Figure 152. Photo. Aerial view of parallel flow intersection in Oaklyn, NJ.

CHAPTER 7. DOUBLE CROSSOVER DIAMOND INTERCHANGE

7.1 INTRODUCTION

The DCD interchange is a new interchange design that is slowly gaining recognition as a viable interchange form that can improve traffic flow and reduce congestion. Similar to the design of a conventional diamond interchange, the DCD interchange differs in the way that the left and through movements navigate between the ramp terminals. The purpose of this interchange design is to accommodate left-turning movements onto arterials and limited-access highways while eliminating the need for a left-turn bay and signal phase at the signalized ramp terminals. Figure 153 shows the typical movements that are accommodated in a DCD interchange. The highway is connected to the arterial cross street by two on-ramps and two off-ramps in a manner similar to a conventional diamond interchange. However, on the cross street, the traffic moves to the left side of the roadway between the ramp terminals. This allows the vehicles on the cross street that need to turn left onto the ramps to continue to the on-ramps without conflicting with the opposing through traffic. There is no patent on the DCD interchange design as there are with some of the other designs discussed in this report.

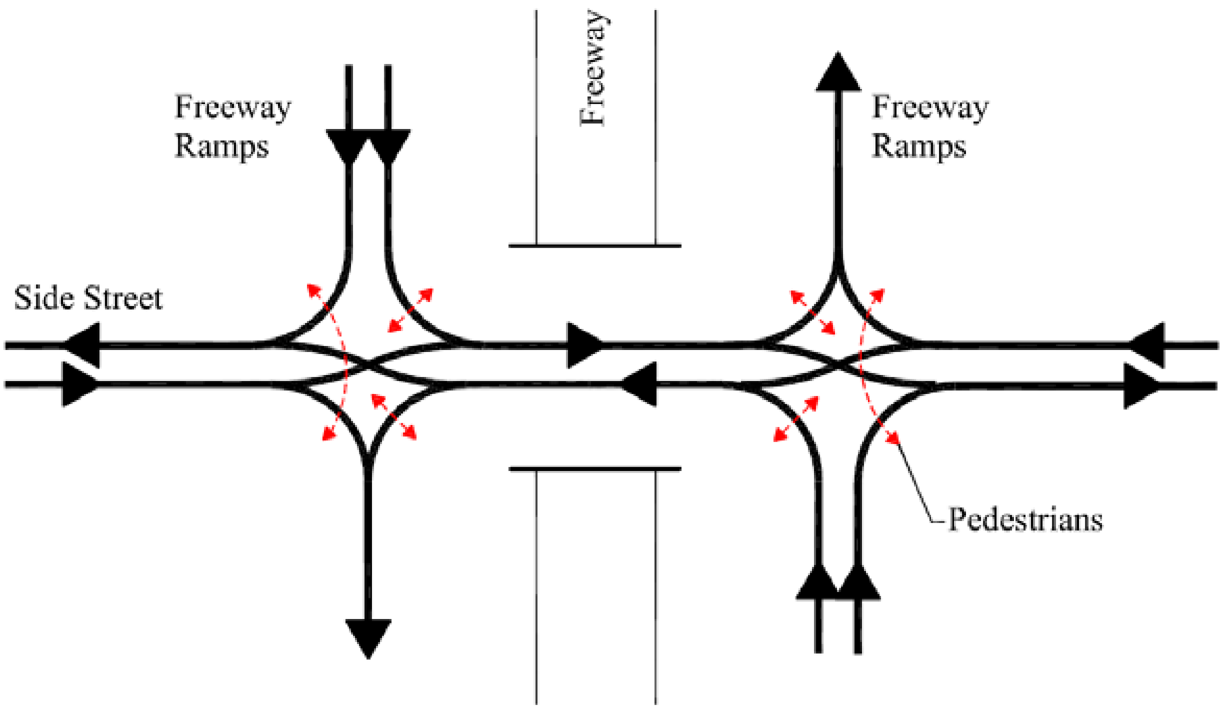


Figure 153. Illustration. Typical DCD interchange configuration.

As in a conventional diamond interchange, the right-turn movements from the cross street to the ramps occur at the ramp terminal intersections. Using figure 154, which shows a situation where the freeway mainline passes under the crossroad, the through and left-turn movements (depicted as yellow arrows) are criss-crossed so that the eastbound traffic travels on the roadway that is to the left, and the westbound traffic travels on the roadway to the right in the interchange area. The intersections where the opposite directions of travel cross are under signal control. Across the bridge, vehicles travel on the opposite side of the road than is normal. After crossing the bridge, the left-turn movements proceed to the ramps of the major street without any further signal control (depicted as orange arrows). The opposing right-turn movements merge with the left-turning traffic on the ramp. The through movements on the crossroad cross over to the right side at the second signal intersection and continue in their respective directions (shown as blue arrows). In addition, the red arrows depict side street right-turn movement while the blue circles show the signal-controlled crossovers. Under this configuration, the two crossovers operate under signal control with two phases.

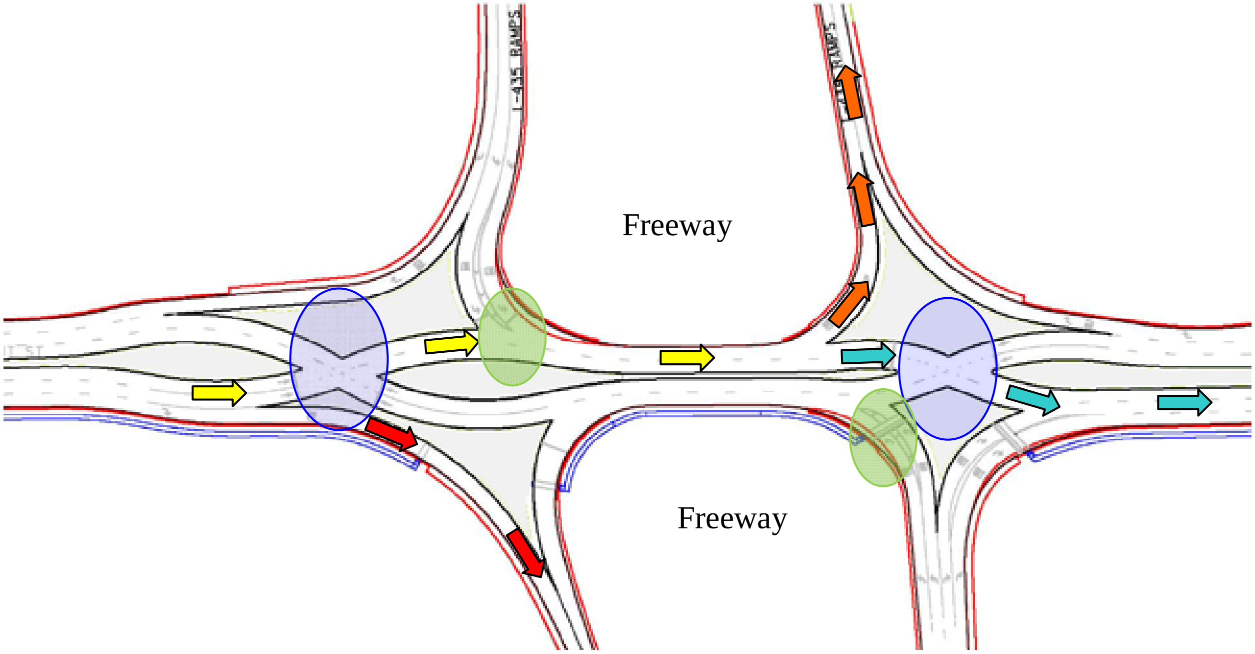


Figure 154. Illustration. Crossover movement in a DCD interchange.

7.1.1 Existing DCD Interchanges

As of this report, there are four known existing applications of DCD interchanges. The first one in the United States opened to traffic on June 22, 2009, in Springfield, MO. Three additional DCD interchanges have existed in France for more than two decades. The four known locations include the following:

- The crossing of I-44 and U.S. Route 13 in Springfield, MO (see figure 155).
- The crossing of Highway A13 and RD 182 (Boulevard de Jardy) in Versailles, France (see figure 156).
- The crossing of Highway A4 (Boulevard des Allies) and Boulevard de Stalingrad in Le Perreux-sur-Marne, France (see figure 157).
- The crossing of Highway A1 (L’Autoroute du Nord) and Route d’Avelin in Seclin, France (see figure 158).

Figure 155. Photo. First U.S. DCD interchange in Springfield, MO.

Source: Google™ Earth

Figure 156. Photo. DCD interchange in Versailles, France.

Source: Google™ Earth

Figure 157. Photo. DCD interchange in Perreux-sur-Marne, France.

Source: Google Earth™

Figure 158. Photo. DCD interchange in Seclin, France.

The DCD interchange in Springfield, MO, was constructed to replace an existing conventional diamond interchange and is in use.(79) Several additional DCD interchanges are under construction and being planned in Missouri. A DCD interchange was developed for the existing conventional diamond interchange at the intersection of I-435 and East Front Street in Kansas City, MO. Construction is expected to begin in 2010.(80) The aerial perspective views of the simulated version of this planned project are shown in figure 159 and figure 160. A second DCD interchange under construction in Missouri is at the existing diamond interchange at the crossing of I-270 and Dorsett Road in Maryland Heights. According to the Missouri Department of Transportation (MoDOT) Web site, construction will be completed by November 2011.(81) A third DCD interchange site under construction is located at the crossing of U.S. Route 60 and National Avenue in Springfield, MO. The DCD interchange is also one of the two alternatives being considered for the interchange of I-590 and Winton Road in Brighton, NY. The construction is anticipated to start in winter 2010.(82) In addition, several agencies in Oregon, Maryland, and New Mexico are considering DCD interchange options as part of project planning studies for interchange design and modification.

Figure 159. Illustration. Simulated DCD interchange.

Figure 160. Illustration. Crossover of a simulated DCD interchange.

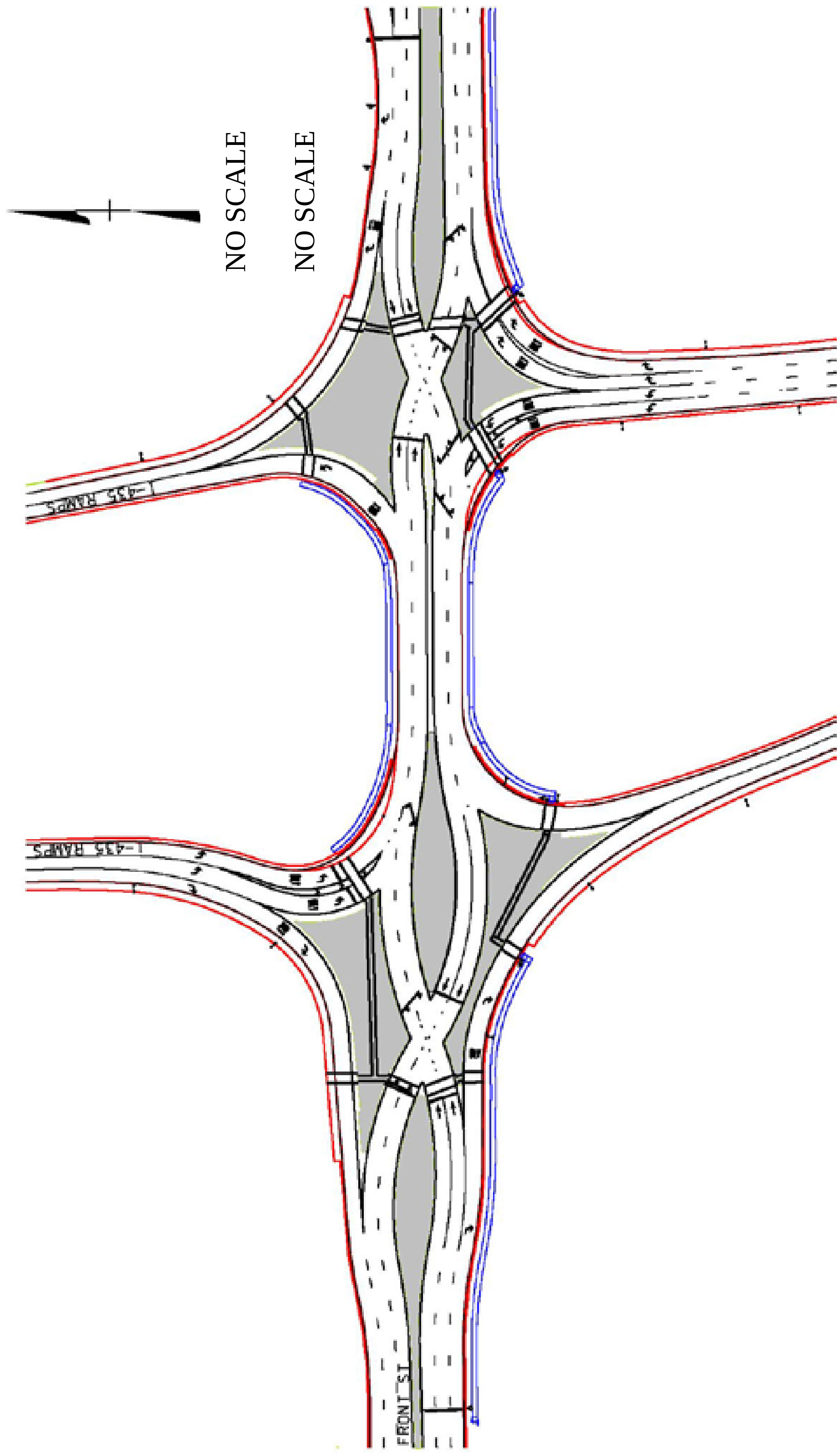
7.1.2 Advantages and Disadvantages of DCD Interchanges

A DCD interchange is expected to be beneficial in situations where high left-turn and through volumes contribute to high delays. The DCD interchange design enables the signal phases to be reduced by allowing movements from the ramps to proceed concurrently with the through movements on the crossroad. As a result, the signal-controlled crossovers operate with two-phase signal control compared to a conventional diamond interchange which normally has three-phase signal control. A DCD interchange has fewer conflict points compared to an equivalent diamond interchange, which can lead to fewer crashes.(76) Another benefit of the DCD interchange is that it combines lane assignments for the left-turn and through movements on the bridge structure and therefore requires a narrower bridge structure compared to a conventional diamond interchange.

A possible drawback of the DCD interchange is driver confusion that may result from the counterintuitive direction of travel between the ramp terminals of the interchange. Driver confusion can be reduced with the help of proper designing, signing, and marking.(83) In addition, glare screens can be used, as discussed later in the chapter, to effectively reduce driver confusion. Pedestrian accommodations for a DCD interchange include crossings and signalization at the ramp junctions or nodes of the interchange. Crossing the arterial crossroad is slightly different from crossing at a conventional diamond interchange. Because the crossover junctions in a DCD interchange operate with two-phase signal control, pedestrians cross the junction in two stages. A central island serves as refuge for pedestrians between each stage or signal phase.

7.2 GEOMETRIC DESIGN CONSIDERATIONS

Figure 161 shows a design for a DCD interchange. As of this report, MoDOT is in the planning stage with this DCD interchange. The primary design element of a DCD interchange is the relocation of the left-turn and through movements to the opposite side of the road within the bridge structure. The turning radii used at the crossover junction to displace these movements is around 300 ft. Consideration should be given to designing radii at crossovers with heavy vehicles in mind. On rural locations where the minor street has high-speed limits, the use of reverse curvature has been suggested. This may result in loon-like flare-outs at the ends of the bridge structure, as shown in figure 162.[(79)] Additional right-of-way may be required to widen the bridge or the underpass structure.



Source: Missouri Department of Transportation guidance in Kansas City, MO

Figure 161. Illustration. Typical full DCD interchange plan view.

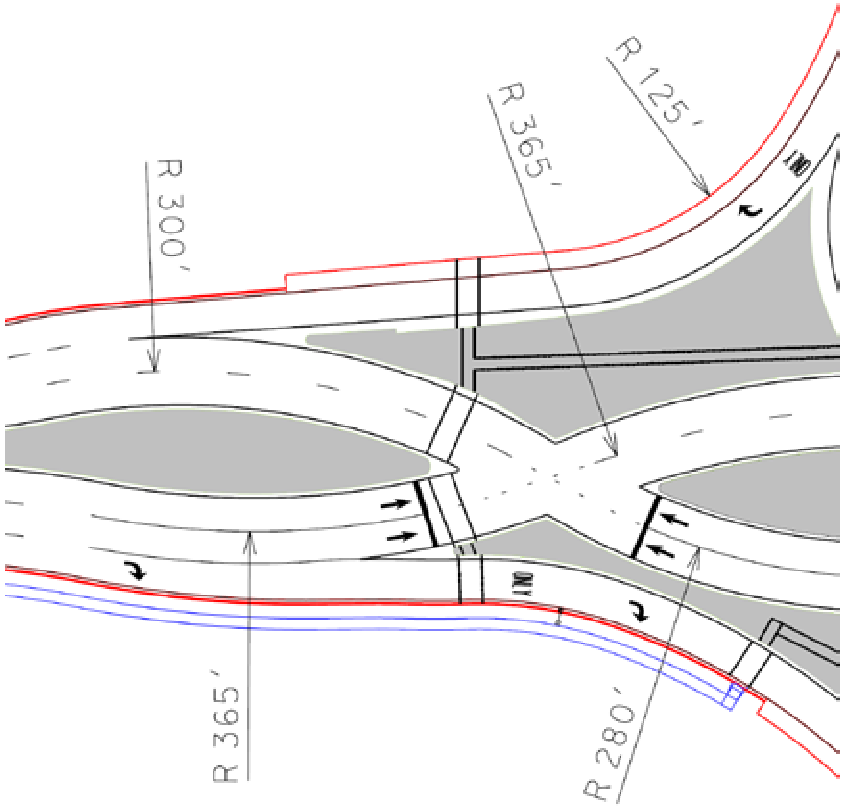


Figure 162. Illustration. Crossover movement in a DCD interchange.

Median width is also an important design element for a DCD interchange. Greater median width is required for the flaring needed for reverse curves. Designers can obtain minimum median widths from the AASHTO *Green Book*.[7] Designers should also take into account the installation of post-mounted signs on medians on the bridge deck for safe and effective channelization of traffic. Appropriate offsets for signs should be in accordance with the *MUTCD*.[8] Recent driver simulator experiments on the DCD interchange, which included the use of glare screens, showed no erroneous maneuvers by tested subject drivers.[8]

MoDOT performed extensive analysis on the benefits of the DCD interchange alternative compared to a tight urban diamond interchange (TUDI).[84] Some of the conclusions from comparing the two alternatives for this location are as follows:

- The DCD interchange design reduces the number of lanes required under bridges from five to four, eliminating the need to build retaining walls for the specific interchange.
- The DCD interchange design reduces the number of lanes needed on cross streets beyond the interchange (see figure 161).
- The DCD interchange design has more storage capacity between the ramp terminals—550 ft for a DCD interchange versus 350 ft in a compressed diamond.

- The DCD interchange design provides better sight distance. With this mainline over situation, bridge columns do not block the views of left-turning drivers to oncoming traffic as they wait to turn left onto the on-ramp.

- The DCD interchange incorporates geometry, which has traffic-calming features, by reducing speeds while increasing throughput. This should result in fewer and less severe crashes.

Some suggested design practices, based on MoDOT input, include the following:

- The minimum crossing angle of intersection should be 40 degrees.

- The radius design should accommodate between 25 and 30 mi/h.

- Superelevation may not be needed because it could detract from any desired traffic calming effect.

- Lane width should be around 15 ft.

- Design should accommodate WB-67 trucks.

- Adequate lighting should be provided.

- Nearside signals should be considered.

- DCD interchange designs may only be appropriate where there are high-turning volumes.

- Nearby intersections with high cycle lengths should be avoided.

- Pedestrians at free-turning movements should be evaluated, and pedestrian signals may be needed.

- The noses of the median island should extend beyond the off-ramp terminals to improve channelization and prevent erroneous maneuvers.

- Left- and right-turn bays should be designed to allow for separate signal phases.

7.3 ACCESS MANAGEMENT CONSIDERATIONS

Effects on adjacent businesses and land users should be reviewed closely on a case-by-case basis, particularly if driveway locations affect signal operation and number of phases. Any driveways should be located beyond the crossover signal-controlled intersection. Many transportation department agencies adhere to minimum spacing policies with respect to the distance from interchange ramps to median openings and signal-controlled intersections. Those same policies are equally applicable to DCD interchanges.

Little consideration has been given to frontage roads as part of DCD interchanges, as it would be more complicated to add them to a DCD interchange than to conventional diamond and single-point urban interchanges. Since the main operational benefit of the DCD interchange is the efficient two-phase control, the inclusion of frontage roads would incorporate additional phasing, thus reducing the benefit of the configuration. Frontage roads are used to enhance local access, and their application usually depends on traffic and land-use needs. In addition, frontage roads can be integrated with interchanges to alleviate congestion on arterials. Chapter 10 of the *NCHRP Report 420* discusses application guidelines for one-way and two-way frontage roads and their key features.(12)

U-turn movements are penalized in a DCD interchange design because the crossover requires turn restrictions. However, U-turn movements can be facilitated upstream of the interchange with the help of a median opening as described in chapter 2. Chapter 4 of the *NCHRP Report 420* discusses design, location, and spacing of driveways in detail.(12) Chapter 9 of the *NCHRP Report 420* discusses the access separation techniques at interchanges and access separation policies for several State agencies in rural and urban areas, which can be applied to a DCD interchange.(12)

7.4 TRAFFIC SIGNALIZATION TREATMENTS

A DCD interchange typically has two signalized junctions or nodes for left-turn crossovers, which are shown in figure 163. These junctions are two-phase signals, with each phase dedicated for the alternative opposing movements. Compared to conventional interchanges, the DCD interchange allows for relatively shorter cycle lengths at the signalized junctions, which reduce the lost time per cycle as a result. Left turns from both off-ramp terminals are preferably operated under signal control because turning angles are very sharp. Moreover, off-ramp right turns are also signalized when no acceleration lanes are provided for merging because right-turning drivers are normally seeking gaps on the right side of the conflicting entry flow and not the left side, as in the DCD geometry. In the figure, the green circles represent typical signal locations.

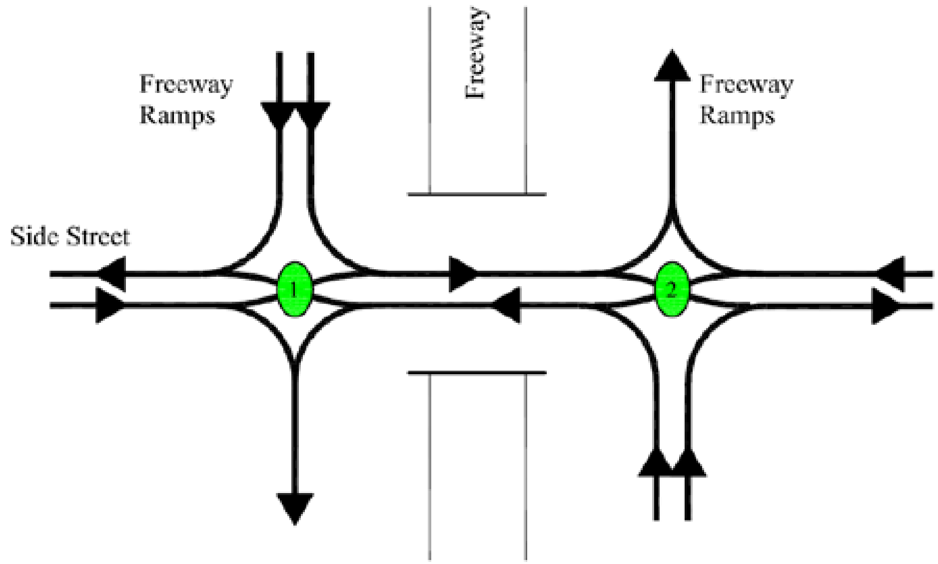
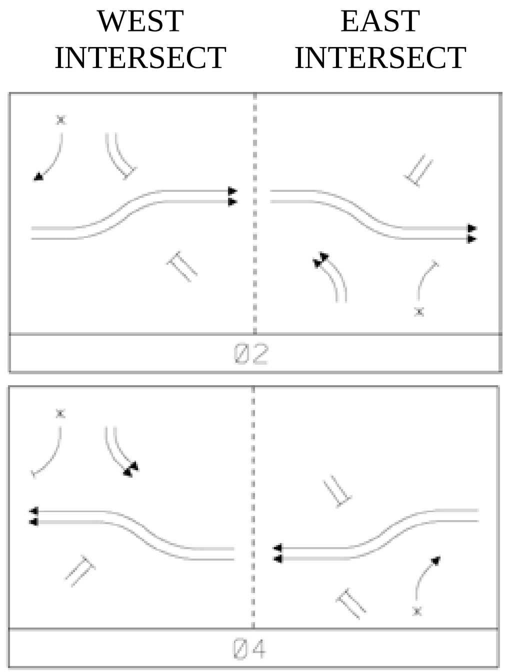


Figure 163. Illustration. Typical DCD interchange signal locations.

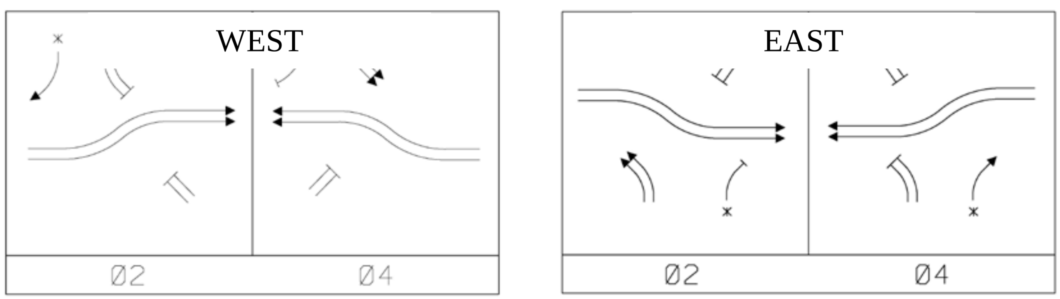
7.4.1 Signal Design and Operations

The DCD interchange design is suitable for interchanges with heavy ramp movements and relatively low through volumes on the arterial or directional unbalanced through volumes on the arterial. Signals on a DCD interchange may be fully actuated to minimize delay. Detectors can be used at all of the crossovers on all approaches, and durations of signal phases can vary on a cycle-by-cycle basis. Both of the signalized junctions can operate under a single controller or each with a separate controller, with phasing schemes similar to those illustrated in figure 164 and figure 165, respectively.



Note: Applicable for right turns operating under signal control.

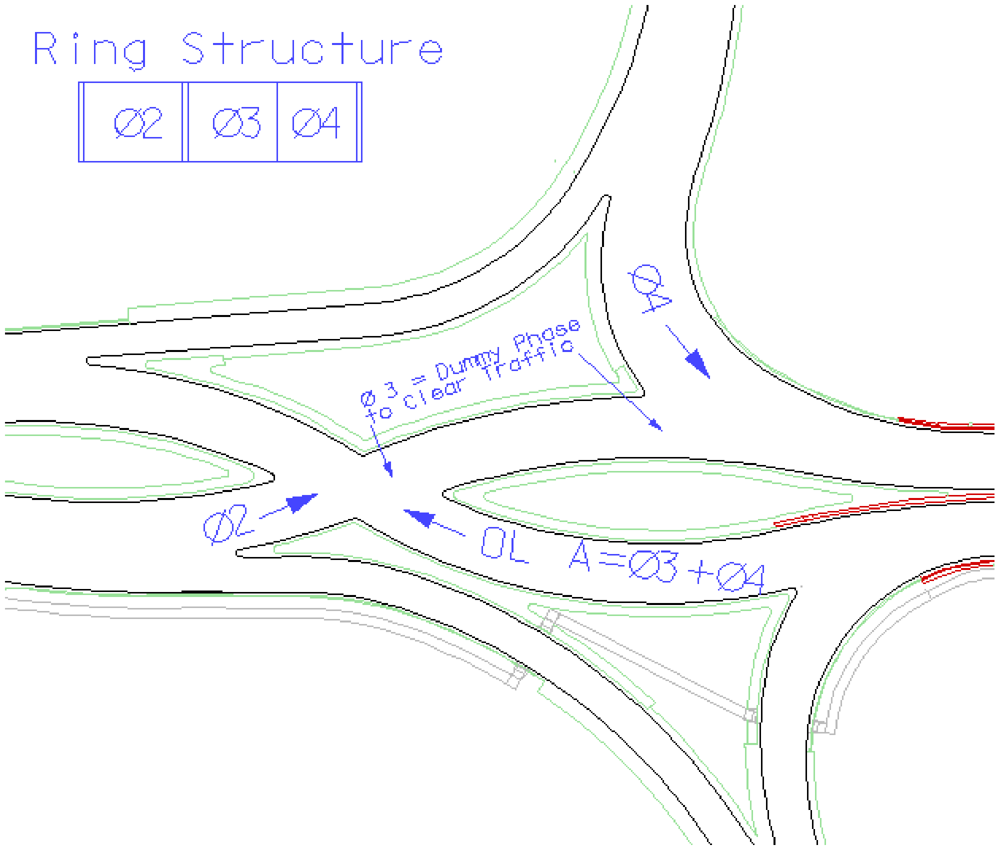
Figure 164. Illustration. Signal phasing for a DCD interchange operating under a single controller.



Note: Applicable for right turns operating under signal control.

Figure 165. Illustration. Signal phasing for a DCD interchange operating under separate controllers.

Signal phasing, as proposed by MoDOT designers for the eastern intersection of the DCD interchange in Kansas City, MO, is shown in figure 166. It should be noted that the geometry of the east crossover junction at the Kansas City DCD interchange allows for the more simplified phasing as illustrated in figure 164 and figure 165. This is because the spacing between the crossover junction and the intersection with the left turns from the off-ramp is very close. However, in the case of the west intersection (or ramp terminal), left turns from the southbound off-ramp merge onto the arterial distance downstream from the crossover intersection. Under the simplified phasing in figure 164 and figure 165, this requires a long clearance interval. It can be seen in figure 166 that MoDOT accommodated this with an overlap phase for the time to clear the intersection.

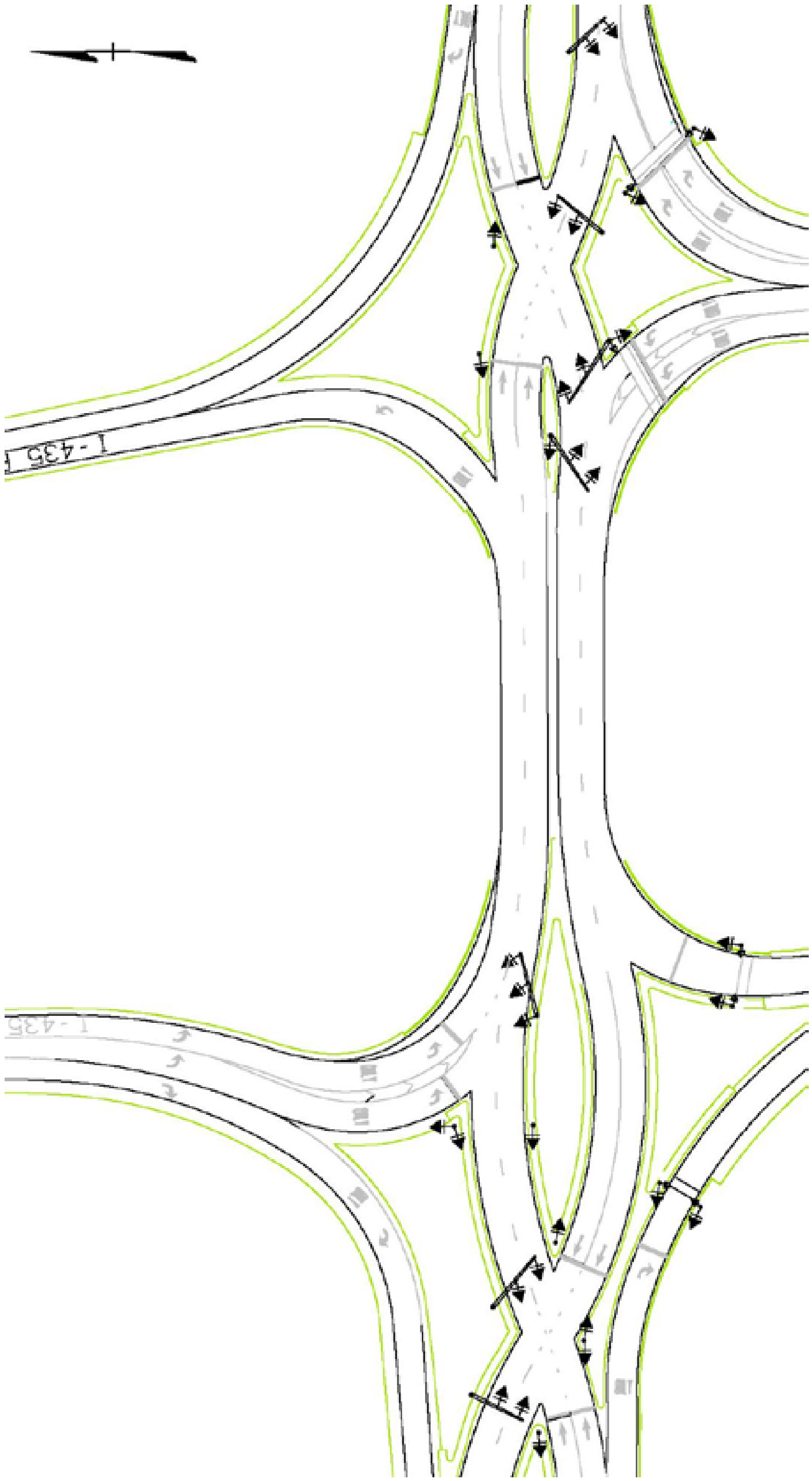


Source: Missouri Department of Transportation

Figure 166. Signal phasing used for proposed DCD interchange at Kansas City, MO.[84]

Signal pole and head locations are shown in figure 167 from an aerial plan view. Typical far side mast arm poles are proposed for each signal-controlled approach. Different views of the signal heads from a driver perspective are shown in figure 168 through figure 170. The use of straight green arrows for the signal heads at the crossovers have been proposed for the DCD interchange in Kansas City, MO (see figure 168). Nearside signal heads have also been proposed to provide additional guidance. The FHWA driver simulation study indicated that sight distance to the traffic signal heads was an issue.[83]

Pedestrian considerations are discussed in detail in section 7.5. In general, the signalized crossovers with two-phase signal control have short cycle lengths and therefore shorter pedestrian clearances and less exposure than conventional intersections.[84] Similar to conventional intersections, under most scenarios, pedestrians are required to cross channelized turning roadways that carry free-flowing traffic. However, in the Kansas City, MO, DCD interchange, signal-controlled pedestrian crossings were proposed on the two on-ramps (ramps exiting the arterial heading toward the merge onto the freeway). Signal control at these locations is unexpected from a driver perspective and could result in additional rear-end crashes at the ramps.



Source: Missouri Department of Transportation

Figure 167. Illustration. Signal mast arm and pole locations being implemented in Kansas City, MO.

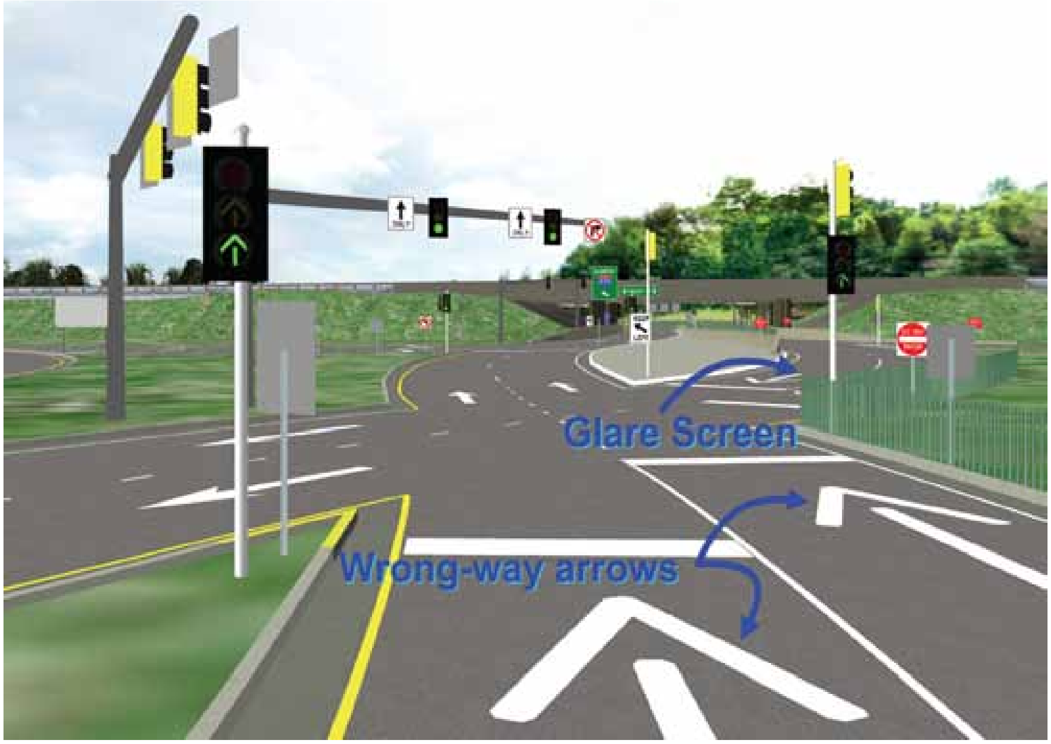


Figure 168. Illustration. Signal pole locations proposed in Kansas City, MO, from the FHWA driver simulator.[(83)]

Figure 169. Illustration. Signal pole locations proposed for the planned DCD interchange in Kansas City, MO.[(83)]

Figure 170. Illustration. Green arrows, overhead lane usage, and skip markings proposed for the planned DCD interchange in Kansas City, MO.[83]

7.4.2 Signing and Marking

The highway signs and pavement markings implemented at a DCD interchange are similar to those implemented at a conventional diamond interchange. The significant differences from a conventional interchange relate to the treatment at the midblock left-turn crossovers and the turning restrictions at the main interchange. Some of the key features of signing and marking a DCD interchange include the following:

- Use of advance signing and guide-sign applications on the exit ramps and on the bridge structure.
- Use of advisory speed signs.
- Use of skip marks on the left-turn lanes for clear guidance through the intersection crossover area (see figure 168 through figure 170).
- Use of overhead signing to clearly communicate lane use and directions. Examples are shown in figure 170.
- Use of “Wrong Way” and “Do Not Enter” signs to reduce the probability of wrong maneuvers. An example is shown in figure 171.

Figure 171. Illustration. "Wrong Way" and "One Way" signs proposed for the DCD interchange in Kansas City, MO.[83]

Figure 172 and figure 173 show the signing and marking plan developed by MoDOT for the planned DCD interchange in Kansas City, MO. Figure 174 through figure 176 illustrate some of the signing and marking techniques used from a driver's point-of-view.

During the planning stages of the DCD interchange alternative, the following issues were debated:

- The prohibition or acceptance of left turns on red for on-ramp left-turn traffic.
- The sufficiency of standard advance signing for drivers.
- The use of "glare screens" with respect to channelization issues and sight distance requirements.
- The use of alternate "Keep Left" (R 4-8b) signs to replace the traditional "Keep Left" signs (R 4-8).

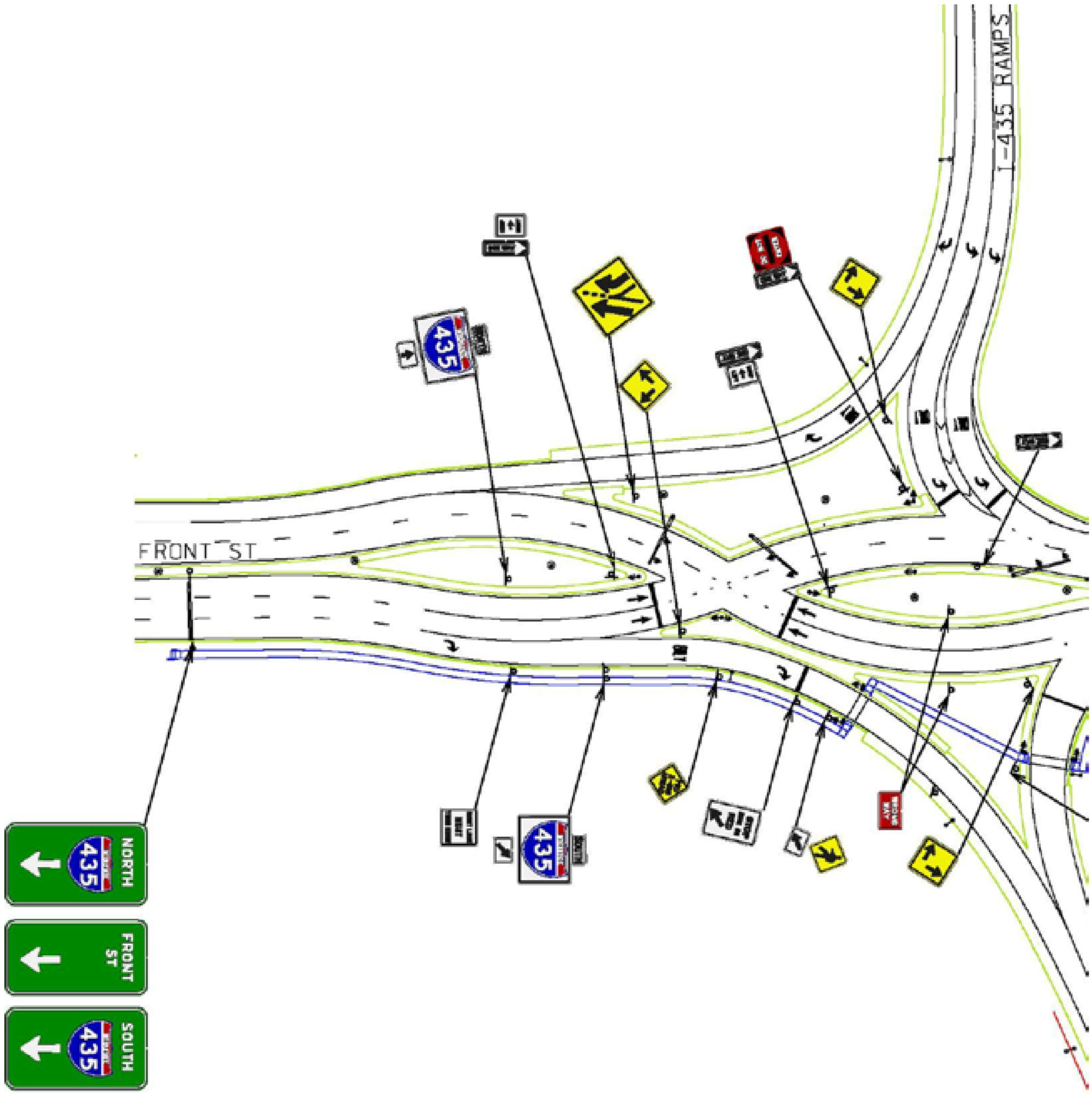


Figure 172. Illustration. DCD interchange signing and marking plan derived from Missouri practice—west end.

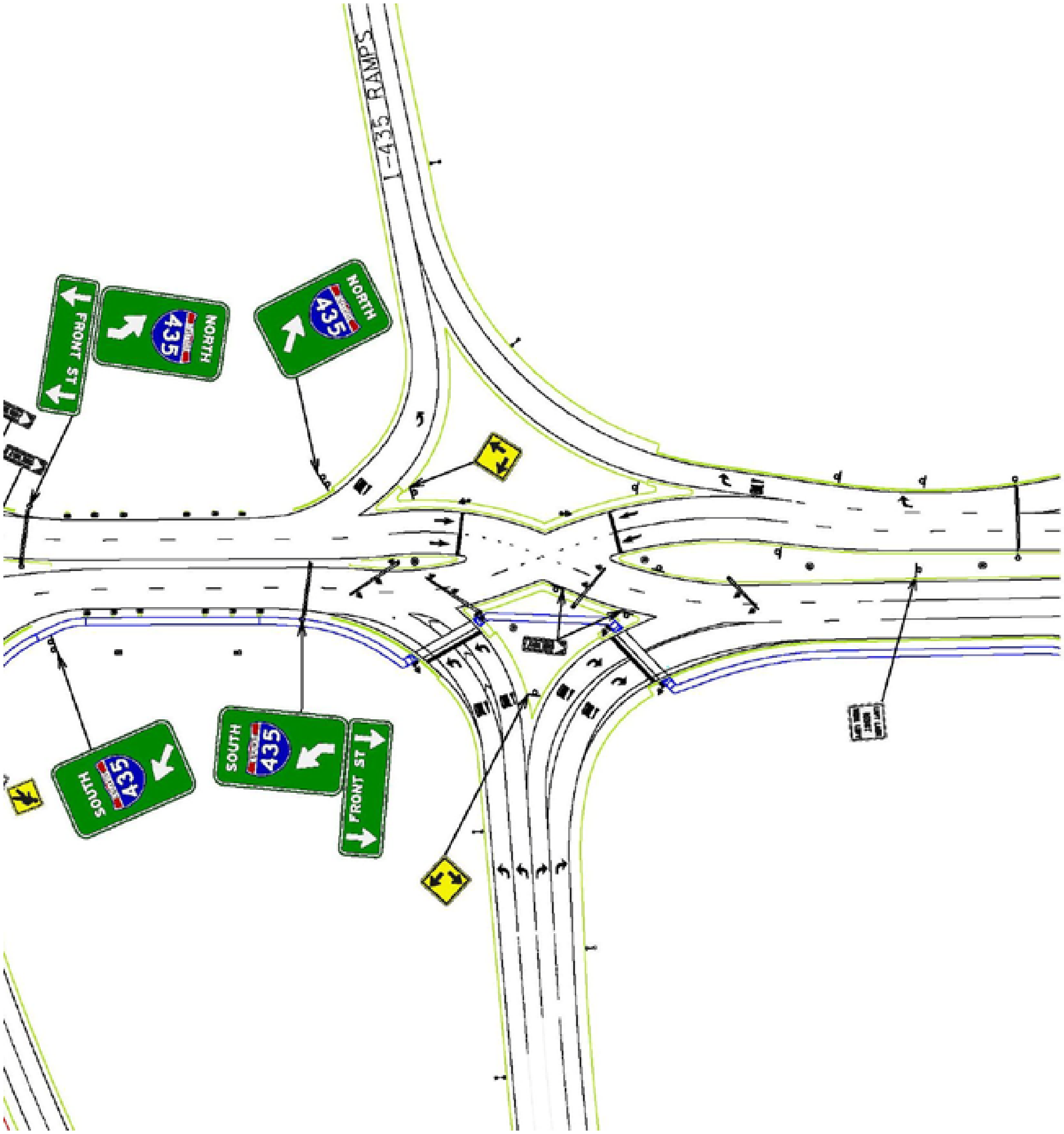


Figure 173. Illustration. DCD interchange signing and marking plan derived from Missouri practice—east end.

Figure 174. Illustration. Overhead signing proposed for the planned DCD interchange ahead of the crossover in Kansas City, MO.[(83)]

Figure 175. Illustration. Signing and pavement marking proposed for the planned DCD interchange ahead of the left turn off-ramp in Kansas City, MO.[(83)]

Figure 176. Illustration. Advanced pavement markings and guide signs from the off-ramp.[(83)]

7.5 ACCOMMODATION OF PEDESTRIANS, BICYCLISTS, AND TRANSIT USERS

As discussed earlier in this chapter, figure 161 shows where pedestrian crosswalks may be located at a DCD interchange. The DCD interchange in Versailles, France, has crosswalks across some of the ramps at the interchange nodes, as can be seen in figure 156. Pedestrian crossings for a DCD interchange involve crosswalks and signalization at the junctions of the interchange. Figure 177 shows the pedestrian movements at a DCD interchange. In this concept, walkways are shown on both the south and north sides of the bridge over the freeway. Depending on the pedestrian network in the vicinity of the interchange, it may not be necessary to have pedestrian walkways on both sides. In MoDOT's design, pedestrians cross only on the south side of Front Street. Since the crossover junctions in a DCD interchange operate on a two-phase signal control, pedestrians are directed to cross the arterial in two stages. Adequate pedestrian refuge should be provided between all stages of the crossing. The central island serves as a refuge for pedestrians between each stage or signal phase.

Figure 177 shows the side street crossing on the west side of the DCD interchange. A pedestrian crossing from the northwest quadrant to the southwest quadrant (i.e., between A and D) has to cross a free-flow off-ramp (that could be signalized), the westbound through lanes, the eastbound side street lanes, and finally a free-flow on-ramp (that can also be signalized). Similarly, pedestrians crossing the freeway ramps (i.e., between D and E and between E and F) would also cross in two stages with the channelizing island acting as refuge. Because pedestrian crossings are separated into stages with refuge islands, pedestrians crossing a DCD interchange experience fewer conflicting traffic streams than at a typical conventional diamond interchange.

An alternative pedestrian accommodation is to have pedestrians walk in the median of the DCD interchange.

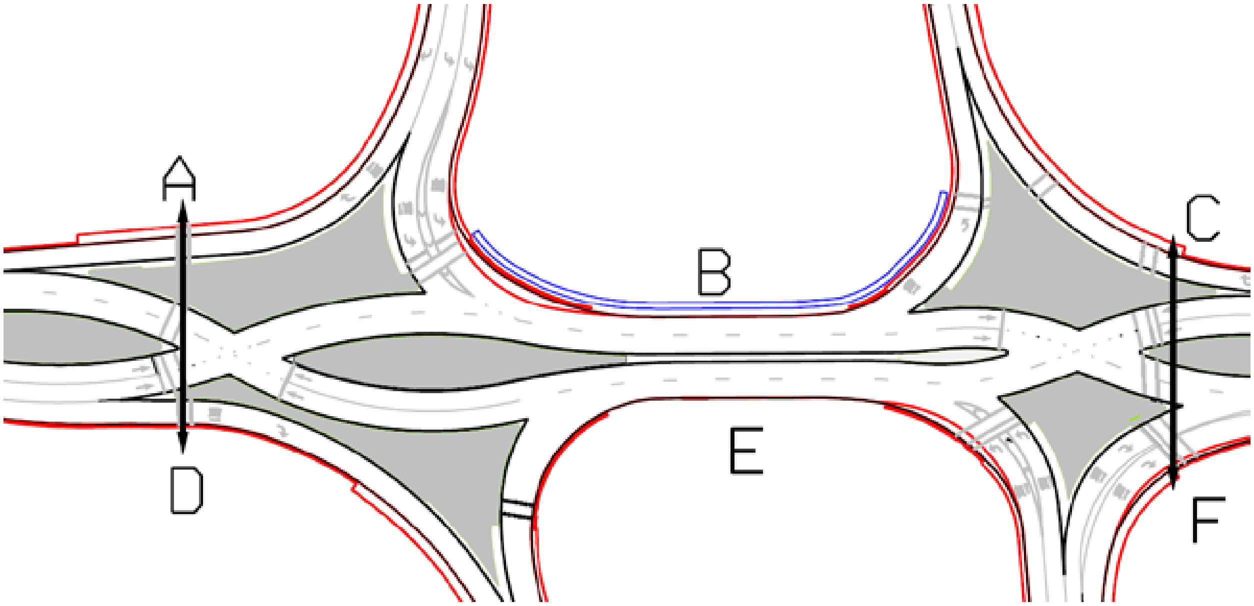


Figure 177. Illustration. Pedestrian movements in a DCD interchange.

Figure 178 shows an example of pedestrian accommodation in the median of the DCD interchange built by MoDOT for the junction of I-44 and MO Route 13 in Springfield, MO.

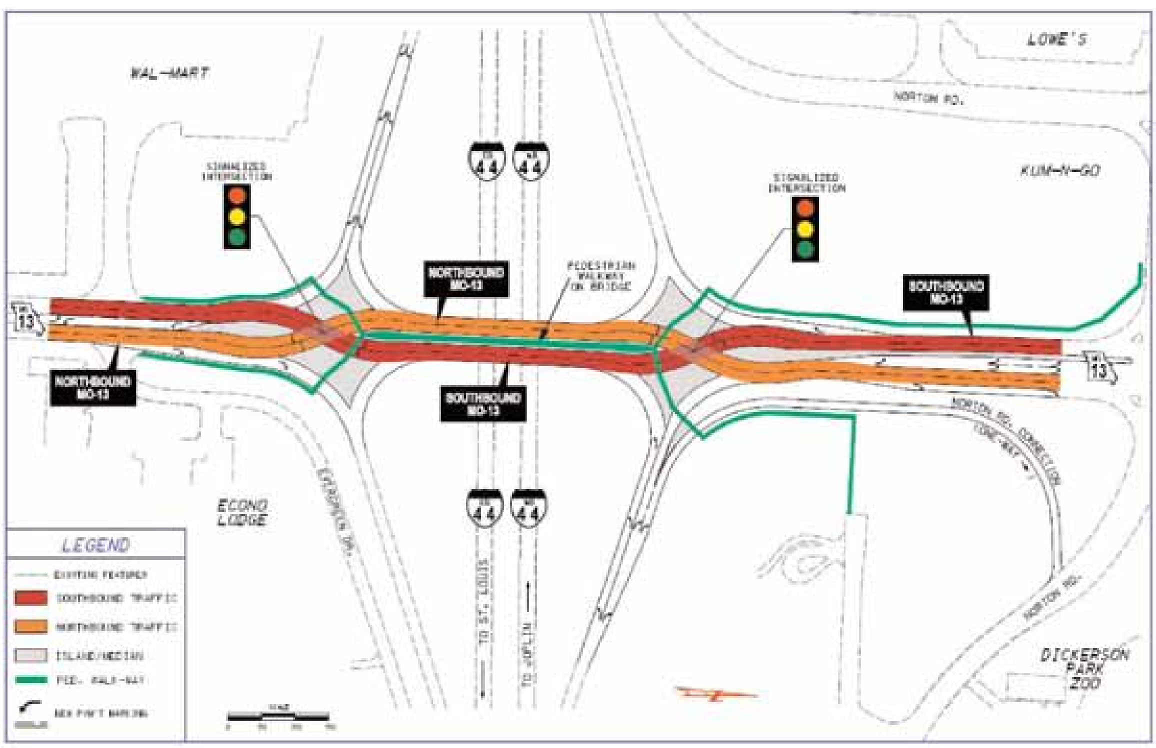


Figure 178. Ilustration. Proposed pedestrian accommodation in the median of the DCD interchange in Springfield, MO.

The DCD interchange may be unfamiliar to pedestrians, especially those with visual impairments. Suggestions to accommodate pedestrians in a DCD interchange are discussed below.

7.5.1 Provide Wayfinding Signing for Pedestrians

As with other alternative intersections, wayfinding signing can help direct pedestrians through the interchange area to desired destinations. Providing adequate wayfinding signing is important given that most pedestrians are unfamiliar with a DCD interchange design and may attempt to cross at undesirable locations. Adequate signing helps reduce pedestrian confusion and may encourage pedestrians to use designated travel paths through the intersection. However, it will likely not eliminate all undesirable crossing actions. Raised tactile surfaces are helpful to people with disabilities.

7.5.2 Channelize Pedestrians

The DCD interchange design involves multiple-stage crossings with islands acting as refuges. In addition, the design of crossovers at the nodes of the interchange typically results in flares and large central islands. Barriers help prevent pedestrians from attempting to cross at undesirable locations. Barriers should be rigid with appropriate end treatment. Alternatively, railing systems that pose a lesser hazard to motorists (i.e., spearing hazard) can be used to channelize pedestrians.

7.5.3 Provide Right-Turn Channelizing Islands to Accommodate Pedestrians

Raised channelizing islands can enhance pedestrian safety by allowing pedestrians to cross a right-turn lane and then reach a refuge area before attempting to cross the through and left-turn lanes. Channelization is often designed to promote movement of traffic by including geometric features that favor high-speed right turns such as a wide turn radius, flat entry angles leaving the right turn, and wide lanes. Configuring the right-turn slip lane with a tighter radius and shorter crossing distance forces turning vehicles to slow down and provides drivers with visibility of crossing pedestrians. This reduces both the crossing distance for pedestrians and the potential for conflict with vehicles.

7.5.4 Ensure Direct Pedestrian Crossings and Paths

Since pedestrians often walk the shortest or most convenient path between two points, it is critical that designers consider the most direct pedestrian paths. Due to the complex design of a DCD interchange, crosswalk and sidewalk placement may not match the desired lines. If the paths through the intersection are not direct, pedestrians may cross outside of crosswalks where drivers are less likely to expect them. Paths should be as direct as feasible.

7.5.5 Consolidate Pedestrian Crossings Across the Side Street Right-Turn Movement

The DCD interchange plan shown in figure 161 shows two pedestrian crossings of the side street right-turn movement: one crosses the side street at the node, and the other follows along the side street and across the ramp. This configuration may be confusing to both motorists and pedestrians. Motorists probably do not expect two pedestrian crossings on the freeway on-ramp, and pedestrians with limited vision or cognitive abilities may have difficulty determining how to cross the street in either direction. Designers should consider consolidating these crossings at one location across the side street right-turn movement. This can be located at either side of the node depending on roadway geometry and pedestrian desire lines.

7.5.6 Enhance Conspicuity of Pedestrian Crossings and of Pedestrians Waiting to Cross

Complex intersection designs, overhead directional signs, and high-speed traffic can create a complex driving environment and divert attention away from pedestrians. Pavement markings should consist of high-visibility continental or ladder-type markings, and signage for pedestrian crossings should include warning signs (W11-2) and a warning sign with a supplemental diagonal downward arrow (W16-7p) at the crossing as a minimum. Glare screens should be placed so that visibility of pedestrians waiting to cross is not obstructed.

7.5.7 Provide Accessible Devices to Assist Disabled Pedestrians

The nontraditional pedestrian and vehicle paths may challenge pedestrians, especially those with vision or cognitive impairments who are not be able to use wayfinding signs. Some of the cues pedestrians with vision impairments rely on to cross intersections, such as the sound of traffic parallel to their crossing, are different. Pedestrians with cognitive impairments will likely find the absence of clear and direct paths challenging and are more likely to use unsafe paths though the intersections. To mitigate some of the potential impacts on pedestrians with impairments, locator tones on pedestrian signals, specialized surface treatments, and APS are recommended. The *American with Disabilities Act Accessibility Guidelines*, available on the U.S. Access Board's Web site, provides extensive information on accommodating visually impaired pedestrians.[15]

Since the DCD interchange is grade separated, designers should proactively consider how minimum design elements such as grade, cross-slopes, and vertical clearance interact to affect pedestrian safety through the intersection. If minimum design standards are not met or other design or operational issues arise at the intersection, pedestrian crosswalks across the arterial at upstream intersections—and prohibition of crossing the arterial in the DCD interchange area—may be a better option contingent on this being compatible with pedestrian traffic generators and desire lines.

Bicycles operating along the side street through a DCD interchange can be accommodated with the use of bicycle lanes or shared-use paths. Bicycle lanes should have long noncurbside sections approaching the first node and passing the second node. Passing vehicles on the right side of bicyclists may present more of a problem, as bicyclists typically are not trained to deal with moving traffic on the right side. On the approach to the first node, separation can be created between bicyclists and vehicles passing on the right by creating a wide bicycle lane. After the second node, a bicycle-vehicle crossing area can be created between the bicycle lane and vehicle lanes, which should require approaching vehicles to yield to bicyclists to allow them to merge back onto the right side of the roadway. Shared-use paths could follow the general alignment of the sidewalks illustrated in figure 161, keeping in mind the desire for the shared-use path should be as direct as possible.

7.6 OPERATIONAL PERFORMANCE

The biggest potential benefit of the DCD interchange is its ability to combine the ramp-turning movement phases with the through movement phases without penalizing other phases.[(5)] This section documents the findings of other operational studies that included the DCD interchange and summarizes findings from a VISSIM® analysis of different traffic volume scenarios. First, a summary of the findings from previous relevant research is presented.

MoDOT conducted analyses of the DCD interchange alternative and a TUDI alternative.[(85)] Some of the operational advantages of the DCD interchange alternative were as follows:

- The DCD interchange was likely to double the throughput of the left-turn lanes and was therefore preferable to a conventional diamond with triple left-turn lanes.
- The DCD interchange design had more storage capacity between the ramp terminals (550 ft for the DCD interchange compared to 350 ft for the compressed diamond).
- The DCD interchange allowed for simpler signal timing and geometry, which accommodated U-turns if necessary.
- The smaller ramp intersections in a DCD interchange indicated that vehicles had shorter clearance times and delays.

Some of the operational concerns of the DCD interchange design included the following:

- Driver expectations.
- The possible need for more extensive public involvement.
- The fact that pedestrians had to cross free-flowing ramps.
- The option of signalized pedestrian crossings on ramps which would mean that traffic turning right from the ramp would have to periodically stop for red signal indications when the pedestrian phase was called into service.

Chlewicki analyzed the DCD interchange and compared results to the conventional diamond interchange.[(76)] The operational analysis was performed using Synchro® to compare phasing and geometrics and SimTraffic™ for the simulation.[(21)] Key findings were as follows:

- Total delay for the DCD interchange was three times less compared to a conventional diamond interchange.
- Stop delay was four times less compared to a conventional diamond interchange.
- The total number of stops was approximately half as those of a conventional diamond interchange.

Speth performed operational analyses to compare the DCD interchange with conventional diamond interchanges and the SPUI.[86] The tools utilized for the analysis were Synchro®, SimTraffic™, and VISSIM®.[21] Some of the highlights from the findings of this investigation included the following:

- System-wide measures of effectiveness (MOEs) of a DCD interchange compared favorably to that of a similar conventional diamond interchange and a single-point urban interchange.

- The DCD interchange had less average delay time per vehicle, average number of stops per vehicle, and total number of stops.

Bared, Edara, and Jagannathan conducted a study of two different designs of DCD interchanges.[87] The simulation experiment evaluated the following:

- A four-lane DCD interchange in the east-west direction.

- A six-lane DCD interchange in the east-west direction.

For the first case, five different traffic flow scenarios were considered including one low-, one medium-, and three high-flow scenarios. The performance of the DCD interchange was measured for high flows beyond the service volumes of a conventional diamond.

Table 26 and table 27 summarize the traffic scenarios and results. For the six-lane case, six traffic flow scenarios were considered, as summarized in table 28 and table 29. After the completion of the analysis for all these cases, the service volumes for the DCD interchange design were estimated.

The two-phase operation was utilized with overlaps permitted to optimize efficiency. For the given phasing sequence, the cycle length of 70 s was found to be optimal for lower to medium flows, and a cycle length of 100 s showed best results for higher flows. The yellow time used was 3 s, and the all-red interval was 2 s at the end of every phase.

Performance criteria for the intersection design included average delay time per vehicle, average stop time per vehicle, average number of stops per vehicle, average queue length, and maximum queue length. After analyzing these four traffic scenarios, the service volumes for the design were calculated based on two criteria—LOS and model throughput. When the input volumes were so high that they resulted in an LOS F for the intersection or when the model throughput was less than the input volume, then the service volume was reached. The simulation period modeled was 1 hour, and the traffic arrivals were Poisson with exponentially distributed headways. The results obtained for DCD interchange were compared with the results of a conventional diamond interchange. The signal design and optimal signal setting for the conventional diamond interchange were obtained from PASSER™ III software.

Table 26. Four-lane DCD interchange versus conventional diamond interchange—traffic scenarios.

Traffic Scenario	Northbound Off-Ramp (veh/h)			Southbound Off-Ramp (veh/h)			Eastbound (veh/h)			Westbound (veh/h)			Total Flow (veh/h)
	L	T	R	L	T	R	L	T	R	L	T	R	
High 3	750	0	450	750	0	450	450	850	550	450	850	550	6,100
High 2	700	0	400	700	0	400	400	800	500	400	800	500	5,600
High 1	650	0	350	650	0	350	350	750	450	350	750	450	5,100
Medium	400	0	200	400	0	200	200	500	300	200	500	300	3,200
Low	200	0	100	200	0	100	100	300	150	100	300	150	1,700

Table 27. Four-lane DCD interchange versus conventional diamond interchange—performance results.

Traffic Scenario	Input Flow (veh/h)	Model Throughput (veh/h)		Delay Time (s/veh)		Stop Time (s/veh)		Number of Stops		Max Queue (ft)	
		DCD	Diamond	DCD	Diamond	DCD	Diamond	DCD	Diamond	DCD	Diamond
High 3	6,100	5,800	5,228	62	105	32	55	1.4	2.4	1,191	1,665
High 2	5,600	5,380	5,187	40	91	24	46	0.9	2.3	1,000	1,170
High 1	5,100	4,912	4,869	32	66	20	35	0.8	1.8	482	1,108
Medium	3,200	3,074	3,104	20	26	12	13	0.7	0.9	239	262
Low	1,700	1,631	1,631	17	20	11	11	0.6	0.8	123	120

Table 28. Six-lane DCD interchange versus conventional diamond interchange—traffic scenarios.

Traffic Scenario	Northbound Off-Ramp (veh/h)			Southbound Off-Ramp (veh/h)			Eastbound (veh/h)			Westbound (veh/h)			Total Flow (veh/h)
	L	T	R	L	T	R	L	T	R	L	T	R	
High 3	1,000	0	700	1,000	0	700	700	1,100	800	700	1,100	800	8,600
High 2	800	0	500	800	0	500	500	900	600	500	900	600	6,600
High 1	700	0	400	700	0	400	400	800	500	400	800	500	5,600
High	650	0	350	650	0	350	350	750	450	350	750	450	5,100
Medium	400	0	200	400	0	200	200	500	300	200	500	300	3,200
Low	200	0	100	200	0	100	100	300	150	100	300	150	1,700

Table 29. Six-lane DCD interchange versus conventional diamond interchange—performance results.

Traffic Scenario	Flow Input (veh/h)	Model Throughput (veh/h)	Delay Time (s/veh)	Stop Time (s/veh)	No. of Stops (per veh)	Max Queue (ft)
High 3	8,600	8,200	58	28	1.1	785
High 2	6,600	6,500	32	19	0.8	450
High 1	5,600	5,500	28	18	0.7	421
High	5,100	5,040	27	18	0.7	305
Medium	3,200	3,170	18	11	0.6	186
Low	1,700	1,690	16	11	0.6	121

Figure 179 depicts the DCD interchange and conventional diamond interchange configuration.

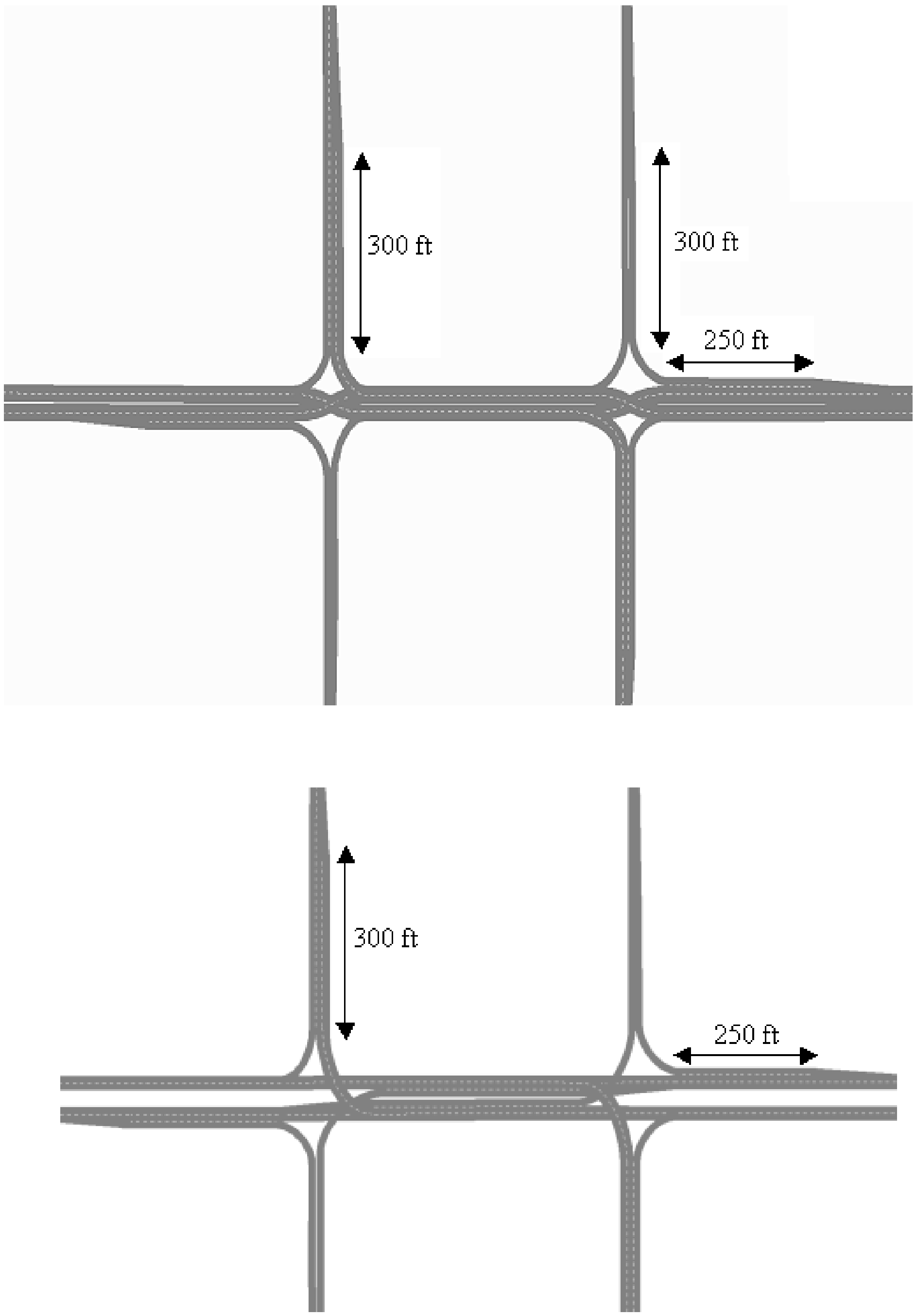


Figure 179. Illustration. Layout of a DCD interchange (top) and a conventional diamond interchange (bottom) in VISSIM®.

As noted in table 30, performances at the lower and medium volumes were quite similar for both the DCD interchange and the conventional diamond interchange. However, results from higher volumes show that this conventional diamond had lower throughput, higher average delay per vehicle, higher stop time, and longer queues as compared to DCD interchanges. The results indicated that the maximum off-ramp flows for a DCD interchange (700 veh/h/lane) were greater than the corresponding flows in the conventional diamond (390 veh/h/lane). When off-ramp flows were set at 390 veh/h/lane for a DCD interchange, the service flow for the crossroad increased by 100 veh/h/lane.

Table 30. Service volumes of conventional and DCD interchange designs.

	North Bound Off-Ramp (veh/h/lane)	South Bound Off-Ramp (veh/h/lane)	East Bound (veh/h/lane)		West Bound (veh/h/lane)	
Service Volumes	**L**	**L**	**L**	**T**	**L**	**T**
Conventional diamond	390	390	330	600	330	600
Double crossover (four lanes)	600	600	600 (L/T)*	600	600 (L/T)*	600
Double crossover (six lanes)	700	700	600 (L/T)*	600	600 (L/T)*	600

Note: (L/T) means that the left turning traffic as well as the through traffic use the lane.

Results for the six-lane analysis are shown in table 31, which also included three higher volume scenarios. Service volumes of each of the three designs are shown in figure 28 and table 29. The service volumes for northbound left turns, southbound left turns, eastbound through, eastbound left, westbound through, and westbound left turns are shown. The DCD interchange design did not have any exclusive left-turn lanes unlike the conventional diamond design, and the left-turning vehicles shared the lane with the through movements. The significant difference between the results of DCD interchange and the conventional diamond related to the service volume of left-turn movements. The service volumes of eastbound and westbound left turns and off-ramp left turns for the DCD interchange were almost twice that of the conventional diamond.

Table 31. Service volumes and delays for tight diamond (TD) and DCD interchange designs.

Geometric Cases			Input Volumes						Simulation Thruput						Average Delay (s/veh)
			Major Road			Ramp		Total Input	Major Road			Ramp		Total Thruput	
			Left	Thru	Right	Left	Right		Left	Thru	Right	Left	Right		
1	DCD interchange	Two thru lanes, one right lane per approach on major road, one shared left-thru lane, one thru lane per approach on bridge and two left lanes, one right lane on each off-ramp	600	300	300	400	250	3,700	592	297	298	404	243	3,665	39.5
			300	600	300	400	250	3,700	297	597	298	408	243	3,684	33.3
2	DCD interchange	Three thru lanes, one right lane per approach on major road, one left lane, one shared left-thru lane, one thru lane per approach on bridge, two left lanes, and one right lane on each off-ramp	900	1,000	300	500	250	5,900	902	984	302	509	236	6,028	60.0
			900	500	300	500	250	4,900	981	502	297	509	236	4,866	41.9
			450	1,000	300	500	250	5,000	444	1,001	296	509	236	4,978	48.5
			1,200	700	300	700	250	6,300	1,040	603	269	719	239	5,740	83.3
			900	1,000	300	800	250	3,500	695	773	215	807	240	5,458	98.2
			900	1,000	300	600	250	6,100	914	999	302	618	236	6,135	89.2
			900	1,000	300	700	250	6,300	843	929	291	717	239	6,036	95.7
			1,400	500	300	800	250	6,500	1,135	407	238	808	239	5,654	87.2

3	DCD interchange	Three thru lanes, one right lane per approach on major road, one shared left-thru lane, two thru lanes per approach on bridge, two left lanes, and one right lane on each off-ramp	500	1,500	300	400	250	5,900	467	1,421	300	407	243	5,838	85.5
			800	1,200	300	400	250	5,900	681	1,017	271	407	243	5,236	96.0
4	TD interchange	Two thru lanes, one left lane, one right lane per approach on major road, two thru lanes, one left lane per approach on bridge, two left, and one right on each off-ramp	600	600	300	400	250	4,300	546	576	283	407	256	4,133	99.3
			300	600	300	400	250	3,700	288	598	301	412	256	3,709	37.4
5	TD interchange	Three thru lanes, two left lanes, one right lane per approach on major road and two left lanes, two thru lanes, one left lane per approach on bridge, and one right lane on each off-ramp	900	1,000	300	500	250	5,900	895	1,010	298	512	257	5,940	52.0
			900	500	300	500	250	4,900	893	500	290	509	257	4,898	58.8
			450	1,000	300	500	250	5,000	449	996	296	513	257	5,021	38.8

Offset ramp terminals were assumed to be about 500 ft; however, the DCD interchange design also worked for shorter offsets. When the offset was reduced to 300 ft for the same signal cycle (100 s), the service volume of northbound and southbound left turns (off ramps) was lower than the capacities obtained for a span of 500 ft, approximately 200 veh/h/lane less for the six-lane design case. Service volumes of all other movements remained unchanged. When a shorter cycle length (80 s) was used, the service volume of these off-ramp left turns decreased by only 100 veh/h/lane, but the service volume of through traffic was reduced by approximately 75 veh/h/lane. In any case, the performance was still better than the corresponding conventional diamond design.

The following summarizes the major findings of the study conducted by Bared, Edara, and Jagannathan:[(87)]

- For higher traffic volumes, the DCD interchange demonstrated better performance and offered lower delays, fewer stops, lower stop times, and shorter queue lengths as compared to the performance of the conventional design. For lower volumes, the performance of the DCD interchange and conventional diamond intersections were similar.

- Service volumes for all signalized movements were higher for the DCD interchange as compared to the conventional diamond. The service volume of left-turn movements was twice that of the corresponding left-turn service volumes of the conventional diamond. This analysis indicated that the DCD interchange design was superior to the conventional diamond because exclusive left-turn lanes were not necessary for the DCD interchange as they can be for through movements.

- A comparable conventional diamond had six lanes on the bridge section (e.g., two through and one left turn in each direction). When higher service volumes were needed, there were benefits to converting to a six-lane DCD interchange instead of pursuing the more costly option of widening bridges and approaches to provide dual left lanes in each direction.

- While the DCD interchange as analyzed did not allow through movements from off- to on-ramps, it did allow U-turn movements with fewer conflicts than at a conventional diamond interchange.

7.6.1 Analysis of Simulation Results

VISSIM® was used to gain additional insight into the operational performance of the DCD interchange in comparison to a tight diamond (TD) interchange. Three geometric design cases of DCD interchanges and two geometric design cases of TD interchanges were simulated. Table 31 shows the geometric design configurations and volumes of the cases simulated. The lane configurations and geometric features for the DCD interchanges and TD interchanges varied considerably since the number of lanes on the major road approach and bridge deck was different. The vehicular volumes on opposing approaches were balanced (50:50 directional split). The VISSIM® simulation network was 1 mi long on the major and minor road approaches for the cases simulated. In addition to the use of standard defaults in VISSIM®, the following constants were maintained for each simulation:

- Optimum fixed signal timing determined using Synchro®.[21]
- Yellow times determined using ITE policy.
- All-red times determined using ITE policy.
- A total of 5 percent heavy vehicles on all legs.
- A 0.5-mi network size in each direction from the main intersection.
- Single right-turn bays on the major road.
- Right-turn on red allowed at each signal, no left-turn on red allowed.
- A 10-ft median width on bridge deck.
- A 45 mi/h desired speed on major road.
- A 25 mi/h desired speed on off-ramp.
- Saturation headway of approximately 1,900 veh/h/lane (alpha = 3 and beta = 2).
- Seeding time of 30 minutes for the simulations.
- Running period of 60 minutes for the simulations.

Based on the VISSIM® simulation results shown in table 31, a DCD interchange processed approximately 6,000 veh/h with a six-lane bridge, while a TD interchange needed an eight-lane bridge to process the same volume. Similarly, a DCD interchange processed approximately 3,700 veh/h with a four-lane bridge, while a TD interchange needed a six-lane bridge to process the same volume. Thus, the DCD interchanges provided tremendous cost savings by having reduced bridge deck sections and conversely increased the capacity of an existing bridge deck. It is important to note that the DCD interchange typically performed better than a TD interchange when the on-ramp left-turn volumes were very high, and the major road through volumes were moderate or directionally unbalanced. Some of the situations where a DCD interchange may be suitable are as follows:

- A heavy on-ramp left-turn volumes and moderate through volumes on the arterial.
- A heavy unbalanced through volumes on the arterial.
- An on-ramp left-turning volume that is greater than 300 veh/h/lane.
- An off-ramp left-turning volume that is less than 700 veh/h/lane.

- A mainline through volume in both directions less than 650 veh/h/lane.

- An existing bridge deck with width limited where the bridge expansion is infeasible or prohibitively expensive.

7.7 SAFETY PERFORMANCE

Theoretically, the DCD interchange design offers a safety benefit due to the reduction in conflict points compared to other interchange forms. As shown in figure 180, a DCD interchange has only 14 conflict points and 2 crossing points. In comparison, figure 181 shows that a conventional diamond interchange has 26 conflict points.[83]

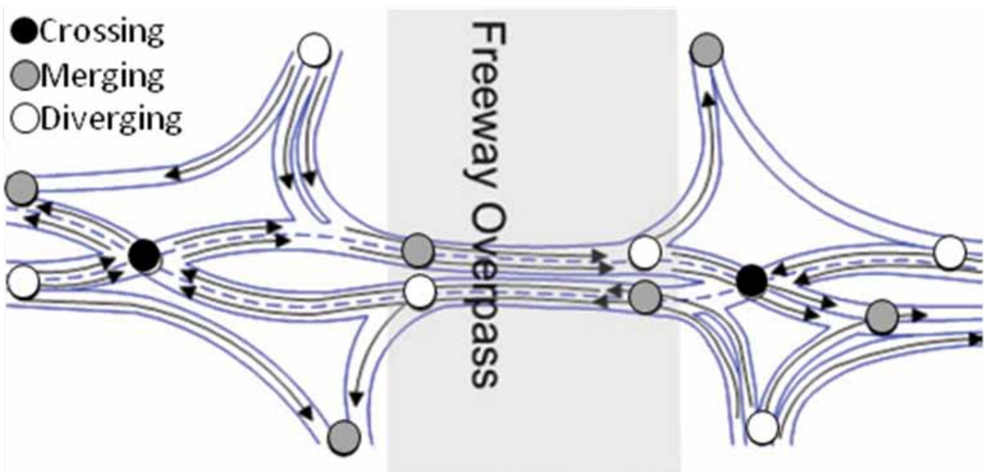


Figure 180. Illustration. Conflict points in a DCD interchange.[83]

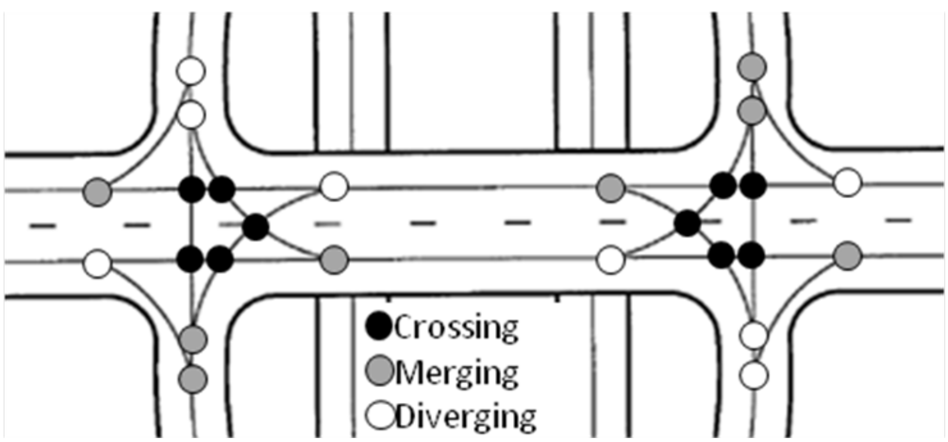


Figure 181. Illustration. Conflict points in a conventional diamond.[83]

Lower design speeds compared to a typical diamond interchange result in lower severity of accidents. Several advantageous safety related features to DCD interchange design were noted by designers of the planned DCD interchange in Kansas City, MO.[84] They included the following:

- The DCD interchange design incorporated geometry which had traffic-calming features and reduced speeds while maintaining capacity, resulting in fewer and less severe crashes.
- The DCD interchange design had ramp intersections with much shorter clearance distances compared to an equivalent compressed diamond or single-point interchange. This meant less exposure time to vehicles and therefore safer conditions.
- With the exception of possible wrong-way movement into opposing lanes at the crossover, the wrong-way movements into ramps were eliminated in the DCD interchange design.

The concern expressed by designers of the DCD interchange alternative in Kansas City, MO, was that despite the theoretical safety benefits there was limited accident history available to support its use. Furthermore, the driver expectancy issues raised safety concerns that drivers would naturally stay to the right to follow typical vehicular paths, thus traveling into the opposing through travel lanes at the crossovers.

Comprehensive tests were performed on the FHWA driver simulator with 74 licensed drivers from the Washington, DC, area of varying ages and sexes. Results from the experiment including the following:

- The simulation suggested that wrong-way maneuvers at the crossovers (staying to the right) were minimal, and navigation errors were not found to be statistically different from that of a conventional diamond interchange.
- Red light violations were not found to be statistically different compared to a conventional diamond interchange.
- Speed reduction in a DCD interchange suggested that the severity of crashes would be less compared to a conventional diamond interchange.[83]

The existing DCD interchange at the intersection of A13 and RD 182 in Versailles, France, has had 11 light injury crashes in the after period of 5 years compared to an average of 23 fatal and injury crashes of a typical diamond interchange in the United States.[88]

7.8 CONSTRUCTION COSTS

As mentioned previously, the ideal comparison of costs and benefits would consist of final construction plans for conventional diamond interchange improvements, the DCD interchange, and other grade-separated alternatives along with an evaluation of operational capacity and safety analysis. Although it is lacking detail and a sufficient number of examples, a basic cost comparison is provided for discussion.

The DCD interchange design eliminates the need for exclusive left-turn lanes on the bridge structure as in a conventional diamond interchange. Additional area might be necessary at the nodes of the interchange due to the wide flare resulting from the crossover design, as shown in figure 182. Mobilization, overhead lighting, pavement markings, and drainage costs are not significantly different between the DCD interchange and a conventional diamond interchange. Similar to a conventional diamond interchange, the DCD interchange has two signalized junctions and therefore similar signalization costs. The DCD interchange may require additional signage, lighting, and potential near-side heads. However, this cost is minimal relative to the overall construction costs.

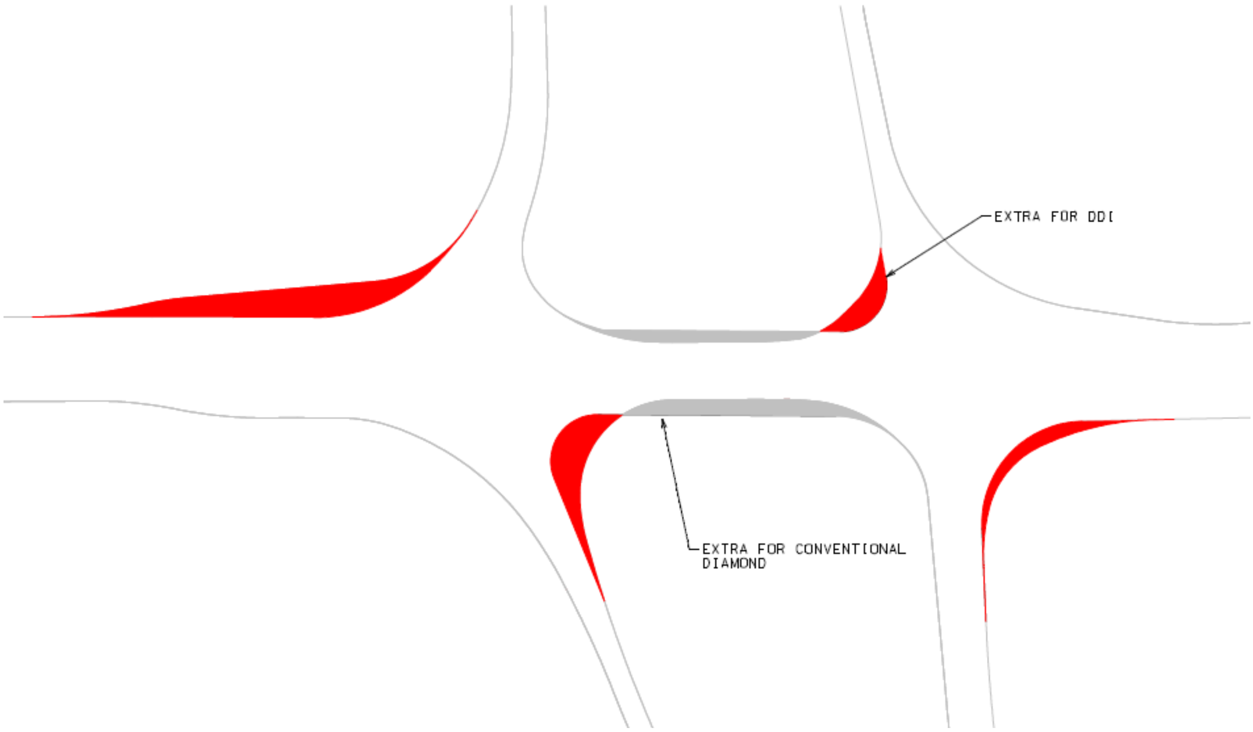


Figure 182. Illustration. Footprint comparison of a DCD interchange versus a conventional diamond interchange.

Cost estimates were obtained from MoDOT for the proposed DCD interchange in Kansas City, MO, as summarized in table 32.(84) Of the alternatives considered, the TUDI alternative was estimated to cost approximately $11.4 million, with approximately $3.9 million expended for right-of-way. For a similar DCD interchange, the estimated cost was $6.8 million, with approximately $1.5 million for a right-of-way.

The DCD interchange design reduced the number of lanes required under the bridge from six to four, eliminating the need to build retaining walls. Also, the DCD interchange design doubled the capacity of the left-turn lanes and eliminated the need for the triple left turn. These factors resulted in tremendous cost savings for the DCD interchange alternative as compared to the TD configuration. Construction costs were generally similar or lower for a DCD interchange than a comparable conventional interchange. However, more conclusive statements could not be taken due to lack of existing interchanges.

Table 32. Cost comparison for TUDI and DCD interchange alternatives.

Type of Cost	TUDI Alternative, $	DCD Interchange Alternative, $
Construction	6,866,000	4,168,000
Right-of-way	3,868,000	1,292,000
Utilities	600,000	312,000
Total	**11,334,000**	**5,772,000**

7.9 SEQUENCING OF CONSTRUCTION

Implementing a DCD interchange can cause challenges in maintaining traffic flow during construction. When MoDOT conducted the alternative analyses of the DCD interchange alternative and the current tight diamond interchange, it was concluded that the amount of time required for construction would last one season compared to a TUDI that would be constructed over two seasons.

Documentation on specific construction sequencing for the DCD interchange has not been identified. The sequence of steps for one possible approach to construct a DCD interchange is as follows:

1. Construct pavement to the outside of the existing traffic in areas where reverse curvature pushes to the outside (upstream and downstream of crossover area) while traffic remains on the existing cross street mainline in the center of the ultimate design area.

2. Construct ramp tie-ins to the new outside pavement.

3. Use the pavement constructed in step 1 as a temporary pavement to detour traffic to the outside of the crossover junctions, and construct crossover intersections in the center.

Ramp construction depends on how far from the existing ramp alignment the new ramp roadways have been designed. It is likely that narrow travel lanes on existing ramps (use of existing shoulder area, etc.) accommodate the modifications during some portion of the construction.

7.10 OTHER CONSIDERATIONS

Agencies contemplating DCD interchange installation should consider other factors in addition to safety, operations, and cost. Such factors include additional lighting, signing, signal heads, enforcement needs, left turn on red policies, and emergency vehicle needs.

Roadway lighting for a DCD interchange, like other alternative intersections and interchanges, should be increased. Since the interchange has counterintuitive movements, supplemental lighting is beneficial for unfamiliar drivers trying to maneuver the interchange during nighttime and inclement weather conditions. *NCHRP Synthesis 345*, "Single Point Urban Interchange Design and Operations Analysis," provides guidelines for roadway lighting for SPUIs.[85] Several features including embedded pavement marking lights, high mast or tower lighting, and illumination levels are discussed in chapter 6, and they can be used as a starting point. Existing lighting standards and specifications outlined in AASHTO's *Roadway Lighting Design Guide*, FHWA's *Roadway Lighting Handbook*, and the IESNA publications including *Recommended Practices for Roadway Lighting*, *Recommended Practices for Tunnel Lighting*, and *Recommended Practices for Sign Lighting* can be used for optimal lighting in a DCD interchange. (See references 26–30.) Figure 183 shows the lighting plan for the DCD interchange in Kansas City, MO.

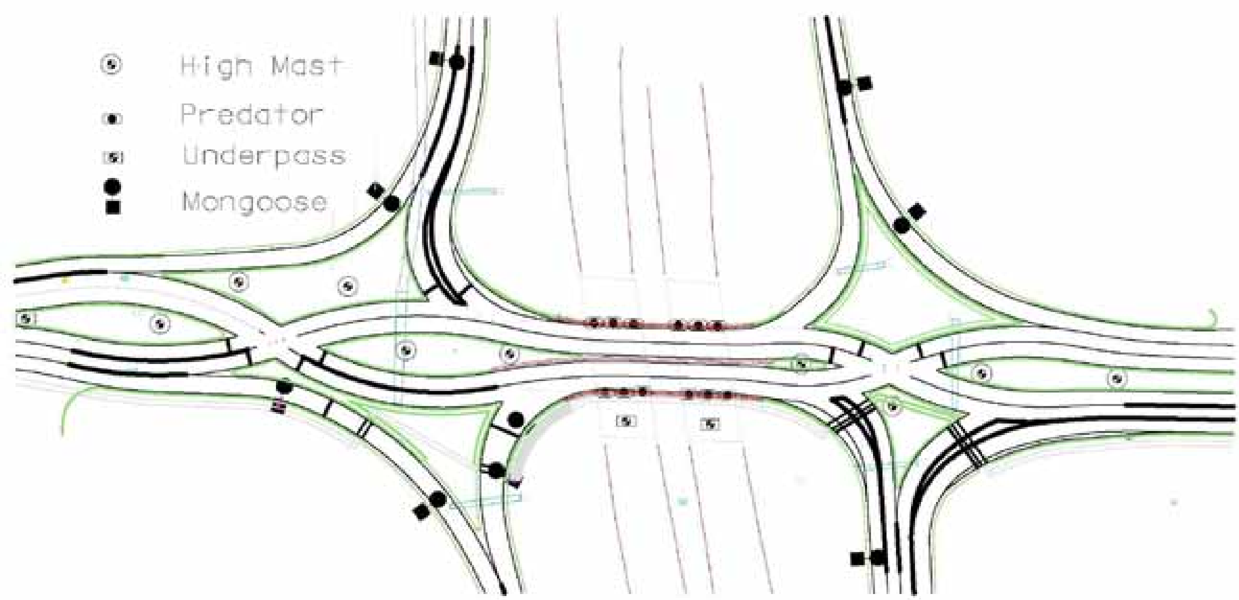


Figure 183. Illustration. Lighting plan being implemented at a DCD interchange in Kansas City, MO.

Supplemental signing and pavement markings described in section 7.4 are recommended to ensure positive guidance for vehicles traversing the new pathways through the interchange. The FHWA DCD interchange simulation demonstrated that the application of the signs and markings could reduce the anticipated driver confusion and minimize wrong-way maneuvers at a DCD interchange.[83]

Enforcement is not expected to be significantly different for the DCD interchange compared to conventional interchanges, although there is no documented or practical experience upon which this is based. Rather, theoretically, a reduction in the number of signal phases and increased efficiency may reduce red light running and congestion-related errant maneuvers. The FHWA DCD interchange simulation also indicated that speeds were effectively reduced for all drivers through the crossover intersections due to the sweeping radii relevant to the design.[83] Therefore, speed compliance would not be likely. One potential problem in the short term may be U-turns at locations where turns are not permitted (if applicable). Because of the lack of familiarity with the DCD interchange following construction, a driver's first intuition after missing a turn or passing a destination may be to perform a U-turn.

Emergency vehicle access is not likely to be an issue at DCD interchanges. The larger radii for turns would likely make for easier turning of larger and heavier emergency vehicles. Should access to adjacent parcels be limited (or removed) due to the conversion to a DCD interchange, emergency vehicle routing should be investigated prior to construction.

Sight distance for left turns from the off-ramps onto the mainline over the bridge should be reviewed to determine if left turns on red are appropriate. This sight distance can be affected by bridge structure, the skew angle of the interchange, and other roadside obstructions such as lighting and signal equipment. Prior to permitting left turns on red, care should be taken to ensure sight distance is clear to oncoming traffic.

Since the DCD interchange is new and has an unusual configuration, advance public involvement is important. News of installation of a DCD interchange should be disseminated among the local population before and during the time of opening. MoDOT is sharing information about the DCD interchange design on their Web site and inviting the general public to open house meetings.(80)

7.11 APPLICABILITY

As with all the designs described in this report, the DCD interchange design is applicable under certain conditions, but not appropriate for all conditions. A primary reason to choose the DCD interchange instead of a conventional diamond interchange is the two-phase signal operation resulting in the ability to process higher left-turn on-ramp volumes.

Some of the situations where a DCD interchange may be suitable are listed as follows:

- Heavy left turns onto freeway ramps.
- Moderate or unbalanced through volumes on the crossroad approaches.
- Moderate to very heavy left-turn volumes from the freeway off-ramps.
- Limited bridge deck width.

Typically, in suburban and urban settings, limited (or costly) right-of-way and reduced duration of construction are issues. MoDOT has demonstrated that the DCD interchange offered benefits in both of these areas.

There are cases where the DCD interchange is not a particularly viable option in urban and suburban areas. In cases where frontage road access (through movement from off-ramp to on-ramp) is needed, the DCD interchange is not preferred. The additional phase would degrade the performance and eliminate the benefit of the two-phase efficient operation. In addition, if progression with nearby signals is required due to proximity, it should be noted that given the operation of the DCD interchange, bidirectional progression may be difficult to achieve.

7.12 SUMMARY

The DCD interchange offers benefits over conventional interchange forms, as follows:

- More efficient and simplified two-phase operation.
- Increased capacity and reduced delay.
- Narrower bridge structure width.
- Reduced cost.
- Decreased speeds.
- Fewer conflict points.

At the time of this report, there were only four DCD interchanges in existence—one in the United States (in Springfield, MO) and three in France. As of this report, MoDOT was planing and about to intiate construction on additional DCD interchanges over the next few years. Their significant contributions to the development of this chapter are recognized. Although driver confusion is the largest concern associated with this design due to the unfamiliar crossover to the left side of the roadway, the FHWA driver simulation of MoDOT interchanges indicated that wrong-way maneuvers, speeds, and red light running were not significant issues.

Agencies considering DCD interchanges should be aware of disadvantages of the design relative to conventional interchanges. That is, access to adjacent parcels from the ramps (frontage road access) is not desirable as additional signal phasing reduces the efficiency of the normal two-phase operation. Furthermore, the impact on platoon progression on the arterial crossroad with adjacent nearby signals can be an issue and should be investigated on a case-by-case basis.

CHAPTER 8. DISPLACED LEFT-TURN INTERCHANGE

8.1 INTRODUCTION

The DLT interchange, also known as the continuous flow interchange, is an innovative interchange design that has several aspects similar to the at-grade DLT intersection and some aspects similar to the DCD interchange. At the time of this report, no known implementations of this treatment could be identified. Moreover, there was no patent on the DLT interchange design. Nevertheless, it is a design treatment that has been advocated as promising because it removes the conflict at the main intersection between left-turning and opposing through vehicles.[87]

The main feature of the DLT interchange design is the left-turn crossovers that are present on the cross street approaches, as shown in figure 184. In a DLT intersection, the left-turning traffic is relocated at a location several hundred feet upstream of the first signal-controlled ramp terminal of the diamond interchange. This left-turning traffic is crossed over the opposing through lanes. This traffic then travels on a new roadway that is situated between the opposing through lanes and a roadway and that carries the right-turning traffic from the ramp. These drivers then make the left turn onto the ramp.

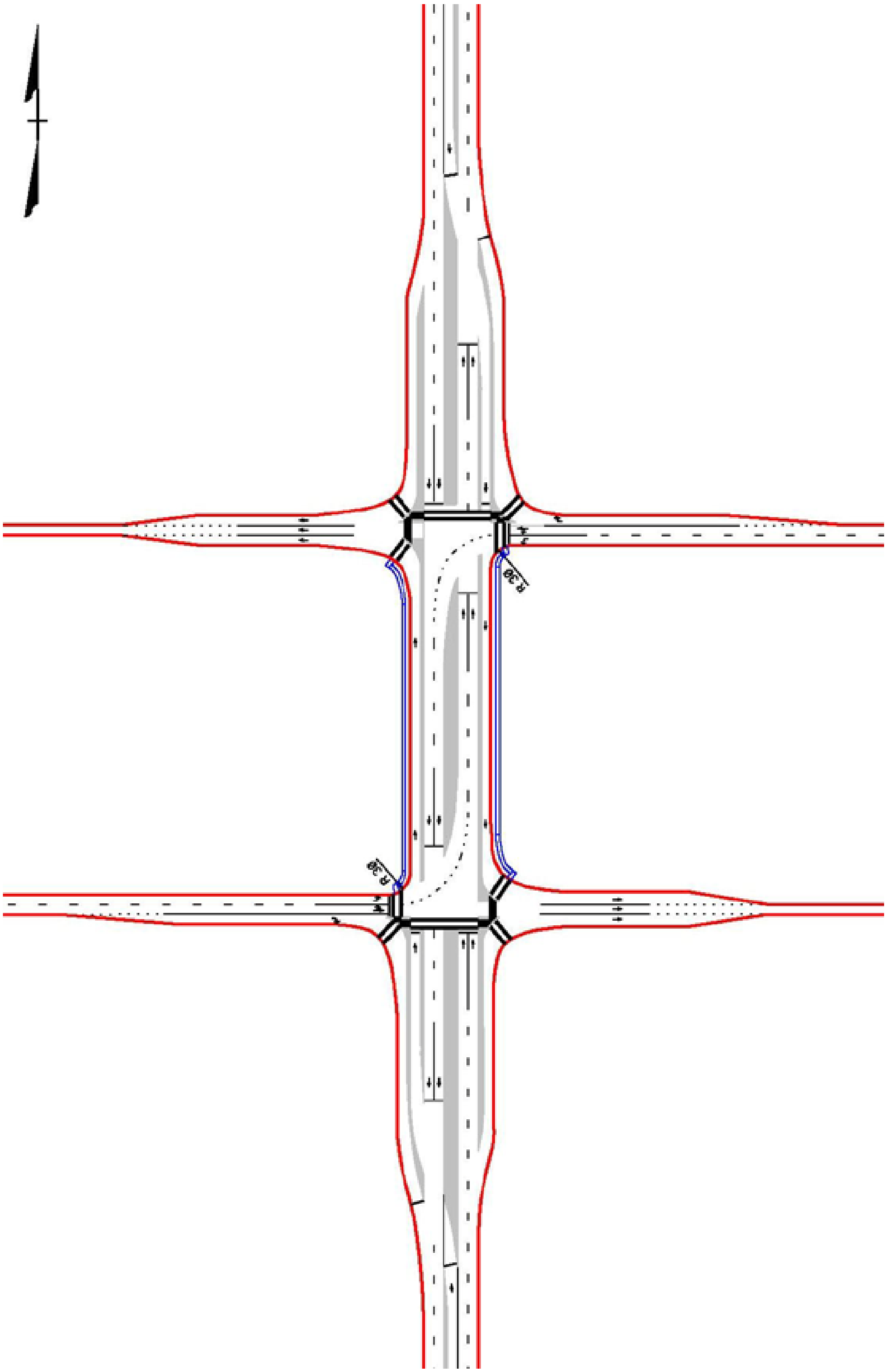


Figure 184. Illustration. Plan view of a DLT interchange.

At the first signalized ramp terminal in the interchange (shown as an oval in figure 185, representing the signal-controlled main intersection), the relocated left-turn movement proceeds straight through the signal-controlled intersection and turns left at the second ramp terminal intersection. Unlike the DCD interchange where both the left and the through movements travel in the flipped direction, only the left-turning traffic travels on the opposite (i.e., flipped direction) side of the road at a DLT interchange. In this figure, the red circle on the right represents the signal-controlled crossover, the orange arrows represent vehicular movements, and the yellow arrow shows the opposing through movement at the signal-controlled crossover.

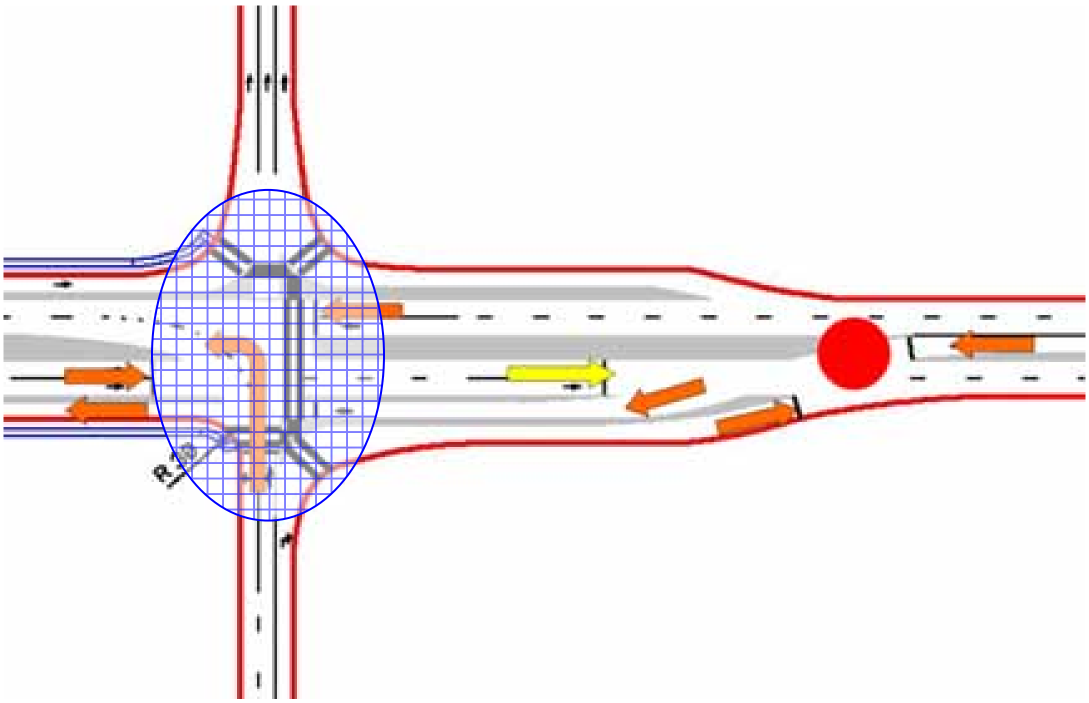


Figure 185. Illustration. Detailed view of movements and paths for half of the DLT interchange.

Figure 186 shows the typical movements in a DLT interchange configuration. The complete interchange has four signalized junctions, with two at the crossovers for the DLT movements and two at the ramp terminals of the interchange. All four signalized junctions are operated in a coordinated system to ensure the smooth progression of traffic on the crossroad. Because the left-turn movement is relocated between the opposing through and right-turn movements, the signalized nodes of the interchange operate under two-phase signal control.

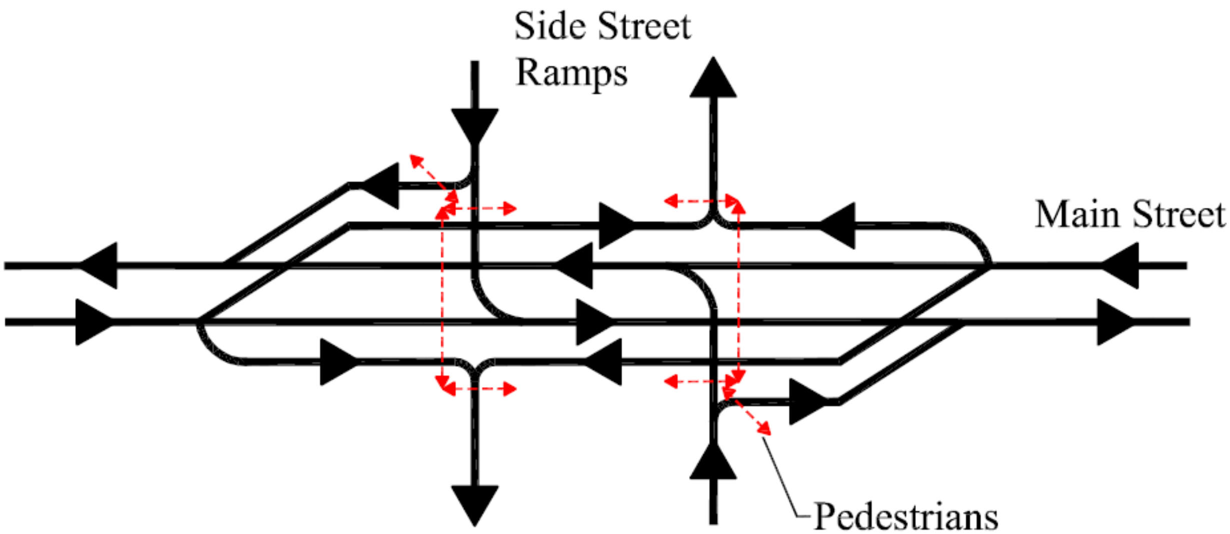


Figure 186. Illustration. Conceptual depiction of the traffic and pedestrian movements at a DLT interchange.

The conversion of a conventional diamond interchange to a DLT interchange has several potential benefits. Introducing the left-turn crossovers reduces the number of phases at the signal-controlled ramp terminals within the interchange. This could reduce delays to drivers, pedestrians, and bicyclists.

A DLT interchange has several disadvantages. Construction of left-turn crossovers and DLTs on the bridge structure for interchanges where the crossroad passes over the mainline freeway likely requires a wider bridge deck and is more expensive compared to a conventional diamond interchange. The design is also counterintuitive to unfamiliar users and therefore could necessitate more extensive signing and marking guidance. In addition, a DLT interchange needs four signalized intersections compared to a conventional diamond interchange where only two signal-controlled intersections are needed.

8.2 GEOMETRIC DESIGN CONSIDERATIONS

As with a DLT intersection, the differentiating design element of a DLT interchange is the left-turn crossover. The DLT lanes typically cross the opposing through traffic at locations that are approximately 400 to 500 ft upstream of the signal-controlled ramp terminals. Appropriate radii that reflect design criteria used at DLT intersections are shown in figure 187. To better communicate the appearance of the approach to a DLT interchange, figure 188 is presented to depict the view of a left-turn crossover at a DLT intersection. This perspective is from a three-dimensional simulation produced for FHWA. While technically the view is of a DLT intersection, it is similar to a perspective view of the approach to a DLT interchange.

Geometrically, the left-turn crossover in a DLT interchange is similar to the design of a left-turn crossover for a DLT intersection. Research into the operation of DLT intersections sponsored by the MDSHA revealed that distance between the crossover and the main intersection was dependent on queuing from the main intersection and on costs involved in constructing a left-turn storage area.[4] Radii of the crossover movements range from 150 to 200 ft. The radii of the left-turn movement at the nodes of the interchange are dependent on the turning movement of a design vehicle.[87]

Median width affects the interchange footprint and consequently the right-of-way acquisition. Designers can obtain minimum median widths from the AASHTO *Green Book*.[7] Offset recommendations for post-mounted signs should be accounted for in accordance with *MUTCD* when determining median width.[8] The minimum median width for any type of intersection or interchange is 4 ft.

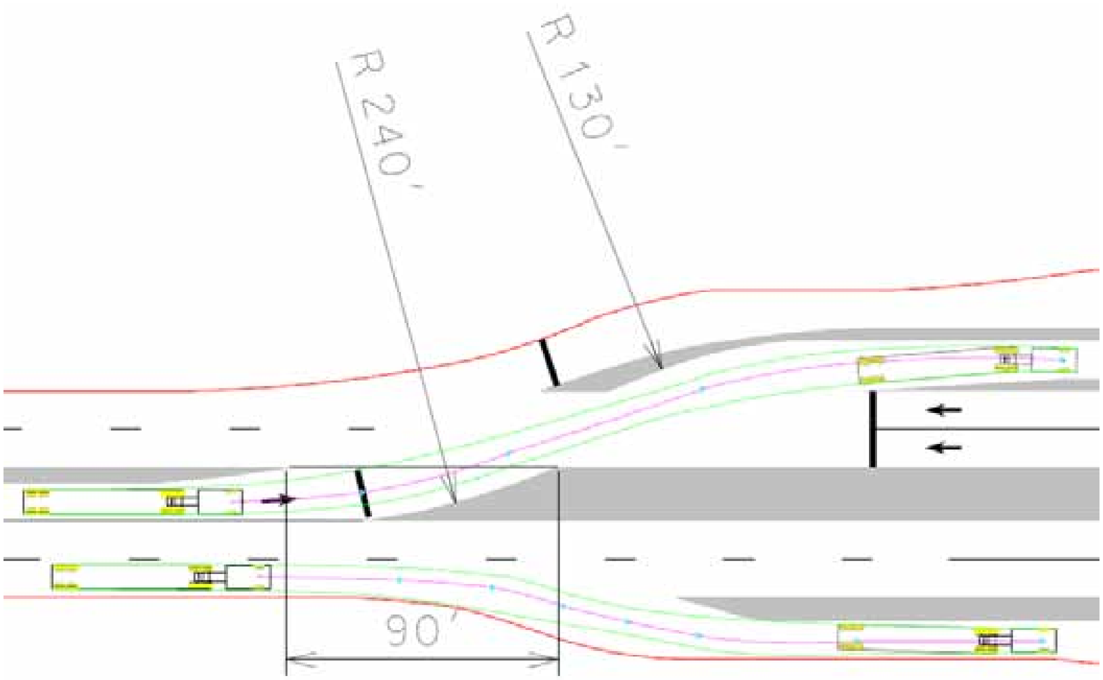


Figure 187. Illustration. Left-turn crossover movement in a DLT interchange.

Figure 188. Illustration. Left-turn crossover movement view, as shown in a DLT intersection driver simulator.

In the case of a DLT interchange, a wide median is counterproductive for the following reasons:

- Wide medians result in long walking distances for pedestrians at the interchange. In turn, this results in the need for long pedestrian clearance intervals and potentially increased cycle lengths, which is counterproductive to traffic efficiency.

- Wide medians necessitate a wide interchange footprint and consequently higher bridge deck construction costs.

As discussed in chapter 7, there is concern that this requires a wider median for better separation of the movements. The use of glare screens has been investigated in the Missouri design of DCD interchange and could also prove to be an effective measure for the DLT interchange.[83]

Many considerations can be obtained in the AASHTO *Green Book*, for example, bridge deck lateral clearance decisions.[7] In addition, typical geometric considerations like interchange spacing, the choice of using an overpass or underpass, sight distance, design speed, horizontal and vertical alignment, superelevation, skew angle, lane widths, shoulder widths, and turning radii can also be found and applied as appropriate. Typical design standards for ramp terminals at on- and off-ramps including ramp location, minimum acceleration, and deceleration lengths can be obtained from the AASHTO publication as well. It also addresses typical standards for median islands, including their installation and use to separate right- and left-turn movements.

Sight distance issues at DLT interchanges are similar to those of conventional diamond interchanges. Typically, there are greater sight distance restrictions on the left-turning vehicles coming from the off-ramps when the side road crosses under the main road. As mentioned previously in the report, the direction of movement at crossovers is counterintuitive to unfamiliar drivers. Proper “Wrong Way” and “Do Not Enter” signing and pavement markings provide mitigation. Signal and lighting equipment on islands at the crossover area should be installed so as not to block drivers’ views of the opposing traffic. As in a DCD interchange, the skew angle between the intersecting roadways is important when considering sight distance.

The U-turn movement is restricted in a DLT interchange design because there are turn restrictions at the crossovers and the main intersection. However, as mentioned previously, alternative strategies can be investigated including facilitating U-turn movements upstream of the bridge structure with the help of a median opening.

8.3 ACCESS MANAGEMENT CONSIDERATIONS

Because there have been no DLT interchanges constructed, discussion of access management is based on theoretical considerations rather than empirical experience. The *NCHRP Report 420* discusses the design, location, and spacing of driveways; access separation techniques at interchanges; and principles that can be applied to DLT interchanges.[(12)] Chapter 9 of the *NCHRP Report 420* discusses in detail the access separation techniques at interchanges. In addition, many States have adopted access management policies for rural and urban areas, and these policies could be applied to a DLT interchange as appropriate.

Access to adjacent properties is limited by this design, and each driveway needs to be considered individually. Driveways should be located outside of the crossover signal-controlled intersection. Turns to and from nearby driveways may need to be limited to right-in and right-out depending on the proximity to the interchange and crossovers. As with the DLT intersection, the U-turn movement is prohibited at the main intersection. Alternative strategies for placement of U-turn movements are mentioned in the last section of this chapter. Chapters 2 and 7 of this report have similar U-turn considerations and contain applicable discussion as well.

As with the DCD interchange, the use of frontage roads in a DLT interchange complicates the design and traffic operations of the interchange. Presence of frontage roads adds one or more additional signal phases; therefore, the frontage roads reduce some of the benefit gained with the DLT interchange design.

8.4 TRAFFIC SIGNALIZATION TREATMENTS

A DLT interchange typically has four signalized junctions or nodes. Traffic signal control is needed at the crossovers and the ramp terminal, as shown in figure 189. The signal control at each of the four junctions operates with two phases for the alternative opposing movements, but the four signal-controlled junctions need to be coordinated to maintain progression on the side street arterial. In figure 189, the green ovals represent typical signal locations.

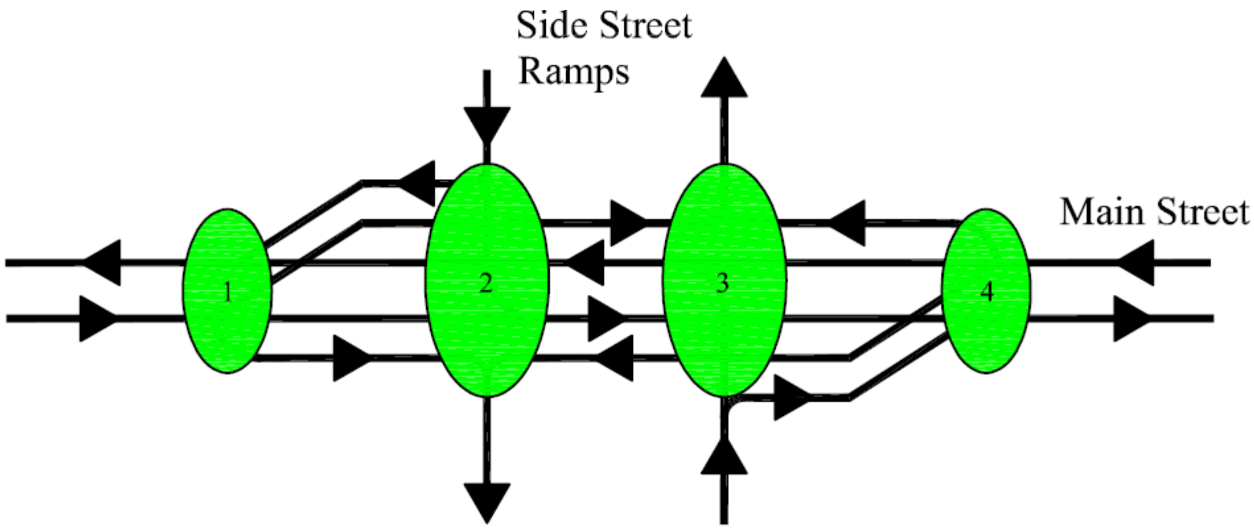


Figure 189. Illustration. Typical DLT interchange signal locations.

8.4.1 Signal Design

As with conventional intersections and DLT intersections, traffic signal control at a DLT interchange may be fully actuated to minimize delay. Detectors in all lanes approaching the crossovers and in the lanes approaching the signal-controlled ramp terminals can be used. The durations of signal phases can vary on a cycle-by-cycle basis. A permissible signal phasing scheme for a DLT interchange operating under one signal controller is shown in figure 190. The possible locations of loop detectors for a DLT interchange are shown in figure 191.

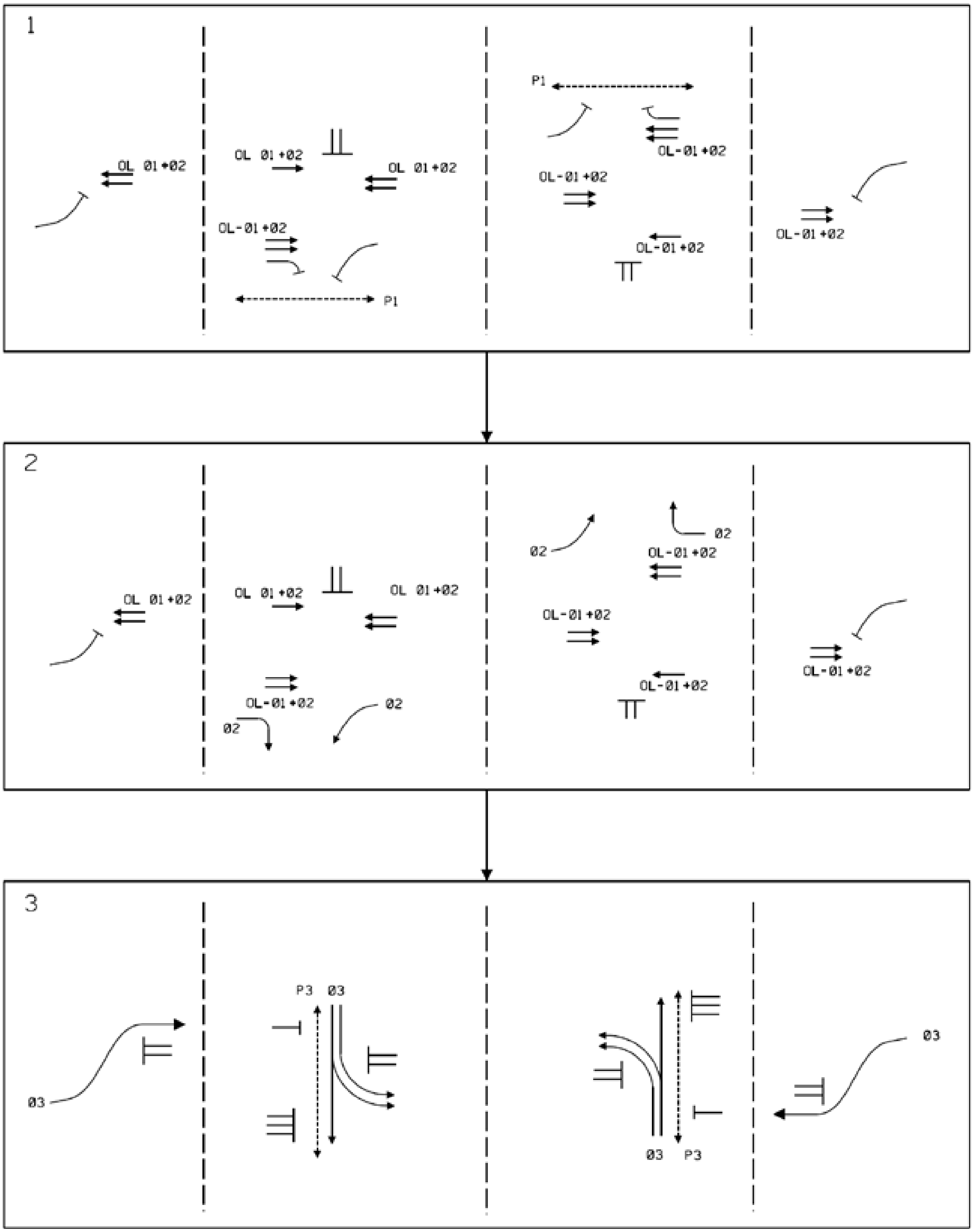


Figure 190. Illustration. Signal phasing for a DLT interchange operating under a single controller.

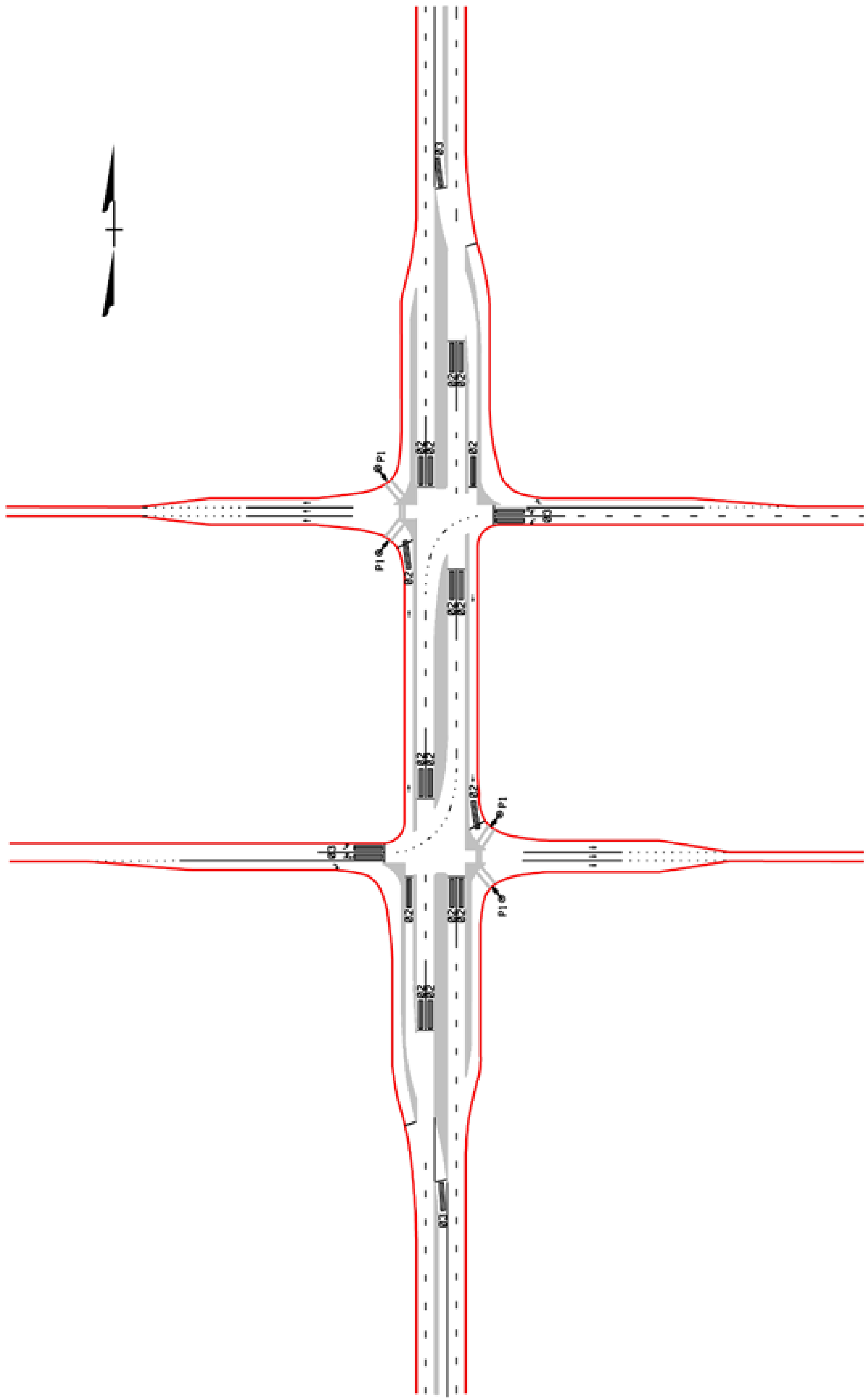


Figure 191. Illustration. Detector locations for a DLT interchange for signal phasing.

One possible signal pole and mast arm layout is shown in figure 192. These locations are similar to a DLT intersection except at two ramp terminals. Since the ramps carry one-way traffic, signal heads are needed for three approaches at the ramp terminals. At a DLT intersection, there is a need for signal heads serving all approaches. Angular left-turn arrows signal displays that can be used in signal heads at the left-turn crossovers.

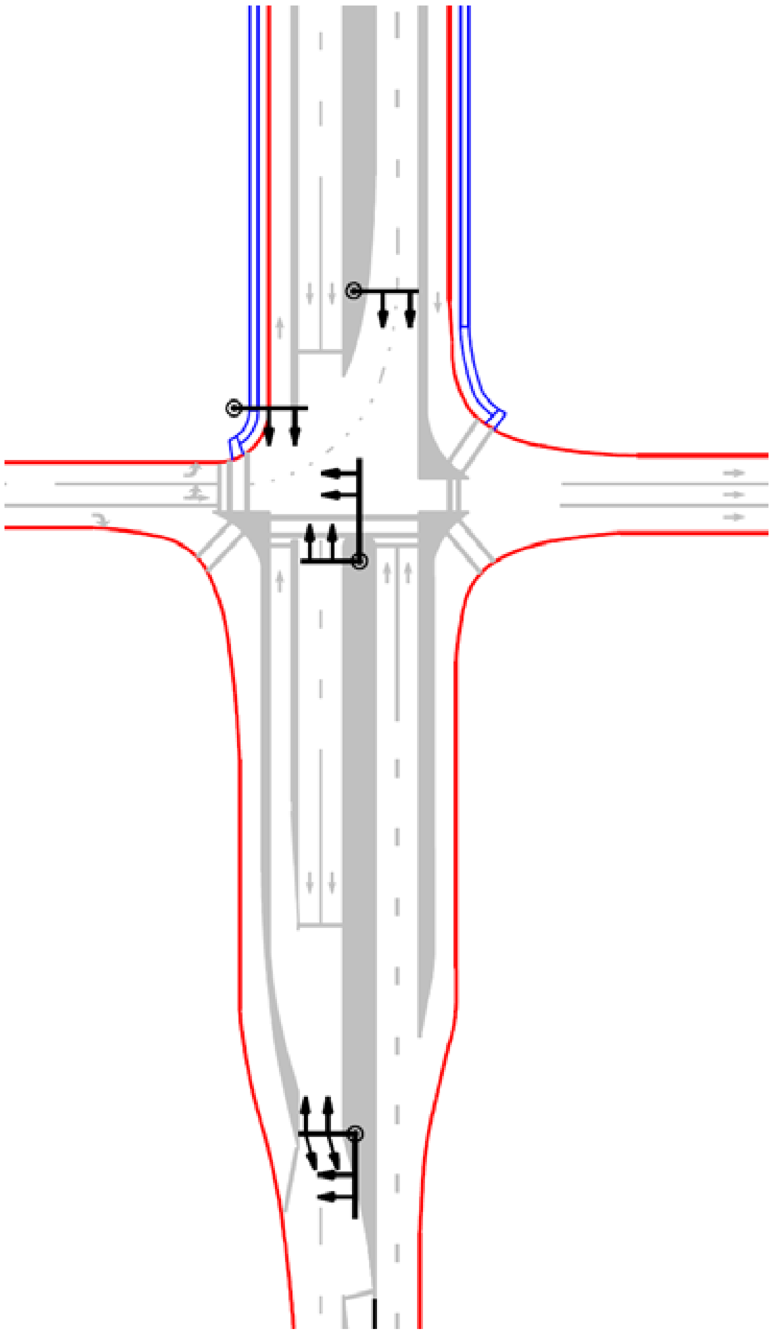


Figure 192. Illustration. Possible signal pole and mast arm locations for a DLT interchange.

8.4.2 Signing and Marking

Signing and marking a DLT interchange entails significant differences from a conventional interchange, especially at the midblock left-turn crossovers and the turning restrictions at the main interchange. As mentioned for the DCD interchange design in the previous chapter, the key features of the signing and marking include the following:

- Use of overhead signing to clearly communicate lane use and directions.
- Use of advance signing and guide sign applications on the exit ramps and on the bridge structure.
- Use of skip marks on the left-turn lanes for clear guidance through the intersection crossover area.
- Use of "Wrong Way" and "Do Not Enter" signs for protection against wrong maneuvers at the left-turn crossovers and the bridge deck structure.
- Use of wrong-way pavement arrows on the through lanes at the crossovers.

In addition, other measures that have been investigated for other alternative intersections and interchanges like the use of glare screens and alternate "Keep Left" signs should be considered.

8.5 ACCOMMODATION OF PEDESTRIANS, BICYCLISTS, AND TRANSIT USERS

Pedestrian accommodation in a DLT interchange involves crossing locations and signalization at the ramp terminal intersection of the interchange. These intersections are similar to a partial DLT intersection with the left-turn crossover side street.

Since there were no existing implementations of DLT interchanges at the time of this report, the existing example of pedestrian implementation at DLT intersection locations referenced in chapters 3 and 7 can be used as starting points for design purposes. These two chapters discuss pedestrian accommodation, including accessibility, in detail. The discussion is also applicable to the DLT interchange, including potential safety measures applicable to the left-turn crossovers in a DLT interchange.

Figure 185 showed crosswalk locations, and figure 186 schematically showed where pedestrian crosswalks may be located at a typical DLT interchange. Figure 193 shows the typical pedestrian movements at a DLT interchange. The direction of DLT vehicles on the crossroad between ramp terminal intersections should not pose a problem to pedestrian movements. Sidewalks should be installed on the roadway depending on locations of pedestrian generators, pedestrian movements, and the future pedestrian needs of the interchange. If right-of-way, access management, or other challenges exist, sidewalks may need to be relocated to nearby intersections along the side street arterial.

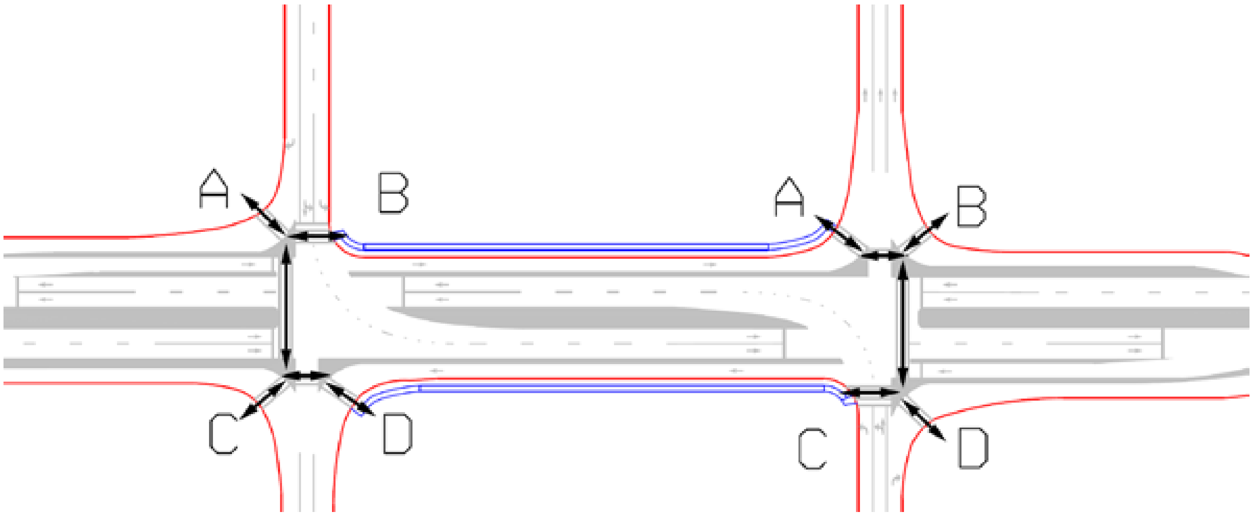


Figure 193. Illustration. Pedestrian movements in a DLT interchange.

Bicyclists operating along the side street through a DLT interchange can be accommodated with the use of bicycle paths or shared-use paths, and the above pedestrian accommodation discussion applies to bicycle traffic. As with SPUIs, pedestrians and bicyclists can also be accommodated with the help of a shared-use overpass.

In the case of a DLT interchange, the location of bus stops is dictated by the location of the left-turn crossovers on the side street arterial and the pedestrian generators. If location of the pedestrian generators dictates near-side bus stop, then the bus stops would be located upstream of the crossover and right-turn bays. Similarly, far-side bus stops would be located downstream of the crossover, as shown in figure 194. Further guidance on bus stop location, design type (curbside, bus bay, etc.), and ADA accessibility guidelines can be obtained from existing literature including *Transit Cooperative Research Program* (*TCRP) Report 19*.[89]

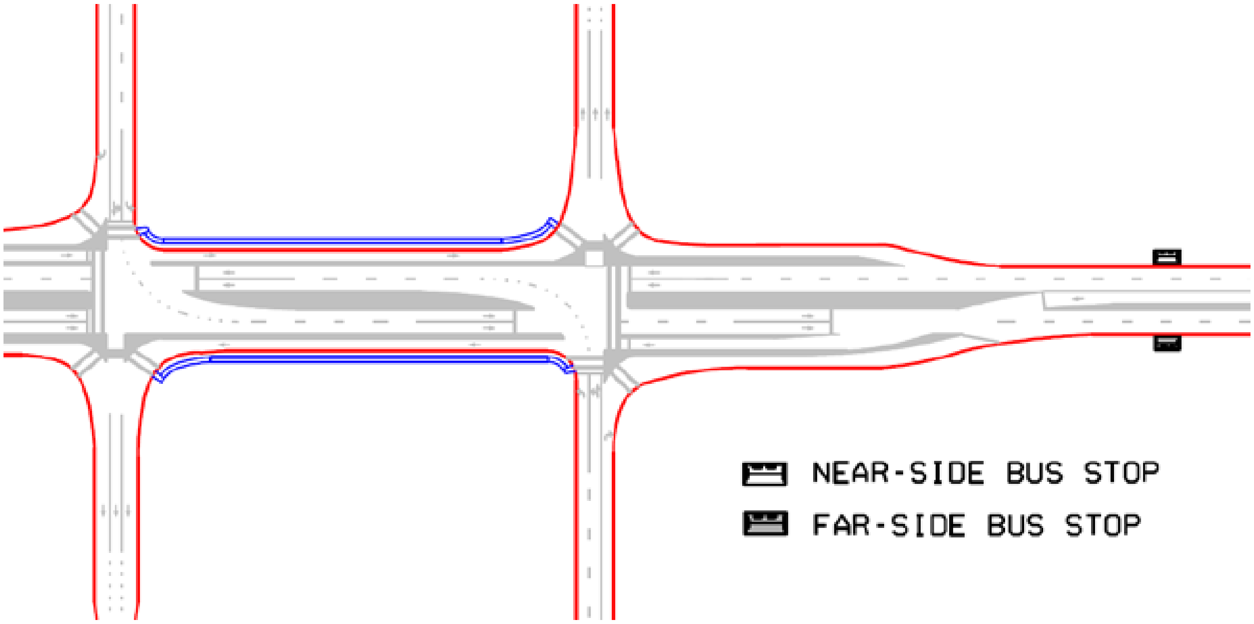


Figure 194. Illustration. Transit stop locations in a DLT interchange.

8.6 OPERATIONAL PERFORMANCE

VISSIM® was used to gain insight into the operational performance of the DLT interchange in comparison to the TD interchange. Two geometric design cases of DLT interchanges and two geometric design cases of TD interchanges were simulated. Table 33 shows the geometric design configurations of the cases simulated. The lane configurations and geometric features for the DLT interchanges and the corresponding TD interchanges were similar. The vehicular volumes on opposing approaches were balanced (50:50 directional split). The VISSIM® simulation network was 1 mi long on the major and minor road approaches for the cases simulated. A discussion of the simulation results for all of the geometric design cases is provided below. The following assumptions were employed in the VISSIM® model for each simulated scenario:

- Optimum fixed signal timing determined using Synchro®.[21]
- Yellow times determined using ITE policy.
- All-red times determined using ITE policy.
- A total of 5 percent heavy vehicles on all legs.
- A total of 350-ft left-turn bay lengths upstream of the displaced crossover junction.
- A total of 325-ft left-turn bay lengths downstream of the displaced crossover junction.
- A 0.5-mi network size in each direction from the main intersection.
- Single right-turn bays on the major road.

- Right turn on red allowed at each signal, no left turn on red allowed.
- A signal at each DLT crossover.
- A 10-ft median width on bridge deck.
- A 45 mi/h desired speed on major road.
- A 25 mi/h desired speed on off-ramp.
- Saturation headway of approximately 1,900 veh/h/lane (alpha = 3 and beta = 2).
- Seeding time of 30 minutes for the simulations.
- Running period of 60 minutes for the simulations.

Based on the VISSIM® simulation results, DLT interchanges with six lanes on the bridge processed approximately 6,200 veh/h, while an equivalent TD interchange processed 4,200 veh/h. Similarly, DLT interchanges with 10 lanes on the bridge processed approximately 8,600 veh/h, while an equivalent TD interchange processed 6,800 veh/h.

Thus, DLT interchanges provided 20 to 45 percent additional throughput on the bridge deck for the same number of lanes when the through flows were balanced. However, it is important to note that DLT interchanges typically performed better than TD interchanges when the on-ramp left-turn volumes were moderate, the major road through volumes were high, and the off-ramp volumes were moderate. The DLT interchange was best suited to conditions where the bridge deck width was limited, but right-of-way was available upstream and downstream of the bridge structure. Several guidelines were derived based on the VISSIM® simulation results. For balanced traffic flows, the maximum capacity of the DLT interchange through and left-turn lanes on the bridge were 800–850 veh/h/lane and 350 veh/h/lane, respectively. For these mainline volumes, the maximum entering capacity was 400 veh/h/lane entering the crossroad from the ramps.

Table 33. Service volumes and delays for TD and DLT interchange designs.

Geometric Cases			Input Volumes						Simulation Thruput						Average Delay (s/veh)
			Major Road			Ramp		Total Input	Major Road			Ramp		Total Thruput	
			Left	Thru	Right	Left	Right		Left	Thru	Right	Left	Right		
1	DLT interchange	Two thru lanes, one left lane, one right lane per approach on major road, two thru lanes, one left lane per approach on bridge, two left, and one right on each off-ramp	250	1,600	300	350	300	5,600	250	1,601	301	355	271	5,554	34.4
			300	1,800	300	600	300	6,600	275	1,635	271	620	309	6,218	80.7
			350	1,600	300	650	300	6,400	333	1,574	292	650	273	6,243	87.8
			600	600	300	400	250	4,300	401	404	199	408	229	3,279	112.3
			600	300	300	400	250	3,700	395	249	205	407	225	2,859	126.4
			300	600	300	400	250	3,700	301	591	313	405	230	3,679	33.6
2	DLT interchange	Three thru lanes, two left lanes, one right lane per approach on major road, three thru lanes, two left lanes per approach on bridge, two left lanes, and one right lane on each off-ramp	550	2,500	350	400	250	8,100	521	2,465	343	402	233	7,924	44.3
			550	2,500	350	800	250	8,900	524	2,484	344	740	207	8,596	70.7
			900	1,000	300	500	250	5,900	742	923	278	505	243	5,378	113.8
			900	500	300	500	250	4,900	743	458	278	507	247	4,462	113.8
			450	1,000	300	500	250	5,000	428	998	299	509	240	4,946	35.2

3	TD interchange	Two thru lanes, one left lane, one right lane per approach on major road, two thru lanes, one left lane per approach on bridge, two left, and one right on each off-ramp	600	600	300	400	250	4,300	546	576	283	407	256	4,133	99.3
			600	300	300	400	250	3,700	552	272	280	413	256	3,545	109.5
			300	600	300	400	250	3,700	288	598	301	412	256	3,709	37.4
4	TD interchange	Three thru lanes, two left lanes, one right lane per approach on major road, three thru lanes, two left lanes per approach on bridge, two left lanes, and one right lane on each off-ramp	550	2,500	350	800	250	8,900	429	1,985	274	454	257	6,797	141.9
			900	1,000	300	500	250	5,900	895	1,010	298	512	257	5,940	52.0
			900	500	300	500	250	4,900	893	500	290	509	257	4,898	58.8
			450	1,000	300	500	250	5,000	449	996	296	513	257	5,021	38.8

8.7 SAFETY PERFORMANCE

It is not possible to present any empirical data on the crash experience at DLT interchanges, as there are no existing installations. One can speculate on the future safety performance of this type of alternative interchange. It may be that the separation of basic conflict areas and the reduction of conflict points positively affect safety. Using a conceptual approach, it can be shown that a conventional diamond interchange has two major conflict areas with a total of 26 conflict points. At a DLT interchange, there are 16 conflict points that occur within 4 conflict areas. The four conflict areas are the four signal-controlled intersections. Figure 195 presents a conceptual diagram that identifies the 16 conflict points at a DLT interchange. (The two additional conflict points would be created if the diverge point for the left turn from the main line was spatially separated from the diverge point for the right turn from the main line.) In comparison, as was shown in figure 181, a conventional diamond interchange has 26 conflict points, but they are concentrated in 2 conflict areas. Until a DLT interchange is constructed and crash data become available, it remains to be seen whether spreading the conflict points over four areas produces better safety performance than concentrating them in two areas.

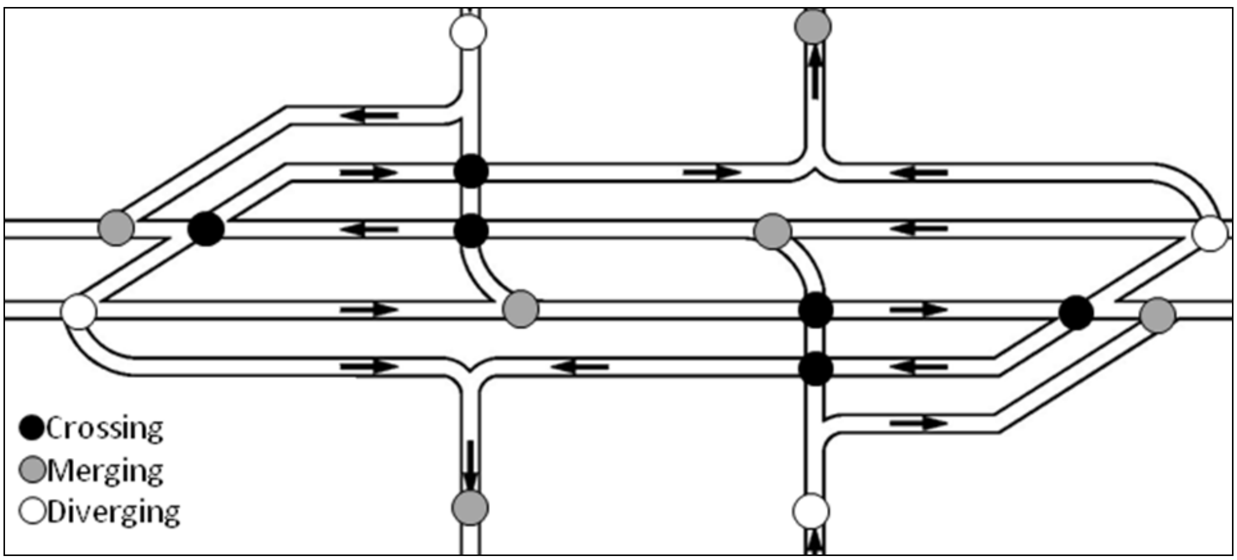


Figure 195. Illustration. Conflict points in a DLT interchange.

The counterintuitive features of the DLT interchange, especially the presence of left-turn crossovers and left-turn movement on the opposite side of the crossroad between ramp terminal intersections, raise questions about safety performance, especially for unfamiliar drivers. Signing and pavement markings as well as public information and education campaigns could be used to reduce the potential for crashes involving unfamiliar drivers.

8.8 CONSTRUCTION COSTS

Since there are no existing installations of a DLT interchange at the time of this report, no data on actual construction costs are available. The presence of left-turn crossovers at the approaches of the side street arterial would result in a wider footprint, which is depicted in figure 196.

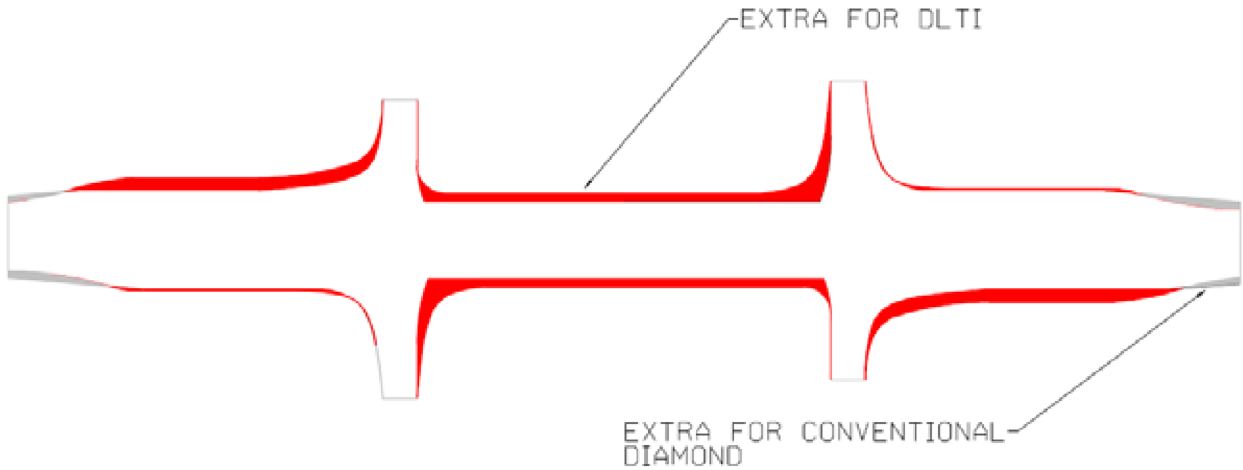


Figure 196. Illustration. Footprint comparison of a DLT interchange versus a conventional diamond interchange.

The wider footprint produces higher right-of-way acquisition costs compared to that of a conventional diamond interchange. This also increases the amount of earthwork and paving construction costs. Items like mobilization, overhead lighting, pavement markings, and drainage costs are not significantly different between the DLT interchange and a conventional diamond interchange. When comparing signal equipment between a DLT interchange and a conventional diamond interchange, four signal mast arms are present at the main intersection similar to a conventional intersection. Additionally, single mast arms are provided at each left-turn crossover. Therefore, for a DLT interchange, the signal equipment is estimated to cost twice as much. The additional signing needed to guide drivers through the interchange would increase the signing-related costs over what are expected for a conventional interchange. Consequently, it is expected that construction costs would generally be higher for a DLT interchange than a comparable conventional interchange.

8.9 SEQUENCING OF CONSTRUCTION

Maintenance of traffic during construction of a DLT interchange is typically an issue of converting an existing conventional diamond interchange into a DLT interchange. Since a DLT interchange is considered to be an amalgamation of a diamond interchange and a DLT intersection, techniques illustrated previously should be referenced in addition to existing literature for conventional and SPUIs.

8.10 OTHER CONSIDERATIONS

There are additional issues to consider when determining whether a DLT interchange is appropriate for a specific situation including enforcement and emergency vehicle needs, lighting, public information, and education. Enforcement needs and emergency vehicle access issues at a DLT interchange are similar to issues documented for a DLT intersection in chapter 2. Similarly, the potential for crossover blockage during traffic incidents or power outages dictate that mitigation options (such as a bypass shoulder and generator) be considered.

Adequate highway lighting should be provided at the ramp junctions and the bridge structure. Important design principles like uniformity of light and minimization of glare should be followed. Since the interchange has counterintuitive movements, overhead lighting would be beneficial for unfamiliar drivers using the interchange area during nighttime and inclement weather conditions. Existing lighting standards and specifications outlined in AASHTO's *Roadway Lighting Design Guide*, FHWA's *Roadway Lighting Handbook*, and the IESNA publications including *Recommended Practices for Roadway Lighting*, *Recommended Practices for Tunnel Lighting*, and *Recommended Practices for Sign Lighting* could be used for optimal lighting in a DCD interchange. (See references 26–30.) *NCHRP Synthesis 345* provides guidelines for roadway lighting for SPUIs. [85]

As with the DLT intersection and DCD interchange designs, a public information and education campaign are important for the safe and efficient use of the interchange and the public acceptance of the design. Distributing information through various media outlets would be important prior to the opening of the intersection as well as monitoring driver behavior after its opening to determine the need for additional education and possible enforcement efforts.

8.11 APPLICABILITY

As with all the designs described in this report, the DLT interchange design is applicable under certain conditions. A primary reason to choose the DLT interchange instead of a conventional diamond interchange is the two-phase signal operation resulting in the ability to process higher volumes approaching the bridge deck. DLT interchanges are best suited when left-turn volumes from the arterial to the on-ramp are moderate to heavy, the major road through volumes are heavy, and the volumes from the off-ramp from the freeway are moderate. Moreover, DLT interchanges provide higher throughput than a conventional diamond when the major through volumes are balanced.

Some of the situations where a DLT interchange may be suitable are as follows:

- Heavy and balanced through volumes on the major (or arterial) road.
- Moderate to heavy left-turn volumes from the major road.
- Low to moderate left-turn volumes from ramps.
- Limited bridge deck width with right-of-way available on approaches.

8.12 SUMMARY

At the time of this report, there were no existing DLT interchange installations. Theoretically, the DLT interchange offers the following benefits compared to conventional interchange forms:

- More efficient simplified two-phase operation.
- Increased capacity.
- Reduced delay.

- Reduced cost.
- Separated conflict points.

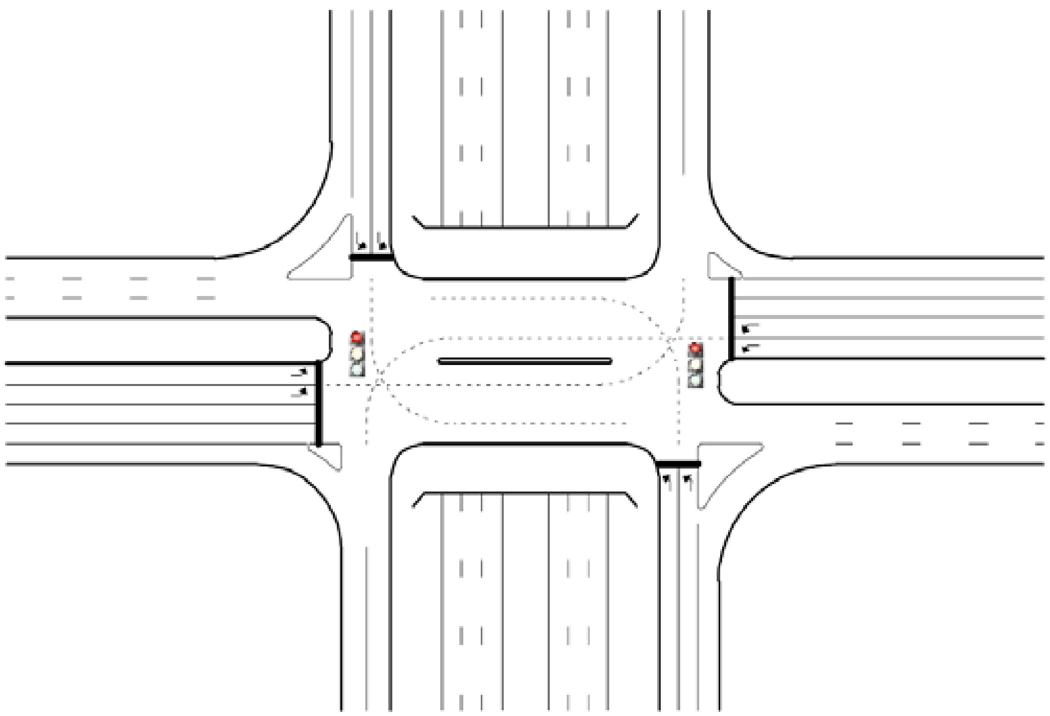
Agencies considering DLT interchanges should also be aware of disadvantages of the design relative to conventional interchanges as described earlier in the chapter. Specifically, additional right-of-way prior to the bridge structure may make this design infeasible.

CHAPTER 9. OTHER INTERCHANGE CONFIGURATIONS

This chapter presents sketches and briefly describes other types of alternative interchanges.

9.1 TIGHT URBAN DIAMOND INTERCHANGE

The TUDI, a type of compressed diamond interchange, is used in urban and suburban areas where right-of-way is a constraint. Figure 197 shows a TUDI, which has two closely spaced signalized intersections at the crossing of the ramp terminals and side street. Typical designs provide 200 to 400 ft of separation between the signal-controlled intersections.(90) Generally, the bridge design of a TUDI has spans between 140 and 180 ft depending on various geometrics of the crossing.(91)



Source: Transportation Research Board

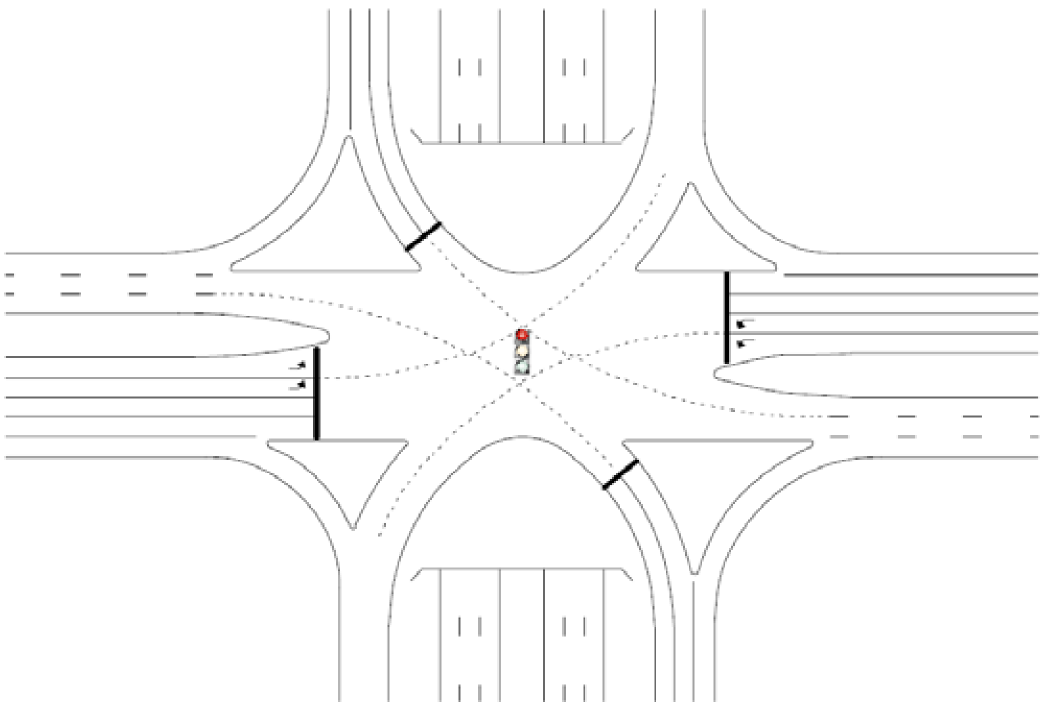
Figure 197. Illustration. TUDI configuration.(92)

The key operational aspect of a TUDI is signal coordination to ensure efficient progression of traffic and minimum storage of vehicles between the terminals.(92) Other traffic flow parameters like saturation flow rate, clearance times, and turning speeds in a TUDI are the same as a conventional at-grade intersection. Typically, a TUDI requires a four-phase signal phasing with overlapping for both intersections.(91)

9.2 SINGLE POINT URBAN INTERCHANGE

The SPUI, another variant of the compressed diamond interchange, was developed in 1970 to improve traffic capacity and operations while requiring less right-of-way than the diamond interchange.[93] The configuration of a typical SPUI is shown in figure 198. The turning movements of the major road ramps and all the movements of the minor road are executed in one central area that is either on the overpass or underpass.

Some of the key design characteristics that need to be considered when designing a SPUI are skew angle; number of through, left-, and right-turn lanes; median width; and islands.[93] Generally, the bridge of a SPUI has a span length from 160 to 280 ft depending on various geometrics of the crossing. The bridge structure of a SPUI has a large deck and is more expensive to construct in comparison to a TUDI, which is relatively easy to design and construct.[91]



Source: Transportation Research Board

Figure 198. Illustration. SPUI configuration.[92]

The actuated signal controller in a SPUI has the option of having concurrent signal phases to serve the crossroad left-turn movement with the adjacent through movement, as per vehicle detection.[94] Typically, SPUIs can operate on a three- or four-phase signal phasing. Most SPUIs use a single actuated signal controller. With an extremely wide intersection, the SPUI requires longer yellow and all-red clearance intervals compared to a conventional intersection.[94] Additionally, if frontage roads are present, a SPUI may need an additional phase to serve through movements on the ramp.[91]

Existing literature points out that SPUIs increase capacity and therefore accommodate more vehicles compared to conventional diamond interchanges. Since a SPUI has one signalized intersection, it allows for a simpler phasing sequence for signal control. This also makes it easy for a SPUI to be coordinated with upstream and downstream signals. Existing research does not reveal significant differences in the crash statistics between TUDIs and SPUIs of similar geometrics.[95] Since pedestrians normally cross the major road in a path that is parallel to the cross street, conventional and compressed diamond interchanges offer benefits in pedestrian accommodation compared to SPUIs.

9.3 OTHER ALTERNATIVE DIAMOND INTERCHANGES

Grade separation is considered at the intersections of major roadways to reduce congestion and increase capacity. Traditional interchanges including the cloverleaf, partial cloverleaf (Parclo), and the directional interchange require large right-of-ways and are costly and often difficult to construct in urban environments. In addition, urban environments have developments such as offices, retail businesses, and commercial and mixed uses that often abut the highway. Traditional interchanges also restrict driveway access.[96]

Some of these concerns are addressed with the help of designs like the TUDI and SPUI. Alternative interchanges endeavor to further reduce right-of-way requirements and to improve traffic operations and safety. Some of the primary elements of alternative interchange design are as follows:

- A smaller footprint with the help of tighter loop ramp radii, reduced lane widths, shorter weaving areas, and the signalization of nodes of the interchange. Smaller footprint areas usually result in smaller land acquisition costs, thereby minimizing construction costs.

- Use of signalization of the interchange to meter traffic for the downstream intersections on the arterial. This helps if the adjacent signalized intersection in the network cannot handle heavy volumes from traditional interchanges.[96]

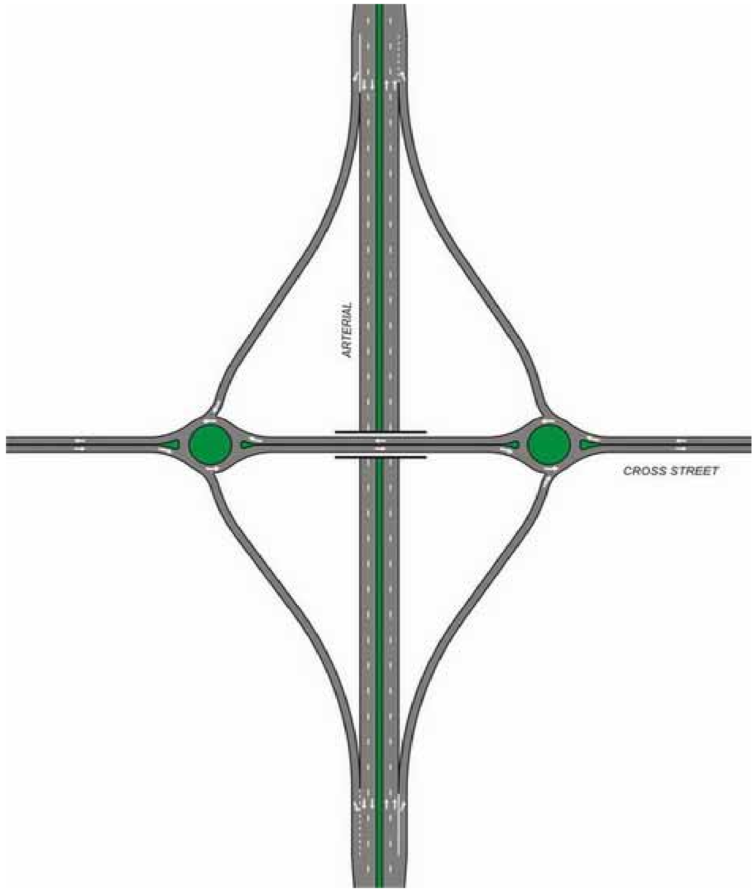
- A design for lower speeds, ease of navigation, and increased safety by reduction of conflict points when compared to the TUDI and SPUI.

- Flexibility of design and ease of construction and maintenance.

- Access to existing roadside properties.[97]

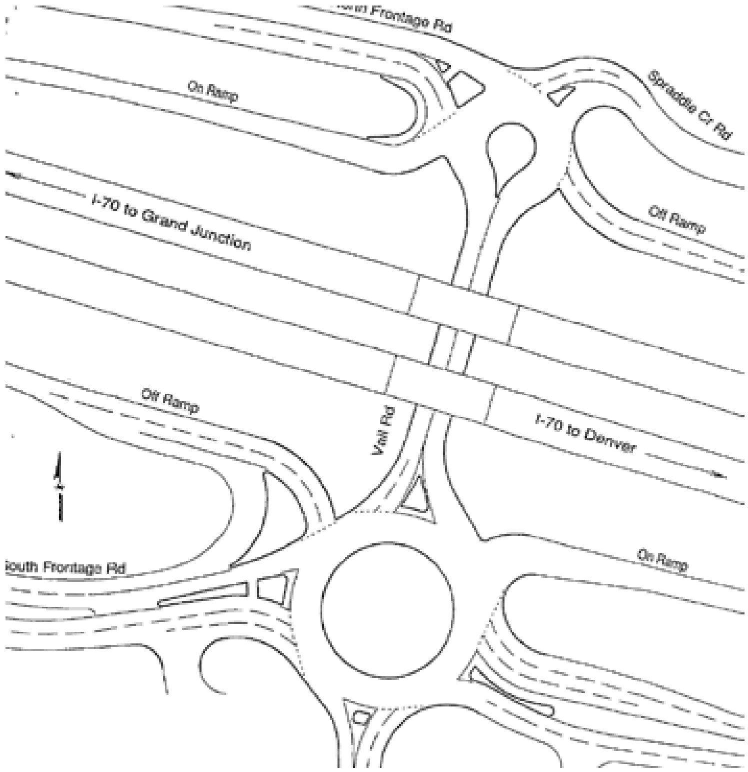
9.3.1 Raindrop Interchange/Roundabout Interchange

The raindrop interchange, alternatively referred to as a roundabout interchange, uses the concept of roundabouts at the grade-separated interchange. In effect, the minor street through movements navigate through roundabouts. There can be two types of raindrop interchanges—double and single. The double roundabout version uses two roundabouts at the ramp terminals (as depicted in figure 199). The single roundabout type has a single large roundabout designed over the arterial and serves as the overpass for the turning movements. Figure 200 shows an application of the raindrop interchange where one of the ramp terminals is a roundabout. Figure 201 shows the existing single roundabout interchange on Loudon Road in Latham, NY.



Source: ATTAP Maryland State Highway Administration

Figure 199. Illustration. Double roundabout interchange.[(4)]



Source: National Cooperative Highway Research Program

Figure 200. Illustration. Raindrop interchange in Vail, CO.[98]

Source: Google™ Earth

Figure 201. Photo. Single roundabout interchange in Latham, NY.

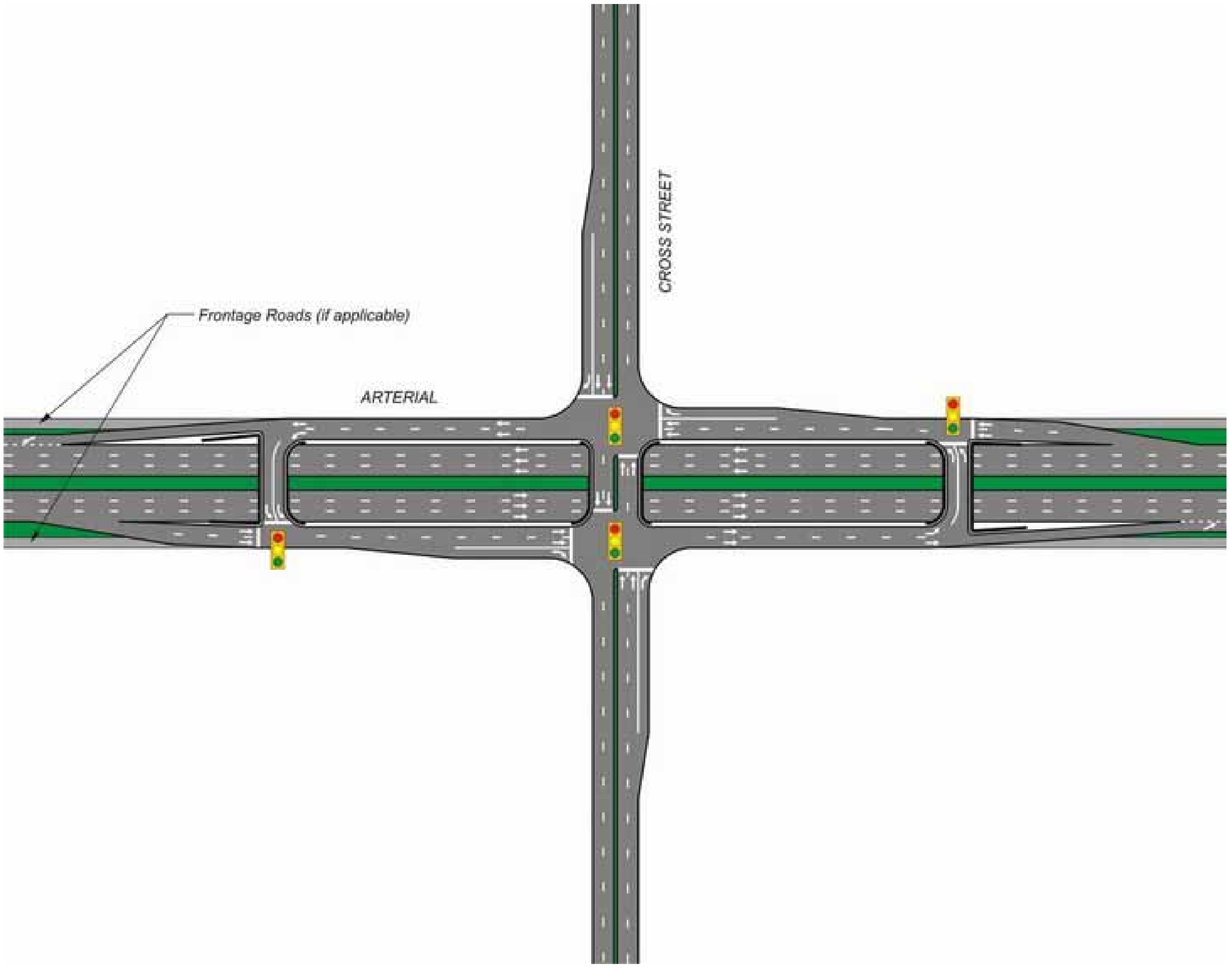
There are several existing raindrop interchanges located in North Carolina, Colorado, Maryland, and Washington, DC.

9.3.2 MUT Interchange

The MUT interchange, also known as the Michigan urban diamond interchange (MUDI), evolved in Michigan from the MUT intersection to be used on freeway facilities, as shown in figure 202.

The MUDI uses directional crossovers beyond the main intersection to handle all left-turn movements. The arterial turn movements are diverted onto separate frontage roads on either side of the grade-separated through lanes. Off-ramps are directed onto one-way frontage approximately 500 to 600 ft prior to the main intersection. At the main intersection, right turns are made. Left turns proceed to the directional crossover beyond the main intersection, and drivers must make a U-turn and then a right turn onto the cross street. The main intersection and the crossovers operate under a two-phase signal control and are coordinated to promote progression.(96)

Pedestrians cross the arterial with the help of a two-stage crossing. The MUDI is good from an access management point-of-view, and access to adjacent business development is possible along the parallel one-way frontage roads. This kind of interchange has been applied in Michigan along freeway corridors where right-of-way acquisition is an issue.



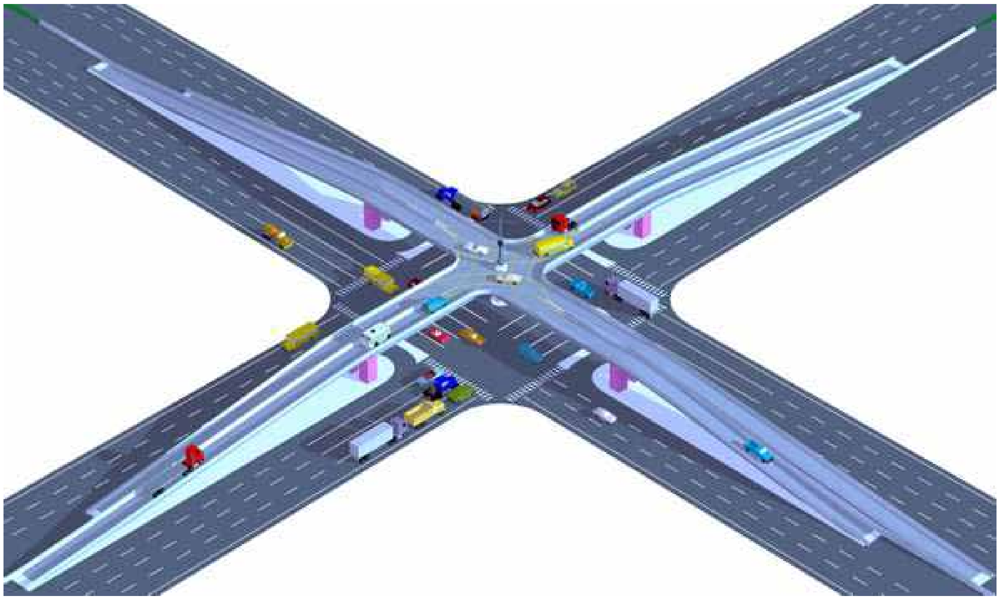
Source: ATTAP Maryland State Highway Administration

Figure 202. Illustration. MUT interchange configuration.[(4)]

Dorothy, et al. researched the operational aspects of the MUDI by performing computer traffic simulation runs using TRAF-NETSIM on geometrically similar MUDI and diamond interchanges models.[(99)] Simulation results indicated MUDI performed operationally better than the conventional diamond interchange for a majority of the cases.

9.3.3 Center Turn Overpass Interchange

The center turn overpass (CTO) interchange separates left-turn movements of all the approaches by relocating them to an elevated structure using narrow ramps within the median.[(96)] The arterial and cross street through and right-turn movements continue to use the roads at normal elevation. Both the elevated and at-grade intersections are controlled by a simple two-phase signal. The left-turn traffic descends from the elevated intersection and merges into through traffic lanes. The concept, which hase been conceived and patented, is shown in figure 203, and the typical movements are shown in figure 204. The elevated structure is usually on a retaining wall or a steel girder structure. In this kind of design, the traffic descending from the elevated structure requires a merging/deceleration lane to merge with the through traffic of the receiving approach. Alternatively, the signal on the elevated structure could be coordinated with the signal at the main intersection such that the descending traffic could merge when the through traffic in the same direction stopped.(96)



Source: ATTAP Maryland State Highway Administration

Figure 203. Illustration. CTO interchange configuration.(4)

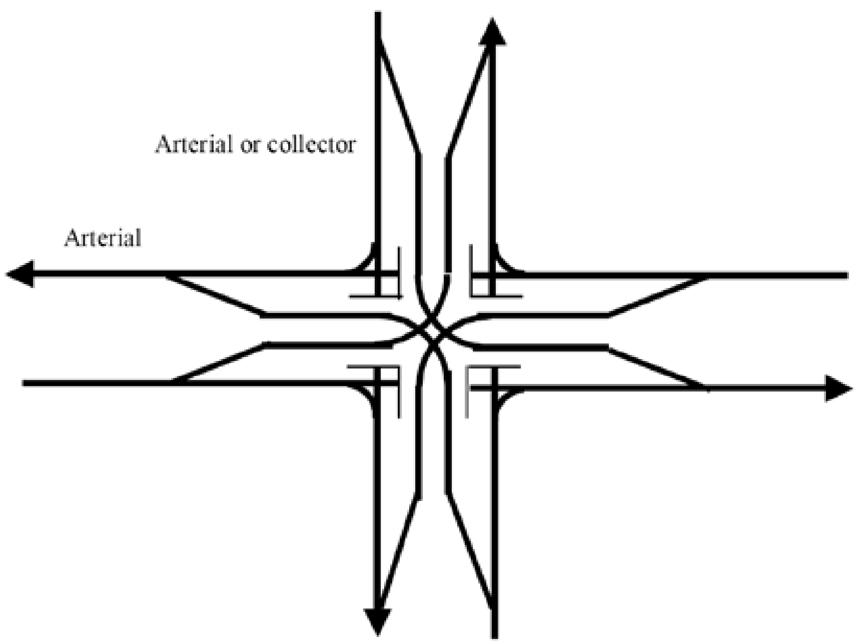


Figure 204. Illustration. Typical movements in a CTO interchange configuration.

Some of the advantages of a CTO interchange compared to a conventional at-grade intersection are as follows:[(100)]

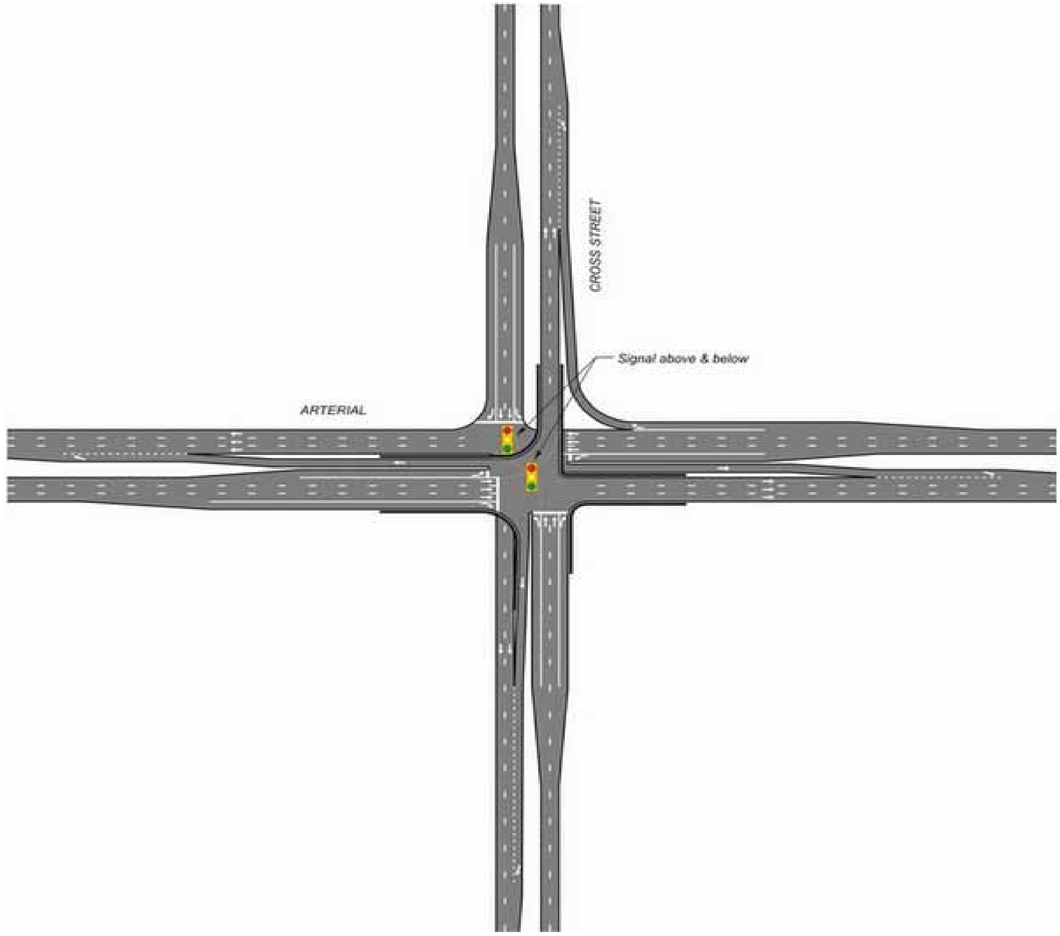
- Higher capacity than at-grade intersections.
- Lower travel time than at-grade intersections.
- Enhanced progression for both streets.
- Metered traffic to help downstream signals.
- Direct pedestrian crossing.
- Roadside access to businesses similar to conventional intersection with medians.

Some of the disadvantages are as follows:

- High structure cost.
- Difficult design if streets are not perpendicular.
- Blocked visibility to businesses by structure.
- Costs for rights to design.

9.3.4 Echelon Interchange

For an echelon interchange, one approach on both the arterial and intersecting cross streets is structurally elevated as the cross streets intersect while the other approach halves on both the arterial and intersecting cross streets intersect at-grade as depicted in figure 205. Typical movements on an echelon interchange are shown in figure 206. The result is a symmetrical but offset pair of two-phase intersections separated by grade, both operated by two-phase signals as in the meeting of two one-way streets. The elevation is provided with the help of retaining wall structures. With the elevation of two of the approaches, the intersections can be operated with two-phase signals. Figure 207 shows the only known application in Aventura, FL, at U.S. Route 1 and NE 203 Street.[(96)]



Source: ATTAP Maryland State Highway Administration

Figure 205. Illustration. Typical echelon interchange configuration.[(4)]

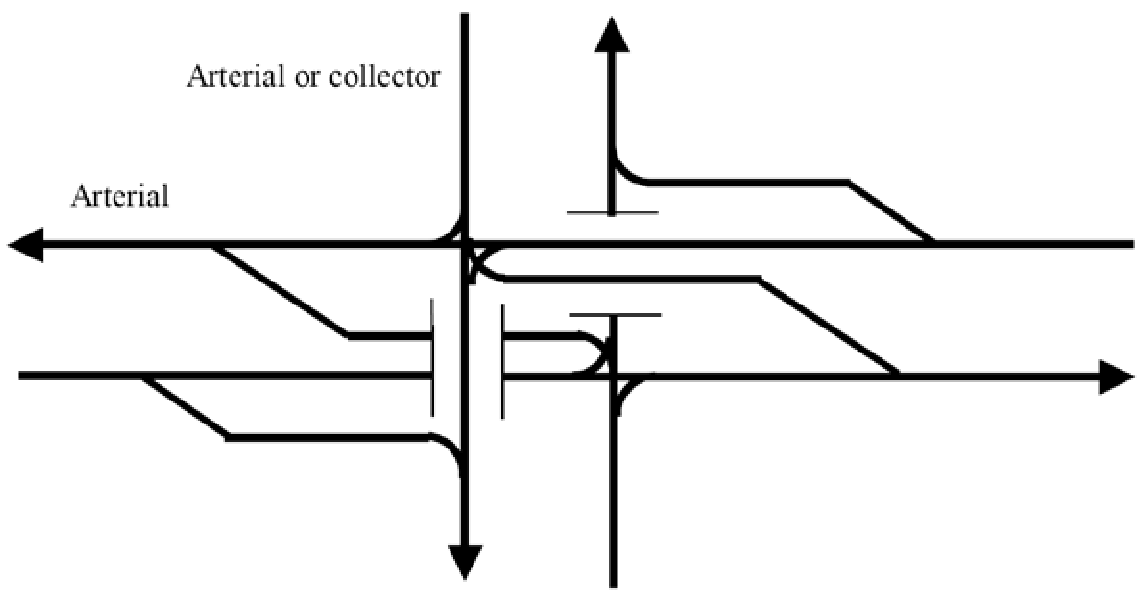
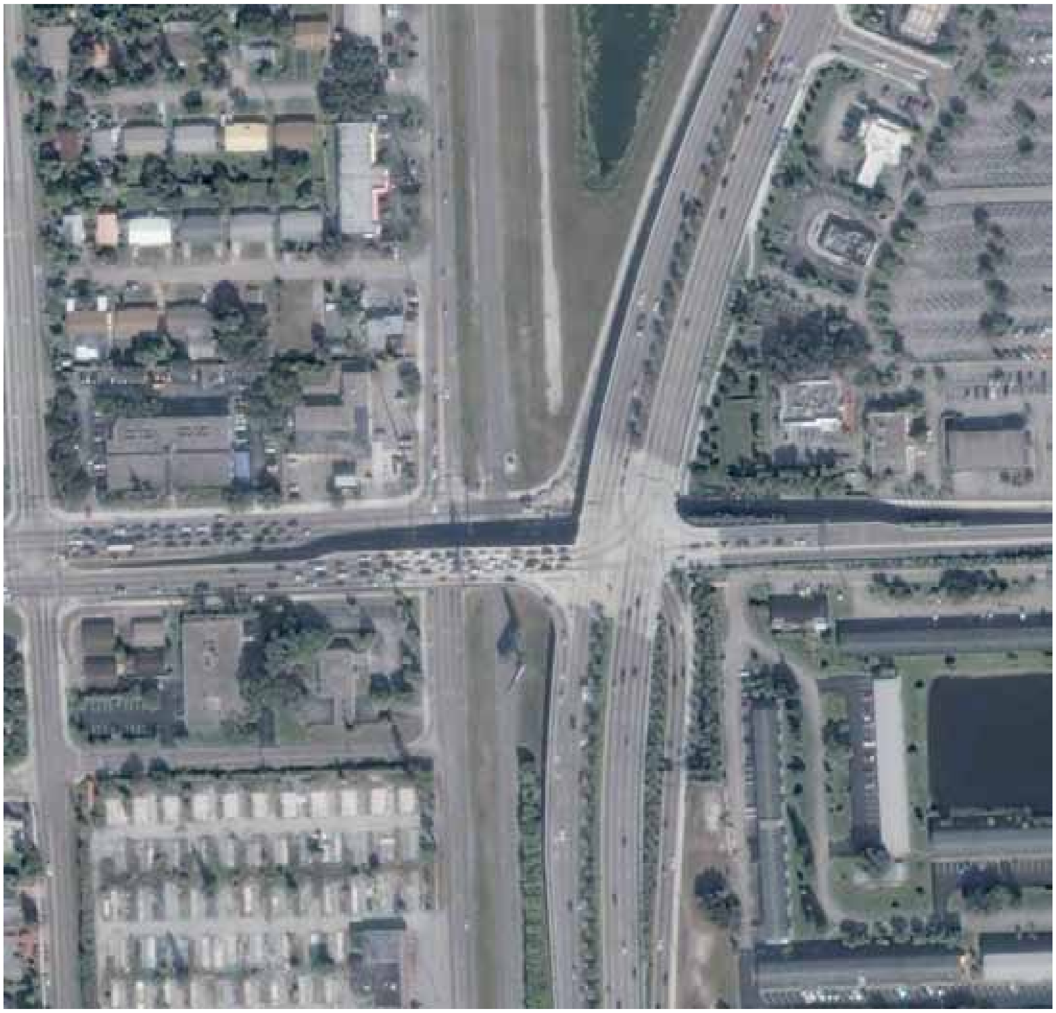


Figure 206. Illustration. Typical movements in an echelon interchange.



Source: Google™ Earth

Figure 207. Photo. Example of an echelon interchange in Aventura, FL.

Some of the advantages of an echelon interchange in comparison to a conventional intersection are as follows:(100)

- Higher capacity than at-grade intersections.
- Lower travel time than at-grade intersections.
- Enhanced progression for both streets.
- Metered traffic to help downstream signals.

Some of the disadvantages are as follows:(100)

- High structure cost.
- Impaired access to three quadrants.

- U-turn opportunities not available at or near interchange.

- Pedestrians cross grades or cross streets unprotected by signals.

Echelon interchanges are appropriate at high-volume urban or suburban intersections located within a signalized network where arterial and cross street volumes are similar.[96]

CHAPTER 10. ALTERNATIVE INTERSECTION ASSESSMENT METHODOLOGY

The methodology that is presented in this chapter attempts to broaden the perspective of transportation engineers so that they will consider alternative intersections and interchanges in their project planning and decisionmaking. Traffic engineers, highway designers, transportation planners, and other transportation professionals who have been involved with the development of intersection and interchange designs, either as part of improvement projects for existing junctions or the design of new junctions, have frequently complained about the lack of guidance on when and where evolving or new conceptual alternatives are appropriate. Guidance developed to date has been somewhat limited, qualitative, and generalized. For example, consider the following information about MUT crossovers presented in the *Signalized Intersections: Informational Guide*:[(49)]

> Due to the design, median U-turn crossovers require a wide median to enable the U-turn movement. Median U-turns may be appropriate at intersections with high major street through movements, low to medium left turns from the major street, low to medium left turns from the minor street, and any amount of minor street through volumes. Locations with high left-turning volumes may not be good candidates because the out-of-direction travel incurred and the potential for queue spillback at the median U-turn location could outweigh the benefits associated with removing left turns from the main intersection. Median U-turns can be applied on a single approach.

This guidance does not contain specific numerical values to assist transportation professionals in knowing when MUTs are applicable or most appropriate. Transportation professionals need more specific guidance. The key aspect of the alternative intersection assessment methodology is a Microsoft Excel® spreadsheet. Users can enter design hour turn movement volumes and turn lanes for an at-grade intersection into a spreadsheet. The resulting CLV sums are then calculated for the full range of alternative intersections in the spreadsheet. A summary sheet indicates whether the total CLV sums exceed a specific threshold, thereby indicating whether the intersection alternative should be advanced for more detailed consideration.

10.1 DESCRIPTION OF ALTERNATIVE INTERSECTION ASSESSMENT METHODOLOGY

Transportation planners, highway designers, and other transportation specialists can employ the process described in this section when they develop or evaluate designs for improvements to at-grade intersections. The process is shown in figure 208 and consists of six steps.

Figure 208. Chart. Alternative intersection assessment methodology.

10.1.1 Step 1. Establish Objectives

As the first step, the specific objectives for the site of interest are established by the stakeholders. The objective setting allows greater flexibility with respect to the prioritization and weighting of factors for different projects. For example, at an urban intersection project near several activity centers, pedestrian mobility and safety could be assigned significantly higher weights compared to an intersection improvement project at a remote rural location in a vastly undeveloped area. If the stakeholders identify an overriding objective, such as pedestrian mobility, then the full range of intersection alternatives should be assessed first with respect to this sole criterion. This serves as a simplified screening of the alternatives to see if that objective matches a particular strength of an alternative. For example, consider a corridor through a resort shopping area. If the stakeholders establish that speed control and minimal excessive delays are the primary criteria, then the RCUT treatment in a super street corridor could be subsequently identified as the most promising among the alternatives. If an intersection alternative is judged to be poor with respect to the primary objectives established by the stakeholders, then that intersection alternative could be eliminated from further consideration.

For this intersection alternative assessment procedure, the next four steps are to screen alternatives with respect to the following specific factors:

- Pedestrians and conflicts.
- Right-of-way.
- Access.
- Capacity and vehicular throughput.

The underlying premise is that some alternative intersection designs are better suited to certain situations compared to others. Similarly, some alternative designs are less appropriate for a given set of conditions. By investigating the range of alternative intersections as part of a first order screening, alternatives that have sufficient promise can be identified and subsequently advanced to more detailed traffic analysis and design stages.

10.1.2 Step 2. Pedestrian and Conflict Assessment

The second step in the intersection assessment is to examine the alternatives with respect to pedestrians and conflicts. As indicated previously in this report, pedestrian mobility needs can be met by all of the alternative intersections, albeit to differing degrees. For example, MUT and QR intersections have been judged to be more favorable to accommodating pedestrians crossing all legs than the other alternative intersections. In the case of the MUT intersection, the removal of left-turn maneuvers and associated left-turn phases from a conventional intersection result in fewer conflict points for pedestrians. In addition, the removal of the left-turn signal phases also allows for a reduction in the cycle length, which consequently reduces pedestrian delays. While the conflicting right-turning volume is expected to be higher at an MUT intersection compared to a conventional intersection, the reduction in the number of expected conflicts between left-turning vehicles and pedestrians on all four legs has a positive safety effect for pedestrians. This pedestrian benefit may offset the increase in the right-turning volume. Similarly, the QR intersection also enhances pedestrian safety at the main intersection by removing all left turns. Depending on their origins, destinations, and directions of travel, some pedestrians may need to cross an additional intersecting leg at a QR intersection.

If the pedestrian activity in the immediate vicinity of the subject intersection is low or nonexistent, then all four at-grade alternative intersections and roundabout designs are viable. However, if pedestrian activity is high on all four legs, then three alternative intersection designs are viable. Depending on the user’s perspective, there are limitations with respect to accommodating pedestrians for two alternative intersection designs, specifically, the roundabout and the RCUT intersection. Because there are no traffic signals to stop traffic at roundabouts, some pedestrian advocates have expressed concerns about the ability of pedestrians, notably pedestrians with disabilities, to safely cross approaches to the roundabouts. As described earlier, the RCUT intersection allows pedestrians to cross diagonally but not directly across the major roadway leg at the main intersection. Pedestrians can be afforded a direct crossing of the major road at a signal-controlled midblock crossing located beyond the main intersection. However, the RCUT intersection's inability to allow direct crossings of all legs at the main intersection may be sufficient to drop this alternative from further consideration if the subject intersection has very high levels of pedestrian activity. Table 34 summarizes general guidance with respect to viable alternative intersections as a function of the level of importance placed on meeting pedestrian mobility needs at a subject intersection.

Table 34. Qualitative assessment of alternatives as a function of pedestrian mobility and degree of conflict.

Relative Level of Importance for the Need to Provide Crosswalks	Alternative Intersection Design to Consider
Low	MUT
	QR
	DLT
	RCUT
	Roundabout
High	MUT
	QR
	DLT
	Roundabout
Relative Level of Importance for Magnitude of Conflicts Between Pedestrians and Vehicles	**Viable Alternative Intersection Design to Consider Further**
Low	MUT
	QR
	DLT
	RCUT
	Roundabout
High	MUT
	QR
	DLT
	RCUT

For the treatment of pedestrians, there are little collision data for the alternative designs to support claims about the relative degree of safety of these alternative intersections. There is also minimal information on the influence of these alternative intersections on pedestrian demand. Some hypothesize that alternative intersections may impose greater risks to pedestrians since they are not conventional and may result in more pedestrian expectancy violations. The relative degree of difficulty that is faced by a pedestrian when crossing at an alternative intersection may be qualitatively assessed.

10.1.3 Step 3. Right-of-Way Assessment

The third step in the intersection alternatives assessment methodology is to assess alternatives in terms of the availability of the right-of-way to accommodate the alternative and the cost of additional right-of-way if more is needed. There are greater challenges to implementing these alternative intersection alternatives if the median width is insufficient to accommodate U-turns and if additional and costly right-of-way is needed for the alternative. In some cases, the cost of the additional right-of-way may make many of the alternative intersections cost prohibitive. Depending on the design and whether existing streets can serve the function of a quadrant, the QR intersection may require a significant amount of additional right-of-way for the new roadway connector. Therefore, as the total cost for additional right-of-way increases, QR intersections may become less attractive as a viable design. However, if the network street exists in one or more of the quadrants, then the QR intersection could be the best design form for a given intersection. Similarly, roundabouts can have larger footprints than other alternative intersections. If the area is densely developed or if right-of-way is limited and very expensive, then roundabouts may not be a viable alternative. If the existing median is sufficiently wide to accommodate the needed number of U-turn lanes, then both the MUT and RCUT intersection are viable. However, if the median width is not sufficient, constructing an MUT intersection or a RCUT intersection in a retro-fit manner is much more challenging but not insurmountable with the use of loons. Table 35 presents a summary of these points.

Table 35. Qualitative assessment accommodation, affordability, and availability.

Adequacy of Median Widths to Accommodate U-Turns	Affordability of Additional Right-of-Way Required	Viable Alternative Intersection Design to Consider Further
Sufficient	Affordable	MUT
		RCUT
		DLT
		Roundabout
		QR
Sufficient	Very costly	MUT
		RCUT
		DLT
Insufficient	Affordable	MUT
		RCUT
		DLT
		Roundabout
		QR
Insufficient	Very costly	MUT with loons
		RCUT with loons

10.1.4 Step 4. Access Assessment

The next step in the methodology is to assess the need to preserve or provide access to adjacent parcels (e.g., via driveways) from either the major or the minor approaches in the vicinity of the subject intersection. These are often important issues in arterial design. All of the alternative intersections should be included as viable alternatives wherever the primary goal of the major road is to serve through vehicles. The RCUT intersection implemented as part of a corridor-wide treatment offers many advantages over all the other alternative intersections and conventional intersections. The median U-turn intersection is also best implemented as part of a corridor-wide treatment. In addition, a DLT intersection may be a highly desirable design to move more traffic through a heavily congested conventional intersection. However, if there is a strong need to preserve or provide access to developments in all four quadrants, then there will be greater challenges to installing a DLT intersection. Adjacent frontage roads would be required to meet the access needs within about 800 ft of the major intersection. Table 36 indicates viable alternative designs as a function of the need to provide access to parcels in four quadrants.

Table 36. Qualitative assessment of alternatives of need to provide access to all four quadrants.

Need to Provide Local Driveways in Close Proximity	Viable Alternative Intersection Design to Consider Further
Low	RCUT
	MUT
	Roudabout
	QR
	DLT
High	RCUT
	MUT
	QR
	Roundabout

10.2 TRAFFIC ANALYSIS OF ALTERNATIVE INTERSECTIONS

This section discusses the final two steps in the intersection alternatives assessment methodology. These steps involve an analysis of the traffic effects of the alternative intersection designs compared to a comparable design. While it is highly desirable to conduct traffic simulation analysis of all alternatives, frequently, there is neither the time nor the budget to do so. Consequently, many decisions are made regarding which alternatives to advance based on judgment without analysis. The intersection alternative assessment methodology recognizes this as a potential limitation. Consequently, a sketch-planning analytical method was developed to perform a level-of-service analysis of all the alternatives using the CLV summation technique. The method considers the CLV entering an intersection.

The underlying premise of the CLV summation technique is that the intersection is viewed as a common space that is shared in a sequential manner by a set of conflicting traffic movements. For example, a southbound left turn cannot be made simultaneously when the northbound movement is being made. Hence, the north-south critical movements may be either the southbound left turn and the northbound through or the northbound left turn and the southbound through according to whichever has the higher sum of lane volumes. Similarly, the east-west critical movements are calculated in an analogous manner. The sum of the CLVs for east-west and the CLVs for the north-south are considered the CLV sum for the intersection. The intersection CLV sums are then correlated to a LOS. The following values in table 37 have been used in determining LOS.

Table 37. CLV sum and corresponding LOS.

CLV Sum	LOS
< 1,200	C or better
1,201–1,400	D
1,401–1,500	E
> 1,600	F

10.2.1 Step 5. CLV Summation/LOS Assessment

The fifth step in the selection methodology is to assess the still-promising alternatives to a sketch-planning operational analysis. To assist transportation professionals with this analysis, a Microsoft Excel® spreadsheet was developed. It allows users to enter design hour turn movements and basic number of left-, through, and right-turn lanes by approach for a conventional intersection. The tabs within the spreadsheet were developed to translate that input information into data that conform to the alternative intersections. Samples of these outputs are shown in figure 209 through figure 216. This spreadsheet will be made available at some future time.

The figures show how the CLV sum indicates that some intersection alternatives will operate. In general, transportation professionals conclude that an alternative will not work if the LOS is LOS F. Consequently, a CLV sum in excess of 1,600 indicates that the intersection does not work. Table 39 presents a summary of results based on the number of lanes for left-, through, and right-turning movements selected by the user. Thus, for these volumes and number of lanes, the promising alternatives include the partial N-S and full DLT intersections.

Table 38. Table for entering input volumes.

Direction	Eastbound	Westbound	Northbound	Southbound
U-turns	10	10	10	10
Left	200	200	550	550
Through	600	600	2050	2050
Right	350	350	350	350

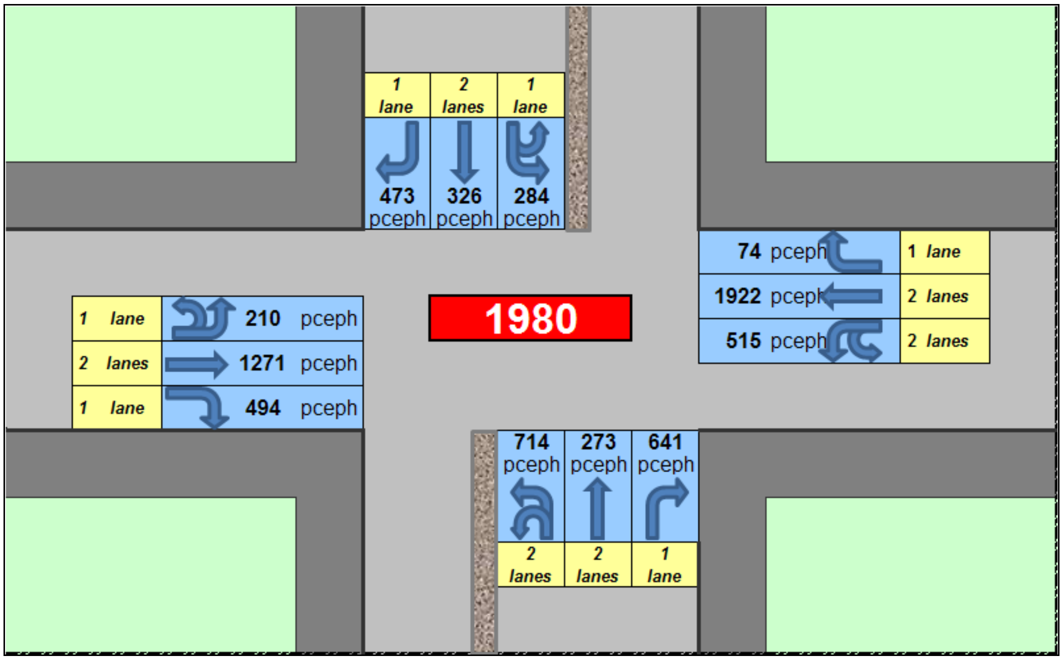


Figure 209. Illustration. Spreadsheet tab pertaining to a conventional intersection.

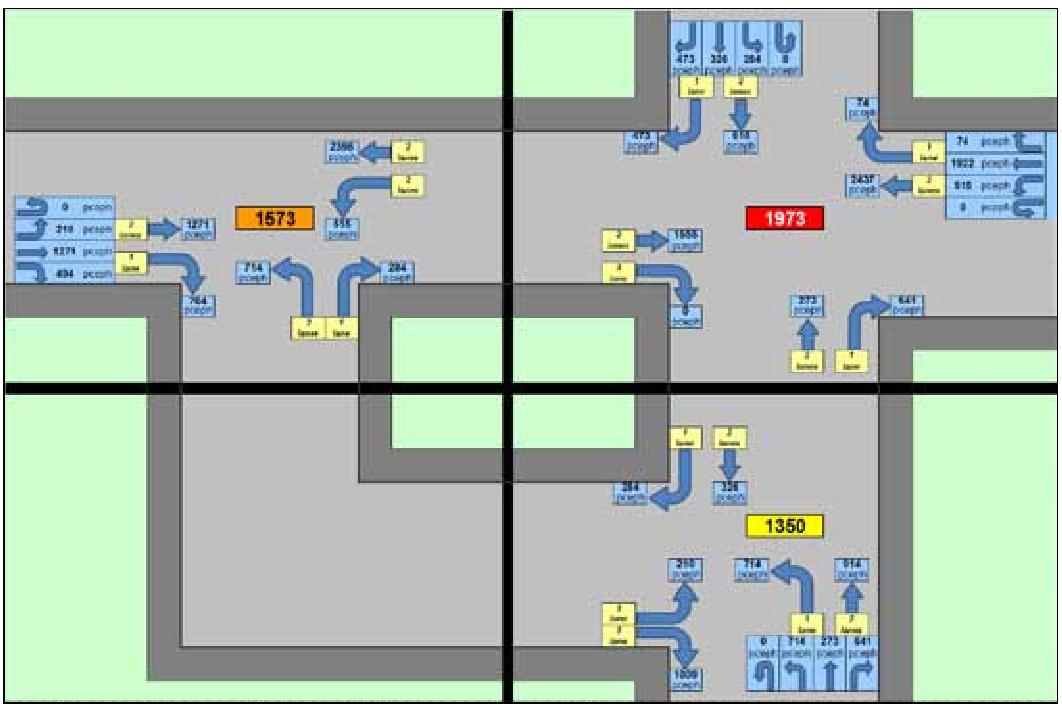


Figure 210. Illustration. Spreadsheet tab pertaining to a QR intersection.

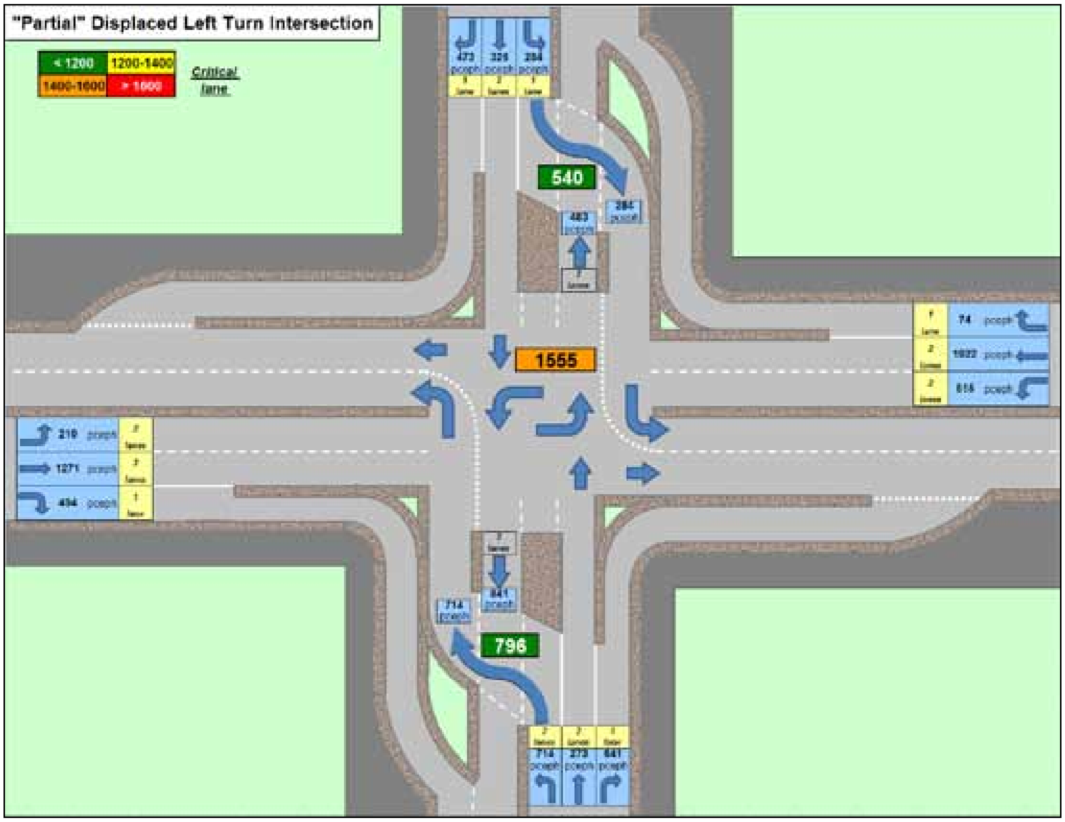


Figure 211. Illustration. Spreadsheet tab pertaining to a partial (N-S) DLT intersection.

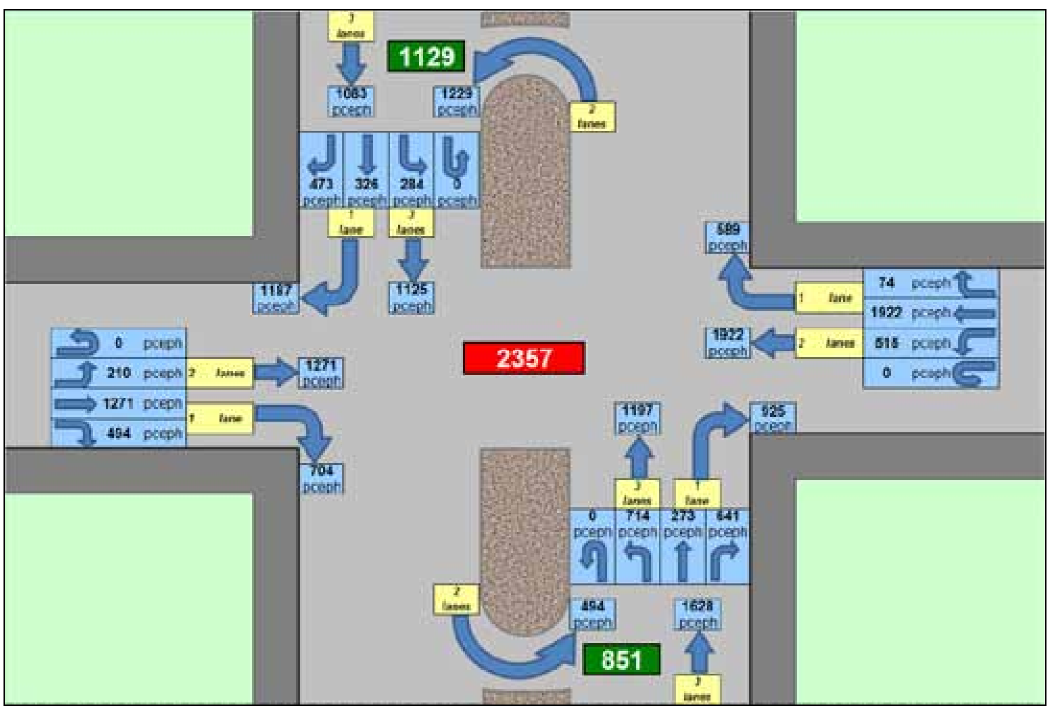


Figure 212. Illustration. Spreadsheet tab pertaining to an MUT (N-S) intersection.

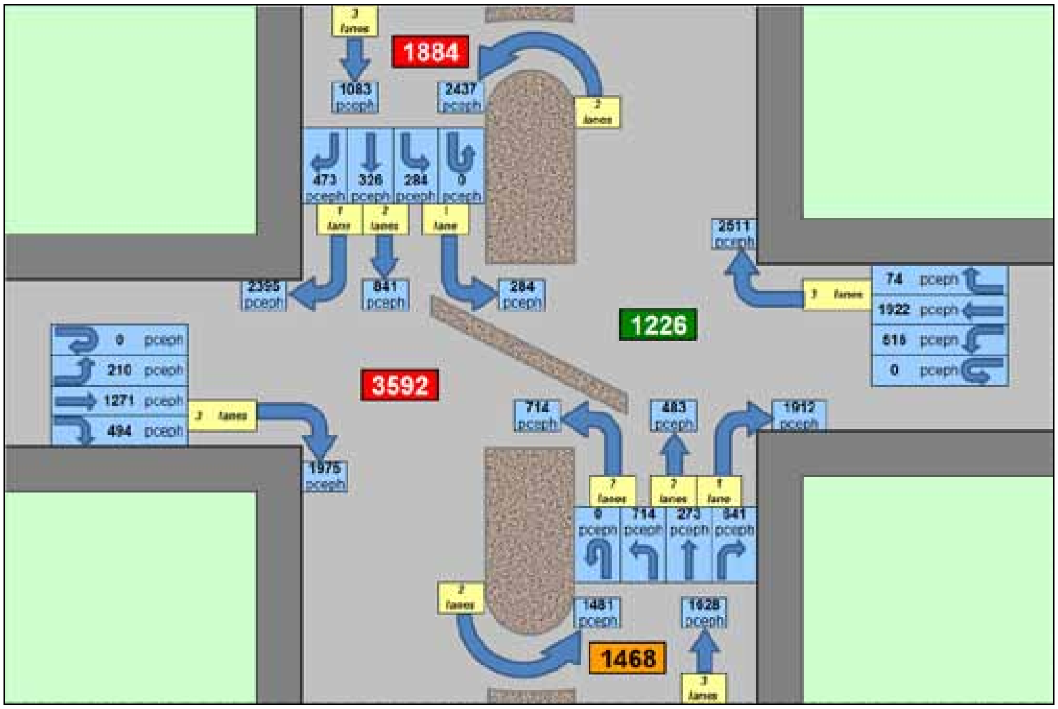


Figure 213. Illustration. Spreadsheet tab pertaining to a RCUT (N-S) intersection.

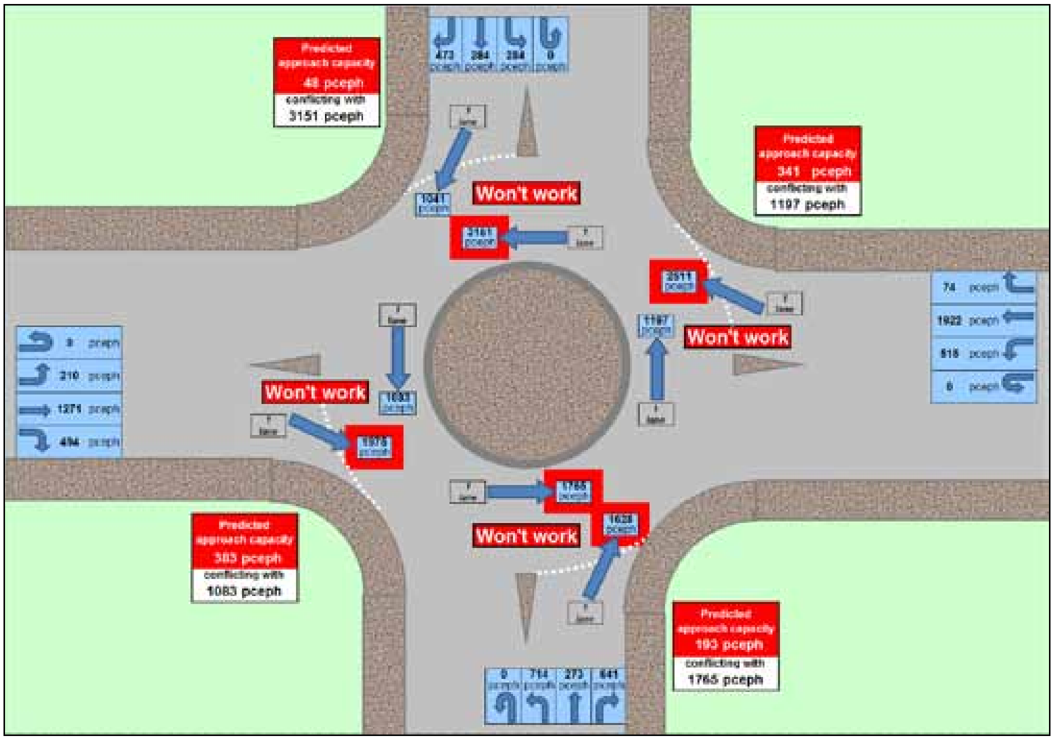


Figure 214. Illustration. Spreadsheet tab pertaining to a one-lane roundabout.

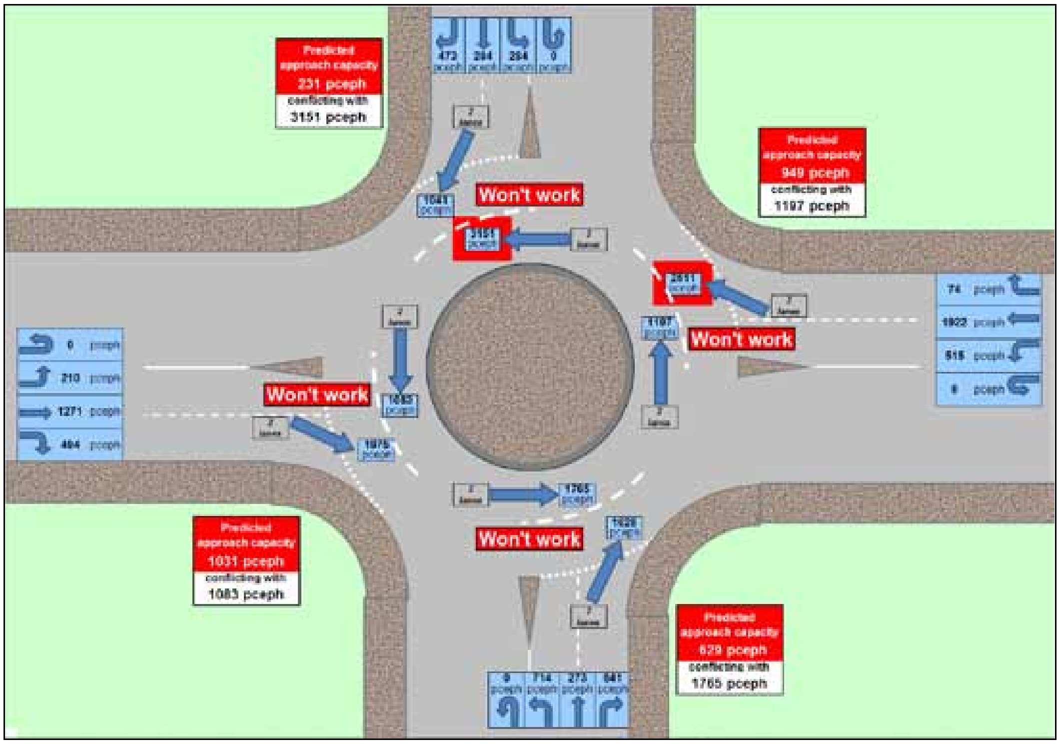


Figure 215. Illustration. Spreadsheet tab pertaining to a two-lane roundabout.

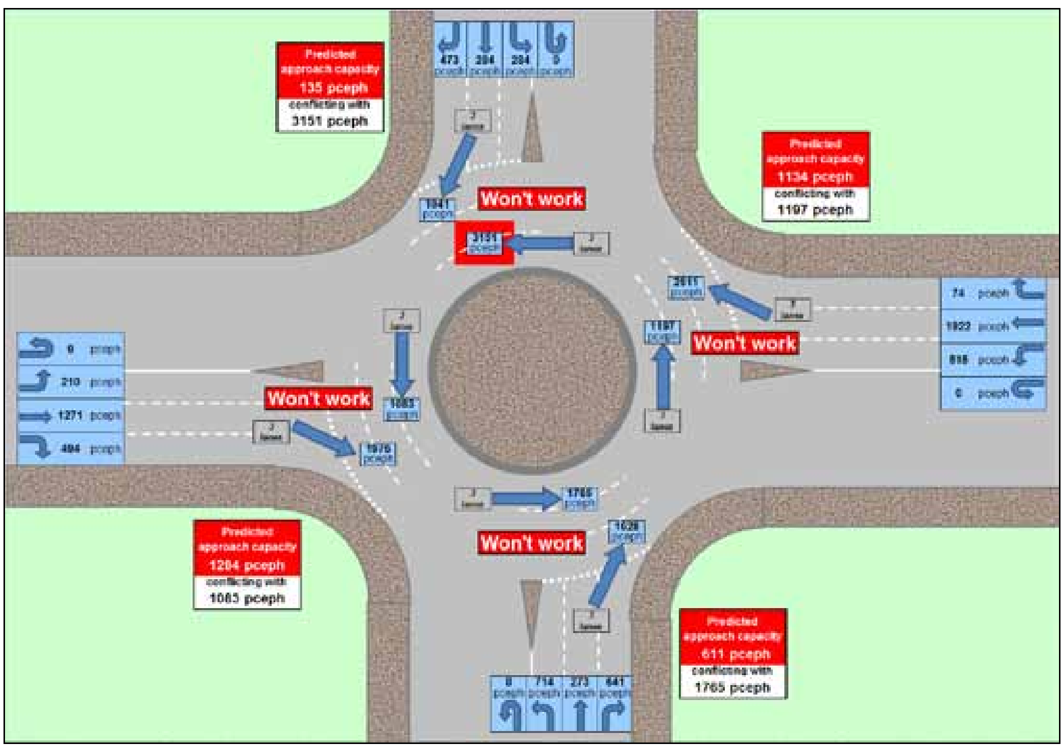


Figure 216. Illustration. Spreadsheet tab pertaining to a three-lane roundabout.

Table 39. Summary of CLV summation results.

Intersection Type			CLV Sum	Adequacy (Adequate at CLV Sum < 1,600)
1	Conventional Intersection		1,980	Inadequate
2	QR intersection	SW	1,973	Inadequate
		NE	2,072	Inadequate
		SE	1,929	Inadequate
		NW	2,357	Inadequate
3	DLT intersection	N-S	1,555	Adequate
		E-W	2,159	Inadequate
		Full	1,444	Adequate
4	RCUT intersection	N-S	3,592	Inadequate
		E-W	1,743	Inadequate
5	MUT intersection	N-S	2,357	Inadequate
		E-W	1,984	Inadequate
	Partial MUT intersection	N-S	2,358	Inadequate
		E-W	2,120	Inadequate
6	One-lane roundabout		Four approaches will not work	Inadequate
7	Two-lane roundabout		Four approaches will not work	Inadequate
8	Three-lane roundabout		Four approaches will not work	Inadequate

10.2.2 Step 6. Traffic Simulation Assessment

The final step in the selection methodology is to develop 25 percent of the design plans and detailed traffic simulation analysis of the most promising alternatives. This allows the development of more reasonable cost estimates for the alternatives. Users have to make a final decision on what alternatives to advance.

10.3 CASE STUDY

To demonstrate this process, the following case study is presented. Consider the intersection shown in figure 217. The intersection is in a suburban area of Summerside, OH. The primary highway is U.S. Route 32, which is a four-lane divided highway with an approximate median width of 42 ft. The crossroad is Bells Lane, which is a two-lane undivided road. A retail center is in the southeast quadrant of the signal-controlled intersection. The north leg of Bells Lane serves primarily as a residential area. Figure 218 shows an aerial view of the intersection.

Figure 217. Illustration. U.S. Route 32/Bells Lane intersection.

Source: Google[TM] Earth

Figure 218. Photo. Aerial view of U.S. Route 32/Bells Lane intersection.

The area is projected to experience an increase in development. As part of a project planning study, turn movement projections are developed for the morning peak hour for the year 2030, which has been selected as the design year. The projections are summarized in table 40.

Table 40. Projected year 2030 morning peak hour turn movement counts for case study intersection.

Approach	Movement	Projected 2030 AM Peak Hour Turn Volume
Eastbound	Left	200
	Thru	1210
	Right	470
	Total	1,880
Westbound	Left	70
	Thru	1830
	Right	490
	Total	2,390
Northbound	Left	680
	Thru	260
	Right	610
	Total	1,550
Southbound	Left	270
	Thru	310
	Right	450
	Total	1,030
Grand Total		**6,850**

The pedestrian activity in the area is limited, and there are few pedestrians observed during the daylight hours on a typical weekday and weekend. The existing right-of-way is approximately 160 ft, and the price for additional land is not considered to be cost prohibitive.

As part of step 1, the stakeholders support the following objectives:

- Enhance safety.
- Reduce delay and congestion.
- Accommodate planned development in smart growth manner.
- Maintain or increase the corridor capacity of U.S. Route 32.

As part of the second step in the process, pedestrian activity is such that the at-grade alternative and the other five nontraditional intersections are all judged to be viable alternatives from a pedestrian perspective. The number of pedestrian-vehicle conflict points and the vehicle-vehicle conflict points differ among the nontraditional intersection designs. However, pedestrian crossing volumes are so low that there is no reason to reject any of the nontraditional intersections from a pure pedestrian service perspective.

As noted earlier, the available right-of-way is approximately 9,160 ft, and the cost of additional right-of-way is not cost prohibitive to purchase. Hence, from a right-of-way perspective, all of the alternative designs are considered viable as part of the right-of-way availability and cost assessment, which is the third step in the process.

The fourth step in the process is to screen the alternatives with respect to access management. Since there are no driveways on U.S. Route 32 in the study area, there is no current or planned need to accommodate access needs on the major road in the immediate vicinity of the intersection. In addition, the existing driveways to commercial development on Bells Lane south of the intersection are judged to be a sufficient distance from the major intersection such that they can be maintained or converted into a right-in right-out if a median is needed on Bells Lane. All of the nontraditional intersections except for the full DLT intersection design are deemed to be feasible despite the limited distance between the main intersection and the minor intersection on Bells Lane north of the major intersection.

The fifth step in the process is to examine all the alternatives from a sketch-planning LOS analysis. The volumes are entered into the spreadsheet, and the results are summarized in figure 219 through figure 223. A summary of the outputs shown in table 41 reveals that only the RCUT intersection design has a CLV sum less than 1,600 veh/h. This result indicates that the RCUT intersection is a promising alternative that should be advanced to subsequent design phases.

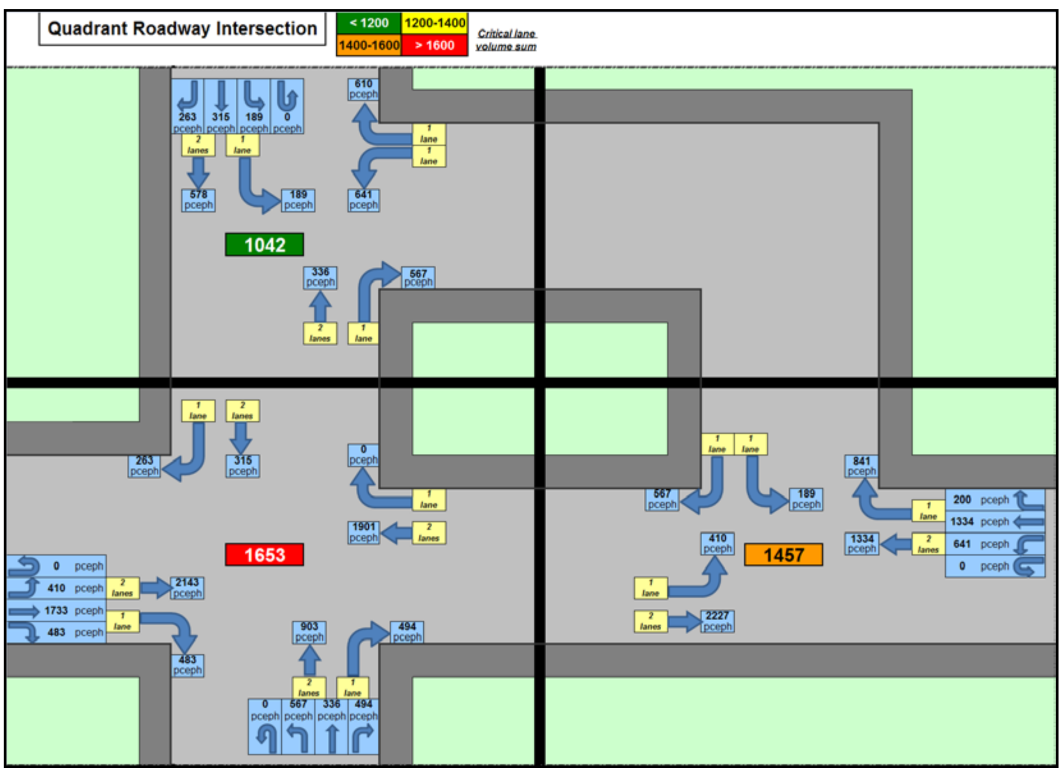


Figure 219. Illustration. Spreadsheet tab pertaining to a QR intersection.

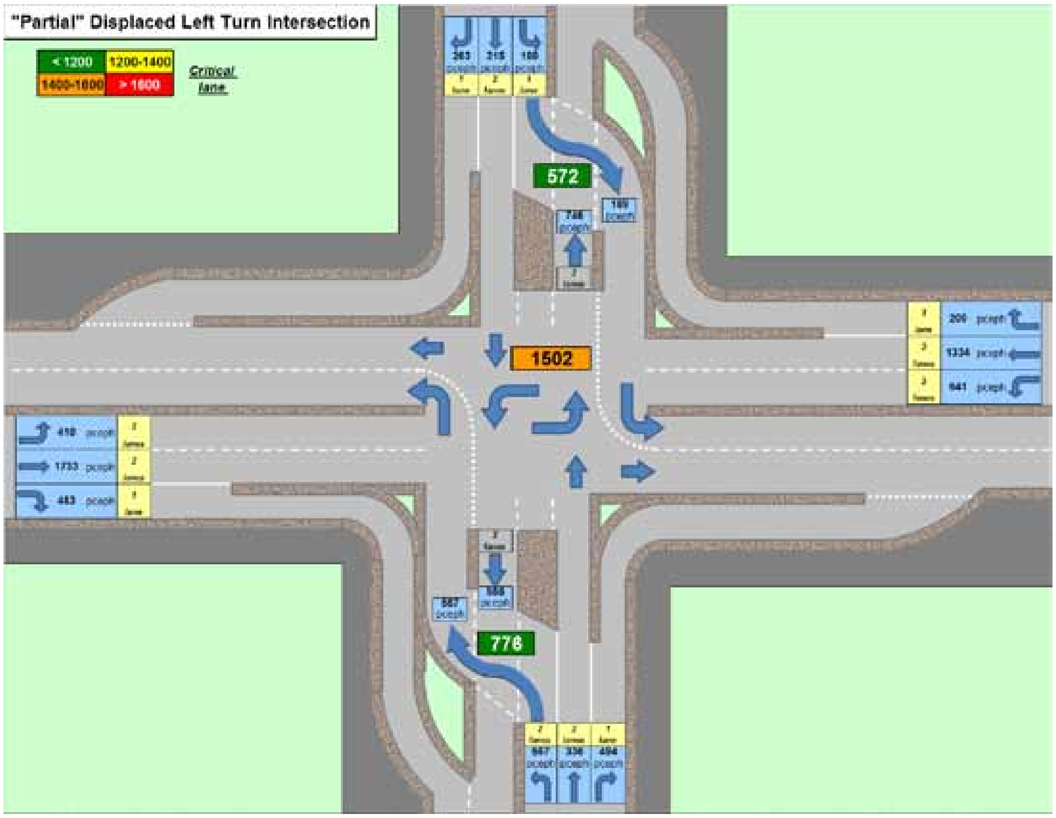


Figure 220. Illustration. Spreadsheet tab pertaining to a DLT intersection.

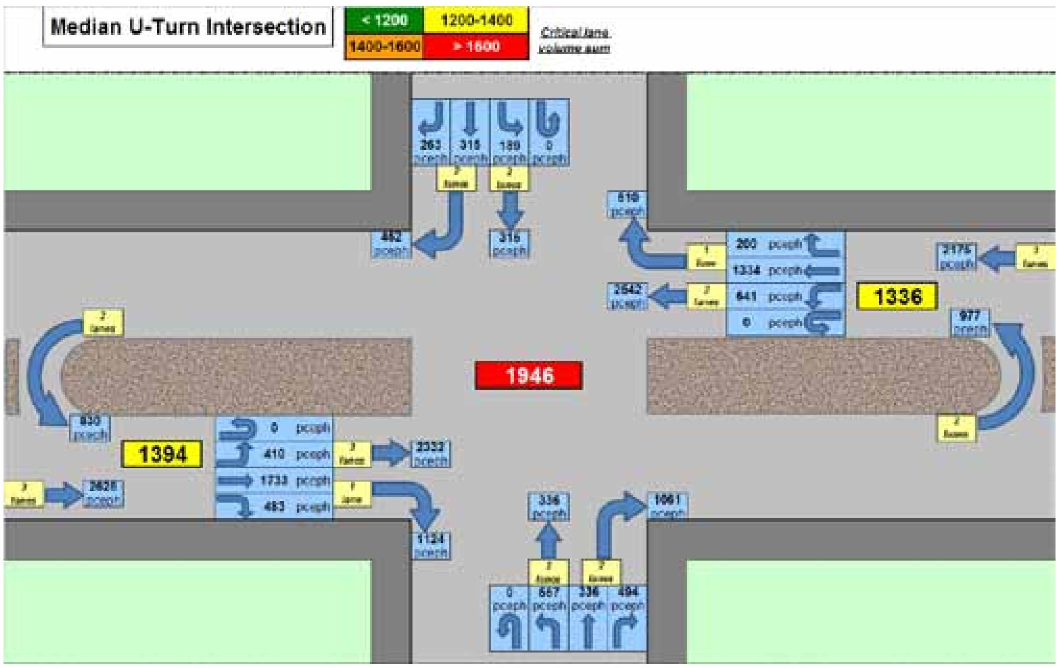


Figure 221. Illustration. Spreadsheet tab pertaining to an MUT intersection.

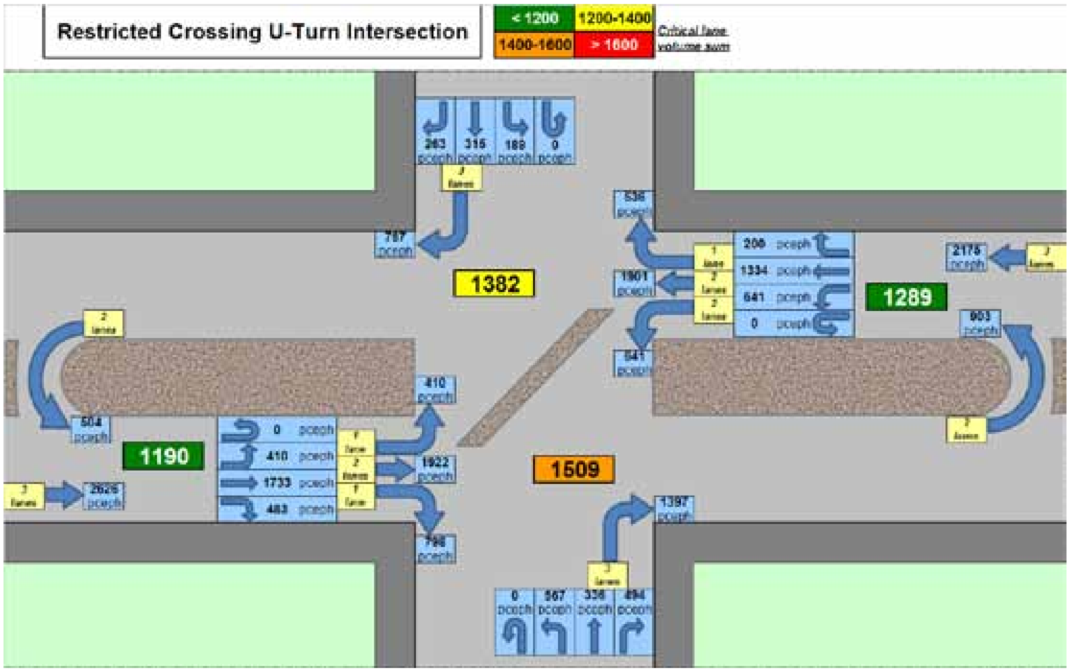


Figure 222. Illustration. Spreadsheet tab pertaining to a RCUT intersection.

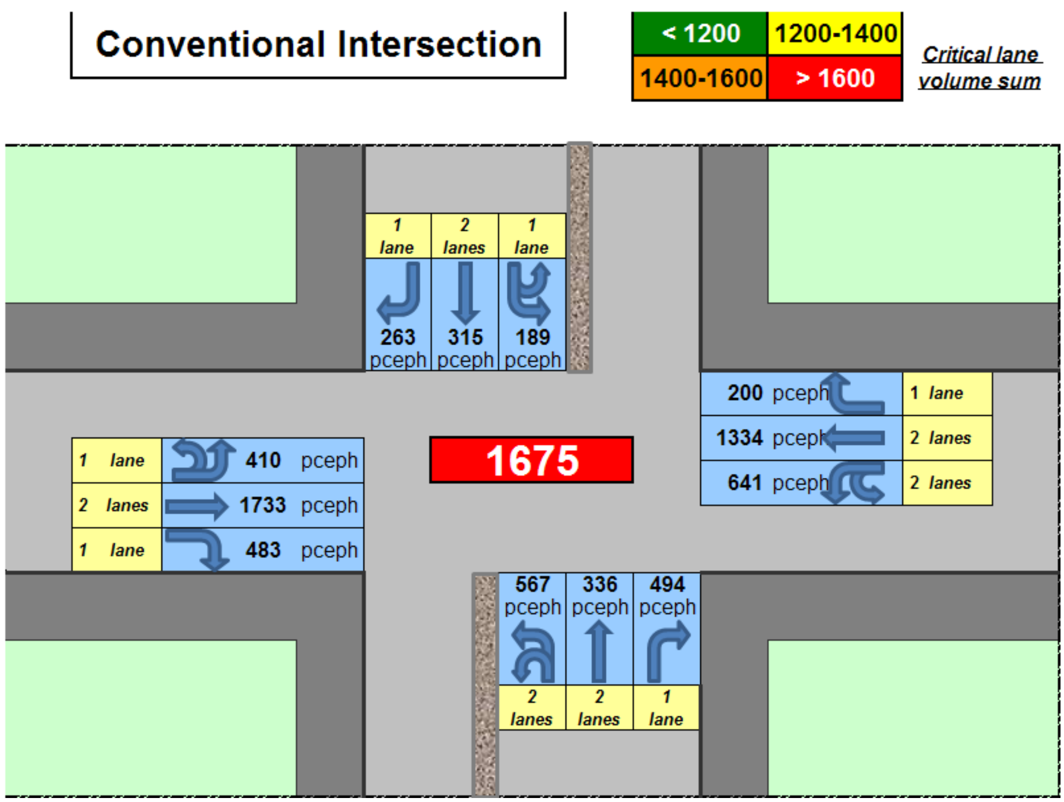


Figure 223. Illustration. Spreadsheet tab pertaining to a conventional intersection.

Table 41. Spreadsheet tab pertaining to summary results.

Intersection Type			CLV Sum	Adequacy (Adequate if CLV Sum < 1,600)
1	Conventional Intersection		1,675	Inadequate
2	QR intersection	SW	1,569	Adequate
		NE	1,653	Inadequate
		SE	2,138	Inadequate
		NW	1,653	Inadequate
3	DLT intersection	NS	1,502	Adequate
		EW	1,621	Inadequate
		Full	1,463	Adequate
4	RCUT intersection	NS	2,909	Inadequate
		EW	1,509	Adequate
5	MUT intersection	NS	2,027	Inadequate
		EW	1,946	Inadequate
	Partial MUT intersection	NS	1,695	Inadequate
		EW	1,978	Inadequate
6	One-lane roundabout	N/A	Four approaches will not work	Inadequate
7	Two-lane roundabout	N/A	Four approaches will not work	Inadequate
8	Three-lane roundabout	N/A	Four approaches will not work	Inadequate

N/A = Not applicable.

The sixth step consists of a more detailed traffic and design assessment of the alternative. The Ohio Department of Transportation (ODOT) used Synchro® to further investigate the traffic impacts of a super street.[21] While Synchro® may not be as robust an evaluation tool as a simulation program such as VISSIM®, it is adequate to provide a better analysis of the alternatives than the sketch planning procedure. The network evaluated is shown in figure 217, and their results confirmed that the RCUT intersection provided acceptable LOS for both the morning and afternoon peak hours. In developing the 25 percent design plans, the ODOT made further refinements to the RCUT intersection in order to accommodate traffic on the northern leg and future planned development. The resulting alternative is shown in figure 224. This alternative was still being considered as a viable alternative by ODOT at the time this report was prepared.

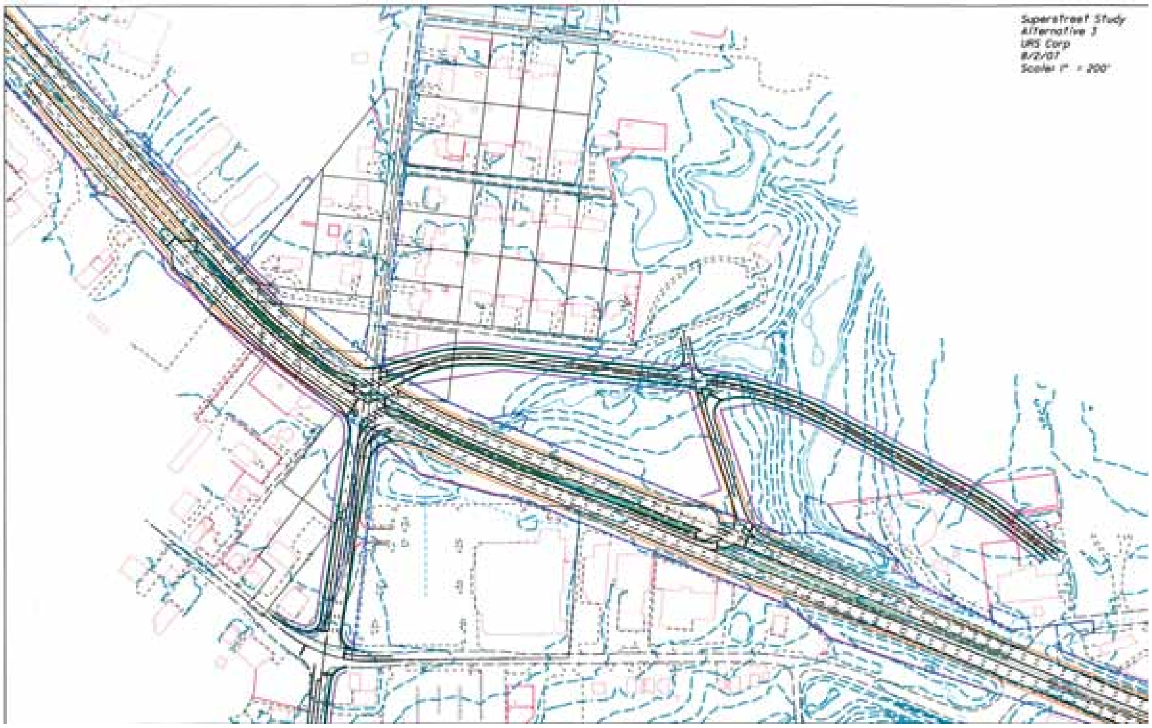


Figure 224. Illustration. Proposed configuration at the intersection of U.S. Route 32/Bells Lane intersection used in case study.

In conclusion, it can be seen that the process developed for this report and documented in this chapter provides a simplified method to consider and to screen a range of nontraditional intersections designs. This process can serve as a means to identify additional nontraditional intersection designs that might not have been included as viable alternatives. The process could be refined in subsequent research efforts. As a first order of magnitude tool, though, it helps to empower the transportation professional to promote creative and innovative thinking and to generate reasons for advancing nontraditional intersections.

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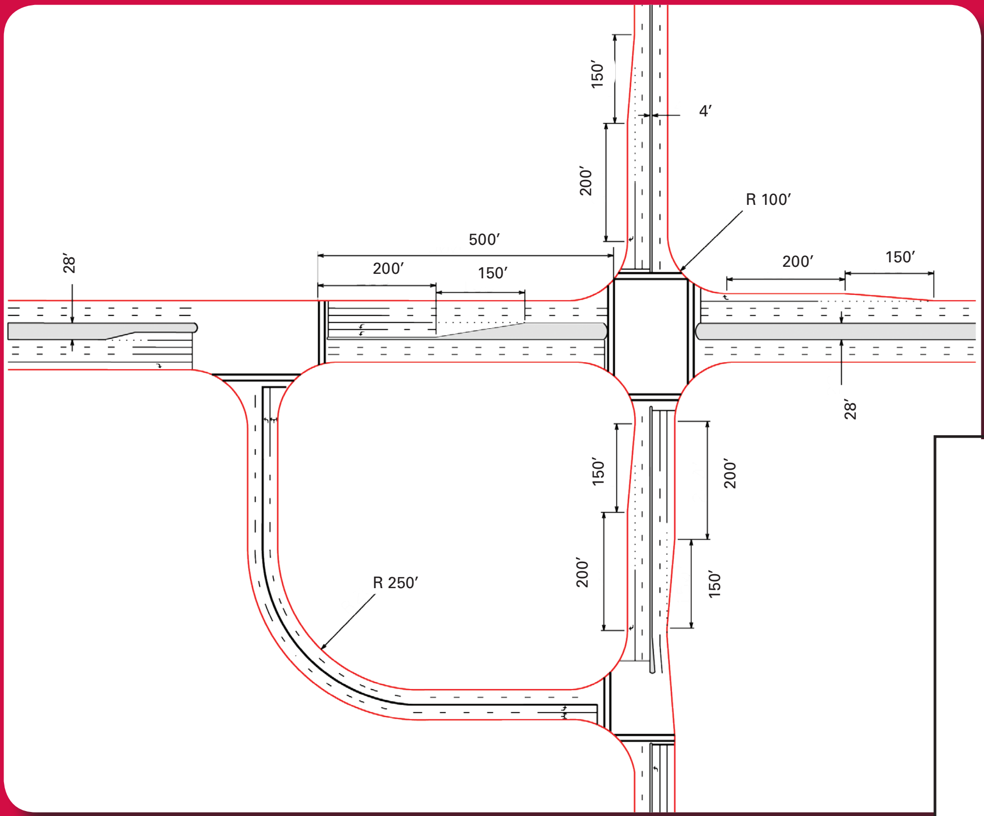

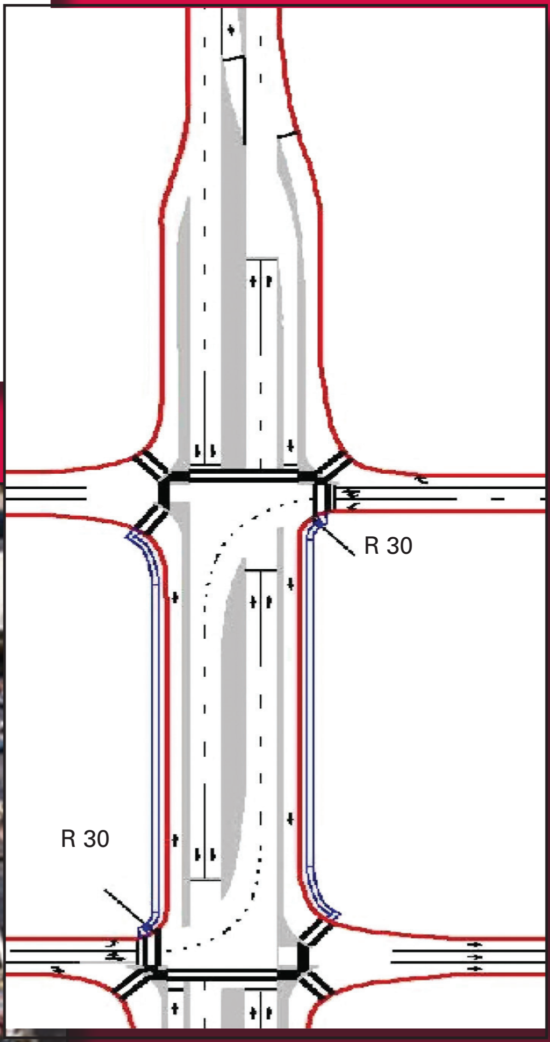

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