U.S. Department of Transportation
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Synthesis of Alternative Intersection Forms

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Research, Development, and Technology
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FOREWORD

Alternative intersections and interchanges (AIIs) are unconventional designs conceived and optimized for specific recurring traffic patterns. AII forms consist of sets of primary and satellite intersections that give designers the flexibility to strategically reroute certain movement(s) to remove, reduce, and relocate key traffic conflicts that tend to induce congestion or severe traffic crashes. The variety of AII designs are as numerous as the possible combinations of land use and associated traffic patterns. Under the right circumstance, AII designs can deliver significant cost benefits over conventional intersections. Given the use of channelization and rerouting present in many AIIs, considering the impact on connected and autonomous vehicles (CAVs) is important.

This report summarizes 20 AII forms and a framework for considering the CAV infrastructure needs of a given design. Practitioners in the concept or feasibility design stages can use the information contained in this synthesis to identify common advantages and challenges of intersection forms and consider the additional infrastructure that may assist CAVs in navigating an intersection. The document provides numerous resources for practitioners to find additional, expanded design guidance for many of the forms.

Carl K. Andersen
Acting Director, Office of Safety and Operations Research and Development

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16. Abstract This report presents a series of aids that summarize key features of 20 forms of alternative intersection designs. These aids will help practitioners become familiar with new forms—or variations of forms with which the design is familiar—and guide practitioners to additional resources. The report also includes an analysis of connected and automated vehicle needs as they relate to specific intersection form categories.		
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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

AII	alternative intersection and interchange
CAV	connected and automated vehicle
CGT	continuous green T-intersection
DDI	diverging diamond interchange
DDT	dynamic driving task
DLT	displaced left turn
DOT	department of transportation
FHWA	Federal Highway Administration
I2V	infrastructure-to-vehicle
MassDOT	Massachusetts Department of Transportation
MUT	median U-turn
NACTO	National Association of City Transportation Officials
NYCDOT	New York City Department of Transportation
QR	quadrant roadway
RCUT	restricted crossing U-turn
SPI	single-point interchange
SSD	stopping sight distance
UDOT	Utah Department of Transportation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VDOT	Virginia Department of Transportation

CHAPTER 1. INTRODUCTION

Roadway designers have been developing new intersection forms for decades. The practice of presenting such designs in technical papers accelerated in the early 2000s, with multiple papers typically published each year since. The Federal Highway Administration (FHWA) has published reports to summarize the design considerations specifically for diverging diamond interchanges (DDIs),[(1)] displaced left-turn (DLT) intersections,[(2)] restricted crossing U-turn (RCUT) intersections,[(3)] median U-turn (MUT) intersections,[(4)] and quadrant roadways (QRs)[(5)] as well as for alternative intersections more generally.[(6)]

This report has two aims:

- Categorize and summarize high-level information regarding more than 50 intersection forms, directing the reader to additional resources where possible.
- Summarize design considerations for intersections in the context of connected and automated vehicles (CAVs).

In the context of this report, the following terms are used:

- **Intersection form:** The geometric alignment of roadways and the associated paths for moving from one roadway to another, irrespective of the traffic control device used.
- **At-grade intersection:** The crossing of two roadways at grade level in which each approach is engaged by a priority rule that may or may not be conveyed by a traffic control device.
- **Grade-separated intersection:** The crossing of two roadways at two or more different grades in which each approach is engaged by a traffic control device.
- **Interchange:** The crossing of two roadways at two or more different grades in which the limited-access roadway experiences a free-flowing movement.

CATEGORIZING INTERSECTION FORMS

Many intersection forms are variations of an existing intersection form or combinations of two or more existing forms. When designers select the appropriate form for a project context, understanding the relationship between similar intersection forms is helpful. This understanding allows a designer to select the form that meets unique right-of-way, grade separation, or site condition requirements.

This report presents information for 20 intersection forms. To the research team’s knowledge, more than 50 forms exist. These forms can be categorized by their dominant feature, presence or absence of grade separation, and presence (intersection) or absence (interchange) of traffic control on the major street. Table 1 shows the components of this categorization. The three types of protected intersections with intersection form aids include a typical protected intersection, a protected intersection with a two-way cycle track, and a protected intersection featuring a one-way street.

Table 1. Forms by intersection category and grade separation.

Dominant Feature	At-Grade Intersection	Grade-Separated Intersection	Interchange
Direct left	• *Continuous green T-intersection* • *Direct left (at grade)* • Offset T-intersection • *Protected intersection* • *Split intersection*	• Center turn overpass • Direct left (grade separated) • *Echelon* • Three-level intersection • Two-level signalized intersection	• Double offset T-interchange • Single-point interchange • *Three-point interchange* • Spread diamond interchange • Tight diamond interchange
Redirection of left turns via U-turn	• *Bowtie intersection* • Double contraflow intersection • *MUT intersection* • *ThrU-turn*	—	• Free-range eagle interchange • MUT interchange • W-interchange
Redirection of left turns via auxiliary road	• *Jughandle* • *QR intersection*	Single-loop intersection	• Partial cloverleaf A • Partial cloverleaf B • Partial cloverleaf AB
Redirection of minor street via U-turn	• Hamburger intersection • *RCUT* • Shifting movement • *Thru-cut* • Unconventional U-turn treatment	—	*Milwaukee A interchange*
Contraflow	—	—	• Contraflow left-turn interchange • Folded interchange • Offset diamond interchange • Parclo progress A • Super DDI
Contraflow and U-turn	—	Contra RCUT	• Milwaukee B interchange • Synchronized interchange
Circular intersection	• Rotary • *Roundabout* • Traffic circle	—	• Double roundabout interchange • Raindrop interchange • *Single roundabout interchange*
Crossover of through vehicles	Upstream signalized crossover	—	• Crossover roundabout • *DDI*
Crossover of left turns	• Left turn bypass • Parallel flow intersection • *DLT*	—	• *DLT interchange* • Displaced partial cloverleaf interchange

Dominant Feature	At-Grade Intersection	Grade-Separated Intersection	Interchange
Dynamic lane sharing	• Combination tandem and exit lanes for left-turn control • Contraflow left-turn lane intersection • Dynamic left-turn intersection	—	—

—No known form.
Parclo = partial cloverleaf.
Note: Italicized intersections indicate forms that have the intersection form aid provided.

CAVs

CAVs are equipped with communication and automation technologies that allow them to coordinate with each other and with infrastructure to maximize safety and network efficiency. CAV technology, applications, and potential benefits have been widely documented. This report focuses on defining the unique needs of CAVs at various intersection forms.

CAVs rely on three core functions that support a vehicle's ability to safely navigate through roadway environments considering the presence of traffic:

- Sensing—Collecting data feeds through the vehicle's onboard sensors as a first step to help the vehicle develop situational awareness about where the vehicle is relative to the roadway environment and surrounding traffic.
- Perceiving—Developing situational awareness through two main tasks:
  1. Fusion and analysis of data feeds coming through the vehicle's onboard sensors.
  2. Additional data and information exchange through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication.
- Detecting and planning—Employing a core automation-enabling function through which the vehicle plans its trajectory and accounts for potential obstructions along that trajectory by using the following parameters:
  1. Data feeds from the sensing function.
  2. The situational awareness formed through the perception function. This function supports the dynamic driving task (DDT) of a vehicle. DDTs are the real-time actions the vehicle needs to perform while traveling on the road, such as lateral and longitudinal vehicle control, object detection, and maneuver planning.

A CAV's ability to sense, perceive, detect, and plan under various conditions depends on the level of automation. Such operational design domains are usually very limited for low levels of automation with a reduction in limitations as the level of automation increases because the sensors on the vehicle and type of perception and control on the vehicle increase with the level of automation. Regardless of the automation level, when the perception function is completely performed through the vehicle's onboard sensing, its operational design domain would be limited compared to when communication is added (i.e., infrastructure assisted). For example, a vehicle's ability to navigate through intersections in mixed traffic is determined by the level of situational awareness that is enabled, which in turn is expanded when infrastructure assistance and communication are provided. This situational awareness determines whether and how a CAV with a certain level of automation can navigate through an intersection, given its geometric configuration and traffic control design.

CHAPTER 2. INTERSECTION FORM AIDS

To help practitioners select an appropriate design form, this report presents aids that summarize key features. The research team anticipates that these aids will help practitioners become familiar with new forms and direct practitioners to additional resources.

Before designers determine which form to use, they should evaluate the context classification of the project site. The intersection form aids can help practitioners consider the five transportation expectations used to define context: users and vehicles, movement, permeability, network, and speed.

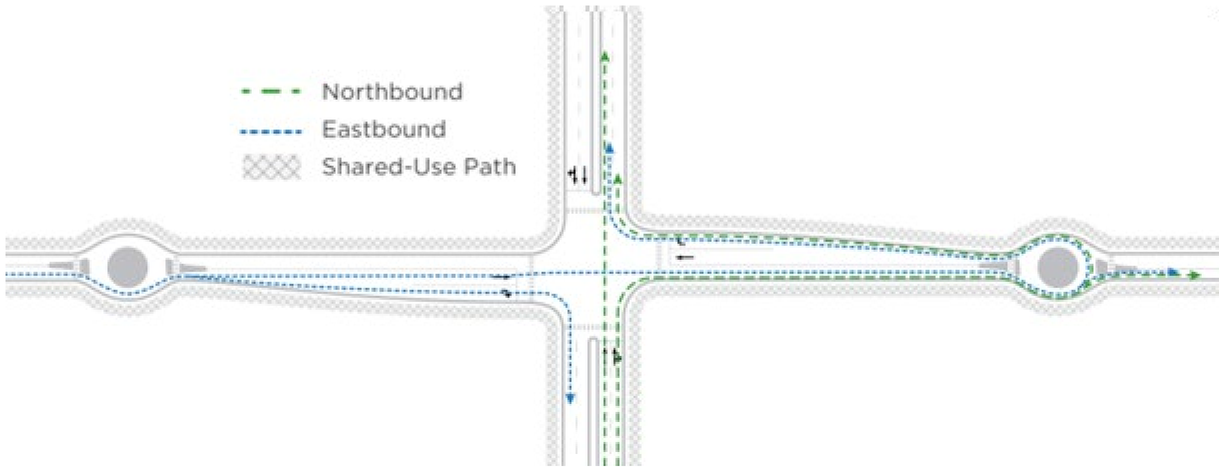
BOWTIE INTERSECTION

Description of Design Features

An efficient at-grade intersection form that moves left turns at an intersection to adjacent roundabouts.

In the bowtie intersection, the main intersection only serves through and right movements. Left turns are directed either through or right at the main intersection to minor street roundabouts, where a U-turn can be executed to then return to the main intersection and proceed in the desired direction of travel. As figure 1 shows, eastbound vehicles go straight through the roundabout and either turn right at the main intersection to head south or continue through. At the second roundabout, eastbound vehicles continue through, while northbound vehicles make a U-turn around the roundabout, proceed to the main intersection, and turn right. Vehicles from the south go through the main intersection to travel north or turn right at the main intersection and continue to the roundabout. At the roundabout, the vehicles can either go straight to head east or execute a U-turn and proceed to the main intersection, where they can continue through to go west.

As figure 1 shows, bicyclists and pedestrians both enter the intersection on a shared-use path. Eastbound bicyclists and pedestrians on the south side of the intersection turn right and continue on the shared-use path to head south. The bicyclists and pedestrians who are continuing east instead cross the south crosswalk in one stage. To head north, the path users turn left after the first stage and continue with an additional crossing.



Source: FHWA.

Figure 1. Illustration. Bowtie intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The bowtie has two critical phases: one for the major street and one for the minor street. The main intersection is signalized. The roundabouts can serve two or more legs. As typical with roundabouts, vehicles yield on entering. Providing two-stage turn boxes for bicyclists at the main intersection reduces out-of-direction travel for bicyclists.

Safety Performance

Bowtie intersections eliminate all left-turn conflicts and reduce the number of points where motorists, pedestrians, and bicyclists may cross paths. The roundabouts also promote lower speeds, giving drivers more time to react.(7) Pedestrians may experience higher exposure to right-turning volumes due to redirected vehicles.

Vehicle Traffic Demand Patterns

Designers should consider bowties at intersections with moderate-volume to heavy-volume through traffic and low-volume to moderate-volume left-turn traffic.(7) Increased volumes on the minor street will require greater spacing between the roundabout and main intersection to avoid queue spillback into the roundabout. This intersection type can be used at intersections with narrow or no medians.

Multimodal Considerations

The bowtie commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or a shared-use path. Pedestrians cross at the main intersection via standard crosswalk markings, and a median refuge may be provided. A signal timing plan with two critical phases, also known as two-critical-phase design, allows for lower cycle lengths and reduced delays for pedestrians. The roundabouts provide additional points for pedestrians to cross the minor street. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6)

Pedestrians can choose to cross the minor street at the main intersection or, if coming from the minor street, at the roundabout.

Bicyclists making through movements encounter relatively higher percentages of green time at bowtie intersections compared to the same experience at conventional intersections. Bicyclists making a left turn at a bowtie intersection have three options:

- Make a two-stage left turn via a bicycle box.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules using the roundabout.

Bicycle facilities in the roundabouts can include any combination of separated facilities, shared bicycle–pedestrian facilities, and shared bicycle–motor vehicle lanes. Where needed, bicycle ramps can provide transitions between onstreet bicycle lanes and separated or shared-use facilities.[8] People who are walking and bicycling have an increased conflict with right-turn vehicle movements due to a higher proportion of right-turning vehicles. Transit stops can be nearside or far side and are best located outside the roundabouts. Transit vehicles turning left experience greater travel distance because they need to make the U-turn at the roundabout, whereas vehicles going through or right get more green time and thus experience a potentially faster travel time.

Freight Considerations

A typical bowtie has roundabouts designed to accommodate large vehicles making the U-turn. A traversable truck apron can serve large vehicles, which helps minimize other roundabout dimensions. The main intersection operates similarly to a conventional intersection.

Corridor Considerations

The two-critical-phase operation results in a wide progression band opportunity. Therefore, the bowtie intersection is well paired with other intersections with a low number of critical phases. The bowtie can be used downstream of an intersection with heavy and consistent discharge, such as a DLT or a DDI. Because the bowtie does not require medians at the main intersection, it needs similar or less right-of-way space than the conventional intersection. However, additional right-of-way may be required to construct the two roundabouts, with the roundabouts' diameters varying depending on speed, volume, vehicle size, and number of legs. Access to parcels close to the roundabout should be limited to right-in and right-out configurations due to the design of the splitter island. Driveways within the roundabout are permissible but discouraged. Spacing from the roundabouts to the main intersection should balance avoiding queue spillback into the roundabout with minimizing extra distance travel for redirected movements.

History and Variation

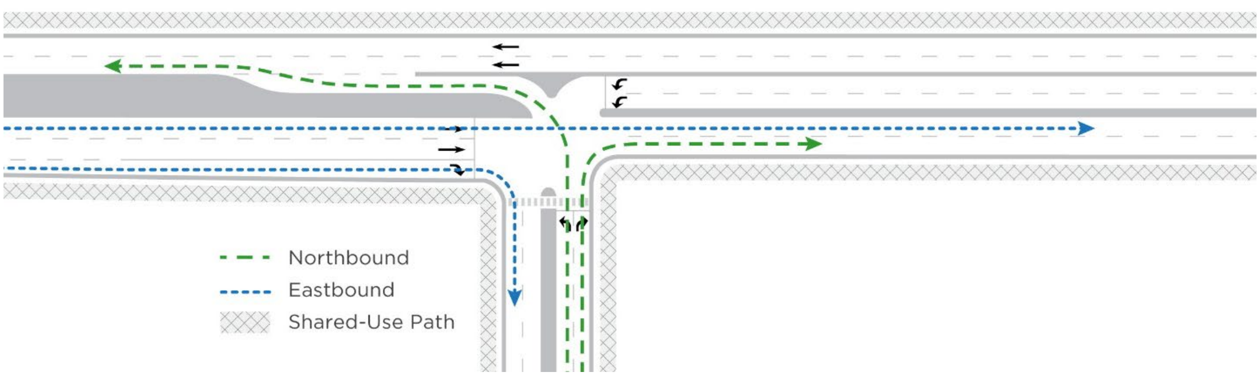
Boone and Hummer conceived the bowtie design in the early 1990s[9] and detailed its concept in a report for the North Carolina Department of Transportation (DOT).[10] While to the research team's knowledge a bowtie has not yet been built, Prince William County in Northern Virginia has developed a preliminary design concept for a bowtie intersection at Clover Hill Road and Prince William Parkway.

CONTINUOUS GREEN T-INTERSECTION (CGT)

Description of Design Features

A three-leg, at-grade intersection form that features uninterrupted vehicle flow for one direction of major street movement.

In the CGT, one direction of major street vehicles can pass through the intersection uninterrupted while the opposing major street direction is controlled by a traffic signal or stop sign.[7] The intersection must have three legs. Left-turning vehicles from the minor street use a channelized receiving lane to merge onto the major street. A directional median prevents left-turning vehicles on the major street from continuing straight. As figure 2 shows, eastbound vehicles pass through the intersection and either turn right to go south or continue through to go east. Vehicles from the south can turn right to head east or left into the receiving lane to merge with westbound traffic. In this scenario, westbound traffic does not stop. Bicyclists and pedestrians both enter the intersection on a shared-use path. Eastbound bicyclists and pedestrians on the south side of the intersection turn right and continue on the shared-use path to head south. Bicyclists and pedestrians who are continuing east instead cross the south crosswalk in two stages through a median island. Crossing the major street would require additional traffic control.



Source: FHWA.

Figure 2. Illustration. CGT displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The CGT has two critical phases: one for the major street (eastbound) and one for the minor street. The intersection can be signalized or controlled with minor street stop control under low minor street volumes. The continuous flow of traffic in one direction allows signal timing engineers to align the green time and offset for vehicles moving in the controlled direction with the adjacent intersections, reducing corridor travel times and vehicle stops.[7]

Safety Performance

Channelizing left-turning vehicles from the side street reduces potential angle crashes, and the CGT results in reduced frequency of injuries and total crashes.[11] Safety risks may include more potential for driver and pedestrian confusion, lack of a protected pedestrian crossing of a major street, and an increase in merging maneuvers.[9]

Vehicle Traffic Demand Patterns

Designers should consider CGTs at intersections with heavy through traffic volumes and low left-turn traffic volumes from the minor street.[7] This intersection type can be used at intersections with three legs.

Multimodal Considerations

The CGT commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or a shared-use path. Pedestrians can only cross the minor street, typically using a two-stage crossing through a median refuge. Pedestrians along the free-flow leg of the major street can continue through with no crossings. Because crossing the major street is not allowed, the project team recommends against using CGT in areas with high pedestrian activity unless additional traffic control is provided. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals. Bicyclists can be served through bicycle lanes in the travel lane or in a shared-use path. Bicyclists from the minor street may take the lane and turn left as a vehicle would. Median-running or left-side bicycle lanes may be suitable until an adjacent intersection is encountered where bicyclists can transition to the right side of the street. This approach may be preferable to multiple at-speed lane changes following the left-turn movement.

Transit vehicles going in the direction of the continuous flow experience a shorter corridor travel time. Transit vehicles making a left turn from the minor street may experience increased delay compared to two-way stop control due to the signal. Vehicles on the major street can use nearside or far-side stops, while vehicles on the minor street should use nearside stops.

Freight Considerations

Curb radii and median widths of a CGT should consider the needs of the design vehicle.

Corridor Considerations

The two-critical-phase operation results in a wide progression band opportunity. Because the CGT controls only one direction of travel, the intersection can be easily integrated into a coordinated traffic control signal system. In the direction with signal control, arterial progression is more likely to be optimal when intersection demands for left turns to and from the T-approach are low.[9] Because major-street pedestrian crossings are typically not at CGTs, designers should implement CGTs at intersections with a limited number of pedestrian crossings across the major street or on a corridor with nearby alternative pedestrian crossing locations.[11] CGTs require modest right-of-way options, because additional width is needed on the major street for channelization and merging. The researchers recommend against having driveways along the major street opposite the side street. If driveways are permitted, designers should consider channelization to prevent drivers from the minor street from passing through the major street to access a driveway.[9]

History and Variation

Engineers have implemented CGTs in Florida, Maryland, Virginia, and Michigan. Their use dates to before 2000.[6] In one variation, the directional median that separates left-turning vehicles on the major street from through vehicles is replaced by a raised median taper. This configuration allows the innermost lane traveling in the uncontrolled direction to proceed through (under signal control), if desired. This variation also eliminates the need for a downstream merge area because the innermost lane continues as a full lane downstream of the intersection.[9] This option may be suitable for narrower right-of-ways. The CGT is also known as a seagull or turbo T-intersection.[9]

DDI

Description of Design Features

> An interchange form that improves safety and mobility by using crossovers to temporarily diverge traffic from the right side of the road to the left side, eliminating left-turn conflicts.

DDI includes direct ramps to and from a limited-access highway. The cross street features the relocation of the left turn and through movements to the left side of the road between ramp terminals. As figure 3 shows, eastbound vehicles either turn right for the southbound ramp or crossover at the terminal to the north side of the street. From there, drivers either turn left onto the northbound ramp or cross back over at the terminal to the south side to continue east. Northbound vehicles either turn right to head east on the cross street or turn left, crossing over to the north side at the outbound ramp terminal and continuing west.

Pedestrians are often routed into the median between ramp terminals, leading to a four-stage crossing to continue through on the cross street. After crossing the right turn to the on-ramp, pedestrians and bicyclists coming from the west cross over to the central median at the first terminal; continue through the median until the second terminal, where they cross back to shared-use paths on the north or south side; and complete the journey by crossing the off-ramp.

Operational Considerations

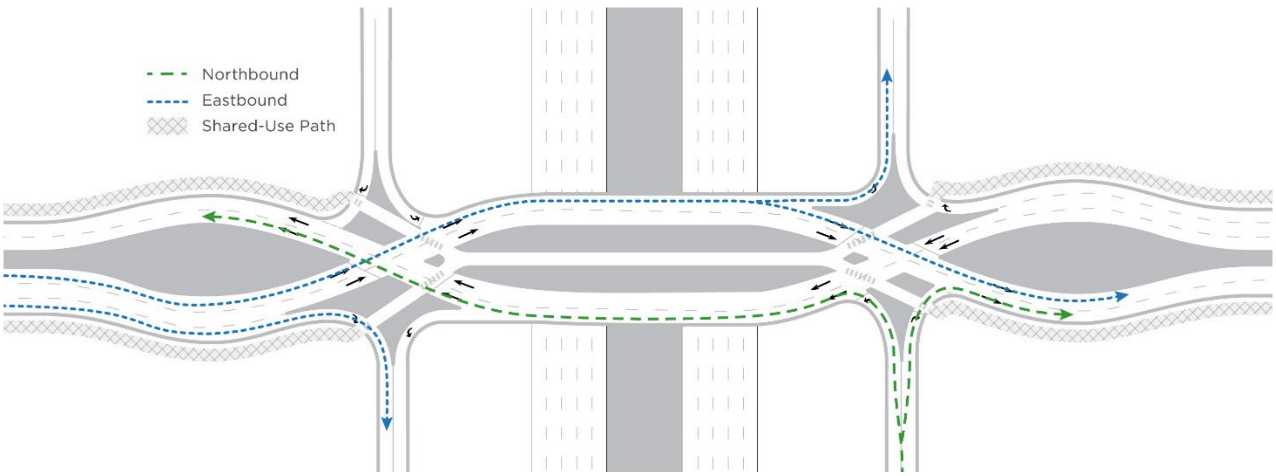
The DDI operates with two, three, or four critical phases.[1] Signal phases are reduced by allowing movements from the ramps to proceed concurrently with nonconflicting through movements on the crossroad. The DDI provides shorter cycle lengths at the terminals. The mainline movements conflict with each other in the DDI design and must have separate phases. However, the left-turn signal phase onto the ramp is eliminated, except as provided for pedestrian crossing. The DDI design increases the number of stages for pedestrians and bicyclists crossing the interchange; however, wait times and crossing distances tend to be shorter.

Safety Performance

DDIs tend to reduce the frequency of fatalities and injury crashes by as much as 70 percent, especially at crossroad speeds below 40 mph.(1) The crossover of left turns in the DDI reduces left-turn conflicts. In addition, turns with the crossover design have better sight distance. While pedestrians have more crossing stages, crossing distances are reduced, thereby reducing the exposure of pedestrians and bicyclists.

Vehicle Traffic Demand Patterns

Designers should consider DDIs at intersections with heavy ramp movements and either relatively low or directionally unbalanced through volumes on the cross street. DDIs also work well where conflicting left turn and through movements have high volumes.(12)



Source: FHWA.

Figure 3. Illustration. DDI displaying shared-use path and northbound and eastbound motor vehicle movements.

Multimodal Considerations

Pedestrian facilities include a sidewalk or a shared-use path with medians that allow refuge areas. The pedestrian path can route through either the center median or along the outside of the roadway.(1) Pedestrians cross each terminal in two stages,(6) with a central island as a refuge for pedestrians between each stage or signal phase. A pedestrian signal may be used at free-turning movements onto and off the freeway, particularly where sight distance is limited.(6) Two-phase signal control and short cycle lengths lead to shorter pedestrian clearances and less exposure than conventional intersections.(6) Because pedestrians may be unfamiliar with the DDI intersection form, the DDI design may necessitate wayfinding signage, channelizing pedestrian movements through islands, ensuring direct pedestrian crossings and paths, and enhancing the conspicuity of crossings and pedestrians who are waiting to cross.

Design elements that improve accessibility to assist users with low or no vision are important in DDIs. Audible signals help pedestrians align at crossings. In addition, surface treatments for paths through median islands should be detectable underfoot. Bicyclists have three basic facility options at a DDI:(13)

- Shared use of the travel lane.
- Marked bicycle lane through the DDI.
- Separated bicycle path or shared-use path.

Bicycle lanes at a DDI should be located to the right of the travel lanes for motorized traffic, similar to other facilities. A wider shy distance is needed when the bicycle lane is next to a median barrier.(1)

Designers should consider nearside and far-side bus stop locations, particularly how their placement and form (e.g., curbside or pullouts) interact with pedestrian and bicycle facility designs. The researchers recommend against having bus stops between ramp terminals unless a transfer station is needed for service along the limited-access corridor. Off-ramp-to-on-ramp through movement for limited-access bus service is not generally provided. Buses operating on the crossroad benefit from the reduced number of signal phases and potentially lower delay when traveling through a DDI. Median-running light rail can remain in the median between ramp terminals but requires a dedicated phase.(1)

Freight Considerations

Lanes in DDIs often widen through the crossover to serve larger vehicle offtracking. Turn radii to and from ramps should be as small as feasible to encourage trucks to yield to pedestrians while meeting the needs of the truck-turning path. Off-ramp-to-on-ramp through movement for overheight trucks is not generally provided.

Corridor Considerations

The DDI can operate with two signal phases, which results in a wide progression band opportunity but also results in a near-continuous flow of discharging vehicles. Therefore, a DDI is well paired with other intersections with reduced critical phase counts, such as RCUT or QR.(14) Such intersections reduce the likelihood of queue spillback into the adjacent intersection. The DDI combines lane assignments for the left turn and through movements on the bridge structure, and therefore a DDI requires a narrower bridge structure for the same vehicle volume compared to a conventional diamond interchange. Expanded right-of-way may be necessary immediately upstream of terminals due to the wide flare that results from the crossover design.(6) Driveways should not be located between ramp terminals. Frontage roads help provide access to destinations but reduce the benefits of a DDI interchange, necessitating an additional signal phase.(6)

History and Variation

DDIs were first constructed in France in the 1970s.(6) In the United States, Gilbert Chlewicki presented the first paper on the DDI at the 2nd Urban Street Symposium in July 2003, and

FHWA published the study in 2005.[15] The first DDI in the United States was opened at Interstate 44 and Kansas Expressway in Springfield, MO, in June 2009.[15] DDI have been built in the majority of States, with the largest deployments in Florida, Georgia, Kansas, Missouri, North Carolina, and Utah. The DDI was previously known as the double crossover diamond interchange.

DLT INTERSECTION

Description of Design Features

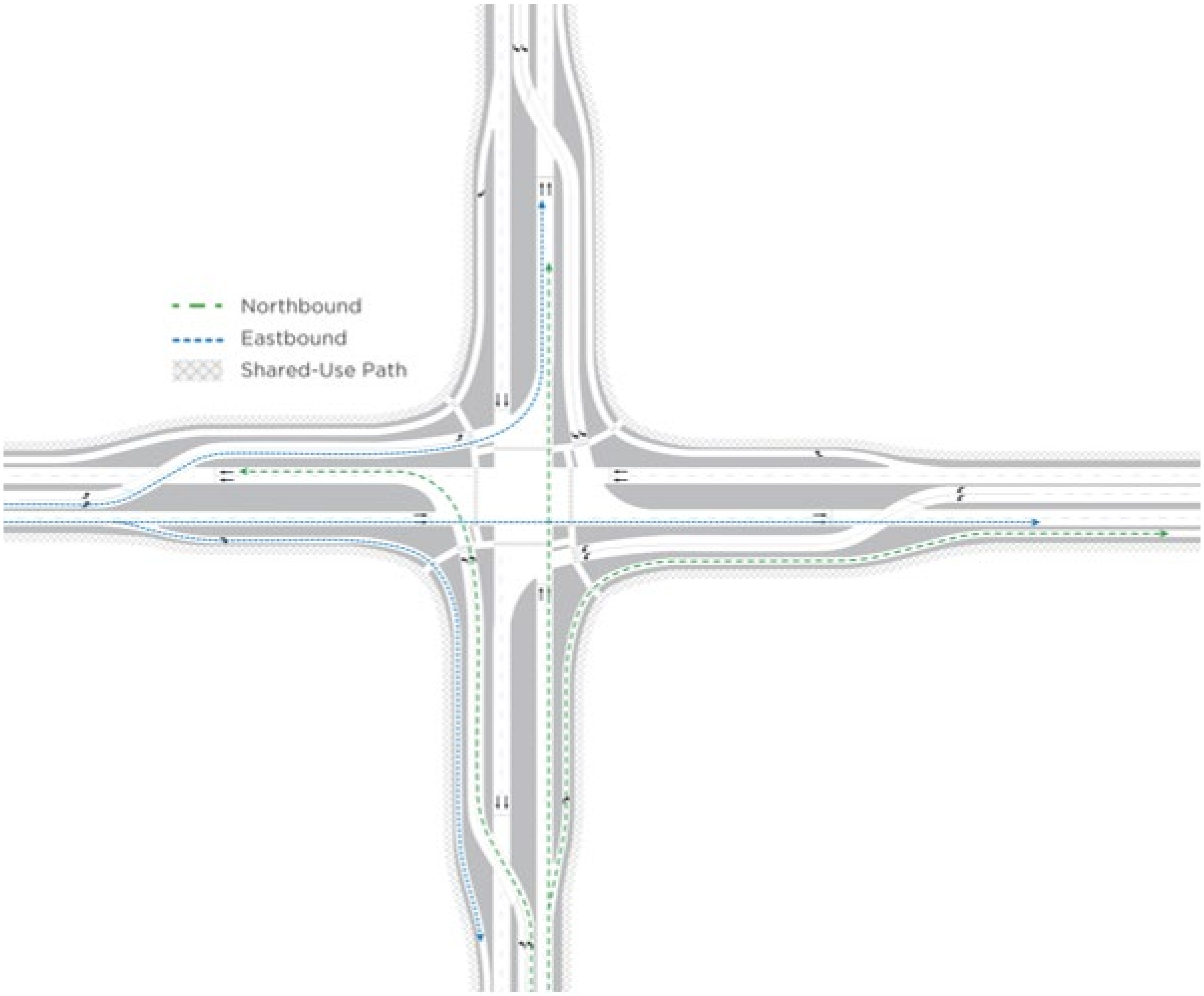
A high-capacity, at-grade intersection form that efficiently processes left turns by crossing them over the opposing through traffic in advance of the main intersection.

In the DLT intersection, vehicles wanting to make a left turn cross to the far side of opposing through traffic at a secondary signalized crossover upstream of the main intersection. At the main intersection, this prepositioning allows for left turns and opposing through movements to simultaneously occur, eliminating the need for a separate left-turn phase. For example, drivers who want to make an eastbound left turn cross over inbound westbound traffic at the upstream crossover and then make a left at the main intersection to head north. Coordination allows left-turning vehicles to arrive at the main intersection on green.

Channelization between the right-turn bypass lane, DLT lane, and opposing through movements provides many refuge areas for pedestrians and bicyclists on shared-use paths. All nonmotorized users cross the right-turn bypass lane followed by the DLT lane and then cross either set of through lanes. Users who desire to make a diagonal crossing then cross the opposing through lanes. To complete the crossing, all users again cross the DLT and right bypass lanes. The number of stages can be reduced by providing sufficient WALK intervals.

Operational Considerations

Figure 4 shows the DLT has two critical phases: one for the major street (through and left can move at the same time) and one for the minor street. This configuration is possible only when the pedestrian facility is located between the DLT and the opposing through movement (creating a five-stage pedestrian crossing). If pedestrian facilities are located outside of the DLT, the DLT will operate with three critical phases, as the pedestrian and left-turn movements cannot operate concurrently. The main intersection and all crossovers are signalized and coordinated such that left-turning vehicles arrive at the main intersection on green, and departing vehicles arrive at the crossover on green.[2]



Source: FHWA.

Figure 4. Illustration. DLT intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Safety Performance

Crossing conflict points between left turns and opposing through movements are relocated to the upstream crossover, allowing drivers to focus on a limited number of interactions at each junction. Inside pedestrian facilities ensure protected crossings from left-turning vehicles. A limited number of field-based safety studies exist due to the small number of installations.[16]

Vehicle Traffic Demand Patterns

DLTs excel with moderate-to-heavy traffic volumes in all directions, including heavy left-turn traffic volumes.[7] These conditions are often found when two major arterials cross.

Multimodal Considerations

The DLT commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities provide multiple points of refuge during crossings, but users may encounter vehicles moving in counterintuitive directions. When facilities are located inside the left-turn path, pedestrians have a protected crossing with through traffic. The number of crossing stages can be reduced with appropriate clearance time to cross the adjacent through approach and receiving lanes as well as the DLT approach lanes. When facilities are located on the outside of the left-turn path, pedestrians can complete a crossing in three stages. However, the conflicting left turn must operate under permitted control. Alternatively, the left turn can be served after the pedestrians use protected control, resulting in an overall timing scheme of three critical phases. Using accessible pedestrian signals will substantially assist pedestrians who are blind or visually impaired. Users who typically rely on vehicle sounds for aligning and crossing can be served through audible signals, reducing their reliance on sounds from vehicles that may be traveling in unexpected directions.

Bicyclists traveling on off-roadway bicycle paths or shared-use paths have similar experiences to pedestrian crossings. DLTs are typically located on arterials with higher speeds and volumes, making them less suitable for onroad bicycle facilities. If onroad facilities are provided, two-stage left-turn bicycle boxes eliminate the need for bicyclists to travel with (faster) vehicle traffic in the channelized left-turn lanes. Transit and school buses turning left through a DLT may be challenged when serving passengers in the immediate intersection area. Nearside bus stops at the main intersection are possible and can be paired with queue jumps for vehicles making through movements.[(2)]

Freight Considerations

As with all intersections, engineers designing DLT elements should consider the maneuverability of the design vehicle. Crossover lane widths may need to be expanded or mountable features may need to be provided to allow for large vehicles.[(2)]

Corridor Considerations

The two-critical-phase operation results in a near-constant flow of traffic from the DLT to a downstream intersection, either from a major street through movement or a minor street left turn. Therefore, a DLT is best paired with a downstream intersection that has increased throughput, which can be achieved by reducing the count of critical phases, as occurs with alternative intersections. Often, DLTs are located in a corridor with other DLTs due to the extended right-of-way requirements and the opportunity for corridor efficiency and progression. Progression between DLTs and between signals at a single DLT allows for speed management along the corridor.

The right-of-way requirements tend to be larger than at a conventional intersection because of the additional medians and the channelized right-turn lanes. To minimize the footprint, median widths can be reduced but should be large enough to accommodate signs and pedestrian storage.[(6)] Access to parcels between crossover and main intersections should be limited to right-in and right-out configurations. Parcels needing additional access can be served through frontage roads.[6] Such access may already be provided through frontage roads at high-volume intersections where DLTs are likely to be considered.

History and Variation

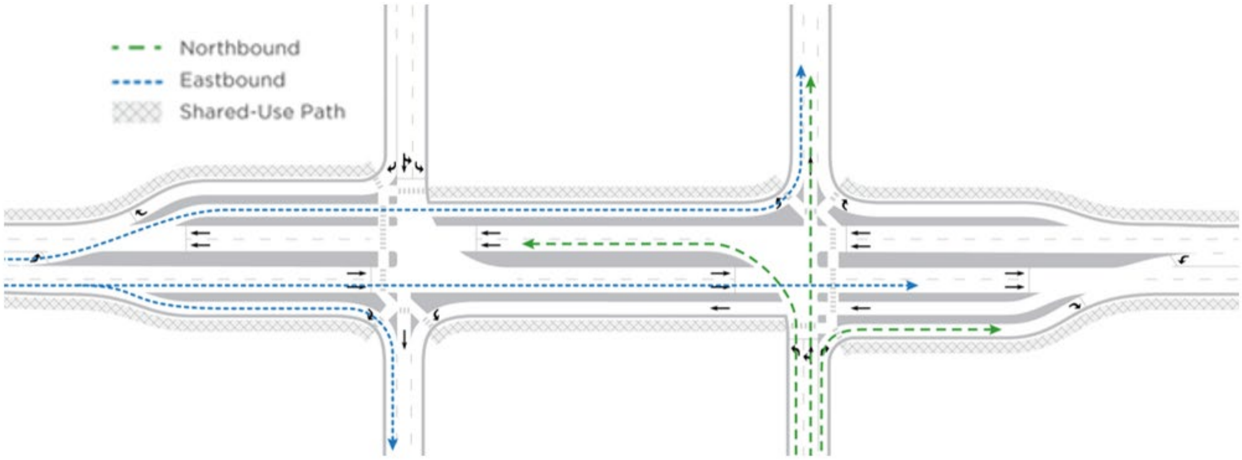
Francisco Mier received a U.S. patent for the DLT in 1991.[17] The DLT was first implemented at 1300 William Floyd Parkway in Shirley, NY, in 1994.[18] The T-intersection featured a displacement of one left turn, which enhances the movement to the stem. Since then, Austin, TX, and Salt Lake City, UT, are both major deployment regions in the United States, in addition to multiple sites in Mexico.[19] In practice, most implementations of the DLT design are partial DLTs, where only the major street left turns are displaced. The DLT is also known as continuous flow intersection and crossover displaced left intersection.

DLT INTERCHANGE

A high-capacity diamond interchange form that processes cross street left turns by crossing them over the opposing through traffic in advance of the main terminals.

Description of Design Features

In the DLT interchange, vehicles wanting to make a left turn onto a limited-access roadway cross to the far side of opposing through traffic at a secondary signalized crossover upstream of the first ramp terminal. Figure 5 shows this configuration allows for left turns and opposing through movements at each terminal to occur simultaneously, eliminating the need for a separate left-turn phase. For example, drivers who want to make an eastbound left turn cross over inbound westbound traffic at the upstream crossover, proceed through the first terminal, and then turn left at the second terminal to head north. Coordination between the crossovers and first terminal allows left-turning vehicles to arrive at the first terminal on green and make a free-flowing left turn at the second terminal after yielding to pedestrians. Channelization between the right-turn bypass lane, DLT lane, and opposing through movements provides many refuge areas for pedestrians and bicyclists on shared-use paths. Crosswalks are provided on the outside of each junction for access across the cross street. All nonmotorized users cross the right-turn on-ramp or off-ramp lane to begin and end each crossing, proceeding across the cross street or ramp in between as desired.



Source: FHWA.

Figure 5. Illustration. DLT interchange displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The signalized crossovers and terminals all operate with two critical phases and can operate with one or multiple controllers. Each junction is coordinated with its upstream crossover such that left-turning vehicles arrive at and proceed through the junction on green, and departing vehicles arrive at the crossover on green.[(2)] Pedestrian and bicyclist delays can be reduced by providing a sufficient WALK indication to allow a single-stage crossing across the cross street. Off-ramp right turns and on-ramp right and left turns can be controlled with a variety of traffic devices, including pedestrian hybrid beacons, rapid rectangular flashing beacons, yield control, or full signals.

Safety Performance

Crossing conflict points between cross-street left turns and opposing through movements are relocated to the upstream crossover, allowing drivers to focus on a limited number of interactions at each signal. One example of a simplified interaction includes left turns from the cross street focusing on yielding only to pedestrians who have already crossed the opposing through movements.

Vehicle Traffic Demand Patterns

DLT interchanges excel with moderate cross-street left turns, high cross-street through volumes, and moderate off-ramp volumes. DLT interchanges can process 20–45 percent more throughput than a conventional diamond interchange with the same number of lanes.[(6)]

Multimodal Considerations

The DLT interchange includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities provide multiple points of refuge during crossings, but users may encounter vehicles moving in counterintuitive directions. The number of crossing stages can be reduced with appropriate clearance time to cross the full cross street. Conflicts with off-ramp right turns and on-ramp right and left turns can be controlled with a variety of traffic devices, including pedestrian hybrid beacons, rapid rectangular flashing beacons, yield control, or full signals. Accessible pedestrian signals will substantially assist pedestrians who are blind or visually impaired. Users who typically rely on vehicle sounds for aligning and crossing can be served through audible signals, reducing their reliance on sounds from vehicles that may be traveling in unexpected directions.

Bicyclists traveling on shared-use paths have similar experiences to pedestrian crossings. DLT interchanges are most suitable for high-volume cross streets, making them less suitable for onroad bicycle facilities. If onroad facilities are provided and ramps serve frontage roads in addition to the limited-access road, two-stage left-turn bicycle boxes eliminate the need for bicyclists to travel with (faster) vehicle traffic in the channelized left-turn lanes.

Designers should select transit stop locations based on pedestrian generators and paths through the interchange. Nearside and far side stops are most likely to be suited for positions upstream and downstream, respectively, of the crossovers.[(6)] The researchers recommend against locating stops between terminals unless they are needed for a connection to the limited-access roadway.

Freight Considerations

As with all intersections, engineers designing DLT elements should consider the maneuverability of the design vehicle.[(2)] Crossover lane widths may need to be expanded or mountable features may need to be provided to allow for large vehicles.

Corridor Considerations

The two-critical-phase operation of the crossover results in a near-constant flow of traffic from the DLT interchange to a downstream intersection, either from cross-street through movement or the off-ramp right turn. This flow is particularly noticeable under heavy directional imbalance on the cross street. Therefore, a DLT interchange is best paired with a downstream intersection, which has increased throughput. This scenario can be achieved by reducing the count of critical phases, as occurs with alternative intersections. DLT interchanges may not be well suited for locations with closely spaced adjacent intersections due to the positioning of the crossovers.

DLT interchanges may be well suited in a corridor with other DLTs because of the extended right-of-way requirements and the opportunity for corridor efficiency and progression. Progression between DLT intersections and interchanges and between signals at a single DLT intersection or interchange allows for speed management along the corridor.

The right-of-way requirements tend to be larger than at a conventional intersection because of the additional medians and the channelized right-turn lanes. To minimize the footprint, median widths can be reduced but should be large enough to accommodate signs and pedestrian storage.[(6)] The DLT interchange may not be suitable for a retrofit as it likely requires a wider bridge deck. Access to parcels between the crossover and main terminals should be limited to right-in and right-out configurations. Parcels needing additional access can be served through frontage roads.[(6)]

History and Variation

Joe Bared, Praveen Edara, and Ram Jagannathan proposed the DLT interchange as an extension of the DLT intersection.[20] Although Francisco Mier received a patent for the intersection form, no patent was filed for the diamond interchange form.[15,17] To the research team's knowledge, no known DLT interchange implementations exist in the United States. The DLT interchange is also known as the continuous flow interchange and crossover displaced left interchange.

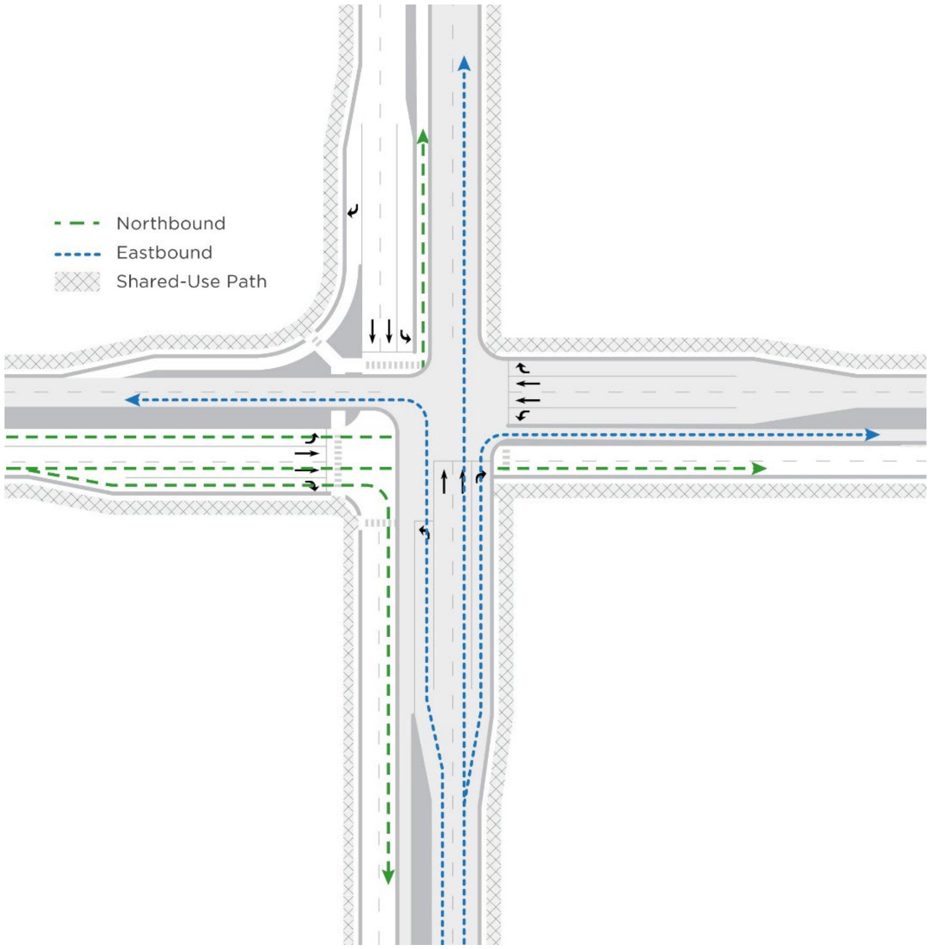
ECHELON

Description of Design Features

> A grade-separated intersection form that elevates one approach from each roadway, resulting in a pair of signalized one-way intersections.

The echelon intersection elevates one approach from each of the intersecting roadways to create a pair of one-way intersections vertically separated in space. Retaining walls are used to provide grade separation with a bridge structure used over the at-grade intersection. Retaining walls are also used to return departure lanes to grade. As the entire approach is elevated or remains at grade, vehicles are not required to pre-position and execute left and right turns and through movements as at a conventional intersection. As figure 6 shows, northbound vehicles proceed along the road as it changes elevation, execute a left or right turn or travel through, and then continue as the road returns to grade and joins the at-grade approach.

Bicycle and pedestrian facilities remain at grade, and, as figure 6 shows, can be served by a shared-use path. The movements of the bicyclists and pedestrians are executed as they are at a conventional intersection, with direct left and right turns and through movements executed in one stage.



Source: FHWA.

Figure 6. Illustration. Echelon intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The upper and lower intersection both operate independently, each with two critical phases. The intersections are typically signal controlled due to the high-volume nature of the major and minor streets. Right and left lanes rejoin the through departure lanes at grade through merges or lane additions. U-turns are not permitted at the intersection. A third critical phase can be added to the lower intersection to serve as an exclusive pedestrian phase, which eliminates the conflict between pedestrians and left-turning vehicles. At locations where onstreet bicycle lanes are used and remain at grade, two-stage bicycle-turn boxes permit bicyclists to execute left turns.

Safety Performance

Echelons reduce the number of crossing conflicts compared to a conventional intersection and likely result in fewer rear-end crashes due to reduced queue lengths. Pedestrians and bicyclists have conflicts with fewer vehicles, but they do encounter conflicts with left-turning vehicles similar to those found at T-intersections.

Vehicle Traffic Demand Patterns

Echelons should be considered in areas where the main and side street volumes are similar and heavy, such as at the intersection of two major arterials.[7] This intersection type can be used at intersections with four legs.

Multimodal Considerations

The echelon commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or shared-use path with wayfinding similar to a conventional intersection with channelized turn lanes. Exclusive pedestrian phases or leading pedestrian intervals can be used to eliminate or mitigate conflicts with left-turning vehicles. Similar to a T-intersection, the left turns do not yield to an opposing through movement. While two right-turn movements are channelized, turn radii can be kept to the minimum needed for a design vehicle to reduce vehicle speeds and encourage yielding. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.[6] As some vehicle movements are relocated to the upper elevation, audible signals assist users with low and no vision who rely on vehicle sounds to understand when to cross safely.

Bicyclists are well served by bicycle lanes or shared-use paths that remain at grade, rather than elevated with vehicles. Two-stage bicycle boxes are necessary to permit bicyclists remaining at grade to turn left. The two-signal phase operation typically requires less total time to serve all movements. This operation results in less delay for bicyclists, reducing the delay of a two-stage movement. For transit vehicles serving the lower intersection, nearside or far side stops are appropriate. As pedestrians are served at the lower intersection only, transit stops for vehicles on the upper intersection would require accessible ramps or elevators for access. Alternatively, stops can be located upstream or downstream of the grade separation.

Freight Considerations

As with all intersection designs, engineers should consider the needs of the design vehicle when designing the curve radii.

Corridor Considerations

The two-critical-phase operation results in a wide progression band opportunity. Therefore, the echelon is well paired with other intersections with low critical phase counts. The runout needed for grade separation depends on the surrounding approach geometry and the necessary sight distance beyond the vertical crest. This distance will impact the required spacing to adjacent intersections on all four approaches.

The echelon is suitable where volumes make grade separation desirable but the right-of-way for diamond or loop interchanges is limited. Vehicle access to frontages along the elevated approaches is limited. Additionally, vehicles traveling on elevated approaches have limited access to the frontages that are otherwise accessible to at-grade vehicles. Frontage roads may be used to provide access to the parcels. Access can also be provided through U-turn bays located downstream of merge points. Such bays would require additional rights-of-way for wide medians or loons.

History and Variation

Engineers designed an echelon for the intersection of U.S. Route 1 and NE 203rd Street in Aventura, FL. To the research team's knowledge, no other echelon is known to be in design or operation in the United States. Don Beccasio of Florida DOT proposed the name as a take on the U.S. Navy Flight Demonstration's echelon formation, where planes fly over one another.[9] A variation of the echelon is possible by elevating opposing rather than adjacent approaches.

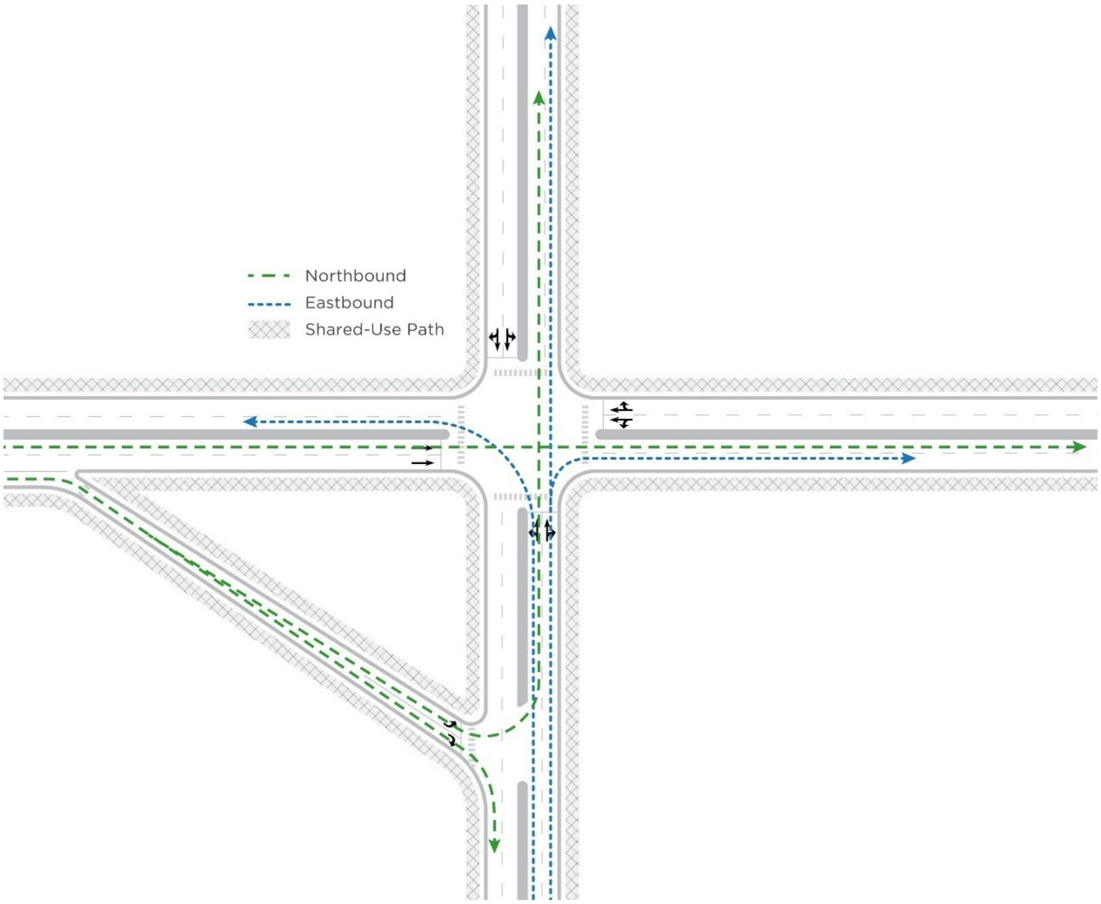
JUGHANDLE

Description of Design Features

An at-grade intersection form that reduces congestion by rerouting one or more left turns through an at-grade ramp connected to the minor street.

The jughandle intersection features an at-grade ramp in advance of the main intersection in one or more quadrants. Left-turning vehicles are redirected to the ramp and make a left turn onto the minor street before proceeding through the main intersection. This redirection eliminates the need for a separate left-turn phase. For example, in figure 7, the eastbound left-turning vehicle uses the right-hand ramp, turns left at the ramp junction onto the minor street, and travels north through the main intersection to complete the movement. Each ramp redirects one left-turn movement. The corresponding U-turn movement is also redirected through the same ramp.

As figure 7 shows, all nonmotorized users travel via a shared-use path. Crossings are provided on all four legs of the main intersection as well as across the ramp. The number of crossings and maneuvers for a pedestrian or bicyclist to execute a right, through, or left turn is the same as for a conventional intersection.



Source: FHWA.

Figure 7. Illustration. Jughandle intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The jughandle has two, three, or four critical phases, depending on the phasing of the left turns. Ramps on additional quadrants would reduce the number of phases. Jughandles are often used at T-intersections where a single ramp allows the intersection to operate with two critical phases: one for the major street and one for the minor street. The main intersection can be signal or stop controlled. The ramp is commonly stop controlled.[9] At the main intersection, drivers may potentially disregard left-turn prohibitions, which designers can mitigate with appropriate signage. Increased lane changing may occur as drivers accustomed to turning from the left lane shift to the right-hand lane.[5]

Safety Performance

The jughandle has fewer intersection conflict points than conventional intersections. At the main intersection, left-turn conflicts are eliminated for the redirected movement, reducing the potential for severe crashes. Higher right-turn volumes increase vehicle–pedestrian conflicts, although left-turn conflicts at the main intersection are eliminated.[5]

Vehicle Traffic Demand Patterns

Jughandles provide the greatest reduction in travel time under the combination of high through volumes on the major street, low-volume to medium-volume left turns on the major street, and low-volume to medium-volume traffic on the minor street.(21) High volumes on the cross street may result in queue spillback, which blocks the ramp.

Multimodal Considerations

The jughandle commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities are provided in a shared-use path or sidewalk with typical crossings at the main intersection, a yield-controlled crossing across the entrance to the ramp, and a typically stop-controlled crossing at the exit of the ramp. The reduced number of signal phases, compared to a conventional intersection, reduces delay for people crossing. Depending on ramp location(s), pedestrians may experience decreased conflicts with left-turning vehicles but increased conflicts with right-turning vehicles at the ramp. Eliminating left-turn lanes at the main intersection may allow more right-of-way for pedestrian facilities, and a reduced number of lanes resulting in lower crossing exposure.(13) Crossing of the side street is not typically provided at the ramp junction due to the free-flowing nature of the side street. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) The direct crossing design benefits pedestrians who rely on vehicle sounds to align with the crossing.

Bicyclists have three options when navigating a QR intersection:(13)

- Make a two-stage left turn via a bicycle box.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules using the ramp.

As with pedestrian facilities, eliminating left-turn lanes may allow more right-of-way for bicycle facilities. Bicyclists using the ramp also avoid needing to merge across through lanes into the left-turn lane. Transit vehicles turning left at the intersection experience additional travel distance. Stops can be nearside or far side, or they can be located in a pullout bay within the ramp.

Freight Considerations

As with all intersections, engineers designing ramp elements should consider the maneuverability of the design vehicle. Large vehicles may require wider turning lanes, paved shoulders, and mountable or traversable features at the ramp junction.

Corridor Considerations

Jughandles are often used in tandem along corridors where spacing between minor streets is large enough to provide space for the ramp junctions. The reverse jughandle may be more appropriate for an intersection closely spaced to a two-critical-phase alternative intersection handling heavy traffic, such as a DLT. The right-of-way requirements along the major street are reduced due to the removed left-turn pockets; however, much greater right-of-way is needed for the ramp.

Development in the ramp quadrant is possible, although development typically is sited beyond the ramp rather than between the ramp and the intersection. Driveways to the development can be provided along the ramp. Implementing jughandles on corridors where development is present on most quadrants will come with additional costs, and a QR may be more suitable.

History and Variation

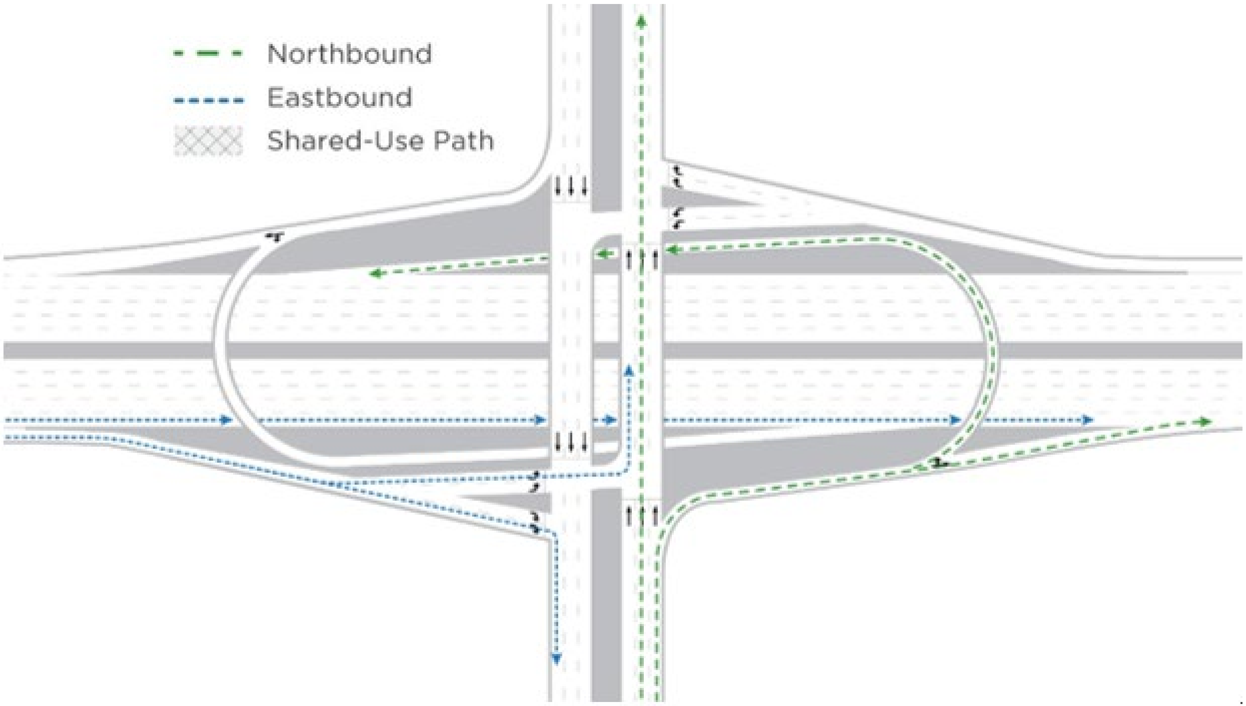
Jughandles are often associated with New Jersey due to the State's implementation of jughandles on hundreds of miles of roadway.[9] Jughandles have been used in New Jersey since at least the 1970s. Jughandles are also found across the Northeast in the United States; in the U.S. States of Florida, Hawaii, and Missouri; and in Alberta, Canada. Although jughandles typically have ramps in one or two quadrants, ramps can be placed in additional quadrants. Jughandles can be used at two-, three-, or four-leg intersections. Ramps at two-leg intersections facilitate U-turns along a median-divided roadway. Reverse ramps can also be used where redirected left turns proceed through the main intersection before exiting on the right-hand side to an at-grade loop ramp that merges onto the minor street. The vehicles then proceed again through the main intersection. Jughandles are also known as Jersey lefts.

MILWAUKEE A INTERCHANGE

Description of Design Features

A three-bridge interchange form that redirects left turns onto the limited-access road to a right-hand U-turn ramp.

The Milwaukee A interchange borrows U-turn features found in MUT intersection forms to redirect left turns. Direct lefts from the off-ramp are permitted. Vehicles turning left onto the on-ramp instead turn right at the first terminal and then diverge onto an auxiliary bridge curving over the limited-access road before merging onto the limited-access road. This configuration removes conflicts between left turns at the on-ramp and opposing through movements, as well as the associated left-turn phase. For example, as figure 8 shows, drivers who want to make a northbound left turn would turn right at the first terminal, diverge to the left and cross over the limited-access road, continue along the ramp under the main bridge structure, and then merge onto the limited-access road.



Source: FHWA.

Figure 8. Illustration. Milwaukee A interchange displaying shared-use path and northbound and eastbound motor vehicle movements.

Pedestrians and bicyclists proceed in a manner similar to a conventional diamond interchange with direct through movements. Crossing of the cross street is provided on the outside of each terminal to avoid conflicts with off-ramp left turns.

Operational Considerations

The terminals each operate with two critical phases and can operate with individual or combined controllers. Pedestrians and bicyclists experience additional exposure at the on-ramp due to increased volumes from the left turn. The movement can be yield controlled or signal controlled with or without additional control devices, such as pedestrian hybrid beacons or rapid rectangular flashing beacons.

Safety Performance

Crossing conflict points between cross-street left turns and opposing through movements are removed, which improves safety. The conflict between cross-street left turns and pedestrians and bicyclists is also removed, although the cross-street right-turn conflict exposure is increased because of the increased volume. To our knowledge, no safety studies have been performed due to the limited deployment of Milwaukee A interchanges.

Vehicle Traffic Demand Patterns

Designers should consider Milwaukee A interchanges where left-turn and through volumes are moderate to high.[22] The benefit–cost ratio of the additional bridges is higher where left-turn queue storage between terminals is insufficient.

Multimodal Considerations

The Milwaukee A interchange includes at-grade pedestrian and bicycle facilities to provide access for all users. Access across the cross street is provided on the outside of each terminal to avoid conflict with off-ramp left turns. Pedestrian facilities can include refuge in the cross-street median. Conflicts with on-ramp right turns can be controlled with a variety of traffic devices, including pedestrian hybrid beacons, rapid rectangular flashing beacons, yield control, or full signals.

Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.[6] If the on-ramp crossing is signalized, audible pedestrian signals assist users who have low or no vision because no parallel vehicle traffic sound is present to assist them in determining the signal state. Bicyclists traveling on shared-use paths have similar experiences to pedestrian crossings. Milwaukee A interchanges are typically located on high-volume cross streets, making them less suitable for on-road bicycle facilities. If on-road facilities are provided and ramps serve frontage roads in addition to the limited-access road, two-stage left-turn bicycle boxes eliminate the out-of-direction travel for bicyclists. Transit stop locations can be positioned similar to conventional diamond interchanges.

Freight Considerations

As with all intersections and interchanges, engineers designing Milwaukee A elements should consider the maneuverability of the design vehicle. The plans for auxiliary ramp curvature, both horizontal and vertical, should allow for large vehicles.

Corridor Considerations

The reduction in critical phases at the Milwaukee A interchange permits additional capacity, which makes it suitable to pair with a high-capacity adjacent intersection upstream with two critical phases. This configuration is particularly useful for corridors with highly unbalanced directionality by time of day. During the inbound peak, the Milwaukee A interchange can efficiently serve vehicles onto the limited-access roadway; while during the outbound peak, the adjacent intersection can serve heavy volumes from the interchange. In both cases, the reduced number of phases at the downstream signal can mitigate queue spillback issues.

The right-of-way requirements for a Milwaukee A interchange tend to be larger along the limited-access roadway due to the curvature of the auxiliary bridges and the space requirements of a second parallel on-ramp. The bridge length must also allow sufficient space outside of the limited-access freeway for the auxiliary on-ramp. The Milwaukee A requires less right-of-way than a partial cloverleaf. The main bridge deck is narrower than a conventional diamond due to the lack of left-turn lanes and may be suitable as a retrofit where additional lanes would otherwise be needed. Access to quadrants along the cross street is similar to a conventional diamond.

History and Variation

One known implementation of the Milwaukee A interchange is located at the I–94 Alternate and South 27th Street in Greenfield, WI, which is south of Milwaukee. The interchange opened to traffic in 2011 as part of the larger Mitchell Interchange project.(23) Variations of the Milwaukee A interchange include the Milwaukee B interchange—which permits left turns onto the limited-access roadway through contraflow lanes but redirects off-ramp left turns through auxiliary bridges—and the MUT interchange, which redirects all left turns to auxiliary bridges.

MUT

Description of Design Features

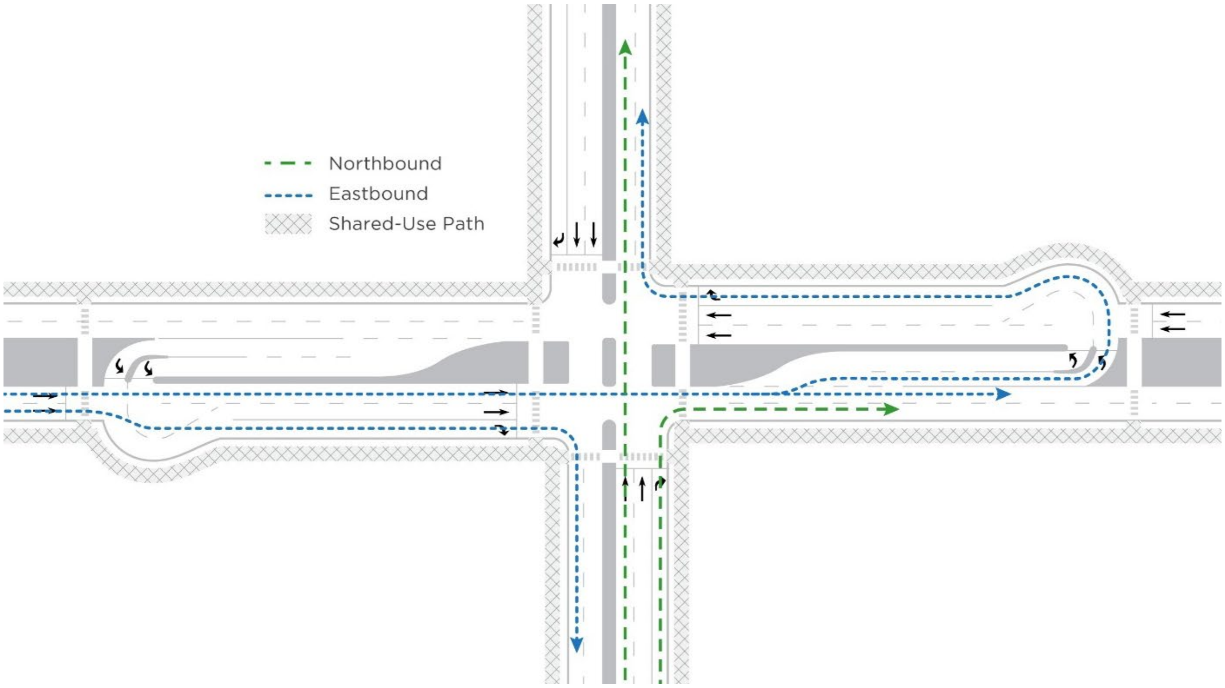
An efficient at-grade intersection form that replaces direct left turns at an intersection with indirect left turns using a U-turn movement in a wide median.

In the MUT intersection, drivers who want to make a left turn on both the major and minor approaches are redirected to a median on the major approaches to make a U-turn. Eastbound drivers who want to turn left drive through the intersection, use the median opening to make a U-turn to head west, and then turn right to head north. Northbound drivers who want to turn left must turn right to head east, use the median opening to make a U-turn, and then drive west through the intersection. MUTs require median-divided highways or a bulb out adjacent to the U-turn bay (referred to as loons).

As figure 9 shows, bicyclists and pedestrians both enter the intersection on a shared-use path. Eastbound bicyclists and pedestrians on the south side of the intersection turn right and continue on the shared-use path to head south. Those path users who are continuing east instead cross the south crosswalk in two stages through a median island. To head north, users turn left after the third stage and continue with an additional two crossings or complete the four-stage crossing directly from the southwest quadrant.

Operational Considerations

As figure 9 shows, the MUT has two critical phases: one for the major street and one for the minor street. The intersection can be signalized or it can be controlled with two-way stop control under low volumes on the minor street. U-turn crossovers should be coordinated with the main intersection such that vehicles traveling along the major street can proceed through both signals. Providing sufficient WALK time for pedestrians to cross the major street and the wide median reduces the number of crossing stages and the delay for the pedestrian.



Source: FHWA.

Figure 9. Illustration. MUT intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Safety Performance

MUTs eliminate all left-turn conflicts and reduce rear-end, angle, and sideswipe crashes compared to conventional intersections. The MUT has increased conflict potential with right turns at the U-turn crossover if the bay aligns with the side street.(6) The greater right-turn volume increases the likelihood of right-turn conflicts with pedestrians.

Vehicle Traffic Demand Patterns

Designers should consider MUTs at intersections with moderate-volume to heavy-volume through traffic and low-volume to moderate-volume left-turn traffic.(7) This intersection type can be used at intersections with three or four legs.

Multimodal Considerations

The MUT commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or shared-use path. The wide medians also allow for refuge areas. The major street crossing can be made in one or two stages,(6) depending on the presence of a median refuge and the signal timing parameters. Greater right-turn volume increases the likelihood of right-turn conflicts with pedestrians. Designers can mitigate this potential conflict by prohibiting right turns on red.(13) Additional opportunities for midblock pedestrian crossings are available by using a traffic signal or pedestrian hybrid beacon at the U-turn crossover.(13) This solution requires outbound major street vehicles to encounter an additional signal, but stops can be mitigated through coordination.

Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) The presence of through movements from all approaches benefits pedestrians who rely on vehicle sounds to align with the crossing. Bicyclists making through movements encounter relatively higher percentages of green time at MUT intersections compared to the same experience at conventional intersections.(13)

Bicyclists have three options when making a left turn at an MUT intersection:(13)

- Make a two-stage left turn via a bicycle box.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules using the U-turn bay.

An increase in conflict with vehicle right-turn movements may occur due to a higher proportion of right-turning vehicles. Exclusive right-turn lanes that allow vehicles to cross bicycle lanes at speed and upstream of the intersection are preferable to designs where right-turning vehicles cross bicycles at the intersection, resulting in a right-hook conflict. The trailing wheels of large vehicles may drift outside of the travel lane, or off-track, while executing a U-turn, causing vehicles to encroach into bicycle paths.(6) Bicyclists may require longer clearance intervals, particularly when crossing the major street, due to the traditionally wide median.

Transit stops for through and right-turning transit vehicles can be on the nearside or far side of the main intersection. Stops for left-turning transit vehicles from the mainline should be on the minor street to allow buses to pre-position for the U-turn bay. Stops in the U-turn bay intersection or loon are strongly discouraged.(6)

Freight Considerations

A typical MUT corridor has a wide median to allow for heavy vehicles to make U-turns. Pavement can be added to the far side of the U-turn crossover in the form of bulb outs or loons as needed.

Corridor Considerations

The two-critical-phase operation results in a wide progression band opportunity. Therefore, the MUT is well paired with other intersections with low critical phase counts and can be used downstream of an intersection with heavy and consistent discharge, such as a DLT or a DDI. Often, MUTs are located in a corridor with other MUTs because of the large median and the opportunity for corridor efficiency and progression. On a wide-median street, right-of-way requirements are similar to conventional intersections. However, for streets with no medians or with narrow medians, additional right-of-way for loons is required. Efficient operation of the MUT can be achieved with a range of spacing between the main and U-turn intersections. Driveways are undesirable in close proximity to the main intersection or aligned with a loon.

History and Variation

The Michigan State Highway Department introduced the MUT at the intersection of Eight Mile Road and Livernois Street in Detroit, MI, in the 1960s.[24] Major MUT deployments have been established in Salt Lake City, UT; Phoenix, AZ; Grand Rapids, MI; and Detroit, MI. The MUT is also known as Michigan left, boulevard U-turn, and Michigan loon.

PROTECTED INTERSECTION

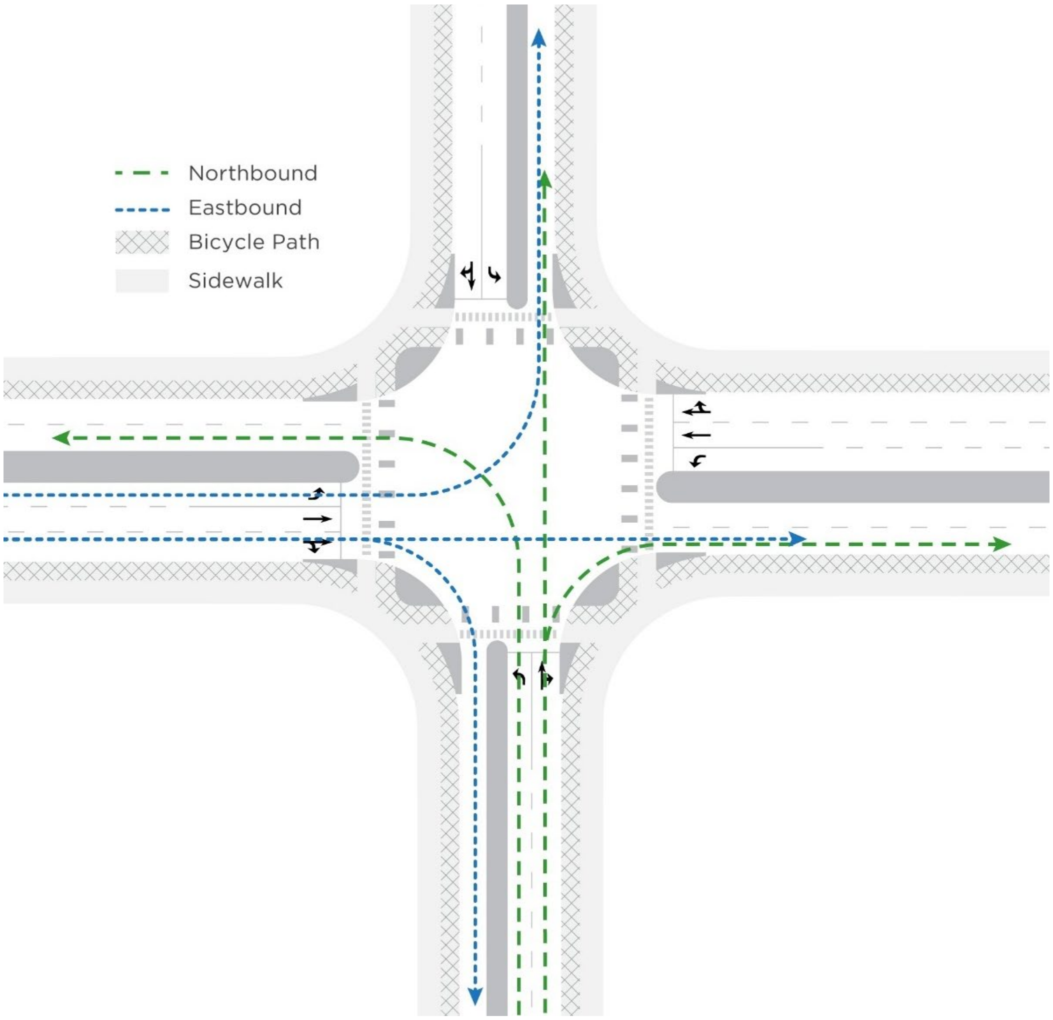
Description of Design Features

A collection of design elements that physically separates bicycles from motor vehicles and features dedicated bicycle crossing facilities.

Eight elements of a protected intersection design provide dedicated space for bicyclists and separate them from motor vehicles:

1. A curb extension or other designated no-stopping zone.
2. Pedestrian refuge islands between the bicycle lane and the motor vehicle lane.
3. A corner island.
4. A bicycle queue area.
5. A motorist waiting zone.
6. An associated bikeway setback that, together with a motorist waiting zone, provides storage between the vehicle lane and parallel bicycle lane.
7. Bicycle crossing markings.
8. Bicycle yield lines immediately upstream of the pedestrian crossing.[25]

These features can be provided at a variety of intersection forms because motor vehicles use the movement paths typical of the base intersection form. At a conventional intersection, direct left and right turns and through movements are permitted from each approach, as shown in figure 10. Protected intersections feature dedicated bicycle lanes separated from motor vehicle lanes, so left turns are executed in a two-stage manner. Pedestrians cross the intersection in a conventional manner with additional refuge areas between the bicycle and vehicle lanes.



Source: FHWA.

Figure 10. Illustration. Protected intersection displaying bicycle paths, sidewalks, and northbound and eastbound motor vehicle movements.

Operational Considerations

Protected intersections operate similar to their base intersection form. The bikeway setback distance impacts the storage area for turning vehicles. A small distance or a high percentage of right-turning heavy vehicles combined with a shared through and right lane may result in additional delay due to blockage.

Safety Performance

Protected intersections reduce vehicle turning speeds, which increase the likelihood of drivers yielding to bicyclists and pedestrians.(26) The bikeway setback improves visibility and expands drivers' sight lines. Because implementation of protected intersection designs tends to be more recent, the research team does not know of any crash modification factors developed to quantify the impacts.

Vehicle Traffic Demand Patterns

Protected intersection designs can be combined with many different base intersection forms. Therefore, the design is flexible to a wide range of vehicle traffic demand patterns. The design may be particularly useful at forms where redirection of vehicles results in additional right-turn volumes.

Multimodal Considerations

Protected intersection design elements improve the safety of bicyclists and pedestrians compared to nonprotected designs. The protected intersection design includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk. Crossings at the main intersection are completed via the conventional manner for the intersection form, and a median refuge is provided between the bicycle crossing and motor vehicle crossings.

Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) Audible pedestrian signals provide additional assistance to users with low or no vision, especially when the intersection form includes redirection of through movements, which the user may typically rely on for audible crossing help.

Protected intersections provide shorter crossings for bicyclists and better visibility between bicyclists and motor vehicles. Due to the separated nature of the bicycle facilities, bicyclists wanting to make a left turn use a two-stage maneuver via the bicycle queue areas. This configuration can increase delay more than a one-stage crossing but reduces bicyclists’ stress of merging across several lanes of traffic to pre-position in the left-turn lane. Because of the increased visibility and reduced vehicle speed, protected intersections are particularly beneficial at intersection forms where right-turn volumes are increased by redirected vehicles’ movements. Transit stops can be enhanced with floating transit stops or side boarding islands to facilitate pedestrian crossings of the bicycle lane.(27)

Freight Considerations

The corner island of the protected intersection can be a combination of both raised and painted median or truck apron to serve the design vehicle’s turning needs. Design vehicles are expected to traverse the painted median, truck apron, or both and can use both the first and part of the second receiving lanes to complete the turn. Design vehicle turns are typically expected to be executed at 3–5 mph.(25)

Corridor Considerations

Protected intersection designs can be used in conjunction with intersection forms as stand-alone intersections or in a corridor context. Engineers can use a protected intersection design in a corridor to provide a consistent experience for bicyclists traversing the corridor, and the design is particularly appropriate for bicycle corridors. The additional right-of-way needed for the separated bicycle facility also supports providing protected intersections along the full corridor. The separated bicycle facility requires additional right-of-way beyond a nonprotected intersection of the same form. However, for a corridor where a separated bicycle facility already exists, the additional right-of-way needs for implementing a protected intersection are minimal. Access to parcels close to the protected intersection is similar to the nonprotected intersection of the same form. Driveways should not be located immediately adjacent to the nearside of the intersection where the clear sight distance for right-turning vehicles would be impeded.

History and Variation

The protected intersection originated in the Netherlands.(28) Knowledge of the design in the United States dates to an early 1970s report by the University of California, Los Angeles, and a separate report from the City of Davis, CA, and the University of California, Davis, which credits a German design for inspiration.(28) The protected intersection can be found in many areas of the United States, with prominent implementation in Massachusetts(29) and New York City, NY.(30) The dedicated intersection is a variation of the protected intersection used when the space for a bicycle setback is insufficient.(25) Protected intersections are also known as setback intersections and offset intersections.(25)

PROTECTED INTERSECTION: ONE-WAY STREET

Description of Design Features

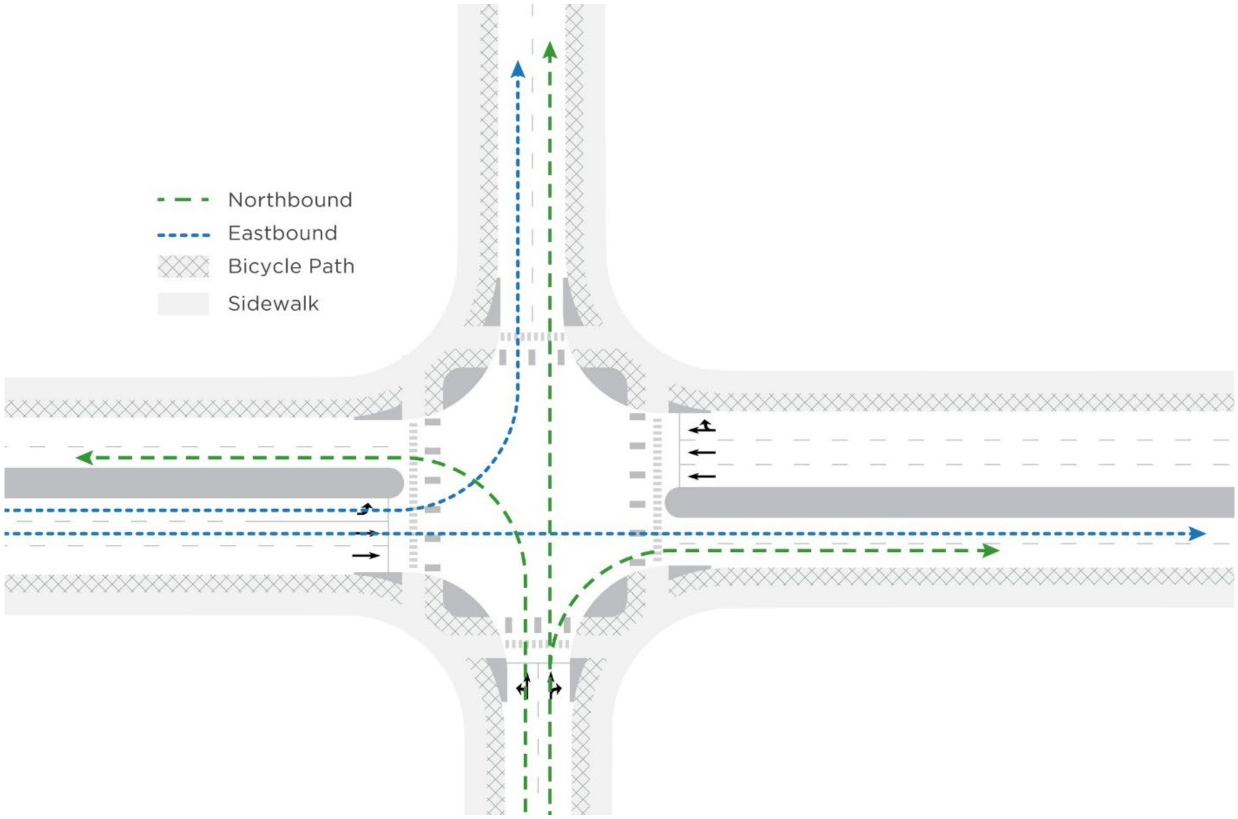
Eight elements of a protected intersection design provide dedicated space for bicyclists that separate them from motor vehicles:

A collection of design elements that physically separates bicyclists from one-way motor vehicle lanes and features dedicated bicycle crossing facilities.

1. A curb extension or other designated no-stopping zone.
2. Pedestrian refuge islands between the bicycle lane and the motor vehicle lane.
3. A corner island.
4. A bicycle queue area.
5. A motorist waiting zone.
6. An associated bikeway setback that together with a motorist waiting zone provides storage between the vehicle lane and parallel bicycle lane.
7. Bicycle crossing markings
8. Bicycle yield lines immediately upstream of the pedestrian crossing.(25)

For a one-way street, bicycle lanes can be provided in one or two directions. Direct motor vehicle movements are permitted from each approach.

The design shown in figure 11 features two one-way cycle tracks—one on each side of the one-way street. As such, bicyclists execute left turns in a two-stage manner. Pedestrians cross the intersection in a conventional manner with additional refuge areas between the bicycle and vehicle lanes.



Source: FHWA.

Figure 11. Illustration. Protected intersection at one-way street displaying bicycle paths, sidewalks, and northbound and eastbound motor vehicle movements.

Operational Considerations

The one-way protected intersection operates similar to a one-way intersection without protection. Design plans may need to include additional signal heads to provide visibility for bicyclists traveling in the contraflow direction.

Safety Performance

Protected intersections reduce vehicle turning speeds, which increases the likelihood of drivers yielding to bicyclists and pedestrians.[26] Left turns from one-way streets can increase conflicts between vehicles and bicyclists, particularly when vehicles are unaware that nonmotorized users are present. The enhanced crossing markings at protected intersections mitigate this concern. The research team does not know of any crash modification factors developed to quantify the impacts of protected intersections featuring one-way streets.

Vehicle Traffic Demand Patterns

Protected intersection designs featuring one-way streets are compatible with typical vehicle demand patterns for one-way intersections. Cycle tracks on both sides of the one-way street provide access for contraflow bicycle demand.

Multimodal Considerations

Protected intersection design elements enhance the safety of bicyclists and pedestrians compared to nonprotected designs. The protected intersection design includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk. Crossings at the main intersection are completed via the conventional manner for the intersection form, and a median refuge is provided between the bicycle crossing and motor vehicle crossings. Pedestrians may not anticipate bicycles traveling in the contraflow direction.

Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) Audible pedestrian signals provide additional help to users with low or no vision. The presence of contraflow bicyclists may be unexpected for users with low or no vision due to the absence of the sound of motor vehicles traveling in the same direction. Protected intersections provide shorter crossings for bicyclists and better visibility between bicyclists and motor vehicles. Due to the separated nature of the bicycle facilities, bicyclists wanting to make a left turn use a two-stage maneuver via the bicycle queue areas, which can increase delay more than a one-stage crossing but reduces bicyclist stress of merging across several lanes of traffic to pre-position in the left-turn lane. Transit stops can be enhanced with floating transit stops or side boarding islands to facilitate pedestrian crossings of the bicycle lane.(27)

Freight Considerations

The corner island of the protected intersection can be a combination of both raised and painted median or truck apron to serve the design vehicle's turning needs. Design vehicles are expected to traverse the painted median, truck apron, or both and can use both the first and part of the second receiving lanes to complete the turn. Design vehicle turns are typically expected to be executed at 3–5 mph.(25)

Corridor Considerations

Protected intersection designs can be used in conjunction with intersection forms as stand-alone intersections or in a corridor context. Engineers can use protected intersection designs in a corridor to provide a consistent experience for bicyclists traversing the corridor and ensure that the design is particularly appropriate for dominant bicycle corridors. The additional right-of-way needed for the separated bicycle facility also supports providing protected intersections along the full corridor. The separated bicycle facility requires additional right-of-way. Designers can reduce the need for right-of-way by providing a two-way cycle track on one side of the street rather than two one-way cycle tracks. Access to parcels close to the protected intersection is similar to the nonprotected intersection of the same form. Driveways should not be located immediately adjacent to the nearside of the intersection where the clear sight distance for right-turning vehicles would be impeded.

History and Variation

The protected intersection originated in the Netherlands.[28] Knowledge of the design in the United States dates to the early 1970s report by the University of California, Los Angeles, and a separate report from the City of Davis and the University of California, Davis, which credits a German design for inspiration.[28] The protected intersection can be found in many areas of the United States, with prominent implementation in Massachusetts[29] and New York City.[30] The dedicated intersection is a variation of the protected intersection used when the space for a bicycle setback is insufficient.[25] Protected intersections are also known as setback intersections and offset intersections.[25]

PROTECTED INTERSECTION: TWO-WAY CYCLE TRACK

Description of Design Features

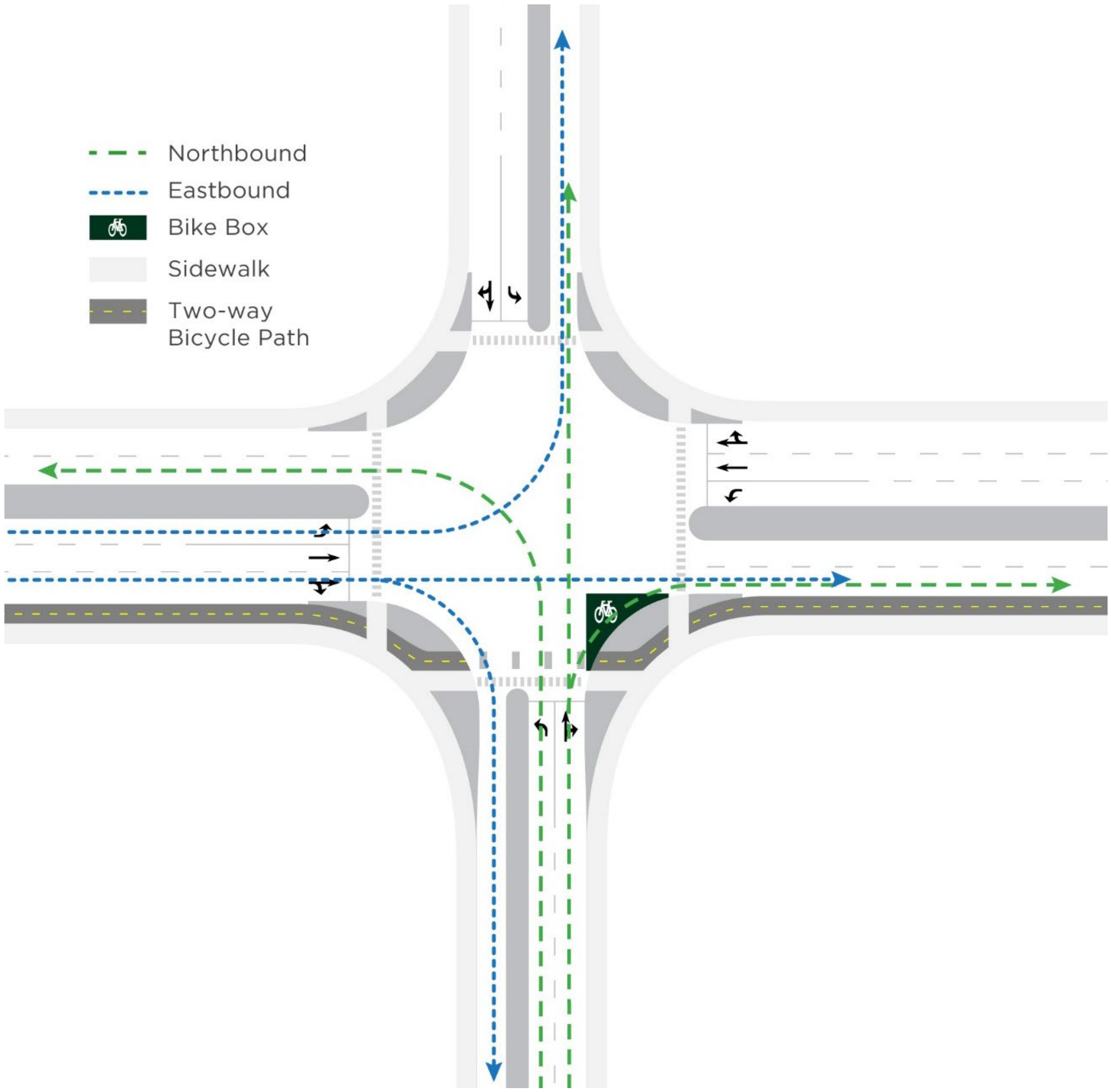
A collection of design elements that physically separates bicyclists from motor vehicles and features a two-way bicycle facility.

A two-way cycle track provides separated bicycle facilities with opposing bicyclist movements both served on the same side of the roadway. A protected intersection design has eight elements that provide enhanced protected for bicyclists and separate them from motor vehicles:

1. A curb extension or other designated no-stopping zone.
2. Pedestrian refuge islands between the bicycle lane and the motor vehicle lane.
3. A corner island.
4. A bicycle queue area.
5. A motorist waiting zone.
6. An associated bikeway setback that together with a motorist waiting zone provide storage between the vehicle lane and parallel bicycle lane.
7. Bicycle crossing markings.
8. Bicycle yield lines immediately upstream of the pedestrian crossing.[25]

These features can be provided at a variety of intersection forms, as motor vehicles use the movement paths typical of the base intersection form. At a conventional intersection, direct left and right turns and through movements are permitted from each approach, as shown in figure 12.

Protected intersections feature dedicated bicycle lanes separate from motor vehicle lanes so that bicyclists moving in the direction of adjacent motor vehicles execute left turns in a two-stage manner. Pedestrians cross the intersection in a conventional manner with additional refuge areas between the bicycle and vehicle lanes.



Source: FHWA.

Figure 12. Illustration. Protected intersection displaying two-way cycle track, sidewalk, and northbound and eastbound motor vehicle movements.

Operational Considerations

Protected intersections operate similar to their base intersection form. The cycle track can be at sidewalk or street elevation. Design plans may need to include additional signal heads to provide visibility for bicyclists traveling in the contraflow direction.

Safety Performance

Drivers and pedestrians may not look for or expect bicyclists traveling in the contraflow direction. Bidirectional lane markings within the cycle track and crossing area may alert users to the presence of bidirectional bicycle traffic. The research team does not know of any crash modification factors developed for protected intersections with two-way cycle tracks.

Vehicle Traffic Demand Patterns

Designers can combine protected intersection designs with many different base intersection forms. The design is flexible to a wide range of vehicle traffic demand patterns. Two-way cycle tracks may be desirable to one-way cycle tracks on one-way streets or where land use is predominately one-sided.

Multimodal Considerations

Protected intersection design elements enhance the safety of bicyclists and pedestrians compared to nonprotected designs. The protected intersection design includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk. Pedestrians complete crossings at the main intersection via the conventional manner for the intersection form, and a median refuge is provided between the bicycle crossing and motor vehicle crossings. Pedestrians may not anticipate bicycles traveling in the contraflow direction.

Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) Audible pedestrian signals provide additional assistance to users with low or no vision. Due to the challenge of identifying contraflow bicycle traffic, WALK indications should provide time for pedestrians to cross from sidewalk to sidewalk and complete a single stage without stopping in the refuge between the bicycle and motor vehicles lanes.

Protected intersections provide shorter crossings for bicyclists and better visibility between bicyclists and motor vehicles. Bicyclists traveling in the direction of adjacent motor vehicles who want to turn left use a two-stage maneuver via the bicycle queue areas. This configuration can increase delay more than a one-stage crossing but reduces bicyclist stress of merging across several lanes of traffic to pre-position in the left-turn lane. Due to the increased visibility and reduced vehicle speed, protected intersections are particularly beneficial at intersection forms where right-turn volumes are increased by redirected vehicles movements. Designers can enhance transit stops with floating transit stops or side boarding islands to facilitate pedestrian crossings of the bicycle lane.(27) Additional assistance can alert pedestrians to the presence of contraflow bicycle traffic.

Freight Considerations

The corner island of the protected intersection can be a combination of both raised and painted median or truck apron to serve the turning needs of the design vehicle. Design vehicles are expected to traverse the painted median, truck apron, or both and can use both the first and part of the second receiving lanes to complete the turn. Design vehicle turns are typically expected to be executed at 3–5 mph.(13)

Corridor Considerations

Designers can use protected intersection designs in conjunction with intersection forms as stand-alone intersections or in a corridor context. Engineers can use the protected intersection design in a corridor to provide a consistent experience for bicyclists traversing the corridor and ensure that the design is particularly appropriate for dominant bicycle corridors. The additional right-of-way needed for the separated bicycle facility also supports providing protected intersections along the full corridor. Two-way cycle tracks generally require less right-of-way than facilities with one-way cycle tracks on each side of the roadway. Two-way cycle tracks may also be preferable where extra right-of-way is available on one side of the roadway.(31) Access to parcels close to the protected intersection is similar to the nonprotected intersection of the same form. Driveways should not be located immediately adjacent to the nearside of the intersection where the clear sight distance for right-turning vehicles would be impeded.

History and Variation

The protected intersection originated in the Netherlands.(28) Knowledge of the design in the United States dates to the early 1970s report by the University of California, Los Angeles, and a separate report from the City of Davis and the University of California, Davis, which credits a German design for inspiration.(28) The protected intersection can be found in many areas of the United States, with prominent implementation in Massachusetts(29) and New York City.(30) The two-way cycle track protected intersection is less common than separate facilities on each side of the roadway. The dedicated intersection is a variation of the protected intersection used when the space for a bicycle setback is insufficient.(25) Protected intersections are also known as setback intersections and offset intersections.(25)

QR INTERSECTION

An efficient at-grade intersection form that reduces congestion by rerouting all left-turn movements onto an adjacent roadway that connects the two intersecting roads.

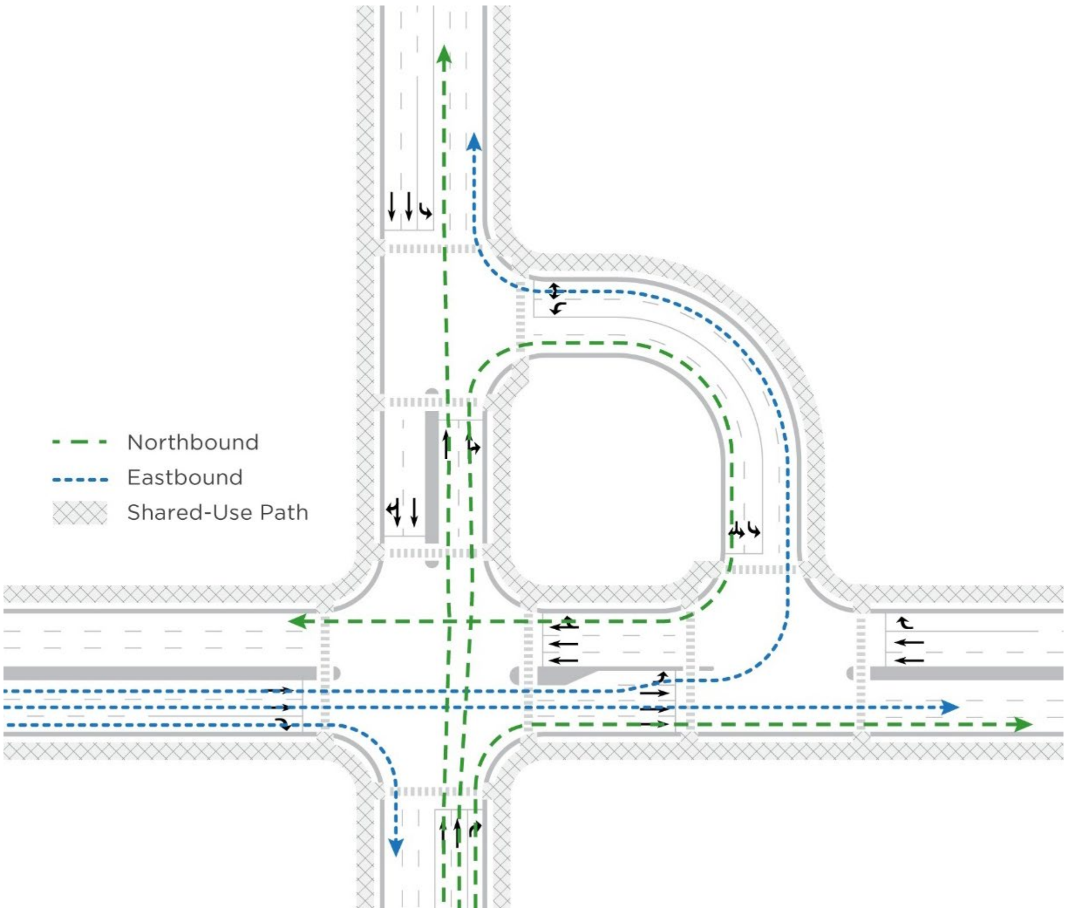
Description of Design Features

In the QR intersection, drivers who want to turn left are displaced to a quarter-arc QR in one intersection quadrant.(5) At the main intersection, this design eliminates the need for a separate left-turn phase. For example, drivers who want to make an eastbound left turn head through the intersection and then turn left onto the QR after the main intersection. Vehicles then turn right to head north. Northbound vehicles head through the intersection, turn right at the QR, and then turn right at the major road to head west. Some QR designs include roadways in two, three, or all four quadrants.

All nonmotorized users travel via a shared-use path. Crossings are provided on all four legs of the main intersection as well as at the three legs of the two QR intersections. The number of crossings needed to execute a right, through, or left turn is the same as for a conventional intersection.

Operational Considerations

Figure 13 shows the QR has two critical phases: one for the major street and one for the minor street. The two secondary T-intersections should be signalized and coordinated with the main intersection. The T-intersections also operate with two critical phases unless an exclusive pedestrian phase is used to serve users crossing the major street. At the main intersection, drivers may potentially disregard left-turn prohibitions, which designers can mitigate with appropriate signage. Increased lane changing may occur as drivers accustomed to turning from the left lane shift to the right-hand lane.[(5)]



Source: FHWA.

Figure 13. Illustration. QR intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Safety Performance

The QR has fewer intersection conflict points than conventional intersections. At the main intersection, left-turn conflicts are eliminated, reducing the potential for severe crashes. Driver confusion or error due to unfamiliarity with the intersection might occur. Higher right-turn volumes increase vehicle–pedestrian conflicts, although left-turn conflicts at the main intersection are eliminated.[(5)]

Vehicle Traffic Demand Patterns

QRs excel with low-volume to medium-volume left-turn traffic, although higher demand can be better served with redirection in two or four quadrants.(32) QRs are suitable in connecting a high-speed street that has heavy traffic volumes to a slower, less-traveled street.(7)

Multimodal Considerations

The QR commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities are provided in a shared-use path or sidewalk with typical crossings at the main and T-intersections. The reduced number of signal phases, compared to a conventional intersection, reduces delay for people crossing. Depending on location of quadrants, pedestrians may experience decreased conflicts with left-turning vehicles but increased conflicts with right-turning vehicles. Eliminating left-turn lanes at the main intersection may allow more right-of-way for pedestrian facilities and a reduced number of lanes that results in lower crossing exposure.(13) Conflicts with left turns at the T-intersections can be mitigated by using leading pedestrian intervals or exclusive pedestrian phases. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) The direct crossing design benefits pedestrians who rely on vehicle sounds to align with the crossing.

Bicyclists have three options when navigating a QR intersection:(13)

- Make a two-stage left-turn via a bicycle box.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules using the QR.

As with pedestrian facilities, eliminating left-turn lanes may allow more right-of-way for bicycle facilities. No unique benefits or fatal flaws exist for transit at QRs compared to conventional intersections, although bus routes turning left at the intersection experience additional travel distance. Bus stops should be located on the far side downstream of the T-intersection. A rail crossing that does not intersect the QR is preferable.

Freight Considerations

As with all intersections, engineers designing QR elements should consider the maneuverability of the design vehicle. Large vehicles may require wider turning lanes, paved shoulders, bulb outs, and mountable or traversable features at T-intersections.

Corridor Considerations

The two-critical-phase operation results in a near-constant flow of traffic from the QR to a downstream intersection. The T-intersections are signalized and can be coordinated with the main QR intersection and with other intersections in the corridor. The right-of-way requirements tend to be smaller at the main intersection due to the lack of left-turn lanes at the main intersection. QRs require right-of-way acquisition and construction for the new roadway in the quadrant. Improved or more controlled access to developments in some quadrants may be possible, although more circuitous access may also be provided to land uses in some quadrants.

The adjacent streets, driveways, or both might need to be relocated to accommodate the T-intersections.[5]

History and Variation

J.D. Reid published the first paper formalizing a QR intersection in the *ITE Journal* in 2000.[33] The first QR intersection was installed at North Carolina Highway 73 and U.S. Route 21 in Huntersville, NC, in 2012.[5] Many such implementations have likely existed formally and informally for decades. Bend, OR; Salt Lake City; Raleigh, NC; Charlotte, NC; and Cincinnati, OH,[19] are all major deployment regions in the United States. The QR can have roadways in one, a few, or all quadrants. The preferred design depends on available right-of-way and the site's turning movement counts.[32] The QR is also known as a quadrant, a quadrant left, and a single quadrant.

ROUNDABOUT

Description of Design Features

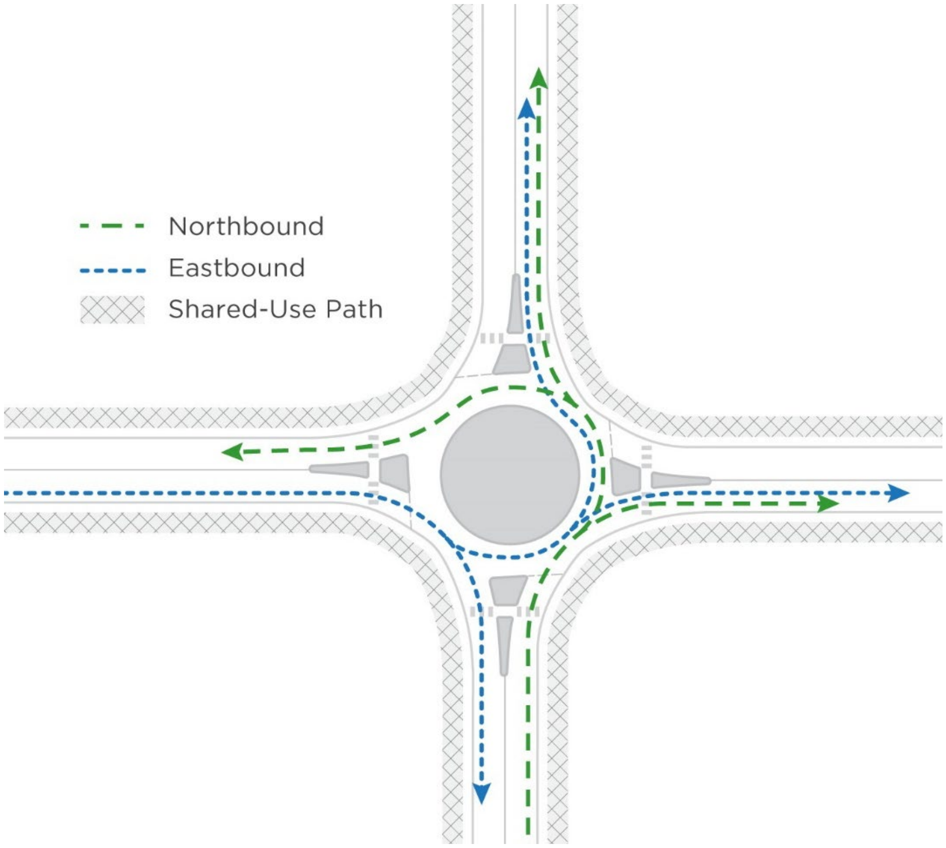
> A circular, at-grade intersection form that moves traffic counterclockwise around a central island and has geometry that reduces motor vehicle speeds and conflict points.

The roundabout is a circular intersection where vehicles move counterclockwise around a central island. Roundabouts feature yield control on entry with channelized, curved approaches that reduce vehicle speed. Each leg has a splitter island, typically with a marked crosswalk. Circular flow with no direct left turns reduces conflict points and reduces the potential for fatal or severe injury crashes. Lower speeds and conflict points can create a more suitable environment for pedestrians and bicyclists.

Roundabouts can have either separated or shared bicycle and pedestrian facilities around their perimeters. These facilities use a refuge area provided within the splitter island on each leg. Bicyclist and pedestrian crossings are separated in space from roundabout entry points to allow drivers to focus on yielding to crosswalk users separately from yielding to vehicles in the roundabout. Roundabout geometry introduces curvature that reduces motor vehicle speeds, thereby increasing the likelihood of drivers yielding to crosswalk users.

Operational Considerations

Figure 14 shows that motor vehicles enter the roundabout and circulate around a central island as needed to complete turning movements. The approach speed is controlled by a combination of horizontal (and sometimes vertical) geometric elements. The yield control of the roundabout generally reduces delay and queuing.[34]



Source: FHWA.

Figure 14. Illustration. Single-lane roundabout displaying shared-use path and northbound and eastbound motor vehicle movements.

Safety Performance

The roundabout is safer than many other forms of at-grade intersections, reducing total and injury crashes by 35 percent and 76 percent, respectively.(34) Low speeds at roundabouts provide more time for drivers to react, allow safer gap acceptance, and make collisions less frequent and severe for all modes. Multilane roundabouts have higher speeds and higher pedestrian exposure, which reduces safety benefits compared to a single-lane roundabout.

Vehicle Traffic Demand Patterns

Roundabouts can accommodate a wide variety of vehicle traffic demand patterns and can vary in the number of lanes at each entry, circulating segment, and exit as needed.

Multimodal Considerations

The roundabout commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities typically include a two-stage crossing through a splitter island refuge to allow pedestrians to cross one stream of traffic at a time. Yielding compliance is higher for entering vehicles than for exiting vehicles.(34) Pedestrian crossings should be set back from the entrance line to enhance visibility and increase yield compliance. Extensive research has been conducted to understand the effective treatments at roundabouts for pedestrians who are blind or have low vision—both for wayfinding around and across the roundabout and for determining when to cross. Effective practice includes providing some form of enhanced pedestrian crossing treatment, up to and including signalization of multilane crossings.(35) Bicycle facilities in a roundabout can include any combination of separated facilities, shared bicycle-pedestrian facilities, and shared bicycle-motor vehicle lanes. Where needed, bicycle ramps can provide transitions between onstreet bicycle lanes and separated or shared-use facilities.(8)

Engineers can verify that transit vehicles can be served at a roundabout by selecting an appropriate design vehicle and designing for a bus to circulate without having to use any aprons. Bus stops should be located appropriately to balance pedestrians' needs with the potential impacts on other roundabout users.(8)

Freight Considerations

As with all intersections, engineers designing roundabout elements should consider the maneuverability of the design vehicle. Large vehicles can be served by a traversable truck apron, which helps minimize other roundabout dimensions. When roundabouts are located near railroad crossings, ensuring that vehicles can clear the tracks ahead of any train passage is important.

Corridor Considerations

Roundabouts are often located in a corridor with other roundabouts because of the opportunity for corridor efficiency and progression, as well as the access management and speed management benefits throughout the corridor. Depending on the diameter of the roundabout, the right-of-way requirements may be larger at the intersection itself compared to other intersection forms because of the circular configuration. A series of roundabouts may allow for fewer motor vehicle lanes between roundabouts, thus reducing right-of-way requirements for the segments between roundabouts. Access to parcels close to the roundabout should be limited to right-in and right-out configurations due to the design of the splitter island. Driveways within the roundabout are permissible but discouraged. Access immediately adjacent to the roundabout, particularly between the entry point and pedestrian crosswalk, is discouraged.

History and Variation

Traffic circles were implemented in the United States as early as 1821.(34) Subsequently, large traffic circles and rotaries were built. Roundabouts have been used worldwide since the United Kingdom first implemented modern roundabout priority rules during the 1960s.(34)

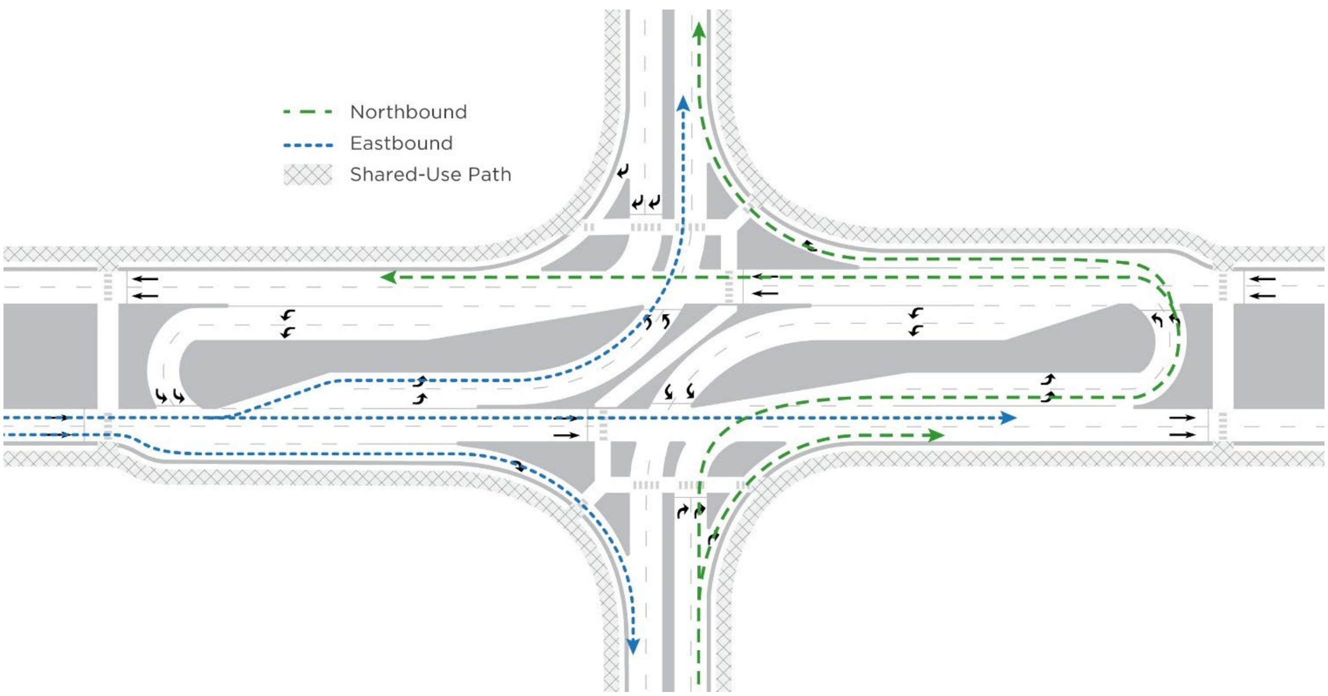
RCUT

Description of Design Features

The RCUT intersection eliminates the left-turn and through movements from minor street approaches. Northbound drivers from the minor street who want to make a left turn or continue through must turn right at the main intersection and execute a U-turn through the median. Drivers then either turn right at the main intersection to continue north or through to continue heading west. Major street vehicles complete movements using traditional paths.

A high-capacity, at-grade intersection form that reduces left-turn conflicts by rerouting minor road vehicles to a U-turn before returning to the main intersection.

Figure 15 shows all nonmotorized users travel along a shared-use path. A median between the left-turn pockets provides refuge for pedestrians and bicyclists on shared-use paths who complete the major street crossing from the southwest to northeast quadrants in two stages. A three-stage or four-stage crossing would be required to travel between other quadrants. The number of stages can be reduced through coordination of the opposing major street directions. Midblock crossings can be added at the U-turn crossover.



Source: FHWA.

Figure 15. Illustration. RCUT intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The signalized RCUT has two critical phases: one for the major street and one for the minor street. Different cycle lengths can be provided in each direction of the major street, and coordination is provided between the main intersection and the U-turn crossover. Common cycle lengths and coordination allows one-stage major street crossings for pedestrians and bicyclists.

Safety Performance

RCUTs simplify decisionmaking for drivers at the intersection and reduce the number of conflict points. These intersection types also eliminate the potential for head-on crashes and lead to less severe crashes overall.(3) The RCUT offers potential safety benefits for nonmotorized users due to the reduced conflict points, but because of indirect paths and multiple stages that can be associated with crossing RCUTs, users may cross at undesignated locations.(13)

Vehicle Traffic Demand Patterns

RCUTs excel with heavy volumes on the major street and with low through and left-turn volumes on the minor street, up to 25,000 vehicles per day.(3)

Multimodal Considerations

The RCUT commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities provide multiple points of refuge during crossings. The wide refuge area between opposing major street movements improves user comfort for those crossing. A Z-crossing is used at the main intersection, which can result in an indirect path.(13)

Several variations of the RCUT intersection can enhance pedestrians' ability to cross the major street:(6)

- Remove the channelized right-turn islands to allow for single-stage crossing.
- Consider using smaller radii and right-turn-on-red prohibitions to enhance safety.
- Provide midblock crossing at the U-turn location.

Short cycle lengths can reduce crossing times for pedestrians to be more comparable to those at conventional intersections.(13) Due to the indirect crossing, RCUTS may be unsuitable in areas with high pedestrian volumes where the desire lines between origin and destination conflict with the diagonal crossing.(6) Users with low or no vision who rely on vehicle sounds for aligning and crossing can be served through audible signals, reducing their reliance on sounds from vehicles that have been redirected. Bicyclists traveling on off-roadway bicycle paths or shared-use paths have similar experiences to pedestrian crossings. RCUTs are typically located on arterials with higher speeds and volumes, making them less suitable for on-road bicycle facilities. In addition to the pedestrian Z-crossing, cut-through paths in the median allow for bicycle through movements from the minor street. When bicycle lanes are used in combination with unsignalized U-turns, enhanced markings alert large vehicles to bicycle presence.(13)

Bus routes along the arterial are enhanced with intersection operations that are likely more efficient and result in fewer conflicts for transit users. Buses turning left or continuing through from the minor street incur extra travel distance.[6] Nearside bus stops allow for easiest pedestrian crossings of the major street.[3] Bus stops in the loon are discouraged to avoid conflict with turning vehicles.

Freight Considerations

Larger design vehicles typically need 40–60 ft to execute U-turns through a combination of median, lane, and shoulder width. On narrower facilities, bulb outs or loons facilitate U-turns.[6]

Corridor Considerations

The two-critical-phase operation allows the RCUT to process high volumes from an upstream intersection, providing the main street with nearly 70 percent of green time.[3] RCUTs pair well with intersections that produce near-constant flows of vehicles, such as DLT intersections or DDIs. Often, RCUTs are located in a corridor with other RCUTs because of the opportunity for corridor efficiency and progression, particularly when coordination is not provided between opposing major street directions. Progression between RCUTs and between signals at a single RCUT allow for speed management along the corridor.

RCUTs are typically located on corridors with wider right-of-ways to provide the necessary space for U-turns at the crossover, which are facilitated through a wide median or a loon adjacent to the turn bay. U-turn locations can be modified to align with existing access points and retain existing driveways. Driveways are undesirable along the length of the loon on both sides of the major street.

History and Variation

Traffic engineer Richard Kramer published the first RCUT concept in the early 1980s, but drivers may have been informally executing the movement before that date.[6] The first RCUT was installed on U.S. Route 301 on Maryland's Eastern Shore. Since then, other major deployment regions in the United States include the cities of St. Louis, MO; Cincinnati; Baltimore, MD; Charleston, SC; New Orleans, LA; Austin; and San Antonio, TX, as well as Washington, DC, and the States of Indiana; Minnesota; Michigan; Delaware; and North Carolina.[19]

RCUTs include the following variations:

- Closed median that results in left-turning vehicles on the major street proceeding to the U-turn crossover.
- Midblock crossings at the crossover intersections.

The RCUT is also known as a continuous flow intersection, a superstreet J-turn (unsignalized), a reduced conflict U-turn, and a reduced conflict intersection synchronized street.

SINGLE ROUNDABOUT INTERCHANGE

Description of Design Features

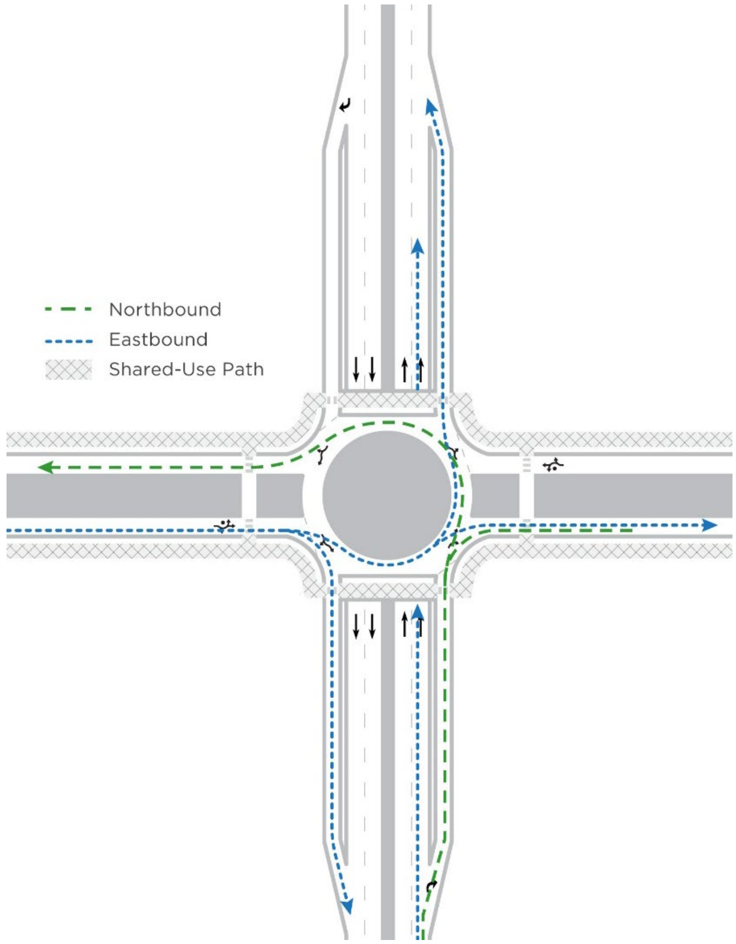
> A grade-separated interchange with directional diamond ramps and a single circular form on the cross street that moves traffic counterclockwise around a central island.

The single roundabout interchange is a grade-separated interchange featuring direct diamond ramps and a single circular intersection on the cross street where vehicles move counterclockwise around a central island. The roundabout features yield control on entry with channelized, curved approaches that reduce vehicle speed, which assists in the transition from interstate to arterial speeds. All on-ramp and off-ramp movements exit or enter, respectively, as legs of the single roundabout. Each cross-street leg has a splitter island, typically with a marked crosswalk. Circular flow and the curved approaches reduce vehicle speeds from the off-ramp, assisting in the transition from higher speed uninterrupted roadways to lower speed cross streets.

Roundabouts can have either separated or shared bicycle and pedestrian facilities around the perimeter of the roundabout. These facilities use a refuge area provided within the splitter islands on the cross street and sidewalks along the outside of the bridge. Bicycle and pedestrian crossings are separated in space from roundabout entry points to allow drivers to focus on yielding to crosswalk users separately from yielding to vehicles in the roundabout. Roundabout geometry introduces curvature that reduces motor vehicle speeds, thereby increasing the likelihood of drivers yielding to crosswalk users.

Operational Considerations

As figure 16 shows, motor vehicles enter the roundabout and circulate around a central island as needed to complete turning movements. The approach speed is controlled by a combination of horizontal (and sometimes vertical) geometric elements. The yield control of the roundabout generally reduces delay and queuing.[34]



Source: FHWA.

Figure 16. Illustration. Single roundabout interchange displaying shared-use path and northbound and eastbound motor vehicle movements.

Safety Performance

The roundabout control strategy is safer than many other forms of at-grade intersections.(34) Low speeds at roundabouts provide more time for drivers to react, allow safer gap acceptance, and make collisions less frequent and severe for all modes. Multilane roundabouts have higher speeds and higher pedestrian exposure, reducing safety benefits (crash modification factor of 1.288) compared to single-lane roundabout interchanges (crash modification factor of 0.672).(36)

Vehicle Traffic Demand Patterns

Roundabouts can accommodate a wide variety of vehicle traffic demand patterns and can vary in the number of lanes at each entry, circulating segment, and exit as needed.

Multimodal Considerations

The roundabout commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities across the cross street typically include a two-stage crossing through a splitter island refuge to allow pedestrians to cross one stream of traffic at a time. Pedestrian facilities across the ramps are separated by the bridge structure. Yielding compliance is higher for entering vehicles than exiting vehicles.(34) Pedestrian crossings should be set back from the entrance line to enhance visibility and increase yield compliance. Extensive research has been conducted to understand effective treatments at roundabouts for pedestrians who are blind or have low vision—both for wayfinding around and across the roundabout and for determining when to cross. Effective practice includes providing some form of enhanced pedestrian crossing treatment, up to and including signalization of multilane crossings.(35)

Bicycle facilities in a roundabout can include any combination of separated facilities, shared bicycle-pedestrian facilities, and shared bicycle-motor vehicle lanes. Where needed, bicycle ramps upstream of the interchange can provide transitions between onstreet bicycle lanes and separated or shared-use facilities.(8) Engineers can verify that transit vehicles are served at a roundabout by selecting an appropriate design vehicle and designing for a bus to circulate without having to use any aprons. Bus stops should be located appropriately to balance pedestrian needs with the potential impacts on other roundabout users.(8)

Freight Considerations

As with all intersections, engineers designing roundabout elements should consider the maneuverability of the design vehicle. Large vehicles can be served by a traversable truck apron, which helps minimize other roundabout dimensions. Roundabout interchanges tend to have larger diameters than roundabout intersections, improving the ease of access for large vehicles. When roundabouts are located near railroad crossings, ensuring vehicles can clear the tracks ahead of any train passage is important.

Corridor Considerations

The single roundabout interchange can be located in a corridor with other roundabouts to enhance the opportunity for corridor efficiency and progression, as well as the access management and speed management benefits throughout the corridor. The interchange can serve additional approaches, such as those from a frontage road. While interchanges are typically used in conjunction with interstates, the single roundabout interchange can also be used with non-interstate limited-access roads. In addition, the single roundabout interchange can be used as a grade-separation technique to permit uninterrupted movement for a major arterial underneath or over the intersection of two or more minor arterials. The curved nature of the roundabout typically requires either a curved bridge structure or a tangential structure that is wider than a typical bridge. Alternatively, the interchange can be designed with two bridges. Access to parcels close to the roundabout should be limited to right-in and right-out configurations due to the design of the splitter island.

History and Variation

The single roundabout interchange at State Route 9 and Troy-Schenectady Road in Latham, NY, dates to at least the early 1990s.[37] Variations of the single roundabout interchange include a grade-separated traffic circle, the double roundabout interchange, and the raindrop interchange. The traffic circle interchange is primarily found in Washington, DC—such as at K Street NW, 23rd Street NW, Pennsylvania Avenue NW, and New Hampshire Avenue NW. The traffic circle interchange features signalization within the circulating roadway. The double roundabout and raindrop interchanges both provide two circular forms, one for each ramp terminal. In the raindrop design, a U-turn maneuver requires traversing both roundabouts because full circulation is not provided at either roundabout. Several roundabout interchanges exist in Colorado, Maryland, and North Carolina.[6]

SPLIT INTERSECTION

Description of Design Features

An at-grade variant of the diamond interchange that uses two signalized intersections to separate traffic on a major street into two one-way streets.

In the split intersection, the major street is separated into two one-way streets at two signalized intersections. As figure 17 shows, eastbound vehicles are split to the southern intersection and can turn right or left or go through as in a conventional intersection. Northbound vehicles turning right or heading through do so as in a conventional intersection, while vehicles turning left head through to the northern intersection where they can turn left to join westbound traffic. Similarly, southbound vehicles turning left must proceed through the northern intersection and then turn left at the southern intersection to join eastbound traffic.

As figure 17 shows, bicyclists and pedestrians both enter the intersection on a shared-use path. Eastbound bicyclists and pedestrians at the southern intersection turn right and continue on the shared-use path to proceed south. Those continuing east instead cross the south crosswalk in two stages through a median refuge. To head north, users cross the major street and proceed along the minor street. After travelling on the shared-use path to the northern intersection, bicyclists use the east crosswalk to access the northeast quadrant of the intersection, and then they either continue north or use the northern crosswalk to execute a two-stage crossing to proceed west.

Operational Considerations

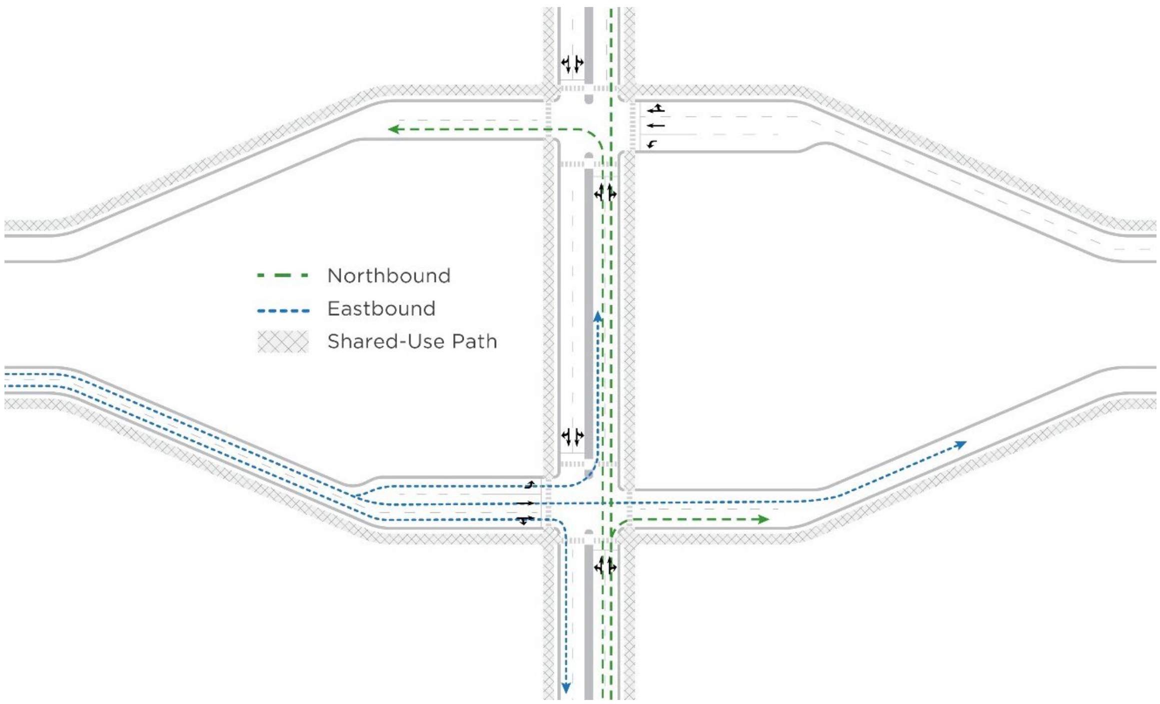
Signal or stop control can be used at split intersections. Under signalization, each intersection operates with two or three critical phases depending on the left-turn phasing. Split intersections can be used in anticipation of future grade separation. Corridor travel times are improved both on the major and side streets by coordinating the two signalized intersections. Fewer traffic signal phases result in increased green time for all movements.[7]

Safety Performance

The split intersection reduces the number of crossing conflict points for vehicles, pedestrians, and bicyclists.[7] Left turns from the major street are unopposed, and drivers may not be prepared to yield to nonmotorized users. Crossings may still be desirable on the inside of each intersection depending on land use between the intersections.

Vehicle Traffic Demand Patterns

Designers should consider split intersections at congested suburban intersections with heavy-volume left-turn traffic, or in urban areas where two-way streets are converted to one-way streets.[38]



Source: FHWA.

Figure 17. Illustration. Split intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Multimodal Considerations

The split intersection commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or a shared-use path with refuge areas if the median width allows. The major street crossing can be made in one stage at each intersection. If turning left from the minor street to the major street, the distance between the two intersections leads to additional travel distance for pedestrians. The location of crossings for the minor street depends on the land use in the space between the two intersections. If desire lines exist to cross the minor street between the intersections, crosswalks can be provided on the inside of each intersection. The left turns from the major street are unopposed by through vehicles, which results in conflicts with pedestrians similar to those at T-intersections. If space between the intersections is undeveloped, crosswalks on only three legs of each intersection may be more suitable. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.[(6)] Bicyclists can be served on a shared-use path, via onstreet bike facilities, or in the vehicle lane.

Bicyclists have three options when making a left turn at a split intersection:

- Make a three-stage left-turn via a bicycle box.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules.

Adding one-way streets and two intersections increases travel time for bicyclists. However, bicyclists crossing the minor street benefit from eliminated left-turn conflicts. Transit stops can be on the nearside or far side of the intersection pair or between the intersections. Transit vehicles going through or turning right at the intersections experience minimal travel time impact, but the vehicles turning left may be impacted by greater out-of-direction travel.

Freight Considerations

As with all intersections, engineers designing split intersections should consider the maneuverability of the design vehicle.

Corridor Considerations

Split intersections can be used in anticipation of future grade separation when each intersection would become a ramp terminal. Therefore, back-to-back split intersections may be suitable along the corridor. Eliminating one left-turn phase at each intersection results in higher throughput for the major street. Right-of-way requirements are high for split intersections because space is needed for each intersection. The physical separation of the major street increases the right-of-way needs along the segment. If a future conversion to grade separation is planned, driveways are undesirable between the intersection pair but may be retained until the full conversion is complete.

History and Variation

Hakkert and Yakon introduced the split intersection in a 1978 research paper in *Traffic Engineering and Control*.[(39)] Bared and Kaisar[(38)] and Polus and Cohen[(40)] conducted simulation analyses on the split intersection in the late 1990s. Few implementations of split intersections are in operation in the United States.[(38)]

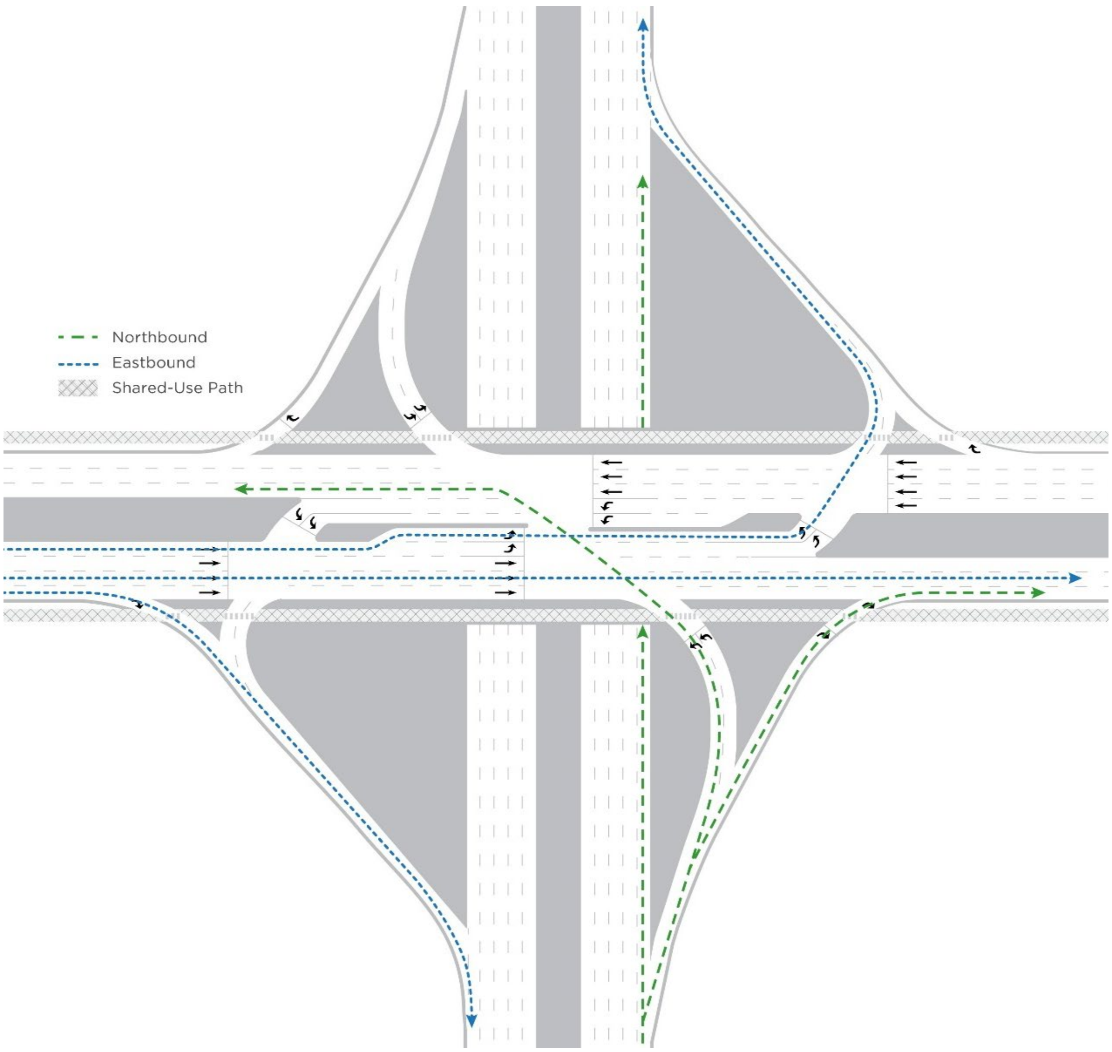
THREE-POINT INTERCHANGE

Description of Design Features

A diamond form suitable for skewed interchanges featuring three terminals with direct access for all movements.

The three-point interchange is so named due to the presence of three ramp terminals. Figure 18 shows the outer terminals include the off-ramp right-turn movement and the cross-street left-turn movement. The center terminal includes both off-ramp left-turn movements. All movements at the three-point interchange are made directly, proceeding similarly to those at a conventional diamond interchange. The three-point interchange can be deployed where a significant skew exists between the cross street and the limited-access roadway, resulting in extended off-ramps. Depending on the orientation of the skew, the interchange can have long right-turn off-ramps with little curvature and left turns with relatively tight radii; however, a skew in the opposite orientation would result in right turns with tight radii and nearly tangential left turns.

Pedestrians and bicyclists proceed in a manner similar to a conventional diamond interchange with direct through movements. Crossing of the cross street can be limited, particularly if the right-turn off-ramp is yield controlled. Under signal control, crossings are provided on the outside of the outer terminals.



Source: FHWA.

Figure 18. Illustration. Three-point interchange displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The terminals each operate with two critical phases, and the terminals are coordinated to provide progression for the dominant movement(s). Left turns at the center terminal operate simultaneously. The right-turn off-ramp can be yield or signal controlled. Aligning the right turn to intersect the cross street more orthogonally will slow vehicles and improve yielding to pedestrians and bicyclists. For mitigation, designers can consider pedestrian hybrid beacons, rapid rectangular flashing beacons, and full signals. If cross-street crossing is provided for pedestrians and bicyclists at the center terminal, designers should use an exclusive pedestrian phase.

Safety Performance

The three-point interchange has two fewer crossing conflict points than a conventional diamond. Wrong-way left turns from the off-ramp may occur, which can be mitigated through design. Keeping right-turn off-ramp radii small will result in lower speeds and higher yielding rates to pedestrians and bicyclists.(26)

Vehicle Traffic Demand Patterns

Three-point interchanges should be considered where left-turn off-ramp volumes are high and where a skew exists between the cross street and the limited-access road.

Multimodal Considerations

The three-point interchange can include at-grade pedestrian and bicycle facilities to provide access for all users. Access across the cross street can be provided at the outside terminals if the outbound movement is signalized or at the center terminal using an exclusive phase. Conflicts with off-ramp and on-ramp right turns are typically yield controlled and can be enhanced with a variety of traffic devices, including pedestrian hybrid beacons, rapid rectangular flashing beacons, or full signals. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) If the on-ramp crossing is signalized, audible pedestrian signals assist users with low or no vision because no parallel vehicle traffic sound is present to assist in determining the signal state.

Bicyclists traveling on shared-use paths have similar experiences to pedestrian crossings. Three-point interchanges are typically located on high-volume cross streets, making them less suitable for on-road bicycle facilities. If on-road facilities are provided and ramps serve frontage roads, two-stage left-turn bicycle boxes eliminate lane changes for bicyclists. Transit stop locations can be positioned similar to conventional diamond interchanges, and the stops can be located inside the outer terminals as needed for access to transit along the limited-access road.

Freight Considerations

Because the three-point interchange is suitable with skews, engineers designing the off-ramps should consider the turning needs of the design vehicle. Wide lanes, paved shoulders, and shaved median noses can assist larger vehicles.

Corridor Considerations

Due to the presence of three terminals, the three-point interchange is best suited for a corridor with sufficient spacing between the interchange and adjacent intersections. Reducing the space between terminals reduces left-turn queue storage at the outer terminals. Three-point interchanges are not well suited when frontage roads are present because additional critical phases would be needed at the outer terminals. The right-of-way requirements along the limited-access road for a three-point interchange tend to be larger than for a conventional intersection, although the difference is reduced as the skew angle grows. The bridge deck is larger—similar to a single-point interchange (SPI)—to serve the left-turn off-ramp movements.(9) Access to quadrants along the cross street is similar to a conventional diamond.

History and Variation

One known implementation of the three-point interchange is at I–55 and Highway 141 in Arnold, MO. The interchange opened to traffic in 2002.(41) The three-point interchange is similar to an SPI in that it removes conflicts between off-ramp left turns.

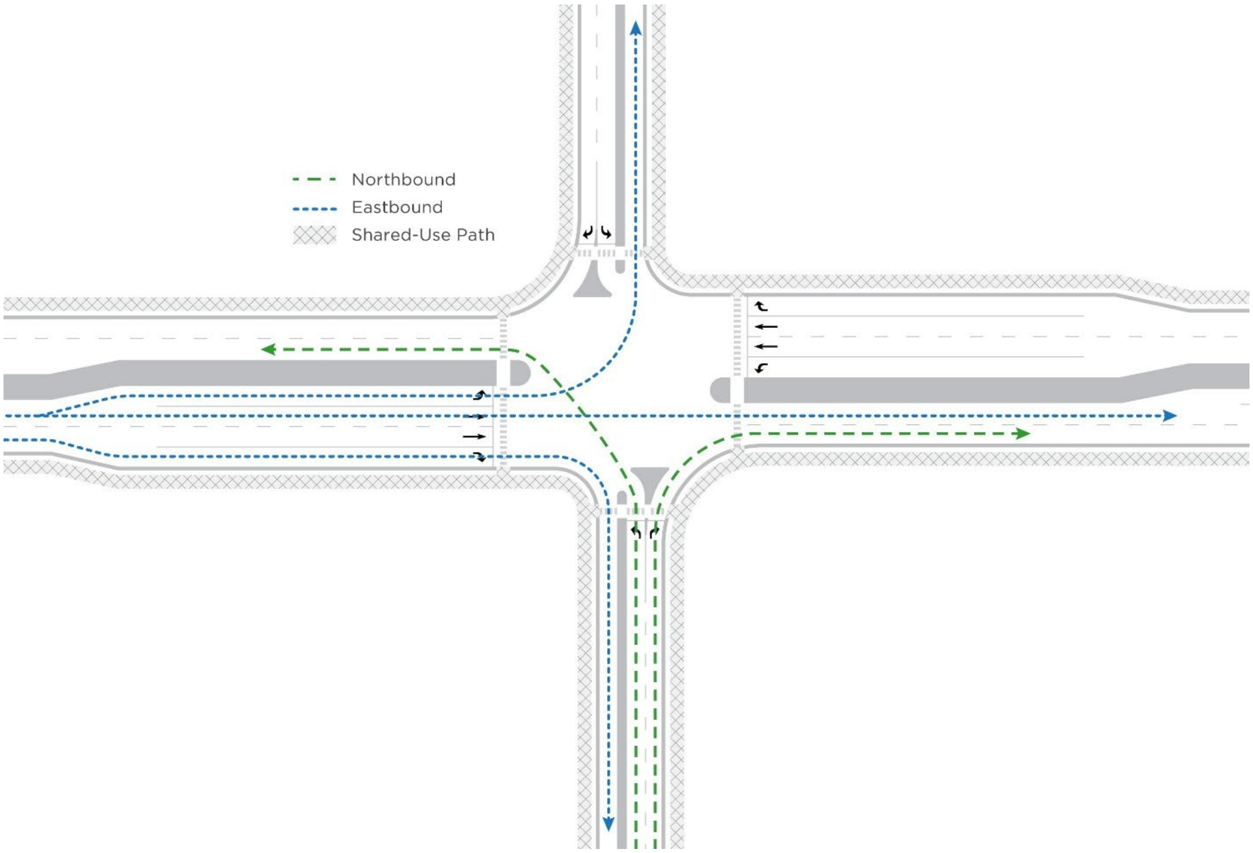
THRU-CUT

Description of Design Features

At a thru-cut intersection, vehicles proceeding from the major street can make a direct left turn, right turn, or through movement. Vehicles proceeding from the minor street can make a direct left turn or right turn, while vehicles crossing the major street first turn onto the major street and then make a U-turn or turn left at a nearby cross street.

> An at-grade intersection form that allows only left and right turns from the minor street with full access from the major street.

Bicyclists and pedestrians can cross the intersection similar to a conventional intersection, as shown in figure 19. Alternatively, a Z-crossing can be provided with direct crossings across the minor street approaches and a diagonal crossing from the southeast to northwest quadrant to cross the major street approaches. The Z-crossing eliminates conflicts with left turns from the minor street. A median refuge island through the center of the intersection assists users in wayfinding and aligning. A channelizing island between left-turning and right-turning vehicles on the minor street also allows for an additional median refuge island.



Source: FHWA.

Figure 19. Illustration. Thru-cut intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

Engineers can control thru-cuts through signalization or two-way stop control. When signalized, the thru-cut has two or three critical phases, depending on the pedestrian facility's design. At minimum, one phase is needed for major street movements and one for minor street movements. A third phase may be added for protected left turns from the major street with overlapping right turns from the minor street, thus eliminating conflicts in time with the diagonal pedestrian crossing. For the traditional box pedestrian crossing across the major street, similar conflicts are expected with the minor street left turn, as seen at a T-intersection. Designers can mitigate or eliminate such conflicts by using leading pedestrian intervals or exclusive pedestrian phases, respectively.

Safety Performance

Thru-cuts eliminate through movement conflicts on the minor street, which likely reduces angle crashes. The reduction in delay may result in reduced rear-end crashes for the minor street approaches. Redirected movements result in increased right-turning volume in conflict with pedestrians. Designers may mitigate this conflict by prohibiting right turns on red.

Vehicle Traffic Demand Patterns

Designers can consider the thru-cut where through volumes are low on the minor street, such as locations with adjacent shopping centers or residential developments.

Multimodal Considerations

The thru-cut commonly includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or shared-use path and can be provided in one of two designs. The first design comprises the direct crossings across each approach, as found at conventional intersections. The second design includes direct crossings across the minor street with a diagonal crossing across the major street, aligned between the turning path of the minor street left-turn movements. This design eliminates conflicts with major street left-turn movements and minor street right-turn movements when crossing the major street.

For the second design, a median refuge island at the center of the intersection assists users in wayfinding and aligning. Greater right-turn volume on the minor street due to redirected through movements increases the likelihood of right-turn conflict with pedestrians. Designers can mitigate this potential conflict for pedestrians crossing the minor street by prohibiting right turns on red.[(13)] Designers can mitigate this potential conflict for pedestrians crossing the major street by using the diagonal crossing. Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.[(13)] The traditional direct crossing design benefits pedestrians who rely on vehicle sounds to align with the crossing. For the diagonal design, audible signals enhance aligning for pedestrians with low or no vision.

Bicyclists have three options when making a minor through movement at a thru-cut intersection:

- Remain mounted and cross via a marked bicycle lane parallel to the pedestrian crosswalk.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules, turning at an adjacent street.

Transit operations are similar to a conventional intersection. Stops for transit vehicles can be on the nearside or far side of the intersection.

Freight Considerations

Radii should serve the appropriate design vehicle. In areas where freight vehicles may predominantly desire to make a through movement from the minor street, adding signing directing vehicles to adjacent cross streets or driveways may be appropriate.

Corridor Considerations

Thru-cuts typically serve as minor intersections along the corridor. A conventional intersection under the same volumes may also operate with two or three critical phases unless geometric considerations require protected left turns. In this scenario, converting to a thru-cut would provide a wider progression band opportunity. Adjacent median openings or intersections should be available with a quarter mile to a half mile for vehicles needing to make a U-turn on a parallel minor street. Right-of-way requirements for the thru-cut are similar to a conventional intersection with shared lanes on the minor street.

History and Variation

Virginia DOT (VDOT) formally presented the idea of a thru-cut as part of its VDOT Justification Screening Tool in 2021.[42] The form has existed in other States, including Maryland and North Carolina, since at least the early 2000s. Many such implementations likely exist across the country and have been used for decades.

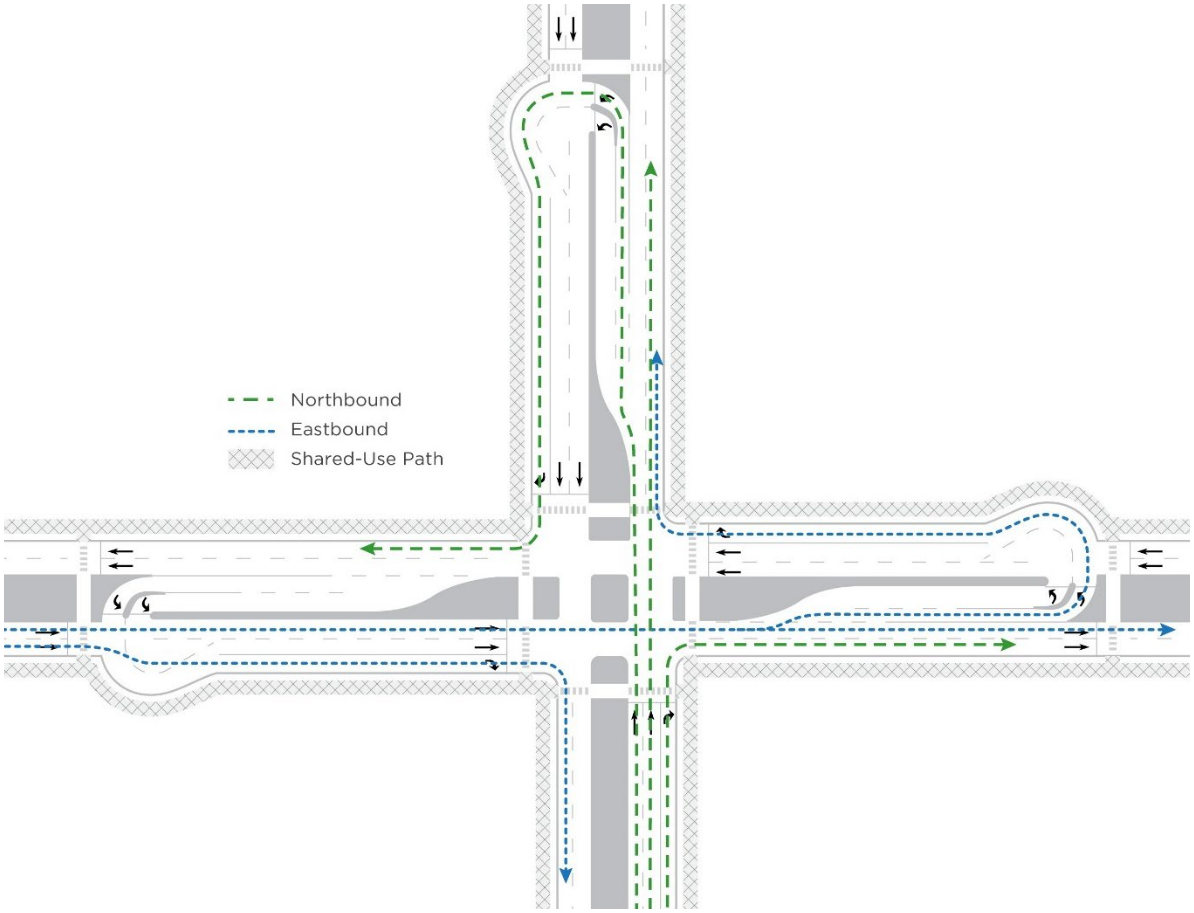
ThrU-TURN

Description of Design Features

An efficient at-grade intersection form that replaces direct left turns at an intersection with indirect left turns using a U-turn movement on three legs.

In the ThrU-turn intersection, U-turn crossovers are provided on three legs of the intersection to serve drivers who want to turn left. Most left-turning vehicles proceed straight through the intersection to the U-turn crossover and then return to the main intersection and turn right. As figure 20 shows, southbound vehicles have no downstream crossover, so left-turning vehicles turn right (westbound), make a U-turn at the crossover, and proceed through the main intersection. ThrU-turns require wide-median divided highways or a bulb out adjacent to the U-turn bay (referred to as loons).

As figure 20 shows, bicyclists and pedestrians both enter the intersection on a shared-use path. Users cross the intersection in a similar manner to a conventional intersection. Bicyclists can use the two-stage left-turn boxes to operate on streets without needing to use the U-turn bay. Designers can provide median refuge areas to allow for two-stage crossing of each approach. Designers can provide midblock crossings at U-turn crossovers.



Source: FHWA.

Figure 20. Illustration. ThrU-turn intersection displaying shared-use path and northbound and eastbound motor vehicle movements.

Operational Considerations

The ThrU-turn operates by using two critical phases: one for the major street and one for the minor street. The intersection can be signalized or can be controlled with two-way stop control under low volumes on the minor street. U-turn crossovers should be coordinated with the main intersection such that vehicles proceeding through the street have a progression band through both signals. A reduction in the number of critical phases increases the proportion of green time available for the minor street, which reduces the impact of longer DO NOT WALK intervals necessary to clear pedestrians from the intersection.

Safety Performance

ThrU-turns eliminate all left-turn conflicts and reduce rear-end, angle, and sideswipe crashes compared to conventional intersections. The ThrU-turn has increased conflict potential with right turns at the U-turn crossover if the bay aligns with a driveway or side street.[6] Greater right-turn volume increases the likelihood of right-turn conflicts with pedestrians.

Vehicle Traffic Demand Patterns

ThrU-turns should be considered at intersections with moderate-volume to heavy-volume through and left-turn traffic, such as near fully developed quadrant intersections near interchanges. ThrU-turns can be considered as an alternative to DLT intersections.

Multimodal Considerations

The ThrU-turn includes at-grade pedestrian and bicycle facilities to provide access for all users. Pedestrian facilities include a sidewalk or a shared-use path. While left-turn conflicts are eliminated, greater right-turn volume from redirected left-turns increases the likelihood of right-turn conflict with pedestrians. Designers can mitigate this potential conflict by prohibiting right turns on red.(13) Additional opportunities for midblock pedestrian crossings are available by using a traffic signal or pedestrian hybrid beacon at the U-turn crossover.(13) This design requires outbound vehicles to encounter an additional signal, but stops can be mitigated through coordination.

Accessibility is provided through traditional design techniques, including detectable warning surfaces and accessible pedestrian signals.(6) The presence of through movements from all approaches benefits pedestrians who rely on vehicle sounds to align with the crossing. Bicyclists making through movements encounter relatively higher percentages of green time at ThrU-turn intersections compared to the same experience at conventional intersections.

Bicyclists have three options when making a left turn at a ThrU-turn intersection:(13)

- Make a two-stage left turn via a bicycle box.
- Cross via a marked crosswalk following pedestrian rules.
- Cross following vehicle rules using the U-turn bay.

Vehicle right-turn movements may be associated with increased conflict due to a higher proportion of right-turning vehicles. Exclusive right-turn lanes allowing vehicles to cross bicycle lanes at speed and upstream of the intersection are preferable to designs where right-turning vehicles cross bicyclists at the intersection, resulting in a right-hook conflict. The presence of loons mitigates conflicts with offtracking U-turning trucks. Designers can further mitigate this potential conflict by signalizing the U-turn crossover and providing sufficient clearance intervals for bicyclists to clear the U-turn conflict point. Stops for through and right-turning transit vehicles can be on the nearside or far side of the main intersection. Stops for left-turning transit vehicles should be located downstream of the U-turn movement, either before or after completing the right turn. Stops in the U-turn loon are strongly discouraged.(13)

Freight Considerations

ThrU-turns should be designed for the appropriate design vehicle. Pavement can be added to the far side of the U-turn crossover in the form of bulb outs or loons where medians do not provide enough width for U-Turns.

Corridor Considerations

The ThrU-turn is commonly located adjacent to an interchange. The two-critical-phase operation allows for efficient processing of vehicles from the interchange, which reduces the likelihood of queue spillback. For intersections closely spaced to the interchange, the design allows additional queue storage for potential left-turning vehicles in the U-turn bay downstream of the intersection. The two-critical-phase operation results in a wide progression band opportunity. Additional right-of-way is needed to allow for the U-turn loon or for an expanded median. Designers can achieve efficient corridor operation with a range of spacing between the main and U-turn intersections. The limited number of deployments to date have allowed driveway access within the loon and right-in-right-out access for driveways between the main intersection and the U-turn crossover.

History and Variation

The Utah DOT (UDOT) first deployed the ThrU-turn at East 12300 South and South State Street in Draper, UT, in 2011.[(43)] The design was selected over the more costly DLT or a grade-separated alternative. The placement of the intersection next to a grade-separated interchange meant a MUT design was infeasible due to the lack of space for a U-turn bay on the mainline between the intersection and the interchange.

CHAPTER 3. CAV NEEDS ASSESSMENT

This chapter analyzes the intersection forms and performs a needs assessment for CAV technology to operate safely through such forms. Three main factors define how safe interactions are between vehicles at intersections: geometry, number and locations of conflict points, and the line of sight vehicles have as they approach the intersection. Since CAV technology relies on onboard sensing, roadside sensing, and wireless communications, analyzing how these factors affect, or are affected, when the technology is introduced is important.

In addition to relying on a localization process that identifies the vehicle's position in the world relative to a base map, CAVs rely on three core functions that support a vehicle's ability to safely navigate through roadway environments considering the presence of traffic. These functions are sensing, perception, and detection and planning. These functions are direct inputs that result in the decisionmaking process CAVs must perform in response to dynamics in the roadway environment.

The following categories of intersection features or attributes affect or influence CAV operations at alternative intersections and interchanges (AIIs). A simplified sequence of activities and interpretation needs are consistent with human and CAV decisionmaking and control:

- Interpreting the intersection influence area, impending intersection, and the necessary actions and workload needed compared to the roadway segment. These activities must be interpreted by the CAV's core functions.
- Identifying navigational and directional needs that result in desired through movements and left-turn, right-turn, or U-turn movements. This activity relates to detection and planning for lane choices consistent with the desired directional navigation. Pavement markings and guide signs help inform this activity.
- Assessing user conflicts and interpreting and responding to traveler priority and restrictions. This assessment can vary by control type and by selecting appropriate gaps for permitted driving, walking, and bicycling movements. The complexity can vary and generally increases with the number of lanes or overall crossing widths.
- Navigating the intersection. This activity applies to each user. For those individuals using a vehicle or travel device, this activity includes controlling the vehicle consistent with the intended travel path and maintaining the intended travel path and corresponding operating speed and orientation commensurate with the provided path.
- Transitioning from the intersection to the adjacent roadway segment, including motor vehicle lanes, bicycle facilities, and pedestrian sidewalks and walkways.

AIIs may have unique features or combinations of features. AIIs may also have variations in how their component intersections function compared to conventional intersection forms. Regarding AIIs and their use by CAVs, the following three intersection attributes must be considered: intersection configuration, user route crossings, and visibility and sight lines. As CAV technology evolves and as combinations of various technologies (e.g., V2V, V2I, and infrastructure-to-vehicle (I2V)) may be implemented over time, temporal considerations influence decisionmaking related to CAVs and AIIs.

INTERSECTION CONFIGURATION

Intersection configurations directly influence choices in determining navigation and vehicle control needs. Intersection geometry and configurations of turning movements—and the associated traffic control—affect travel speeds and vehicle maneuverability. Drivers rely on their ability to view their surroundings to make informed decisions on their choice of speed and lane of travel. With CAVs, drivers could be supported or replaced by onboard sensors to provide the required situational awareness about the intersection configuration for the vehicle to make the speed and lane-change decisions.

Onboard sensors, especially at higher levels of automation (SAE Level 3™ and higher),[44] would be able to perform the DDT without additional input from roadside sensors or wireless communications. In specific scenarios where intersection geometry is highly complex (with narrow lanes and a need for high maneuverability), relying on wireless communication might be necessary to send MAP messages from the infrastructure to approaching CAVs. MAP refers to a highly precise digital map CAVs use to locate their position in the environment. MAP messages define the static physical geometry of an intersection and the allowable vehicle movements for each lane. These messages provide clear information to CAVs about what to expect at an intersection and how to navigate through the geometry of that intersection.

USER ROUTE CROSSINGS

All intersections have specific travel routes for each user. These routes may cross, and the overall objective of intersection design is to allow user routes to cross without conflict. Traffic control and user interpretations (i.e., gap acceptance) of crossing without a conflict are methods inherent in conventional intersections and AIIs. The number and type of crossing points are determined by the number of movements at an intersection, intersection geometry, and control strategies at the intersection. Similar to intersection geometry, drivers of human-driven cars completely rely on their ability to view the surrounding environment and assess risks to drive through conflict points. Drivers also rely on their ability to identify the type of control (e.g., all-way stop, stop, roundabout, traffic signal) to make decisions and navigate through an intersection. Pedestrians and bicyclists rely on traffic control or determine acceptable gaps to safely cross travel routes. CAVs require the onboard sensors and wireless communication.

The onboard sensors would support most of the required situational awareness around a CAV for decisionmaking. A CAV may completely rely on its onboard sensors when an intersection is stop controlled with traditional traffic signs or with a roundabout design. When the intersection is controlled by smart traffic signs or signals, a CAV’s onboard sensors may still be able to perform the task to detect the signal status or identify the sign type. However, ideally in these situations, a CAV would rely on wireless communication with the infrastructure (i.e., V2I/I2V) or other vehicles to identify the type of control, control status, and planned movements of other approaching vehicles and to make an optimal decision to navigate through the intersection.

Alternatively, when other vehicles at the intersection are not CAVs, roadside sensing may be needed.

VISIBILITY AND SIGHT LINES

Intersection visibility and sight lines are key attributes for users to interpret an impending intersection, assess their navigation and planning tasks, and conduct appropriate operational actions to the intersection. Visibility includes a user in the approaching segment recognizing the intersection operational and geometric influence areas and initiating early actions to safely navigate the intersection. Visibility could include assessing the back of a queue or speed reduction needs or identifying and appropriately navigating pedestrian and bicyclist crossings.

Designers must consider various types of sight lines for humans. The intent of any sight line is to have a clear view to stop and avoid an observed conflict. Stopping sight distance (SSD) is a requirement on roadway approaches and at intersections to view, assess, and stop forward movement in advance of an object.

Intersections require a second type of sight line to provide intersection sight distance (ISD). Sometimes known as sight triangles, ISD is the distance for a driver without the right-of-way to see and react to a conflict. Intersection approaches also require assessing a view angle for human drivers. A view angle allows drivers an easy look upstream to avoid a conflicting vehicle. View angles that require craning the neck or using side mirrors are undesirable and may be difficult for some drivers.

The concept of visibility and sight lines includes a human factor of perceiving and reacting to a potential conflict. CAVs process data at a different rate than humans, and the visibility and distance values associated with various sight lines for CAVs would be different than for human drivers. Until a 100-percent integration of driving technology exists, engineers designing any intersection must meet human factor needs.

Driving through intersections with different geometric features and conflict-point configurations completely relies on a driver’s ability to have a clear line of sight to safely navigate through intersections. Assisted driving is needed in complex situations with hard-to-navigate intersection geometries or high-risk conflict points with a limited line of sight. In such situations, infrastructure-assisted CAV technology could be an efficient solution. While CAV technology could completely rely on onboard sensing, scenarios with a limited line of sight could benefit from infrastructure (or roadside) sensing and wireless communication. One example is a CAV driving through a yield-controlled intersection with limited sight lines. The CAV may require that all vehicles on the conflicting movements have wireless communication capabilities to inform each other of their locations and planned trajectories. Alternatively, roadside sensing equipment that would detect approaching traffic and communicate the locations and anticipated trajectories of the incoming traffic to the CAV could be deployed. Such data would help the CAV make an informed and safe decision to either merge into the incoming traffic stream or wait and adjust its trajectory before merging.

ASSESSMENT LEVELS

Intersection Configuration

The three levels of intersection configuration are based on the complexity in the geometry: complex, intermediate, and simple. Table 2 defines each level and the specific needs for CAV technology deployment.

Table 2. Intersection configuration complexity levels.

Complexity Level	Description	CAV Deployment Needs
Complex	High maneuverability is needed when several channels and medians manage most of the traffic movements.	MAP messages could support CAV operations to provide detailed information about the intersection geometry. Thus, in addition to onboard sensing, wireless communication could provide the needed support.
Intermediate	Somewhat high maneuverability may be needed when a few traffic movements are managed by physical channels and other physical management means.	MAP messages may be needed but not completely required. Hence, onboard sensing could perform the required job to support navigation of CAVs through AIIs. Wireless communications would be considered a good add-on but not a requirement.
Simple	No complex movements are present.	Wireless communication is not needed. Onboard sensing would be able to perform support navigation of CAVs through AIIs within this level.

User Route Crossings

For user route crossings, three levels are used to classify intersection forms: high complexity, medium complexity, and low complexity. Table 3 summarizes each level and the specific needs for CAV technology deployment.

Table 3. User route crossing levels.

Complexity Level	Description	CAV Deployment Needs
High	High-complexity user crossing routes are defined if two conditions are fulfilled: 1. Through movements crossing through movements coming from other intersection approaches. 2. Two-way stop control or other control requiring yielding to multiple traffic streams.	Onboard sensing is required. Wireless communication is also needed when smart signals or signs are used to inform CAVs of the control type and status along with the status of approaching vehicles to the same conflict points from different directions. Roadside sensing could be a preferable add-on, but it is not required in all situations since control is in place, unless a line-of-sight issue occurs, which is discussed in table 4.
Medium	Medium-complexity user crossing routes are defined as those with either of the following conditions: • Through + left and signal controlled with permitted left turns. • Through + right and signal controlled with permitted right turns on red.	In addition to onboard sensing, wireless communication is required when smart signals or signs are used to inform approaching CAVs of the control type and status along with anticipated user crossing routes. Roadside sensing is not required in this level, since user crossing routes are not complex, and visibility usually is not an issue.
Low	Low-complexity user crossing routes are any other type of user crossing routes not listed in the other levels, including the following examples: • Through + through and signal controlled or all-way stop controlled. • Through + left and all-way stop controlled or signal controlled with protected left turns. • Through + through or through + left and roundabout controlled. • Through + right and all-way stop controlled or signal controlled with prohibited right turn on red.	Since all user crossing routes are highly controlled, low complexity, or both, onboard sensing is enough to facilitate the navigation of CAVs. Wireless communication could be a preferable add-on in some situations, especially to inform CAVs of the control status when smart signals or signs are used, but it is not necessarily needed.

Visibility and Sight Lines

Three levels rate how intersection visibility sight line values for human drivers could be different with full CAV integration. Table 4 defines the levels and the specific needs for CAV technology deployment.

Table 4. Visibility and sight line levels.

Visibility and Sight Line Level	Description	CAV Deployment Needs
Limited	AIIs with visibility and sight lines that are less than the minimum required SSDs.	CAVs would require additional support through infrastructure sensing of vehicles approaching from other directions. Once those vehicles have been detected, information about those vehicles' status and planned trajectories can be communicated to approaching CAVs so proper control actions can be made.
Intermediate	AIIs with visibility and sight lines equal to or slightly less than the minimum required SSDs.	Although onboard sensing could be enough, low skid resistance in certain weather conditions is a potential risk. In these situations, wireless communication can support onboard sensing by providing timely information about road surface status and other important safety factors.
Open	AIIs with visibility and sight lines that are significantly greater than the minimum SSDs required.	CAVs can completely rely on their onboard sensing to perform the DDT. Wireless communication is not needed.

ASSESSMENT

Engineers can use the high-level analysis and criteria set in the previous discussion to assess the CAV needs for a given intersection design. The infrastructure required to meet those needs may include additional infrastructure onboard sensing, infrastructure sensing, and wireless communication, as described in the previous section. For each category, practitioners should separately perform the technology needs assessment based on the design of the intersection configuration, user route crossing, and visibility and sight lines; the criteria with the highest technology needs dominates. Recognizing that two implementations of the same form may have unique design elements that may result in different technology needs is important. This recognition is particularly true for the user route crossing levels, which are dependent on traffic control decisions. Two example assessments are provided in the following sections, one for DDI and one for RCUT.

DDI Assessment Results

The DDI intersection configuration is classified as intermediate due to its need for somewhat high maneuverability. Crossovers at the ramp terminals are managed by physical channels. The user route crossing is considered low complexity because the crossover of movements is managed by a signal. Visibility and sight lines are open because the visibility and sight lines provided are significantly greater than the minimum SSDs required. To facilitate CAV deployment, wireless communications would be considered a good add-on and could provide good support where friction is limited.

RCUT Assessment Results

The RCUT intersection configuration is classified as simple due to the lack of complex movements and the elimination of left-turn and through movements from minor street approaches. The user route crossing is considered medium complexity because the major street has through and right movements that are signal controlled but have permitted right turns on red. Visibility and sight lines are open because the visibility and sight lines provided are significantly greater than the minimum SSDs required. To facilitate CAV deployment, wireless communications would be required when smart signals or signs are used.

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