CHAPTER 7
FINAL DESIGN

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CHAPTER 7. FINAL DESIGN

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7.3 SIGNAL EQUIPMENT

While traffic signal design tends to come relatively late in the process of designing an interchange, there are a few critical issues that should be considered before the geometric design is complete. In particular, the location of signal cabinets and poles should be determined in parallel with the geometric design of the interchange.

7.3.1 Signal Cabinet

The signal cabinet houses the signal controller, among other pieces of equipment. As part of the initial signal design, a designer must decide how many controllers are required at a DDI, as well as where to locate the cabinet(s).

7.3.1.1 Number of Controllers

Due to the relatively low number of phases at DDIs, it is possible to operate both crossovers using a single controller. As of publishing, many agencies have chosen to use a single controller, but several agencies are now using two, with each controller operating one crossover. Exhibit 7-1 details tradeoffs to consider when choosing whether to use one or two controllers.

Exhibit 7-1 Considerations for One versus Two Signal Controllers at a DDI

	One Signal Controller		Two Signal Controllers
+	Reduced hardware and installation costs	+	More transparency in signal design and cabinet set-up for designers and technicians
+	Potentially avoids the need for communication infrastructure between crossovers (if no adjacent intersections)	+	Ability to control offsets directly rather than through overlap phases or other programming
+	Improved flow during “free” signal operations (e.g., late night)	+	Easier for technicians to see operations from the cabinet
–	More complicated signal design and cabinet set-up for designers and technicians	+	More room in each cabinet to allow for complicated scenarios (e.g., light rail)
–	More difficult maintenance and troubleshooting for technicians	–	Additional hardware and installation costs
–	Additional wiring required from signal equipment to controller	–	Need for controllers to communicate and potential for time drift that may impact progression
–	More difficult for technicians to see operations at both crossovers from the cabinet	–	May result in undesirable gap-out situations during low-volume periods

Note: Benefits are shown with a (+) and challenges with a (-).

The primary appeal of using two controllers is that the signal design is simple and intuitive for designers, operators, and technicians; the DDI crossovers can function more like traditional signalized intersections. An important goal for any signal designer should be to make the design as understandable as possible to operators and technicians. The more standard the design, the more quickly technicians can respond to and resolve field issues. If an agency has a lot of situations where a single controller operates two intersections, this design will become commonplace to operators and technicians in that area. Otherwise, if this configuration is new, training may be needed to make sure everyone understands the operations.

The decision to use one versus two signal controllers may be related not only to the tradeoffs mentioned here, but also to specific functions of the traffic signal hardware and software used by the agency as well as agency preferences.

The distance between crossover intersections directly influences many of the factors that should be considered when deciding between one and two controllers. More-tightly spaced crossovers will significantly increase the importance of perfectly-synced progression, lessen the impact of long detection cables, and increase the visibility of both crossovers from one location. Crossovers that are spaced farther apart will likely result in platoon dispersion that will make tight synchronization less critical. A longer spacing will also exacerbate the extensive cabling that would need to run between the crossovers and the issue of seeing both crossovers from one location. Each of these points is discussed in more detail in the following sections.

7.3.1.1.1 Progression Considerations

With two controllers, the offset between the crossovers can be modified directly without the use of ring-offset functionality or dummy phases. When using a single controller, generally each ring is used to operate one crossover. Although progression can be achieved with one controller using the phasing schemes discussed in this guidebook, two controllers may be preferable if they do not have ring-offset functionality.

Some form of reliable communication between two controllers will be necessary to make sure that they are synced at all times because the interaction between crossover movements is critical; use of GPS units to prevent clock drift between two controllers may be required. With one controller, communications infrastructure may still be needed to progress traffic along the entire corridor, but there is no concern that a communication failure would disrupt progression between the crossovers.

In lower-volume situations with two controllers, there is a potential for a phase to gap out early at one of the crossovers, sending a platoon from one crossover towards the other too soon. Use of pretimed operations may be required to prevent early return to green; for more information, reference the section on pretimed control in Chapter 5. With one controller, full actuation may be used such that if a phase gaps out early, as long as the corresponding phase at the other crossover also gaps out, a waiting platoon may be served early without fear of stopping downstream. This capability makes full use of the interchange capacity. Additionally, late at night when coordination with adjacent intersections or maintaining a particular cycle length may not be a priority, the interchange can run free because a single controller will keep movements between the crossovers synced.

7.3.1.1.2 Wiring Considerations

Aside from operational concerns, there are additional construction and maintenance factors to consider when making the decision to use one or two controllers. If one controller is used, all of the cabling for detection input and signal display output must run from the cabinet across the interchange to the other crossover. The installation method for this cabling must be considered up front, especially in the case of an overpass where any conduit would need to be routed along or inside the bridge deck.

For loop detection cable, the longer a cable is the more voltage is lost between the loop and the controller. Increasing the number of “turns” (times that the cable is wrapped around the loop form) or the gauge of the wire will increase the inductance of the detector to help mitigate this problem. However, with very long crossover spacing, this should be accounted for early in the design.

7.3.1.1.3 Visibility Considerations

One way to assist operators and technicians with maintenance and troubleshooting is to make sure that all intersection movements are visible from the traffic signal cabinet. This allows a person to stand at the cabinet and observe the impact of programming or wiring changes instantly as well as to put the signal into and out of flash operation at times that are safe based on where vehicles are currently located. If one controller is used to operate both crossovers, it may be difficult or impossible to see all movements. One way to mitigate this concern is to install supplemental display boards or video output in the cabinet for the movements that are not visible.

7.3.1.2 Other Cabinet Equipment

Signal cabinets come in standard sizes so have inherent limitations on the amount of equipment that can be accommodated inside of them. A common constraint at intersections is the number of phases and overlaps, which in the cabinet are tied to load switches. A load switch is a mechanical device that operates the signal head indications, and a typical signal cabinet may house between 12 and 18 of them.

For the three different DDI phasing schemes presented in Chapter 5, it is possible to accommodate all movements using 12 load switches. As such, this guidebook presents a way to control both crossovers using one controller. However, there are circumstances that may require more load switches than can fit in a single cabinet. For example, use of exclusive phases for transit or bicycles could push the number of required load switches over the available space in the cabinet. Signal designers/technicians should consider cabinet limitations prior to deciding between one and two controllers.

7.3.1.3 Locating the Cabinet(s)

Once the number of controllers and resulting cabinets is determined, the next step is to identify good locations for cabinet placement. The traffic signal cabinet will need to be located in a place that is easily accessible by technicians for maintenance and does not block the view of drivers trying to turn on red. It is also helpful if the cabinet is located such that a technician can stand at the cabinet and view the entire interchange.

One potential location is in the median that separates the left turn and right turn at the on-ramp, as this area is generally large enough to provide a safe place for a technician to work (although positive protection may be needed to limit exposure), does not impede the vision of motorists, and provides good sight lines for a technician. This location has the added advantage of always being within the right-of-way so no easements or additional right-of-way acquisition would be required of adjacent property owners. For a DDI with only one controller, either crossover location is permissible. Exhibit 7-2 is a picture of a cabinet in this area, and Exhibit 7-3 is a graphic showing both possible locations at a DDI.

Note that if a median area is too small to accommodate a cabinet, a cabinet can also be placed on the right side of the on-ramp right-turn lane. This area may be outside of the right-of-way or easement and put a technician further away from being able to see all movements, but it will not impede the vision of motorists.

Exhibit 7-2 Signal Cabinet Located in a Landscaped Median with Good Visibility

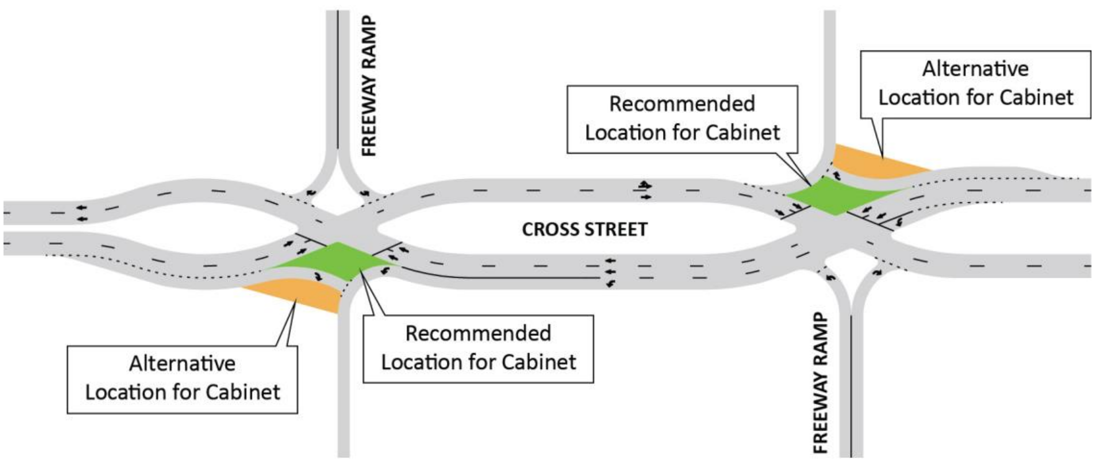


Exhibit 7-3 Recommended Locations for Signal Cabinet(s) at a DDI

Locating a power source for the cabinet is also useful at this stage of design to ensure that accommodations can be made for providing power concurrently with any other utility work needed for the interchange. If two cabinets and controllers are used (one for each crossover), it is also important to identify the method for providing communication between them.

7.3.2 Signal Poles and Displays

The location of signal poles is another important step in the traffic signal design process. All signal head and pole installations must be in compliance with the *Manual on Uniform Traffic*

Control Devices (MUTCD) (*1*), and the reader should refer to the latest edition for specific requirements.

Because there are a limited number of places where a traffic signal pole can be placed to align the signal heads, mast arms are generally the best option for DDI signals. Some signal heads may also need to be placed on pedestals on either side of the roadway to achieve maximum visibility. Mast arm poles require a large reinforced concrete foundation, and if any are needed on the bridge structure, they will need to be incorporated into the design loading. It is also possible that a pole will be needed outside of existing right-of-way or in a median where proper clear zone requirements will need to be considered in the design. To determine where poles may be needed, a designer should first determine the location of signal heads.

7.3.2.1 Types of Vehicle Signal Heads

Three types of signal heads may be used at a DDI:

- Type 1: Red ball, yellow ball, and green ball
- Type 2: Red ball, yellow arrow, and green arrow
- Type 3: Red arrow, yellow arrow, and green arrow

For through traffic at the crossover, either a Type 1 or Type 2 signal head may be used for each lane, with the Type 2 signal heads showing an angular arrow to denote a through movement. Type 2 signal heads may help convey and confirm to drivers that they are not supposed to turn at the intersection (as seen in Exhibit 7-4).

Exhibit 7-4 Type 2 Crossover Signals with a Type 1 Supplemental Signal on Left

Source: Google Earth (*2*).

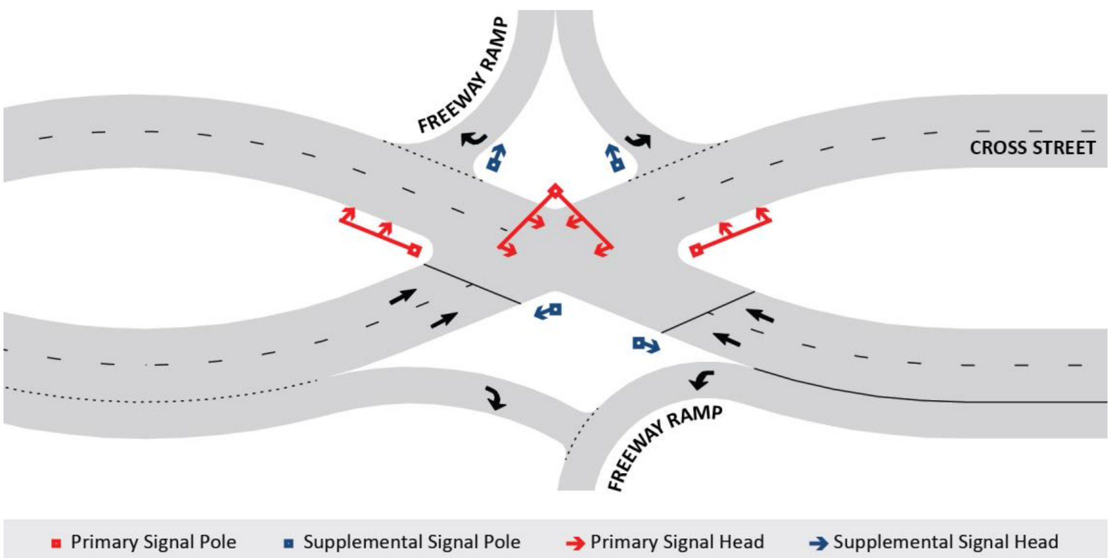
For turning movements, Type 3 signal heads should be used to clearly identify that the indications are intended for left- or right-turning traffic. However, in some states, a Type 3 signal does not allow vehicles to turn on red; these situations may require the use of a Type 2 signal for those movements. In states where the right-turn-on-red (RTOR) rule is controlled through supplemental signage, either configuration may be acceptable. Also, while most states allow RTOR, several states do not allow for left-turn-on-red (LTOR). Adequate signage should supplement the signal heads to promote conformity with state laws.

7.3.2.2 Vehicle Signal Head Placement

Stopping sight distance must be provided at all signalized and yield-controlled approaches to the DDI. The visibility of the signal heads and the distance to clearly view traffic signal heads must be considered for all movements. This is especially true at the crossovers where the small curve radii leading into the curve can impede visibility of the signal heads. To reduce the likelihood of false indications, louvered or programmable signal heads may be needed.

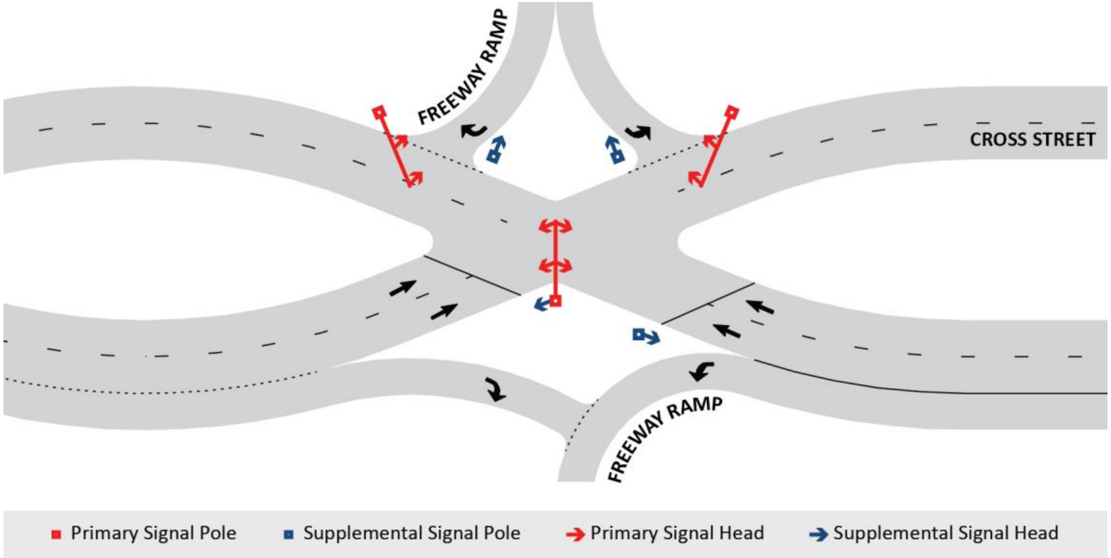
The crossover signal heads are typically placed on the opposing side of the intersection to allow for the necessary set-back from the stop bar (as shown in Exhibit 7-5). Signals placed on the opposite side of the crossover provide motorists an additional visual cue to guide them into the appropriate travel lanes. The trade-off of this downstream placement is that it may be difficult to see the signal heads from a distance due to the crossover curvature. When adequate visibility of the signal heads is not provided, supplemental near-side signal heads can be used to provide advanced warning to drivers. One or more pedestal mounted signal heads in the median(s) can help with visibility on the crossover approaches.

Exhibit 7-5 Option 1 for DDI Signal Pole and Head Placement



A less common alternative strategy is to use a single mast arm with signal heads in both directions (as shown in Exhibit 7-5). This strategy does not provide the same guidance through the intersection; however, green arrows in the bulb assembly can be used to assist with proper direction. A single mast arm installation generally provides drivers better visibility of the signal heads when approaching the crossover. Care must be taken with this option to ensure that the signal heads are placed far enough away from the stop bar to allow visibility of the heads. At least 40 feet of separation between the stop bar and the signal heads is desirable.

Exhibit 7-6 Option 2 for DDI Signal Pole and Head Placement



Mast arms should not impede the visibility of signal heads. This blocked view most-frequently occurs with the mast-arm assembly of one approach impeding visibility of the other approach. The mast arms for ramp turning movements can have a similar effect. An example of these visibility effects for an outbound DDI movement approaching the crossover is shown in Exhibit 7-7, where the presence of multiple overhead mast arms and signal heads creates visual clutter and makes it difficult to identify the appropriate signal.

Exhibit 7-7 Mast Arm Assembly Limiting Approach Visibility

Source: Google Earth (*2*).

7.3.2.3 Supplemental Vehicle Signals

Supplemental signal heads are recommended when the visibility of overhead-mounted signal heads is limited because of the horizontal curvature of the crossover or vertical alignment of the bridge structure. Examples of supplemental signals at DDIs are shown in Exhibit 7-8, Exhibit 7-9, and Exhibit 7-10.

Exhibit 7-8 Supplemental Signal on Right for an Inbound Movement at a DDI

Source: Google Earth (*2*).

Exhibit 7-9 Supplemental Signal on Left for an Outbound Movement at a DDI

Source: Google Earth (*2*).

Exhibit 7-10 Supplemental Signal for a DDI Off-Ramp from Freeway

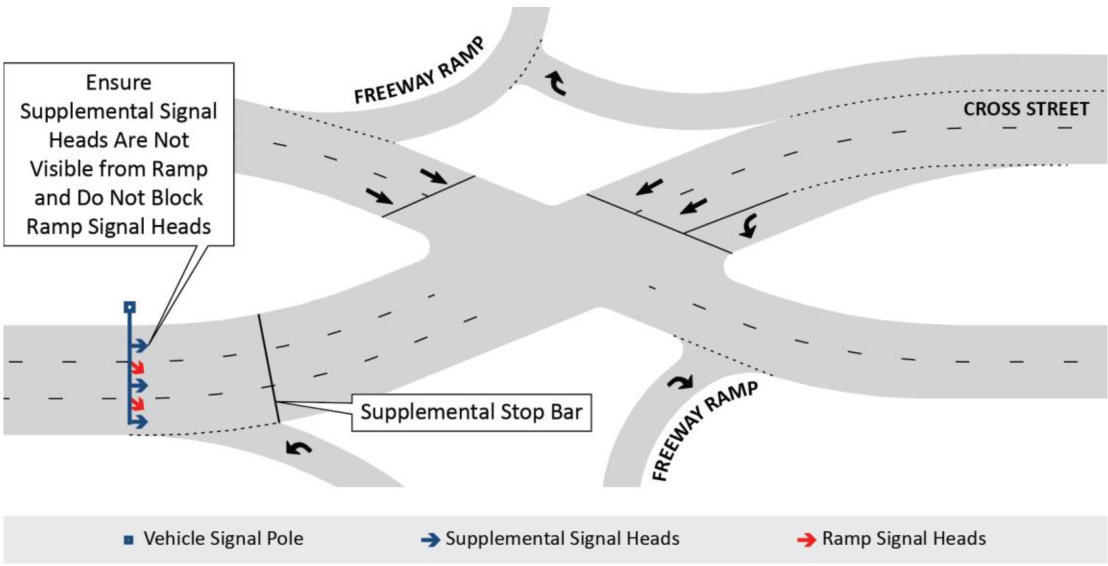
Source: Google Earth (*2*).

For the inbound movement, the supplemental signal head is typically installed on the right-hand side of the street as illustrated in Exhibit 7-8. For the outbound movement, the supplemental signal head is typically installed on the left-hand side of the street as illustrated in Exhibit 7-9. Supplemental signals may also be required for the freeway exit ramp movements as shown in Exhibit 7-10. For exit ramps, supplemental signals are placed on the right side of the road for the left-turning movement and on the left side of the road for right-turning movements. Notice that the right-turn signal in Exhibit 7-10 is supplemented with a sign to convey the nature of the signal to drivers: “Right Turn Signal.”

For a DDI where a turning movement from the off-ramp has a large radius, the distance between the crossover itself and the ramp traffic can be significant (over 100 feet at some existing DDIs). More detailed information related to the clearance intervals associated with this distance is provided in Chapter 5. In addition to signal timing options for clearance, an additional measure may be needed at DDIs with a long distance between the crossover and ramp. When a vehicle passes through the crossover, a driver may perceive that he or she has left the signalized intersection and may not anticipate an additional conflict point ahead with the ramp traffic. One way to mitigate this issue is to provide an additional set of signal heads at the ramp terminus for traffic internal to the DDI; this would stop any residual traffic in the DDI that had not yet cleared the conflict point (as illustrated in Exhibit 7-11).

This supplemental set of signal heads is sometimes used in single point diamond interchanges for the same reason. Where these heads are used, it is critical to ensure that the supplemental heads are not placed in such a way that they would confuse drivers outside of the DDI. Where possible, modifying the geometric design to tighten the off-ramp radius and reduce this distance would be preferable, but for existing DDIs or locations where the long distance is unavoidable, supplemental heads may be necessary.

Exhibit 7-11 Use of Supplemental Signal for DDI Inbound Through Movement



7.3.2.4 Pedestrian Signals

Anywhere pedestrian signals are provided at a DDI, Accessible Pedestrian Signal (APS) devices and detectable warning surfaces need to be installed to comply with the Americans with Disabilities Act (ADA). While no specific ADA regulations exist for DDIs, the proposed

Public Rights-of-Way Accessibility Guidelines (PROWAG) can be applied to all intersections and interchanges (*3*). Specifications for push button locations and APS devices can be found in the MUTCD (*1*).

An APS consists of a push button with a push-button locator tone to assist pedestrians who are visually impaired to find the device, as well as a tactile arrow and an audible message. The audible message communicates to the visually-impaired traveler when the walk interval phase is active. The audible message can be in the form of a rapid ticking or beeping/chirp sound or can be a speech message. The latter is required for two APS devices that are separated by less than 10 feet, while a rapid tick message is required for APS that are more than 10 feet apart. The APS devices for different crossings should be installed on two separate poles if at all possible.

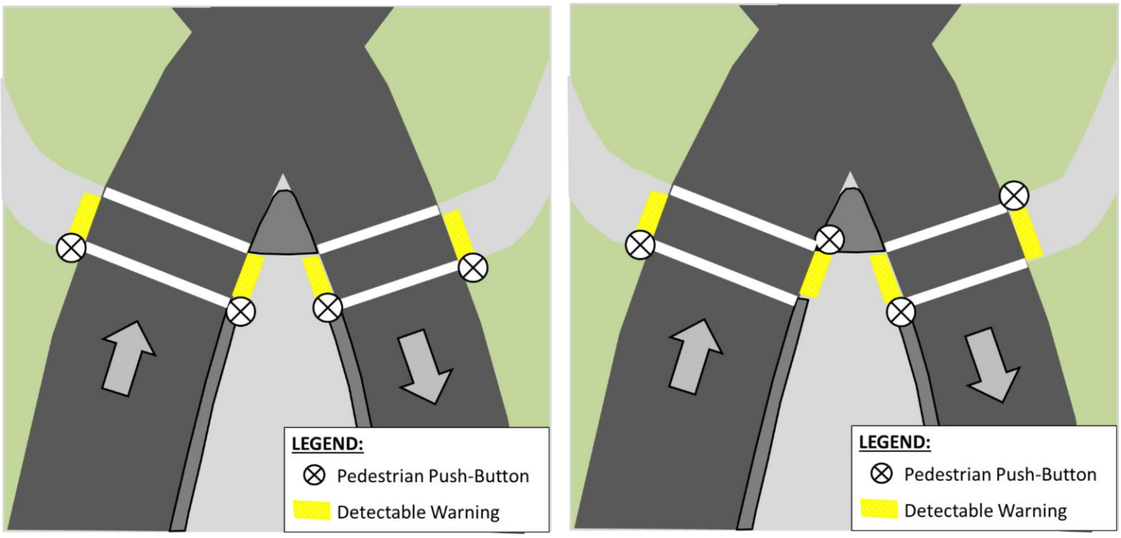
At the DDI, providing 10 feet of separation between the two APS devices may pose a challenge in the median island. Exhibit 7-12 shows an example of an undesirable pedestrian push button installation with the push buttons for the two directions on the same pole. Note that the example shown does not provide APS devices or any audible information about the crossing. As installed, the lack of separation may make it difficult for pedestrians to distinguish which push button is intended for which crossing.

Exhibit 7-12 Undesirable Use of Single Pole with Two Pedestrian Push Buttons, No APS, and Insufficient Separation of the Two Detectable Warning Surfaces

Source: Google Earth (*2*).

Given that the “point” of the median island does not provide adequate room to allow the pedestrian push buttons to be on separate poles, it is recommended that the poles are located on the opposite side of the waiting area where the island is generally wider. This is shown in the left illustration of Exhibit 7-13. Alternatively, pedestrian push buttons could be separated diagonally, with the push buttons being consistently to the right of the pedestrian (in direction of travel), as shown in the right illustration of Exhibit 7-13.

Exhibit 7-13 DDI Splitter Island with Pedestrian Signals



(a) Pedestrian Signals on Same Side **(b) Diagonal Pedestrian Signals**

Alternatively, the crosswalk may be moved back from the crossover by some small distance to result in a wider splitter island and provide the necessary space for push buttons (or APS devices) on separate poles. However, this would require the vehicle stop bar to be moved back accordingly, which can have other implications for visibility.

In general, wider islands are strongly recommended to provide a true refuge area for pedestrians (of at least six feet in length). This assures a minimum of two feet between the detectable warning surfaces for the two directions as well as adequate storage for wheelchair users. A wider island may be desired to provide additional storage, passing ability for multiple wheelchair users, and a 10-foot separation of pedestrian push buttons.

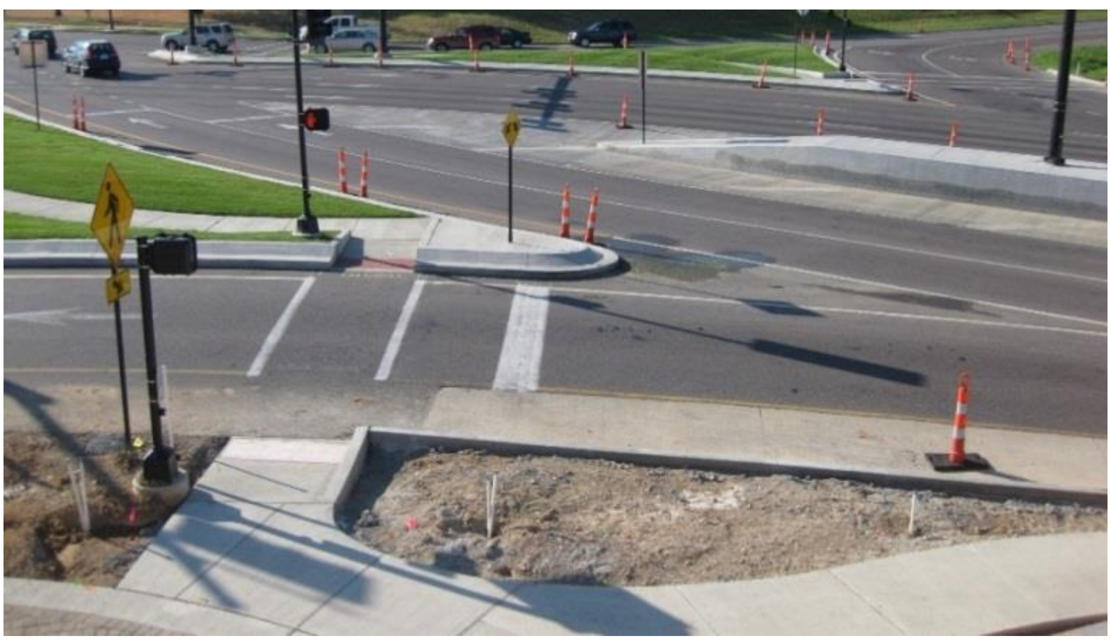
If two APS devices are less than 10 feet apart, speech messages are required with customized wording specific to the DDI. One potential for such wording after activating the push button (i.e. the push-button information message, see MUTCD 4E.13, *1*) may be: “Wait to cross eastbound lanes Airport Road at Highway 26. Traffic coming from your left.” During the walk interval, the message then would be: “Eastbound lanes Airport Road, walk sign is on to cross eastbound lanes Airport Road.” An expert in accessibility installations may need to be consulted for specialized applications and signal installations at a DDI to assure that the crossings are accessible to and usable by all users as required by ADA.

The placement of pedestrian signals is more straightforward for the crossing towards the median island and the crossing of a right- or left-turn lane. In both cases, only a single pole and single APS device (on each side of the crossing) is needed. Reach ranges for wheelchair users need to be carefully measured and considered in installation. An example of a pedestrian signal crossing toward the median island is shown in Exhibit 7-14; an example of a pedestrian crossing for a left turn onto the freeway is shown in Exhibit 7-15. For both examples, the cut-through widths as shown could be increased further to enhance the pedestrian experience and to allow opposing pedestrian movements (including wheelchairs) to pass, especially given the additional right-of-way already provided in the channelization islands.

Exhibit 7-14 Pedestrian Signal and Push Button on Outside of Crossover (Pedestrian Facility in Median)

Source: “Early Findings on the Operational Impacts of Double Crossover Diamond Interchanges” (*4*).

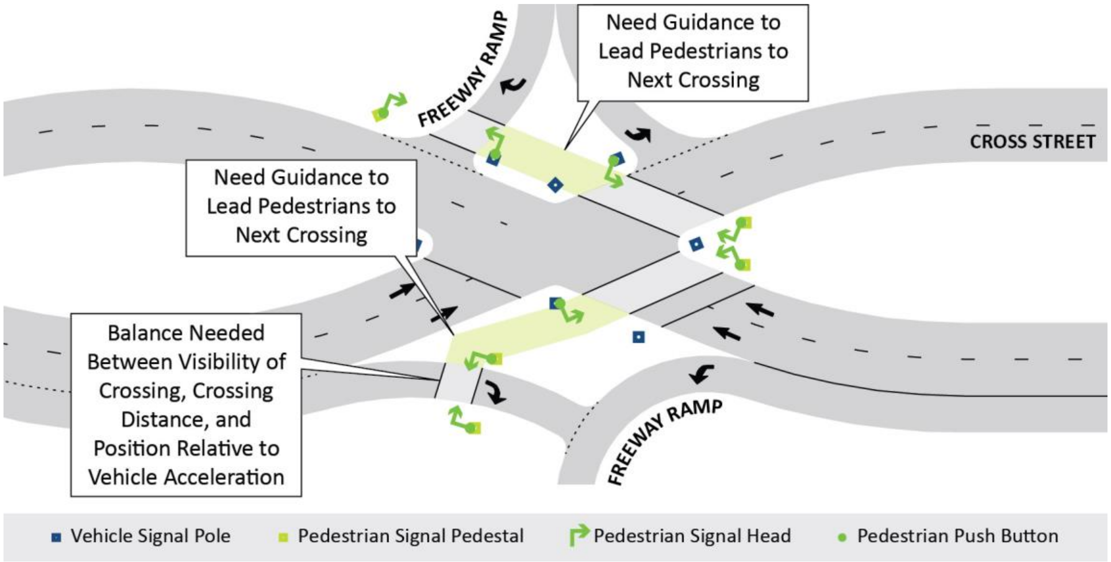
Exhibit 7-15 Pedestrian Signal and Push Button for Left-Turn onto Freeway (Pedestrian Facility on Outside)



Source: “Early Findings on the Operational Impacts of Double Crossover Diamond Interchanges” (*4*).

Where pedestrians need to travel through a channelized island to complete their crossing, clear guidance (such as a raised curb) is needed to help pedestrians navigate through the island to the next crossing point. This is illustrated in Exhibit 7-16, which also shows a potential layout of pedestrian push buttons and signal heads.

Exhibit 7-16 Pedestrian Signal Head Placement at a DDI



7.3.2.5 Bicycle Signals

If bicycles remain in the street on bicycle lanes, they are controlled by vehicular signals and bicycle signals are unnecessary. If bicycles use a shared-use path such as a median walkway, bicycle signals could supplement pedestrian signals and reinforce the intended route of travel for bicyclists.

7.3.3 Detection

Many of the existing traffic signals at DDIs are operating as pretimed traffic signals and are not making use of detection. However, most do still have detection installed and could operate as fully-actuated signals if desired. One benefit of installing detection at a DDI even if the intention is to operate it as pretimed is that it allows for free operations in off-peak or late-night conditions and allows for flexibility in future operations.

Any of the forms of in-pavement or above-pavement detection used at other signalized intersections could also be used at a DDI. If in-pavement loops are being installed, the distance to the controller cabinet should be considered; as discussed in Section 7.3.1, longer distances resulting from use of a single controller cabinet may require more cable “turns.” For lanes on a bridge deck, a form of above-ground detection may be desirable to avoid cutting into the bridge deck.

Stop bar detection alone could be deemed sufficient to adequately operate a DDI if speeds are low. However, for more-complicated signal timing schemes, it may be desirable to have upstream detection to locate gaps in traffic early and transition to the next phase.

7.3.4 Communications

When two controllers are used or when the DDI is part of a larger network of traffic signals, communication will need to be provided between the controller(s) at a DDI. If the DDI is in an isolated area and two controllers are selected, wireless communication could be used to avoid the need to install cabling on the bridge. In this instance, it would be advisable to also have GPS units or another backup option installed to ensure that the clocks stay synced. Alternatively, interconnect cable could be used to provide a hard-wired connection between the signals. In this case, the method for installing the cable should be identified early in the design process to make sure that a location for the cable has been reserved.

7.3.5 Preliminary Cost Estimate

The key signal equipment that should be included in a preliminary cost estimate includes:

- Signal cabinets,
- Controllers,
- Poles and foundations,
- Pedestals, and
- Communication equipment.

Having determined these primary cost items, the next level of equipment to include in the cost estimate includes

- Vehicle signal heads,
- Pedestrian signal heads,
- Bicycle signal heads, and
- Detection.

Finally, much of the cabling may need to be installed via directional drilling at a DDI. Determining the paths through the intersection to connect the cabinet to all of the poles, pedestals, and detection will help to approximate a number of linear feet of directional drilling.

7.4 SIGNAL TIMING PARAMETERS

After the signal equipment has been installed, a range of timing parameters will need to be programmed into the signal controller, including minimum green, passage time, pedestrian intervals, recalls, detector configurations, cycle length, and offsets. For most items, the timing practices are not unique to DDIs, and the reader is referred to other references for additional details, such as *NCHRP Report 812: Signal Timing Manual, Second Edition* (*5*). Cycle lengths and offsets for DDIs are sensitive to the respective signal phasing scheme chosen, and the reader is referred to Chapter 5 for more discussion.

In general, most local signal design parameters can be derived at a DDI just as they would be for a typical signalized intersection. Clearance intervals, however, need careful consideration at a DDI. One reason to pay special attention to clearance intervals is that travel speeds at DDIs are a function of the design speeds at the crossovers. Research has shown that design speeds are more influential than speed limits in determining travel speeds (as illustrated in Exhibit 5-28). Local speed measurements of existing DDIs may be necessary to better inform an appropriate value for the red clearance interval. Even after opening to traffic, both yellow and red clearance times should be carefully monitored and adjusted as needed to either provide an additional safety buffer or shortened for enhanced efficiency if the DDI appears to be operating safely.

For yellow clearance intervals, using a higher speed will produce a longer interval, so using an agency standard calculation for the yellow clearance interval will generally yield a conservative value. The red clearance interval, however, needs more thought. Because a higher speed used in a red clearance calculation will yield a lower value, the design speed is likely not appropriate for providing a conservative value.

The key issue for calculating the red clearance interval is the clearance distance. As discussed in Chapter 5, there are two key distances for a through vehicle to traverse at a DDI crossover. One is the relatively short distance to cross the opposing lanes. The other is the sometimes significantly longer distance past the conflict point with ramp traffic. Chapter 5 discusses the use of overlap delay and short, fixed-time phases to allow opposing traffic to begin earlier and reduce the overall lost time at the DDI. If one of these options is used, the red clearance interval can be calculated using only the distance through the crossover. If overlap delay or short, fixed-time phases are not used, the red clearance interval should be calculated using the entire distance between the crossover and the ramp conflict point.

7.5 DOCUMENT LOCAL PRACTICES

This guidebook is intended to provide a starting point and frame of reference for many of the common issues encountered at DDIs. As every agency has specific preferences for signal design and timing parameters, documenting the local practices and preferences for DDI-specific parameters based on this guidebook is strongly recommended. Taking a standard approach to all DDIs operated and maintained by an agency can help to reduce confusion during the design, construction, maintenance, and troubleshooting of the DDI signals going forward. Existing examples of this are available from Missouri and Utah Departments of Transportation (DOTs) (*6*, *7*).

7.6 REFERENCES

1. *Manual on Uniform Traffic Control Devices for Streets and Highways*, Federal Highway Administration, Washington, D.C., 2009.
2. Google Earth, Google, Inc. [accessed July 2014].
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4. *Field Evaluation of Double Crossover Diamond Interchanges* (Contractor’s Draft Submittal), Federal Highway Administration, Project No. DTFH61-10-C-00029, 2014.
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6. *Missouri’s Experience with the Diverging Diamond Interchange*, Missouri Department of Transportation (MoDOT), Report No. OR10- 021, Jefferson City, MO, 2010.
7. *DDI Guideline: A UDOT Guide to Diverging Diamond Interchanges*, Utah Department of Transportation (UDOT), 2014.