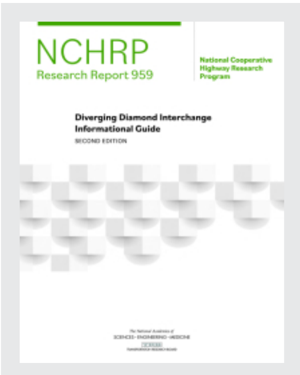

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 959

Diverging Diamond Interchange Informational Guide

SECOND EDITION

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 959

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The authors of this guide are Chris Cunningham (Principal Investigator) (ITRE NCSU); Thomas Chase, Yulin Deng, Chris Carnes, and Kihyun Pyo of ITRE; Pete Jenior, Bastian Schroeder, Brian Ray, Thomas Urbanik II, Julia Knudsen, Lee Rodegerdts, and Shannon Warchol of Kittelson; and Alison Tanaka of the City of Portland, Oregon. During the project, Bastian Schroeder and Shannon Warchol transitioned from ITRE NCSU to Kittelson; Alison Tanaka transitioned from Kittelson to the City of Portland, Oregon. The authors wish to thank other members of the project team who contributed to this document, including Tim Nye, Katy Salamati, and Chunho Yeom, all formerly of ITRE NCSU; Brandon Nevers, Jim Bonneson, Ralph Bentley, Sara Parks, Alek Pochowski, and John Ringert of Kittelson; Stacie Phillips of Kimley-Horn; Taylor Honeycutt of Exult Engineering (formerly of Kimley-Horn); Joe Hummer of North Carolina Department of Transportation (formerly Wayne State University); and Michael Murkley of the City of Orem, Utah (previously Horrocks Engineers and Pinetop Engineering). These individuals oversaw experiments, performed supplemental analysis, served as expert advisors, and provided graphics support.

The authors also wish to thank the states of Georgia, Utah, and Missouri for hosting focus groups to identify safety and geometric research needs and the participants in the focus groups.

The research team also acknowledges the NCHRP Project 07-25 project team. Chapter 3 of this diverging diamond interchange (DDI) guide was developed from content currently being prepared for NCHRP Project 07-25, "Guide for Pedestrian and Bicycle Safety at Alternative Intersections and Interchanges."

Finally, the project team thanks the authors, FHWA reviewers, and FHWA task manager of the first edition guide, which formed the basis of this guide and undoubtedly influenced a large percentage of the DDIs in existence in the United States today.

FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

NCHRP Research Report 959 presents a comprehensive guide to the design and operation of diverging diamond interchanges, and updates material found in the FHWA's *Diverging Diamond Interchange Informational Guide*. It addresses the needs of planners, designers, and operators, and considers all modes of travel.

The diverging diamond interchange (DDI, also known as a double crossover diamond interchange) is a relatively new design to the United States. This design can increase throughput and safety without widening bridge structures. Determination of the best geometric and traffic signal design depends on the appropriate use of analysis tools, particularly microscopic simulation models. Many traffic signal designers and operators and geometric designers lack experience with this novel design.

Under NCHRP Project 03-113, "Guidance for Traffic Signals at Diverging Diamond Interchanges and Adjacent Intersections," the research team led by the Institute for Transportation Research and Education of North Carolina State University developed guidance on the geometric and traffic signal design of DDIs and safety and operational analysis of design alternatives.

The research included a literature review for this new design that continued throughout the project, interviews with experienced practitioners, identification of problematic situations that arise at DDI installations (including for pedestrians and bicyclists), simulation of promising design and control strategies, and validation of the guidance with agencies. Ten training workshops were conducted with agencies that represented a broad range of experience with DDIs; the workshops were funded under NCHRP Project 20-44, "NCHRP Implementation Support Program."

CONTENTS

CHAPTER 1

Introduction

1.1 Overview of Alternative Intersections and Interchanges

Alternative intersections and interchanges offer the potential to improve safety and reduce delay at a lower cost and with fewer impacts than traditional solutions. However, transportation professionals are generally unfamiliar with many alternative intersection and interchange forms, partially because some forms have only a few installations in operation or because installations are concentrated in a few states. Furthermore, at the national level, well-documented and substantive resources needed for planning, analysis, design, and public outreach and education are limited compared to those for traditional intersections.

1.2 Intersection Control Evaluations and Considerations

The term "intersection" refers to the junction of two or more street facilities. A number of state and city transportation agencies have or are implementing intersection control evaluation processes or policies as a means of integrating the widest range of intersection forms as project solutions. In the context of an interchange, this intersection control evaluation refers to an evaluation of ramp terminal intersections. Approximately 10 states currently have policies or processes to objectively consider and select the most appropriate intersection form for a given project context.

Many of the policies or processes include common objectives in selecting the optimal or preferred intersection control alternative for a given project context. The common objectives generally include but are not limited to the following:

- Understanding the intended context and how operations, safety and geometry fit that context for each intersection or corridor including intended users [e.g., pedestrians, bicyclists, passenger cars, transit vehicles, freight, emergency responders, and oversize/overweight (OSOW) vehicles].
- Identifying and documenting the overall corridor or intersection context including the built, natural, and community environment and the intended performance outcomes of the intersection form.
- Considering and assessing a wide range of traffic control strategies and other practical improvement concepts to identify worthy project-level technical evaluation.
- Comparing engineering and economic analysis results of practical alternatives that consider implementation costs, performance benefits and impacts (e.g., safety, multimodal, operations, environment, etc.), and the estimated service life of alternatives.

1.3 Organization of the Guidelines

This guide has been structured to address the needs of a variety of readers, including the general public, policy makers, transportation planners, operations and safety analysts, and conceptual and detailed designers. This chapter distinguishes diverging diamond interchanges (DDIs) from conventional interchanges and provides an overview of each chapter in this guide. The remaining chapters in this guide increase in the level of detail provided.

Chapter 2: Policy and Planning—This chapter provides guidance on when to consider alternative interchanges in general and DDIs in particular. Considerations discussed include policies, project challenges, and performance measures as well as the project development process throughout the duration of the project to balance trade-offs.

Chapter 3: Multimodal Considerations—This chapter provides an overview of multimodal facilities at DDIs and how various types of users can be safely integrated into the design. Guidance for pedestrian and bicycle facilities is also discussed in this chapter.

Chapter 4: Safety—This chapter summarizes the safety performance at DDIs based on studies completed by state agencies and research efforts conducted as part of the development of this guide. Conflict points, wrong-way maneuvers, and emergency services at DDIs are discussed in this chapter as well.

Chapter 5: Conceptual Operations—This chapter provides information on the unique operational characteristics of DDIs and how they affect elements such as traffic signal phasing and coordination. It provides considerations for developing the lane configuration and traffic signal phasing scheme of a DDI.

Chapter 6: Geometric Design—This chapter describes the typical DDI design approach and provides guidance for geometric features.

Chapter 7: Traffic Control Devices and Illumination Applications—This chapter presents information relating to the design and placement of signals, signs, pavement markings, and intersection lighting at DDIs.

Chapter 8: Construction and Implementation—This chapter focuses on the constructability and maintenance of a DDI.

The appendix included at the end of this guide presents detailed information on the safety study that developed the crash modification factors presented in Chapter 4.

1.4 Scope of the Guide

This document provides information and guidance on planning and designing a DDI for a variety of typical conditions commonly found in the United States. To the furthest extent possible, the guide provides information on the wide array of potential users as it relates to the interchange form. The scope of this guide is to provide general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing a DDI. This guide does not include specific legal or policy requirements; however, Chapter 2 provides information on planning topics and considerations when investigating intersection control forms.

1.5 DDI Overview

The DDI is also known as a double crossover diamond (DCD) and is an alternative to the conventional diamond interchange or other alternative interchange forms. The primary difference between a DDI and a conventional diamond interchange is the design of directional

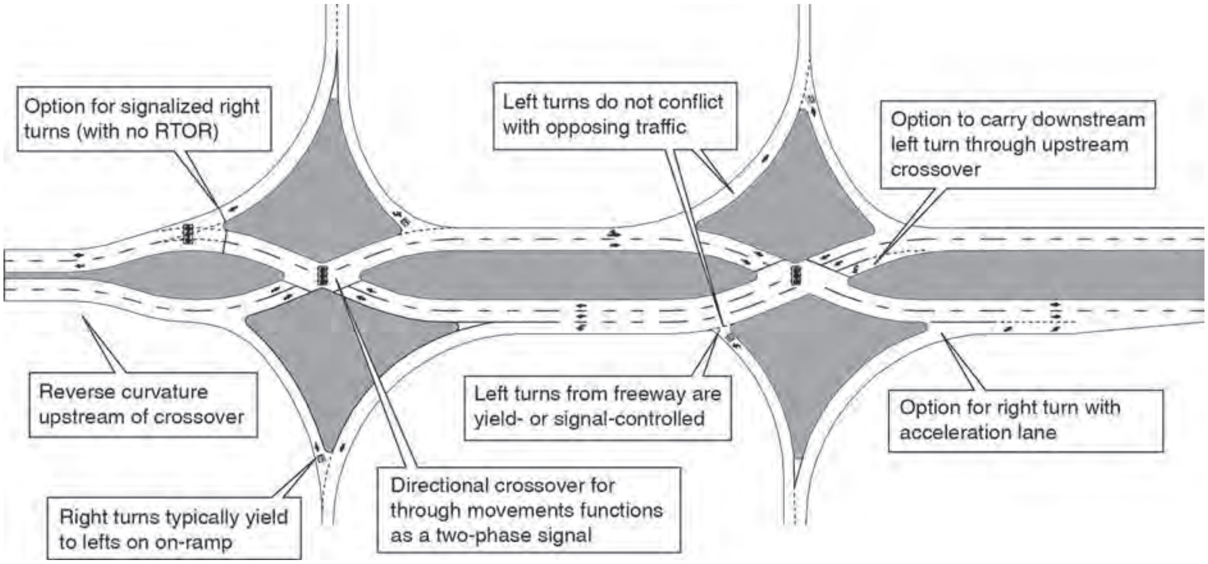

Exhibit 1-1. Key characteristics of a DDI. RTOR = right turn on red.

crossovers on either side of the interchange. This eliminates the need for left-turning vehicles to cross the paths of approaching through-vehicles. By shifting cross-street traffic to the left side of the street between the signalized crossover intersections, vehicles on the crossroad making a left turn on to or off of ramps do not conflict with vehicles approaching from other directions.

The DDI design has been shown to improve the operations of turning movements to and from the freeway facility and significantly reduces the number of vehicle-to-vehicle conflict points compared to a conventional diamond interchange. The DDI also reduces the severity of conflicts, as conflicts between left-turning movements and the opposing through movement are eliminated. The remaining conflicts are reduced to merge conflicts for turning movements, and the reduced-speed crossover conflict of the two through movements. Chapter 4 provides additional discussion of these conflict points and DDI safety benefits.

Exhibit 1-1 illustrates an example of a DDI and highlights the key features of this interchange design.

The street segment between the crossovers can be designed as an underpass or overpass depending on the site characteristics. The interchange design will be directly affected by whether the arterial passes over or under the limited access facility. In most cases, DDIs designed with a cross road as an overpass offer the most design flexibility in serving pedestrians. The majority of DDIs evaluated have reconstructed existing diamond interchanges, and the decision to go over or under the limited access facility had already been determined.

1.6 Application

DDIs have been implemented in many different locations with a variety of design features. This section includes photos of several of these locations and some of the different environments and design features of the constructed DDI.

Exhibits 1-2 to 1-5 show several of the DDIs recently constructed in the United States. Exhibits 1-6 to 1-11 show some of the unique features of a DDI such as the crossover location, overhead signing, pedestrian-crossing location and markings, sidewalk location, and recessed lighting on the bridge for pedestrians.

Exhibit 1-2. First constructed DDI in Utah at Pioneer Crossing and Interstate 15 (American Fork, Utah) (1).

Exhibit 1-3. First constructed DDI in Georgia at Ashford Dunwoody Road near Perimeter Market (2).

Exhibit 1-4. First constructed DDI in Minnesota at Highway 15 (3).

Exhibit 1-5. First constructed DDI in Idaho at Interstate 86 and US-91/Yellowstone Highway (Pocatello-Chubbuck, Idaho) (4).

Exhibit 1-6. Crossover location at the DDI located at SR-92 and Interstate 15 (Utah County, Utah) (5).

Exhibit 1-7. Overhead signing at the DDI located at SR-92 and Interstate 15 (Utah County, Utah) (5).

Exhibit 1-8. Pedestrian crossing at the right-turn lane of the exit located at Pioneer Crossing and Interstate 15 DDI (American Fork, Utah) (6).

Exhibit 1-9. Sidewalk and recessed lighting located on the bridge at the Pioneer Crossing and Interstate 15 DDI (American Fork, Utah) (6).

Exhibit 1-10. DDI (overpass) at 500 East American Fork (American Fork, Utah) (1).

Exhibit 1-11. DDI (underpass) at Dorsett Road and Interstate 270 (St. Louis, Missouri) (7).

1.7 Geometric Design Considerations

The fundamental design features of the DDI are the directional crossovers on either side of the interchange, which ultimately improve the operations of turning movements to and from the freeway facility. The geometric design necessary to allow for these crossover movements results in the use of reverse curvatures in advance of the interchange as vehicular traffic is directed to the right before it can cross to the left.

Several overarching principles guide users in conceptualizing and designing DDIs. The following principles may support DDI concept development, considering the context of the interchange and nearby adjacent intersections:

- Accommodate design vehicles at the crossover ramp terminal junctions.
- Promote reduced and consistent design speeds through the interchange.
- Channelize inbound and outbound movements in the crossover design at each intersection to guide drivers to use the intended lanes and discourage wrong-way movements.
- Create a vehicle path alignment directing vehicles into appropriate receiving lanes.

DDI concept design involves balancing and optimizing trade-offs associated with user performance, capacity, costs, maintenance, and construction staging, among other items. For instance, considering heavy vehicle design at the crossover may lead designers to contemplate larger design radii or wider lanes; however, this could promote higher speeds through the crossover for other vehicle types. Instead, to provide adequate facilities for the design vehicle while maintaining safe speeds for other motorists, designers may want to consider designs that offset one or more of the approaches to the DDI. This method may increase street alignment radii, resulting in comparatively narrower lanes to serve design vehicle off-tracking. These and other trade-offs of DDI geometric design are discussed in detail in Chapter 6.

Exhibit 1-10 and Exhibit 1-11 illustrate typical designs for an overpass and underpass at a DDI.

1.8 Resource Documents

This DDI guide is supplemental to major resource documents including but not limited to:

- *A Policy on Geometric Design of Highways and Streets* (AASHTO "Green Book") (*8*).
- *Highway Capacity Manual* (HCM6) (*9*).
- *Manual on Uniform Traffic Control Devices* (MUTCD) (*10*).

- *Highway Safety Manual* (HSM) (*11*).
- Other research documents that appear in this guide and are more specialized to specific areas of the guide include various National Cooperative Highway Research Program (NCHRP) reports, Transportation Research Board (TRB) papers, and Federal Highway Administration (FHWA) publications.

The following supplemental resource documents related to the DDI are available:

- FHWA *Techbrief* on double crossover diamonds (FHWA-HRT-09-054) (*12*).
- FHWA Project DTFH61-10-C-00029: *Field Evaluation of Double Crossover Diamond Interchanges.* Contractor's Draft Submittal (*13*).
- Missouri Department of Transportation (MoDOT) Report: *Missouri's Experience with the Diverging Diamond Interchange* (*14*).
- Utah Department of Transportation (UDOT): *DDI Guideline: A UDOT Guide to Diverging Diamond Interchanges* (*15*).

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CHAPTER 2

Policy and Planning

This chapter contains guidance on how to consider alternative intersections and interchanges in general and diverging diamond interchanges (DDIs) in particular. This chapter summarizes policy and planning considerations related to a DDI. The subsequent chapters of this guide will provide specific details of the multimodal, safety, operations, geometric design, and traffic control features of a DDI.

Alternative intersections are often initially considered for operational or safety needs, and other key factors may include spatial requirements and multimodal needs. This chapter provides approximate footprints for different types of DDIs to allow for planning-level screening and feasibility analysis.

2.1 Planning Considerations for Alternative Intersections and Interchanges

Alternative intersection evaluations may vary depending on the stage of the project development process. Each project stage can affect how each of the policy and technical considerations is assessed. In many states, intersection control evaluation policies and processes described in Chapter 1 guide this evaluation. While the operational, design, safety, human factors, and signing controls should be considered at every stage of the development process, a planning-level design evaluation may not require the same level of analysis or detailed evaluation as projects in later development stages. Evaluations should be as comprehensive as needed to answer key project questions for each unique project context.

2.1.1 Serving Pedestrians and Bicycles

A DDI offers an excellent opportunity to integrate multimodal facilities into an interchange. Almost all DDIs constructed to date include some combination of pedestrian and/or bicycle facilities.

The reduced number of signal phases can make it easier to serve nonmotorized movements compared to a multi-phase signal. In most cases, the two-phase DDI signal provides sufficient time per phase to serve pedestrians. Any pedestrian clearance phases are further minimized, as crossing distances are shortened to only cross one direction of traffic at a time. Through the separation and channelization of the two directions of vehicular traffic, pedestrians only have to interact with one direction of traffic at a time. This simplifies the pedestrian gap acceptance process and reduces the risk for pedestrian-vehicle conflicts, provided pedestrians understand which direction traffic is coming from.

The reduced crossing distances can also benefit bicyclists by reducing exposure time within the intersection (crossover) and minimizing the chance for vehicular conflicts. Some DDIs to date have been constructed with bicycle lanes through the crossovers, providing dedicated right-of-way for those road users. Several others have been constructed with bicycle facilities in the form of shared-use paths on the outside of the interchange.

While there are many opportunities for multimodal accommodations at a DDI, these design elements are not without challenges. Chapter 3 of this guide discusses challenges and considerations and provides recommendations for how to achieve safe and efficient provisions for multimodal users of a DDI.

2.1.2 Traffic Volume Relationships

Exhibit 2-1 conceptually depicts the relationship of conventional intersections, alternative intersections, and grade separations in their ability to serve increasing traffic volumes.

The DDI is an alternative to the conventional diamond interchange, high-capacity diamond forms such as the tight diamond and single-point diamond, as well as other interchange forms like a partial cloverleaf. The primary difference between a DDI and a conventional diamond interchange is the design of directional crossovers on either side of the interchange. This eliminates the need for left-turning vehicles to cross the paths of approaching through-vehicles. Cross-street traffic is shifted to the left side of the street between the signalized ramp intersections.

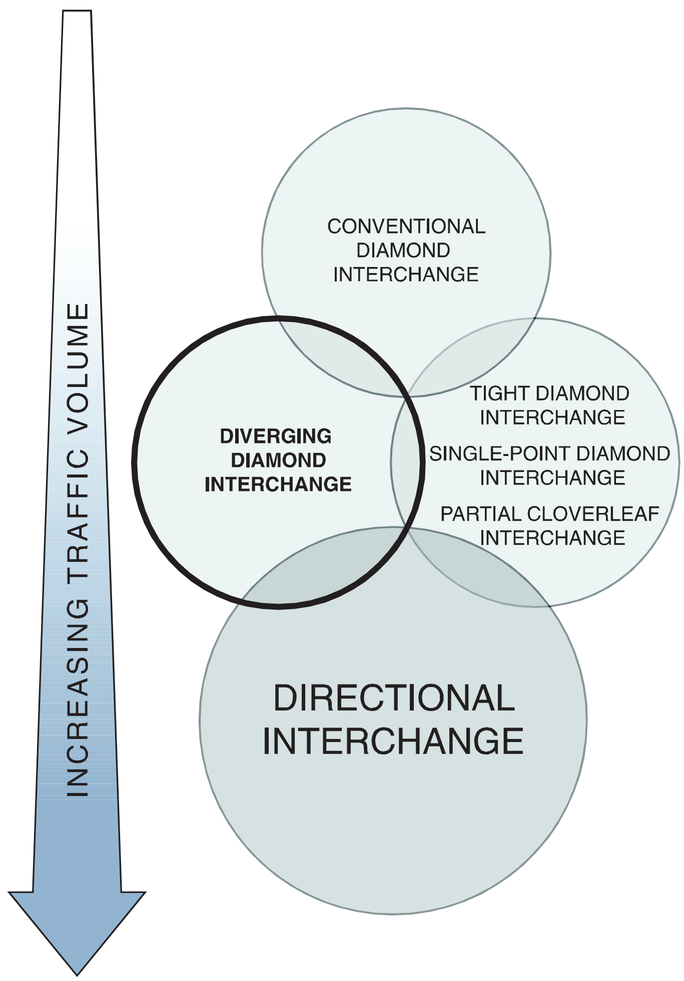

Exhibit 2-1. Relationship between volume and interchange type.

Drivers on the cross street who are making a left turn onto the ramps are allowed to continue to the ramps without conflicting with opposing through-traffic. The DDI design has been shown to improve the operations of turning movements to and from the freeway facility and significantly reduce the number of vehicle-to-vehicle conflict points compared to a conventional diamond interchange.

2.2 Stakeholder Outreach

Similar to other transportation projects, stakeholder outreach is a critical part of the overall planning process. Successful implementation of the first DDI in a community may benefit from explicit and proactive outreach and education to affected stakeholders and the general public. This would create opportunities to familiarize others with how the intersections work while creating opportunities to hear of general project and DDI-specific issues and considerations. Special considerations may include minimizing the likelihood of a wrong-way maneuver into opposing traffic. The greater the crossing angle, the more the intersection will appear to intersect in a familiar manner. Public information and educational campaigns prior to opening a DDI intersection can help promote an understanding of unique features. Creating multiple forums to engage the public (including presentations at local council or board meetings, briefs at community organization functions, and project-specific open house meetings) results in opportunities to listen to community interests and share objective information about the interchange form.

Exhibit 2-2 and Exhibit 2-3 are two examples of using video animation to describe how to travel through a DDI. The video clip includes animation and narration to provide the general public with a clear message of how a DDI functions. Both videos were included on the UDOT and Nevada DOT project websites. Exhibit 2-4 is an example of a fact sheet of how

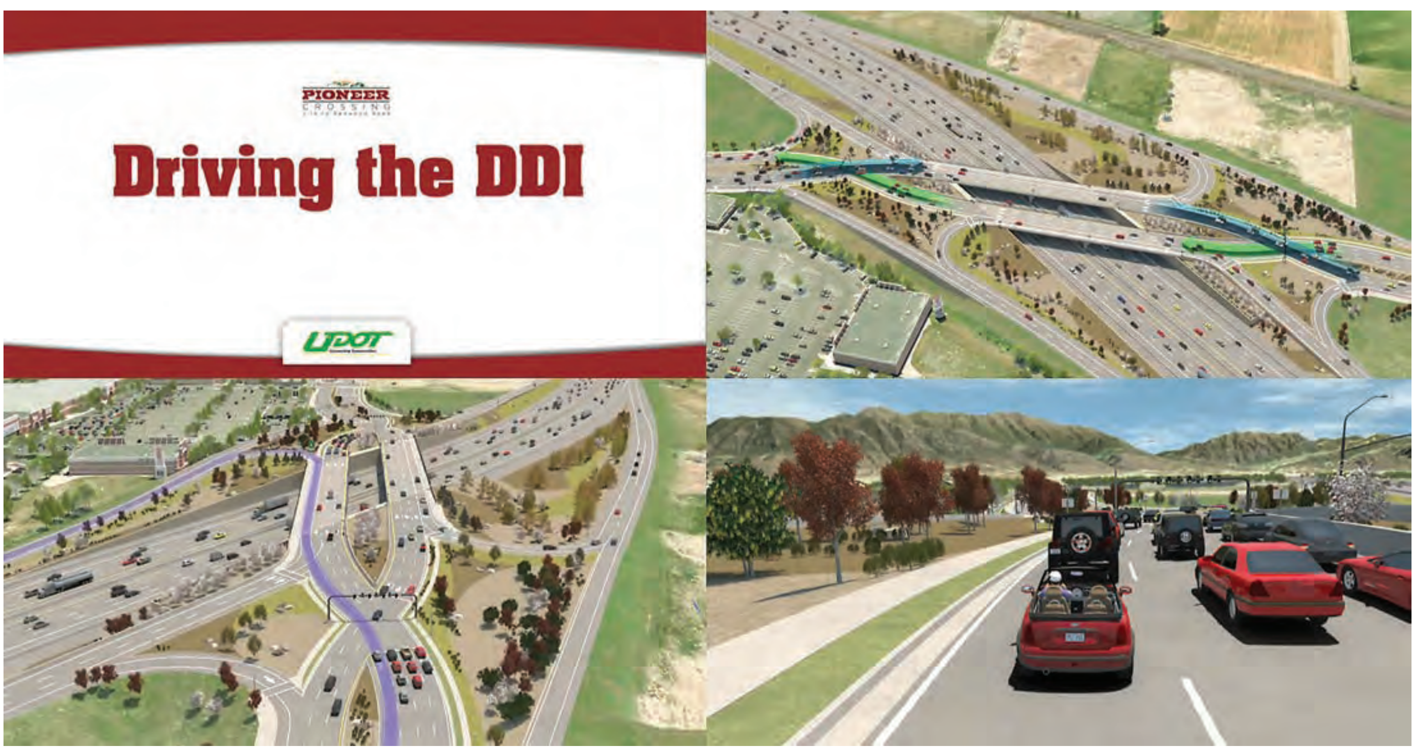

Exhibit 2-2. Example video screen captures from UDOT of how to travel through a DDI (1).

Exhibit 2-3. Example video screen capture from Nevada DOT of how to travel through a DDI (2).

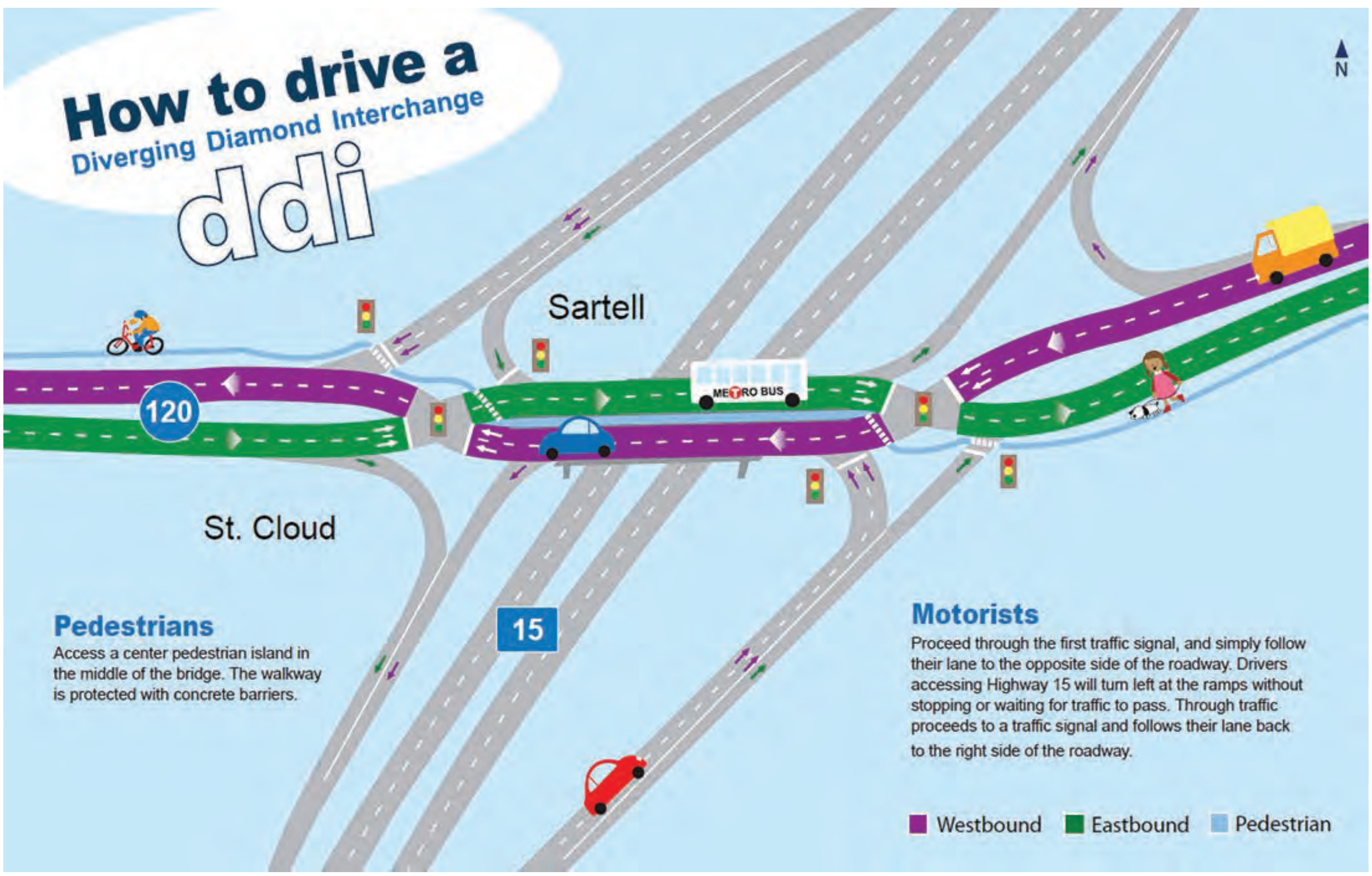

Exhibit 2-4. Fact sheet from Minnesota DOT on how various users travel through a DDI (3).

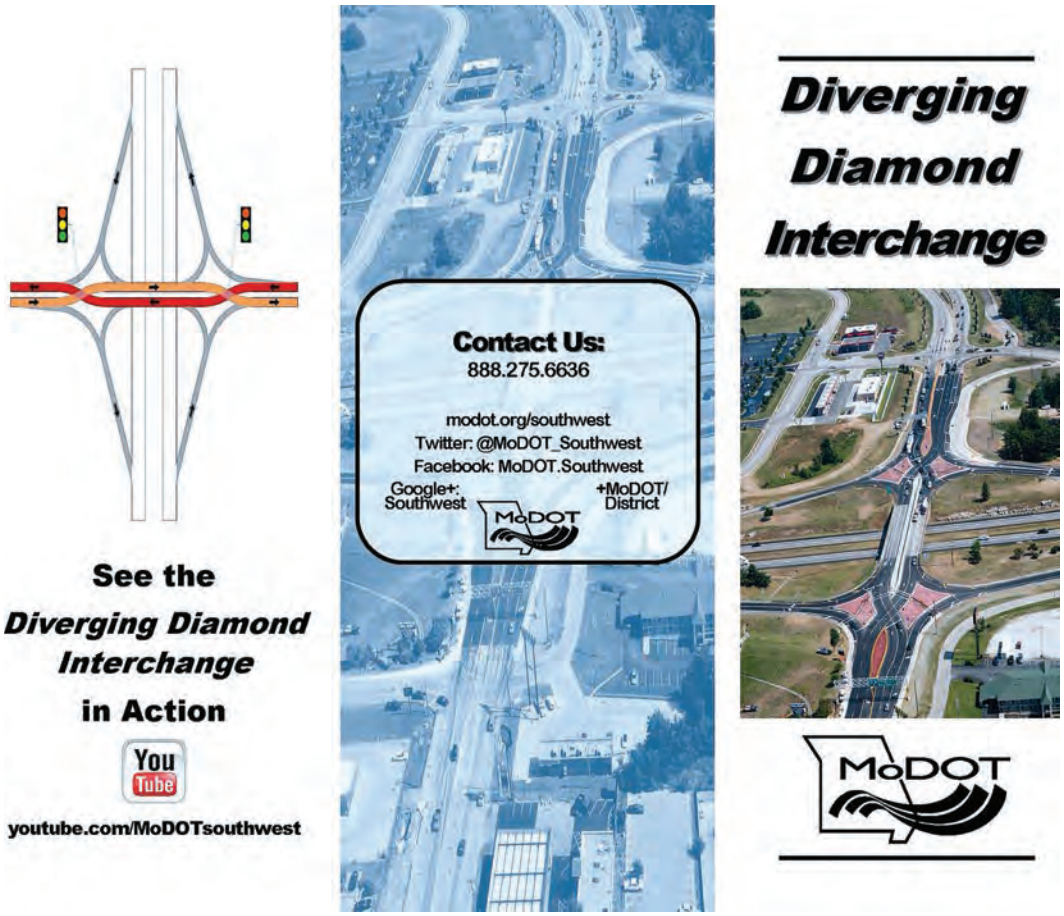

Exhibit 2-5. Public outreach brochure used by MoDOT (4).

to travel through a DDI, with an emphasis on all users of the system. The fact sheet highlights how a pedestrian, bicyclist, and motorist would travel through a DDI in Minnesota.

Exhibit 2-5 is an example of a DDI explanation brochure used by Missouri Department of Transportation (MoDOT) for a DDI. Once the interchange is open to the public, monitoring driver behavior and using law enforcement as necessary to promote proper use of the new form can aid driver acclimation.

Exhibit 2-6 is an example of a DDI branding campaign used by Georgia Department of Transportation (GDOT) and a local improvement district. The branding campaign included a website, a unique logo, and a slogan titled, "Can You DDI? Arrive-Crossover-Drive." This branding effort provides the public with an easy, identifiable look to this planned, urban DDI.

FHWA has created alternative intersection and interchange informational videos and video case studies, which can be viewed on the FHWA YouTube channel (*6*). In addition, FHWA has developed alternative intersection brochures that can be found on the FHWA website (*7*).

2.3 Policy Considerations

Designing, operating, and managing a street and its intersections should align with the appropriate jurisdictional policies associated with that facility. The facility location and type can often dictate the appropriateness of the right-of-way and access management needs

CAN YOU DDI?

ARRIVE ▸ CROSSOVER ▸ DRIVE

What is the DDI?

Project Updates

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A joint project of PCIDs, GDOT, SRTA, Dunwoody and DeKalb County.

1st In GEORGIA!

The Perimeter Community Improvement Districts (PCIDs) and the Georgia Department of Transportation (GDOT) have launched a project to redesign the busy I-285 and Ashford Dunwoody Road Interchange near Perimeter Mall to improve traffic flow and safety. The new configuration is called a Diverging Diamond Interchange or DDI. This innovative design shifts the flow of traffic to the opposite side of the road to reduce points of traffic conflict and improve traffic flow and safety. The DDI is a proven, cutting-edge, low-cost design that provides immediate traffic relief. Under normal, free-flowing traffic conditions on surrounding highways, the I-285 and Ashford Dunwoody DDI can reduce traffic delays in evening rush hours up to 20 percent. The Perimeter DDI will be the first DDI in Georgia and could become a model for congested interchanges throughout the state.

QUICK FACTS ABOUT THE DDI

The Ashford Dunwoody DDI is an interim design concept that doesn't require rebuilding the interchange or widening the bridge.

Restriping, altered signal timing, improved turning conditions and one reconstructed ramp will be used to move traffic faster and reduce accidents due to fewer traffic points of conflict.

Pedestrian access will also improve with the installation of a sidewalk down the center of the bridge protected from traffic by concrete barriers.

The Ashford Dunwoody DDI design will be implemented and open to traffic within 2 years of preliminary engineering notice to proceed – much faster than any full interchange reconstruction.

GDOT awarded a $4.6 million construction contract in August 2011 to E.R. Snell Contractor of Snellville to reconfigure the I-285 interchange at Ashford-Dunwoody Road.

The PCIDs initiated the project in 2009 by making a $100,000 business investment in hiring Moreland Altobelli engineering firm to find an innovative way to improve the interchange.

PCIDs secured project design and engineering funding from the State Road and Tollway Authority and DeKalb County - Project received an $800,000 grant from SRTA and $450,000 from DeKalb County.

GDOT says this project may become a model for congested interchanges throughout Georgia.

Construction work began in January 2012; the project will be completed in Fall 2012.

The DDI design originated in France.

The Ashford Dunwoody DDI is the 12th DDI in the US and the first in Georgia. There are currently 11 other DDIs in four states.

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Exhibit 2-6. Example public outreach brochure used by GDOT (5).

associated with alternative intersections. The degree to which motor vehicle throughput should or should not be prioritized over other modes also plays a role in determining the appropriateness of alternative intersections at specific locations.

Some of the considerations that should be addressed before construction of a DDI include the following:

- Access management considerations.
- Operational measures of effectiveness.
- Pedestrian facilities with access and wayfinding for persons with disabilities, including the requirements of the Americans with Disabilities Act (ADA) and Section 504 (the Rehabilitation Act) (*8*).
- Bicycle facilities.
- Managed lane scenarios, including ramp metering.
- Snow removal and storage.
- Design vehicle.
- Incident management.
- Emergency response needs.

2.3.1 Access Management

The subject of adjacent intersections has been one of the biggest concerns noted by practitioners building and operating DDIs and by academics who study the effects of DDIs on operations and safety. Adjacent intersections are problematic for many interchange configurations that may be considered as a replacement to conventional diamond interchanges; the specific issues relative to the DDI are discussed here.

From an operational perspective, the DDI's efficient two-phase signals provide much higher throughput than nearby adjacent signals that often allow many more signal phases. This, combined with the close proximity of the adjacent intersection, causes limited queue storage and spillback into the DDI. To the motoring public, the DDI design will often appear to be a wasted effort when, in fact, the DDI is operating as intended. Safety concerns arise for motorists turning right from an exit ramp and weaving across traffic to make a left at the adjacent intersection, especially if right-turn-on-red operations are allowed from the exit ramps.

Transportation agencies considering the DDI with nearby signalized intersections and congested cross roads have had to make geometric and signal design modifications to nearby intersections. Some potential geometric treatments that could improve operations and/or safety include:

- Relocating an intersection to the next closest signalized intersection, if nearby.
- Using grade separation to eliminate one or more signal phases at the intersection.
- Using alternative intersection designs could be considered to reduce the number of necessary signal phases at adjacent intersections along the corridor. This treatment has been used along Poplar Tent Road in Charlotte, North Carolina, and at several locations in Utah.

2.4 Planning Considerations

Transportation professionals should address the following planning considerations when developing an alternative intersection design:

- **Community goals**—Outside of formalized land use policies, cities and communities often have general goals that provide insights about the nature and character of their community.

These goals can range from concepts that preserve a historic character or identified heritage. Some goals may be to create walkable communities or complete streets. Other goals can be to encourage economic development by preserving existing business or residential areas while encouraging thoughtful development. Regardless of the specific goals or vision, these considerations may influence street and intersection design.

- **Surrounding land uses and zoning**—DDI intersections are well suited for suburban and urban environments. They are more challenging to implement on streets with nearby adjacent traffic signals or numerous driveways.
- **Project context**—Key questions that help identify key stakeholders for a particular project might include:
  - What is the purpose and function of the existing or planned road facilities?
  - What are the existing and planned land uses adjacent to and in the vicinity of the road facilities?
  - Who will likely desire to use the road facilities given the existing and planned land uses?
  - What are the existing and anticipated future socio-demographic characteristics of the populations adjacent to and in the vicinity of the existing or planned road facilities?
  - What are the perceived or actual shortcomings of the existing road facilities?
  - Who has jurisdiction over the facility?
  - Where is capital funding for the project originating (or expected to originate)?
  - Who will operate and maintain the facility?
- **Multimodal considerations**—As with any street segment or intersection, each configuration must consider and serve the various users who currently or may be expected to use the facilities. This includes pedestrians and bicyclists and can also include users with special needs such as the visually impaired, elderly users, or young users.
- **Access management**—Access near a DDI needs to be restricted based on local, state, and federal requirements for intersection spacing.
- **Design vehicles**—The interchange geometry will need to accommodate transit, emergency vehicles, freight, and potentially oversize/overweight (OSOW) vehicles.

2.5 Planning Challenges

The following are several challenges associated with planning DDIs:

- **Driver education**—Successful implementations of DDIs are often preceded by public outreach and education campaigns, which are typically not conducted for conventional intersection improvements.
- **Driver expectation**—DDIs relocate through and left-turn movements at the crossovers from their conventional location. This is different from what most drivers would expect and must be accounted for in the intersection planning and design.
- **Multimodal accommodation**—As with any street segment or intersection, each configuration must consider and serve the various users who currently or may be expected to use the facilities. This should always include pedestrians and bicyclists, understanding that the exact provisions may necessarily vary from site to site. Pedestrian facilities must always be made accessible. DDI intersections are generally compatible with transit as well.
- **Sufficient right-of-way**—Right-of-way constraints may limit a designer's ability to provide safe movement of vehicles through the crossover or limit the use of alternative design configurations.
- **Complex signal timing and phasing**—The opposing directions of the crossroad cross each other.
- **Proximity to adjacent intersections**—Nearby adjacent intersections have been found to hinder the ability of the DDI to process traffic as efficiently as it was intended.

2.6 Project Performance Considerations

Measuring the effectiveness of a project's overall performance depends on the nature or catalyst for the project. Understanding the intended specific operational, safety, and geometric performance context for each intersection or corridor, including intended users, can help determine project-specific performance measures. The project performance may be directly linked to the specific design choices and the specific performance of the alternatives considered. The project performance categories described below can influence and are influenced by the specific DDI design elements and their characteristics (*9*).

2.6.1 Accessibility

Chapter 3 of this guide describes accessibility as it relates to special consideration given to pedestrians with disabilities including accommodating pedestrians with vision, mobility, or physical impairments. However, for the purposes of considering a project's general context and the performance considerations, the term "accessibility" goes beyond the conversation of policy related to ADA and Public Rights-of-Way Accessibility Guidelines (PROWAG) and is meant to be considered in broader terms (*8*). With respect to considering applicable intersection forms for a given project context, accessibility is defined broadly as the ability to approach a desired destination or potential opportunity for activity using highways and streets (including the sidewalks and/or bicycle lanes provided within those rights-of-way). This could include the ability for a large design vehicle to navigate an intersection as much as it might pertain to the application of snow mobiles or equestrian uses in some environments or conditions.

2.6.2 Mobility

Mobility is defined as the ability to move various users efficiently from one place to another using highways and streets. The term "mobility" can sometimes be associated with motorized vehicular movement and capacity. For the purposes of this guide, "mobility" is meant to be independent of any particular travel mode.

2.6.3 Quality of Service

Quality of service is defined as the perceived quality of travel by a road user. It is used in the HCM 6th edition to assess multimodal level of service (MMLOS) for motorists, pedestrians, bicyclists, and transit riders. Quality of service may also include the perceived quality of travel by design vehicle users such as truck or bus drivers.

2.6.4 Reliability

Reliability is defined as the consistency of performance over a series of time periods (e.g., hour to hour, day to day, year to year).

2.6.5 Safety

Safety is defined as the expected frequency and severity of crashes occurring on highways and streets. Expected crash frequencies and severities are often disaggregated by type, including whether or not a crash involves a nonmotorized user or a specific vehicle type (e.g., heavy vehicle, transit vehicle, motorcycle). In cases where certain crash types or severities are small in number, as is often the case with pedestrian- or bicycle-involved crashes, it may be necessary to review a longer period of time to gain a more accurate understanding.

2.7 Project Development Process

For the purposes of this report, the project development process is defined as consisting of the stages described below. Federal, state, and local agencies may have different names or other nomenclature with the overall intent of advancing from planning to implementation. Exhibit 2-7 illustrates the overall project development process.

2.7.1 Planning Studies

Planning studies often include exercises such as problem identification and other similar steps to ensure there is a connection between the project purpose and need and the geometric concepts being considered. Planning studies could include limited geometric concepts on the general type or magnitude of project solutions to support programming.

2.7.2 Alternatives Identification and Evaluation

The project needs identified in prior planning studies inform concept identification, development, and evaluation. At this stage, it is critical to understand the project context and intended outcomes so potential solutions may be tailored to meet project needs within the opportunities and constraints of a given effort. FHWA describes context sensitive solutions as ". . . a collaborative, interdisciplinary approach that involves all stakeholders in providing a transportation facility that fits its setting" (*10*). In considering the concept of "context sensitive design/solutions," this stage calls for meaningful and continuous stakeholder engagement to progress through the project development process.

2.7.3 Preliminary Design

Concepts advancing from the previous stage are further refined and screened during preliminary design. For more complex, detailed, or impactful projects, the preliminary design (typically 30% design level plans) and subsequent documentation are used to support more complex state or federal environmental clearance activities. The corresponding increased geometric design detail allows for refined technical evaluations and analyses that inform environmental clearance activities. Preliminary design builds upon geometric evaluations conducted as part of the previous stage (alternatives identification and evaluation). Some of the common components of preliminary design include:

- Horizontal and vertical alignment design,
- Typical sections,
- Grading plans,
- Structures,
- Traffic/intelligent transportation systems (ITS),
- Signing and pavement markings,
- Illumination, and
- Utilities.

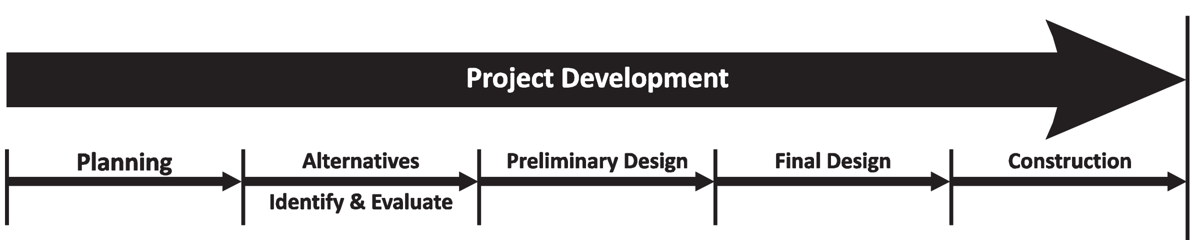

Exhibit 2-7. Project development process.

2.7.4 Final Design

The design elements are advanced and refined in final design. Typical review periods include 60%, 90%, and 100% plans before completing the final plans, specifications, and estimate. During this stage, there is relatively little variation in design decisions as the plan advances to 100-percent. Functionally, in this stage of the project development process, the targeted performance measures have a lesser degree of influence on the form of the project.

2.7.5 Construction

Construction activities could include geometric design decisions related to temporary streets, connections, or conditions that facilitate construction. Project performance measures may relate to project context elements.

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CHAPTER 3

Multimodal Considerations

3.1 Introduction

This chapter presents guidance when considering pedestrians, bicyclists, and transit vehicles at a diverging diamond interchange (DDI). While many existing interchanges do not have facilities for pedestrians, bicyclists, or transit, almost all DDIs constructed to date include some combination of such facilities. The overall objective is to develop a design, regardless of the type of intersection, compatible with a complete street. A complete street is a facility that serves many types of users including freight, transit, and nonmotorized users. This chapter describes the unique characteristics of nonauto modes (pedestrians, bicyclists, and transit) that should be considered when analyzing and designing DDIs. The transportation professional needs to work to identify and understand the needs of these various users in order to produce a balanced design that serves them all.

3.1.1 Benefits and Challenges

Selecting the DDI as an alternative intersection choice has both benefits and challenges in the areas of safety and efficiency for multimodal users. Multimodal benefits of DDIs include:

- Reduced overall right-of-way footprint compared to a conventional diamond interchange,
- Opportunity for two-phase traffic signal control with reduced pedestrian wait time,
- Minimized crossing distances,
- Simplification of conflicts to one-directional vehicular traffic,
- Opportunities for bicycle lanes and multiuse paths through the interchange, and
- Reversed lane direction between crossovers allows for a single transit stop facility in median serving both directions of travel.

Some of the challenges of multimodal provisions at DDIs include:

- Altered travel paths, often with travel in the center of the interchange between vehicular lanes,
- Traffic approaching from unexpected directions,
- Unfamiliar signal phasing schemes,
- Uncontrolled crossing of turn lanes, and
- Long clearance interval needed for bicycles in the outbound direction at crossover intersections if the off-ramp right turn is signalized.

A DDI generally generates higher capacity per lane for motor vehicles compared to a conventional diamond. This frees up right-of-way that can be used for multimodal facilities in the form of sidewalks, bicycle lanes, or even transit facilities.

The reduced crossing distance can make it easier to serve nonmotorized movements compared to a conventional interchange. At long crossings, the need to provide adequate pedestrian clearance may result in the pedestrian movement controlling the phase lengths, leading to longer cycle lengths and greater pedestrian delay. In contrast, vehicle movements typically control phase length at DDI signals resulting in sufficient time per phase to also serve pedestrians. Although pedestrian crossings at the crossovers are signalized, pedestrian crossings of the turn lanes to and from the freeway may not be signalized. These potentially uncontrolled crossing locations require special attention and consideration to ensure pedestrian safety.

Pre-timed DDI signals can provide for extended pedestrian walk phase times, which can reduce pedestrian delay and provide added time for pedestrians with disabilities. The reduced crossing distances can also benefit bicyclists who have a reduced exposure time within the crossover intersection, thereby minimizing the chance for vehicular conflicts.

Finally, through the separation and channelization of the two directions of vehicular traffic, pedestrians interact with one direction of traffic at a time. This simplifies the pedestrian gap acceptance process and reduces the risk for pedestrian-vehicle conflicts, provided pedestrians understand from which direction traffic is coming at a given crossing.

3.1.2 Anticipating Multimodal Needs, Behavior, and Patterns

A fundamental challenge in developing any new intersection or interchange form is deciding how to best provide for pedestrian and bicycle movements and anticipating the desire lines between different origins and destinations for these modes (e.g., how they travel through the intersection or interchange). Forecast volumes for nonmotorized users are rarely available, and if they are, they typically do not capture travel patterns within the intersection or interchange. However, the majority of DDIs constructed to date feature pedestrian and bicycle facilities. For many retrofit sites, the existing pedestrian and bicycle facilities were improved with construction of the DDI. For example, DDIs at MO-13 in Springfield, Missouri; Dorsett Road in Maryland Heights, Missouri; and Harrodsburg Road in Lexington, Kentucky all added shared-use paths through the interchange (see Exhibit 3-1, Exhibit 3-2, and Exhibit 3-3).

At all three of these sites, the construction of multimodal facilities was a priority for agencies, garnering positive feedback from local residents and users of the facility. At interchanges, land use development can sometimes lag interchange construction, resulting in pedestrian and bicycle needs not readily apparent on opening day. Early consideration and provision for pedestrian and bicycle movements should be a priority consideration for any DDI and should be accounted for even in early design concepts.

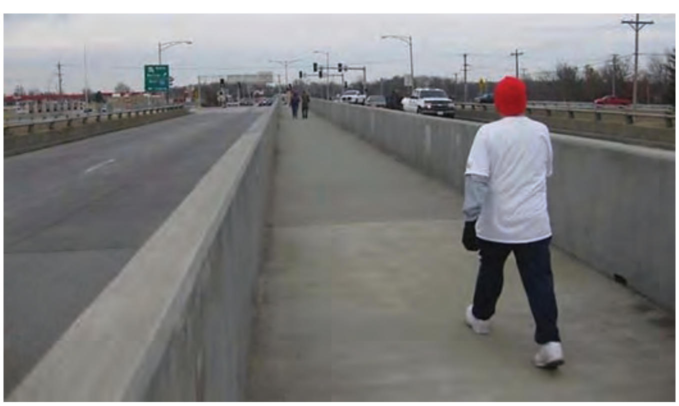

Exhibit 3-1. Inner walkway at MO-13 (Springfield, Missouri) (1).

Exhibit 3-2. Outer walkway at Dorsett Road (Maryland Heights, Missouri) (1).

3.2 Facility Selection

This section discusses the operational considerations at a DDI that have relevance to the pedestrian and bicyclist experience, so the reader can understand trade-offs associated with various facility types. As discussed in Chapter 1, identifying project outcomes should be conducted as early in the design process as possible. This includes identifying outcomes for pedestrian and bicycle users. These outcomes can then inform the facility selection process. Selection should occur early enough to allow for design simultaneous to the roadway design.

3.2.1 Pedestrians

Pedestrian facilities at grade-separated interchanges can generally be challenging due to high vehicular volumes and a focus on providing unimpeded capacity to vehicular flow. Nonetheless, interchanges can be designed to be safe and comfortable for pedestrians if the designer applies intersection-level design concepts that slow traffic flow, provide proper lines of sight for pedestrians and drivers, and manage conflict points to maximize pedestrian safety.

A major consideration for pedestrian facilities at a DDI is whether to provide inner or outer walkways. Several design decisions flow from this choice. Pedestrian facilities in the center of the interchange (within the median) may be preferable to minimize conflicts with left-turning

Exhibit 3-3. Shared-use path on outside at Harrodsburg Road (Lexington, Kentucky) (1).

traffic to and from the freeway and naturally allow crossing the interchange in all directions (i.e., travel along the cross road and crossing the cross road from one side to the other). For underpass DDIs, placement of bridge columns, especially at a retrofit, may restrict the choice of the inner versus outer walkway.

In general, pedestrian safety and comfort can be enhanced by reducing vehicle speeds, improving sight distances between drivers and pedestrians, and appropriately locating the crosswalks. At DDIs, the required channelized right- and left-turn lanes to and from the freeway present an opportunity for pedestrian-focused designs through the use of reduced curve radii and other geometric changes. Exhibit 3-4 and Exhibit 3-5 illustrate this concept for a DDI with an inner walkway and a DDI with outer facilities, respectively.

The key concepts underlying pedestrian-focused design of DDIs include four primary principles:

- Tighten vehicle curve radii to reduce speeds at the crosswalk. In research, lower vehicle speeds have been linked to increased driver yielding rates and lower risk of serious injury or death for the pedestrian in the event of a crash.
- Provide adequate sight distance for vehicle approaches to crosswalks by locating the crosswalk in the tangent portion of the approach or in the beginning portions of the curve. A crosswalk located in the middle of a large swooping turn is difficult for drivers to see and react to. Improved vehicle sight distance also provides enhanced pedestrian sight distance for pedestrians to make adequate gap-crossing decisions at unsignalized crossings.
- Provide one or more vehicle lengths of storage downstream of the crosswalks for yield-controlled vehicle movements. Similar to the crosswalk placement at roundabouts, this separates the driver decision points of yielding to pedestrians at the crosswalk and screening for gaps at the yield sign. It also prevents drivers who are waiting at the yield line from blocking the crosswalk with their vehicle.
- Locate crosswalks downstream of the stop bar for signalized vehicle turns, consistent with driver and pedestrian expectations at signalized intersections.

These configurations apply equally to DDIs with inner or outer pedestrian facilities. One key difference between the two is that the turn radius for the left turns to and from freeways can be selected independent of pedestrian considerations for the inner walkway because pedestrians do not cross these turn movements with an inner walkway DDI configuration.

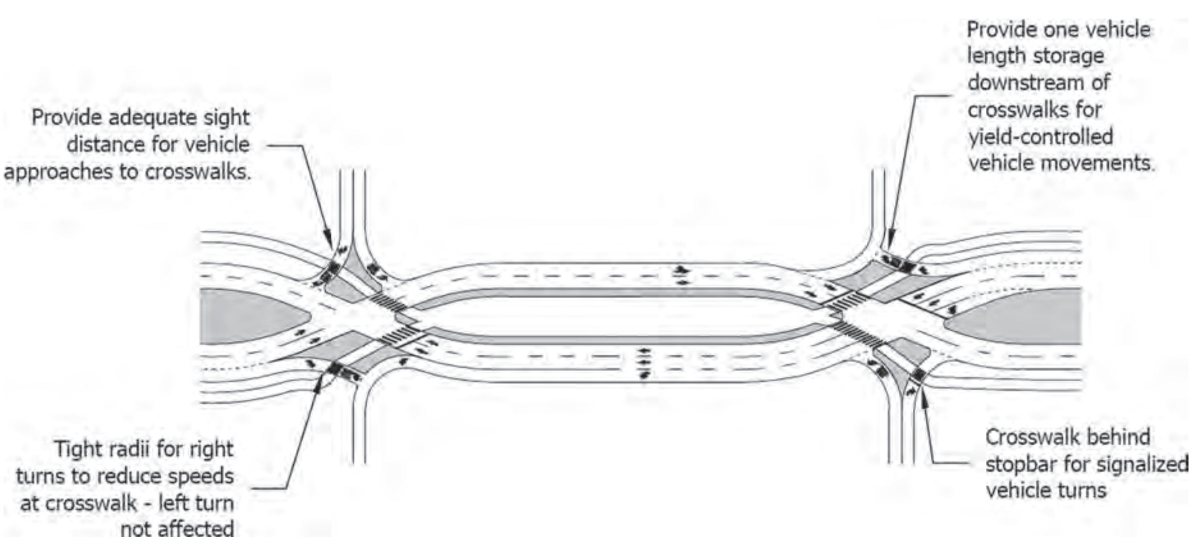

Exhibit 3-4. Pedestrian-focused DDI—Inner Walkway.

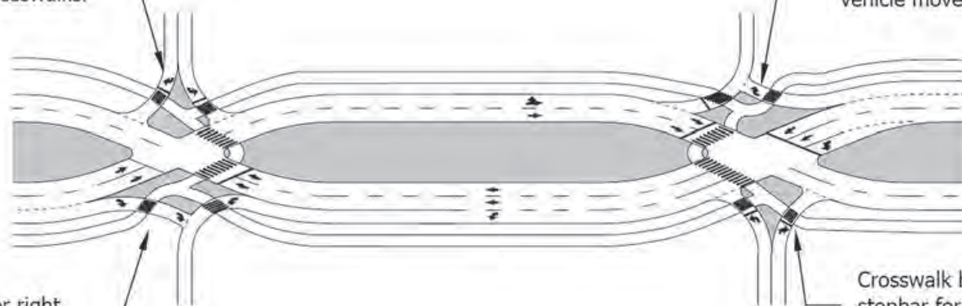

Exhibit 3-5. Pedestrian-focused DDI—Outer Walkway.

3.2.1.1 Inner Walkways

Exhibit 3-6 gives an example of a pedestrian facility located in the center of a DDI. While on- and off-ramp movements may be signalized or unsignalized, the exhibit shows movements that would time together if all ramp movements were signalized. For pedestrian movements across unsignalized ramp movements, geometric design or enhanced crossing treatment options may be incorporated to enhance pedestrian safety (discussed in Section 3.3.2).

In the case of a DDI with inner walkways, pedestrian facilities to cross into the center can be co-located with these vehicle signals at crossover movements, and a pedestrian crossing phase can be provided with the concurrent vehicle phase. The right turns may be unsignalized or signalized crossings and should, in either case, be configured in a way that promotes low vehicle speeds and good sight distance to the crosswalk.

A pedestrian-vehicle conflict point exists anywhere pedestrian walkways and vehicular travel lanes cross. The pedestrian-vehicle conflict points for inner crossing DDIs are illustrated in Exhibit 3-7.

The advantages and challenges of inner pedestrian facilities at the street crossing and along the walkway are summarized in Exhibit 3-8 and Exhibit 3-9, respectively.

3.2.1.2 Outer Walkways

Exhibit 3-10 gives an example of an outer pedestrian walkway. While on- and off-ramp movements may be signalized or unsignalized, the exhibit shows movements that would run together if all ramp movements were signalized. For pedestrian movements across unsignalized ramp movements, geometric design or enhanced crossing treatment options may be incorporated to enhance pedestrian safety (discussed in Section 3.3.2).

In the case of outer walkways at DDIs, traversing pedestrians may cross four separate vehicle turning movements (the ramps). These may be free flowing or controlled. In some existing DDIs with outer walkways, no pedestrian crossing of the cross road is provided. This is an undesirable design that limits pedestrian access. Crossing opportunities should be provided. Otherwise, pedestrians can be expected to pursue their desired lines, often at considerable risk.

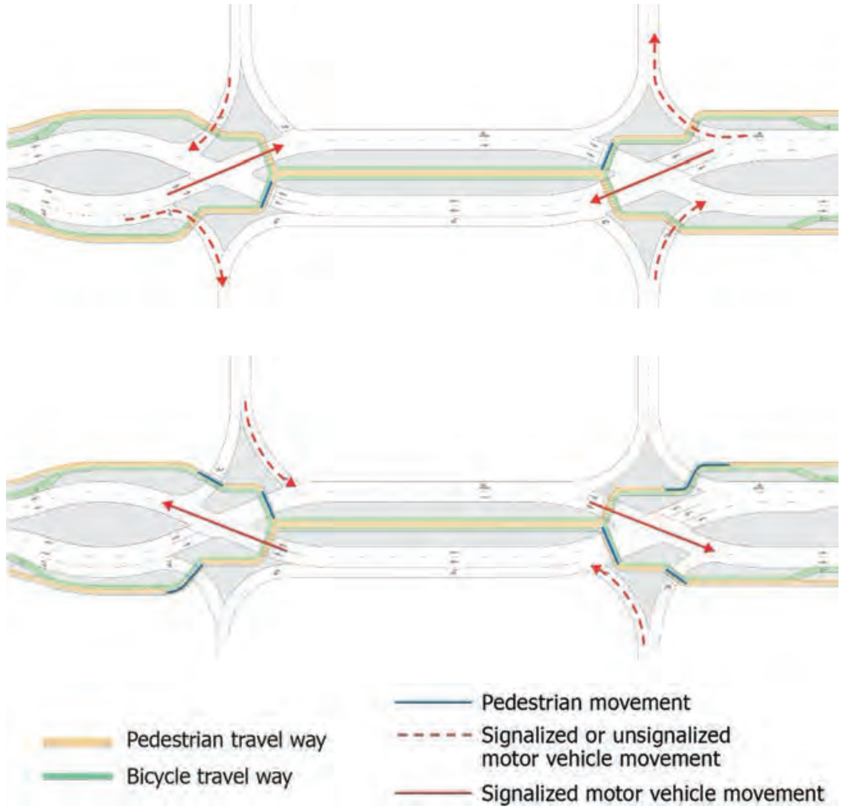

Exhibit 3-6. Pedestrian movements given an inner walkway at a DDI. The top figure shows movements that time with the inbound crossover movements, while the bottom figure shows movements that time with the outbound crossover movements.

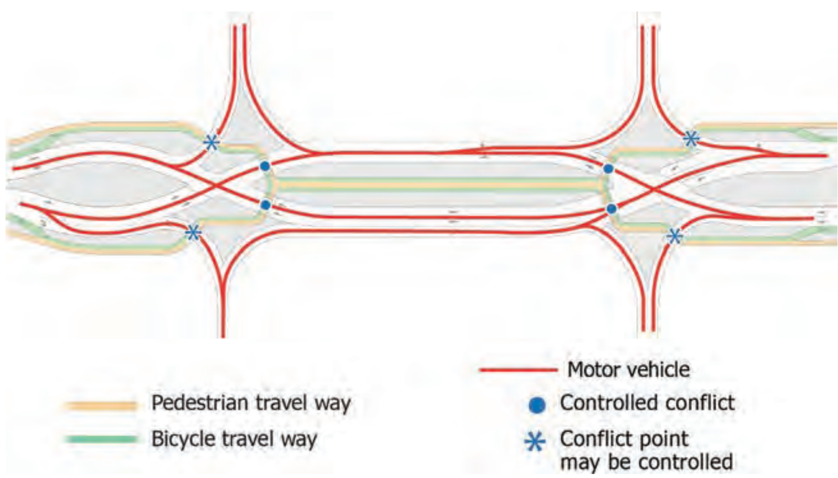

Exhibit 3-7. Pedestrian-vehicle conflict point diagram for a DDI with an inner walkway.

Exhibit 3-8. Inner walkway pedestrian safety and comfort at street crossings.

Benefits		Challenges	
+	Crossing of the cross road naturally provided at DDI for full pedestrian access	–	Possible crossing of free-flow right-turn movements to/from freeway
+	Crossing one direction of traffic at a time	–	Pedestrians may not know to look to the right when crossing from center
+	No exposure to left turns to freeway (typically free flowing)	–	Wait at center median dictated by length of signal phase for through traffic
+	Protected signalized crossing to walkway	–	Pedestrian signals can conflict with vehicle signals at crossovers
+	Pedestrian clearance time generally provided in crossover signal phasing	–	Out of direction travel for pedestrians not desiring to cross the cross road
+	Pedestrian delay to center minimized by short cycles at two-phase signals		

A pedestrian-vehicle conflict point exists anywhere pedestrian walkways and vehicular travel lanes cross. The pedestrian-vehicle conflict points for outer crossing DDIs are illustrated in Exhibit 3-11.

Note the key conflict points denoted by asterisks (the freeway on-ramps). These conflict points may be controlled or uncontrolled conflict points, depending on the design of the intersection. Vehicles at these conflict points are accelerating, so it is critical to consider how speeds and yielding rates can be controlled through design.

The advantages and challenges of outer pedestrian facilities at the street crossing and along the walkway are summarized in Exhibit 3-12 and Exhibit 3-13, respectively.

Exhibit 3-9. Inner walkway pedestrian safety and comfort along walkway segments.

Benefits		Challenges	
+	Side walls provide a positive barrier between vehicular movements and pedestrians. (Walls low enough to avoid "tunnel" effect could have lesser impact on pedestrian comfort.)	–	Design of side walls must be managed to avoid impeding sight distance
+	Need for only one facility inside the intersection footprint (inner walkway) can offer more enhanced features within the same right-of-way constraints	–	Potential discomfort from moving vehicles on both sides of walkway
		–	Potential challenge in placing all necessary signs and signal control equipment while maintaining full pedestrian access

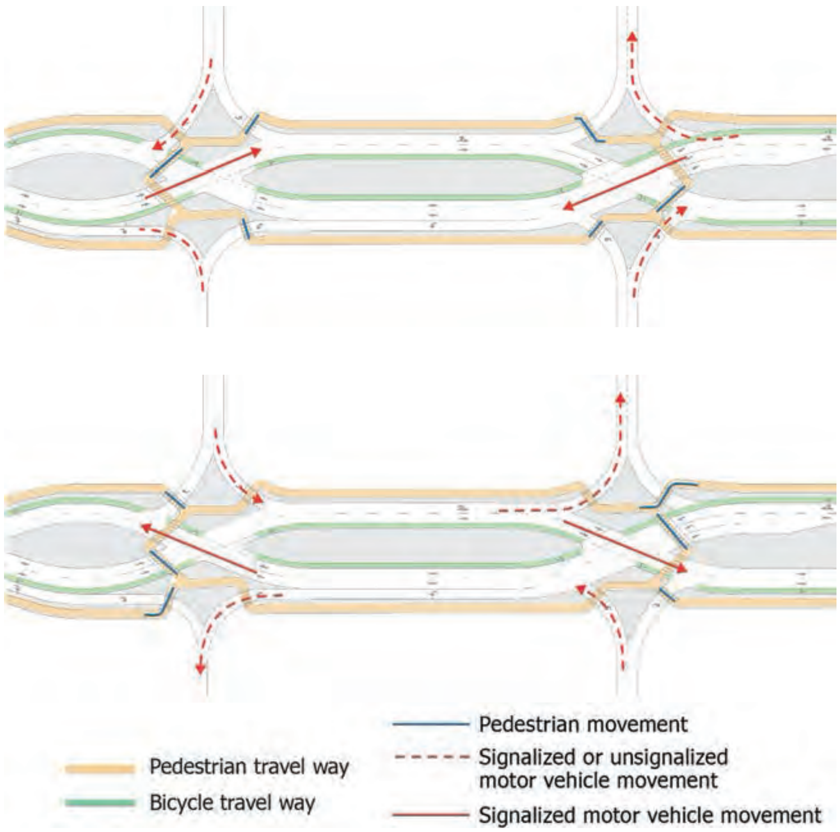

Exhibit 3-10. Outer pedestrian facilities at a DDI. The top figure shows movements that time with the inbound crossover movements, while the bottom figure shows movements that time with the outbound crossover movements.

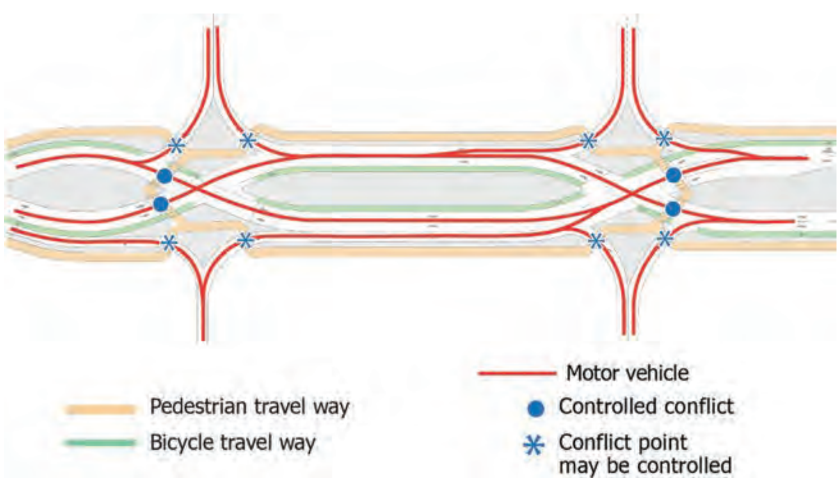

Exhibit 3-11. Pedestrian-vehicle conflict point diagram for a DDI with an outer walkway.

Exhibit 3-12. Outer path/sidewalk pedestrian safety and comfort at street crossings.

Benefits	Challenges
+ Crossing one direction of traffic at a time	– Crossing of free-flow right-turn movements to/from freeway
+ Ramp crossing distances are often shorter than through traffic crossing distance due to fewer travel lanes	– Conflict with left turns to freeway (typically free flowing) where high vehicle speeds are likely (acceleration to freeway)
	– Potential sight obstruction of pedestrian crossing left turns from behind any structures
	– Pedestrians may not know which direction to look when crossing turn lanes
	– Unintuitive traffic directions to check when crossing out of the crossover
	– Providing signalized crossings requires more complicated timing and potential safety risks associated with motor vehicle queuing

3.2.2 Bicycles

Three basic facility options exist for bicyclists at a DDI. These options include providing:

- Shared use of the travel lane,
- A marked bicycle lane through the DDI, or
- A separated bicycle path or shared-use path.

One or more of these options may be viable for a project and would be determined in a Stage 1 intersection control evaluation (ICE) process as detailed in Chapter 1. FHWA's *Bikeway*

Exhibit 3-13. Outer path/sidewalk pedestrian safety and comfort along walkway segments.

Benefits	Challenges
+ Extension of existing pedestrian network (natural placement on outside of lanes)	– Need for widened structure on outside for overpass
+ Pedestrian typically has view of path ahead (depends on sight lines and obstructions)	– Potential for additional right-of-way for underpass or construction of retaining wall under bridge
+ Walkway does not conflict with center bridge piers (at underpass)	– Need for additional lighting for underpass
+ Opportunity to use right-of-way outside of bridge piers (at underpass)	
+ Does not create potential tunnel effect that could make pedestrians feel "trapped"	

Selection Guide (*2*) provides facility selection guidance with respect to motor vehicle volume and operating speed, as shown in Exhibit 3-14.

A shared use of the travel lane should be reserved for conditions where vehicle operating speeds are below 25 mph and vehicle volumes are below 3,000 vehicles per day (vpd). Separated bicycle facilities are recommended where actual vehicle speeds exceed 35 mph or volumes exceed 7,000 vpd. Note that, as described in Chapter 5, operating speeds at DDIs are rarely at or below 25 mph, so a shared use of the travel lane is likely not an appropriate option. Low volume DDIs, such as those installed in rural areas for safety benefits, may be appropriate for on-street marked bike lanes; however, medium-to-high volume DDIs installed for safety and operational benefits will likely exceed the volumes appropriate for on-street facilities. In all cases, the signal timing should allow a bicyclist to complete all movements and phases and provide adequate clearance time for bicyclists to clear the intersection before releasing conflicting traffic.

Bicycle lanes at a DDI provide bicyclists with dedicated road space to travel across the interchange. As shown in Exhibit 3-15, bicycle lanes should be located to the right of the travel lanes for motorized traffic, which is generally where bicyclists and motorists expect bicyclists to travel. A wider bike-appropriate shy distance is critical where the facility is next to a barrier such as between the crossovers where a center barrier wall is present. By providing the additional width, it reduces the bicyclist's feeling of being "trapped."

Green-colored pavement and/or dashed bicycle lane lines can be used to connect the solid bicycle lane lines at intersections. The bicycle lane should only be interrupted by stop bars at

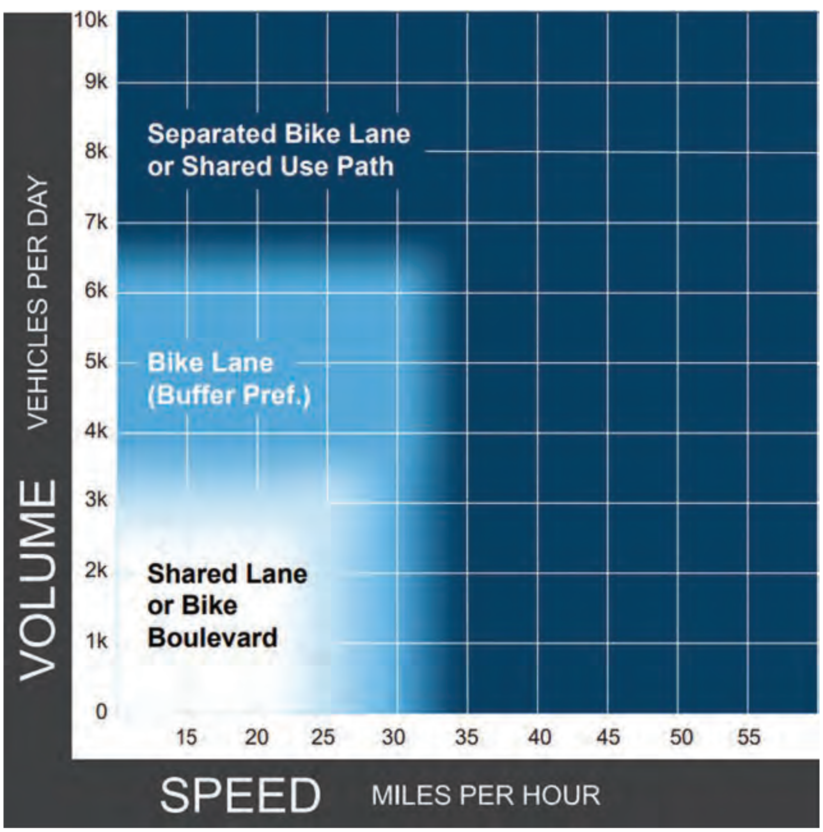

Exhibit 3-14. Bicycle facility selection guidance by motor vehicle volume and operating speed (2).

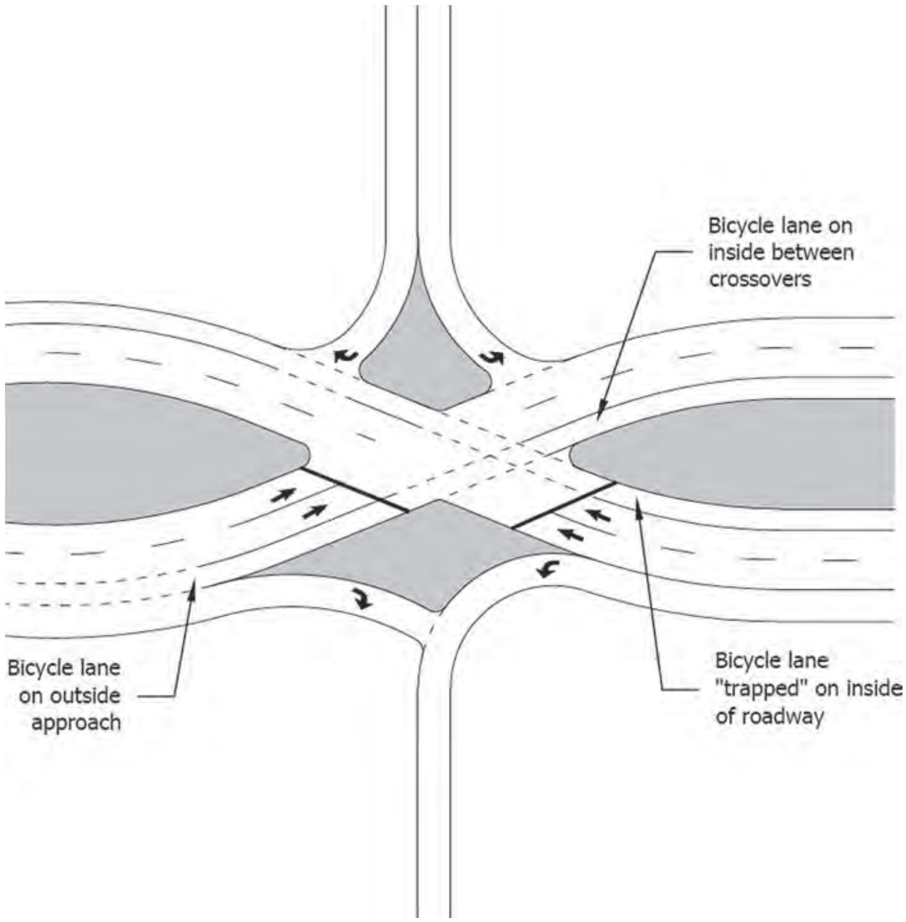

Exhibit 3-15. Schematic for bicycle lane placement on right side of vehicular traffic.

the signalized crossovers. The bicycle lane should continue through the off-ramps from freeway, where motorized traffic would generally be required to yield to cross road traffic, including bicyclists. Where bicycle lanes cross off-ramps, the use of colored pavement may increase bicyclist visibility to motorists. Exhibit 3-16 and Exhibit 3-17 show a DDI bicycle lane in Reno, Nevada, that highlights some of these features.

An alternative to providing bicycle lanes through a DDI is to provide separated facilities. Where an inner path is possible, the inner walkway may instead be an inner shared-use path. Bicyclists crossing at the signalized intersections would either share a crossing with pedestrians or cross in adjacent crossings. A shared-use path option can be provided as part of an outer path option as well, as depicted in Exhibit 3-18.

If separated facilities are not provided on the approach to the DDI, a ramp can transition bicyclists from the roadway to the separated path (see Section 3.4.1 for example). Note that this can be accomplished in advance or in conjunction with the development of vehicle right turns to avoid a conflict. For any shared-use path design, attention should be paid to locations where bicycle-pedestrian conflict points exist, such as at ramps onto and off of the roadway.

A bicycle-vehicle conflict point exists anywhere bicyclist paths and vehicular travel lanes cross. Bicycle-vehicle conflict points for an inner bicycle path are presented in Exhibit 3-19. The asterisks represent conflict points that may be along accelerating vehicle paths, subject to the design of the intersection.

Exhibit 3-16. Bicycle lane extending through inbound crossover (3).

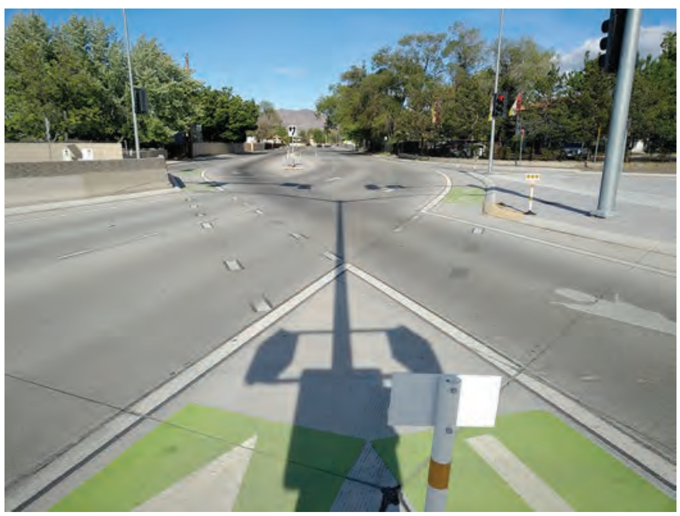

Exhibit 3-17. Bicycle lanes through the crossover (3).

Exhibit 3-18. Outer shared-use path at DDI in Lexington, Kentucky (4).

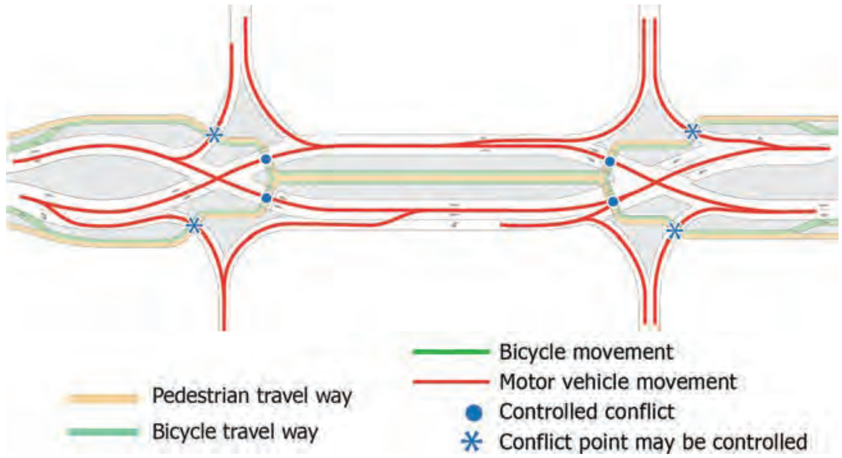

Exhibit 3-19. Bicycle-vehicle conflict point diagram for a DDI with an inner bicycle path.

3.3 Pedestrian & Bicycle Assessment

Research has documented vehicular safety benefits for DDIs. The reduction in vehicular crashes relative to a traditional diamond interchange is attributable to the separation of conflict points and the elimination of high-risk and high-severity crash patterns (e.g., angle crashes between left-turn and opposing through movements). For pedestrian and bicyclist safety, insufficient data are available to draw any conclusions regarding observed crash performance of DDIs. In the absence of quantitative crash data, an investigation of conflict points provides insight into the expected safety of DDIs. Common intersection and interchange design principles apply to pedestrian and bicycle facilities and can be assessed using the method presented in the following section.

3.3.1 Assessment Methodology

NCHRP Project 07-25, "Guide for Pedestrian and Bicycle Safety at Alternative Intersections and Interchanges (A.I.I.)," developed an assessment method for bicycle and pedestrian facilities at intersections and interchanges. While a summary is provided below, full details can be found in *NCHRP Research Report 948: Guide for Pedestrian and Bicycle Safety at Alternative Intersections and Interchanges* (*5*).

As a surrogate for quantitative performance measures, a series of performance measures—also known as *design flags*—can be used to assist in the identification of potential safety, accessibility, operational, or comfort issues for pedestrians and bicyclists. A design flag does not necessarily represent a fatal flaw for an alternative; rather, it presents a design issue that should be addressed in the iterative development and evaluation of the alternative.

These design flags are not unique to DDIs, as they may also apply to traditional intersections and interchanges.

Design flags generally apply to conflict points within the intersection rather than to segments. Outputs related to safety or accessibility are generally higher priority items that need to be addressed in design refinements. Outputs related to delay, travel time, and level of comfort are generally of lesser priority relative to safety and accessibility, suggesting items of concern but not necessarily fatal flaws in the design. Both levels of priority can be used to differentiate alternatives during the ICE process, and the relative balance of these levels of priority can be customized to the context of the location. Exhibit 3-20 summarizes all flags, including their applicability (pedestrian versus bicyclist) and the measure of effectiveness associated with the flag.

Exhibit 3-20. Summary of design flags and measures of effectiveness.

Flag #	Design Flag	Bicycles	Pedestrians	Measure of Effectiveness
1	Motor Vehicle Right Turns		X	Vehicle Turning Speed and Vehicle Volume
2	Uncomfortable/Tight Walking Environment		X	Effective Walkway Width
3	Nonintuitive Motor Vehicle Movements		X	Vehicle Acceleration Profile
4	Crossing Yield-Controlled or Uncontrolled Vehicle Paths	X	X	Vehicle Turning Speed and Vehicle Volume
5	Indirect Paths	X	X	Out of Direction Travel Distance
6	Executing Unusual Movements	X	X	Local Expectation
7	Multilane Crossings	X	X	Number of Lanes without Refuge
8	Long Red Times	X	X	Delay
9	Undefined Crossing at Intersections	X	X	Path Markings
10	Motor Vehicle Left Turns	X	X	Vehicle Turning Speed and Vehicle Volume
11	Intersection Driveways and Side Streets	X	X	Count of Access Points in Area of Influence
12	Sight Distance for Gap Acceptance Movements	X	X	Sight Distance
13	Grade Change	X	X	% Grade
14	Riding in Mixed Traffic	X		Vehicle Speed and Vehicle Volume
15	Bicycle Clearance Times	X		Vehicle Speed and Clearance Zone Length
16	Lane Change Across Motor Vehicle Travel Lane	X		Vehicle Speed and Vehicle Volume
17	Channelized Lanes	X		Vehicle Speed and Channelization Length
18	Turning Motorists Crossing Bicycle Path	X		Motor Vehicle Lane Configuration
19	Riding between Travel Lanes, Lane Additions, or Lane Merges	X		Motor Vehicle Lane Configuration
20	Off-Tracking Trucks in Multilane Curves	X		Turn Angle

3.3.2 Pedestrians—Key Safety Challenges

DDIs present a reduced number of conflict points for pedestrians relative to a conventional intersection or interchange. At the same time, there are design factors inherent to a DDI that should be flagged as the design is developed. They are listed below.

- **Nonintuitive vehicle direction**—A DDI often entails crossing traffic approaching from a potentially counterintuitive direction, which presents wayfinding challenges and risks for pedestrians. While each crossing conflicts with only a single direction of vehicle traffic, pedestrians may not intuitively know in which direction to look for vehicles.

- **On-ramp movements**—In general, the capacity benefits provided by unsignalized on-ramps at a DDI degrade the crossing environment for pedestrians and bicyclists on separated paths. While left turns are typically free flowing, the right turn is either free flowing with an acceleration lane (Exhibit 3-21) or yield controlled at the merge point with the left turn. Yield-controlled turns are likely to have slower vehicle speeds and would therefore be easier for pedestrians to cross than free-flowing turns. Both types of crossings can be improved by ensuring that roadway geometry manages motor vehicle speeds and that sufficient sight distance is provided. The decision of whether to control these vehicle movements should be weighed during the design process. Both movements can potentially be signalized, especially if an appropriate curve radius (intended to lower vehicular speeds) is difficult to obtain in design. Any potential queuing from signal control of these movements should be accounted for as part of the iterative design process.

Exhibit 3-22 presents the most likely design flags that are applicable to pedestrians at DDIs.

3.3.3 Bicycles—Key Safety Challenges

Bicyclists at DDIs face challenges that either create safety risks or stress for riding through the intersection.

- **Provision of space**—The existing bicycle facilities at DDIs have consisted of traditional bike lanes to the right of motor vehicles, passing through the crossover and back. A design principle for bicyclists is to provide a relatively straight line of travel for bicyclists through an intersection (or at least to avoid abrupt turns). Given the speed difference between motorists and bicyclists through DDIs and the crossover section, as well as the curvature throughout the entire intersection, a bike lane width or buffer larger than the typical size would improve bicyclist safety and comfort. Alternatively, separated facilities would address this issue.

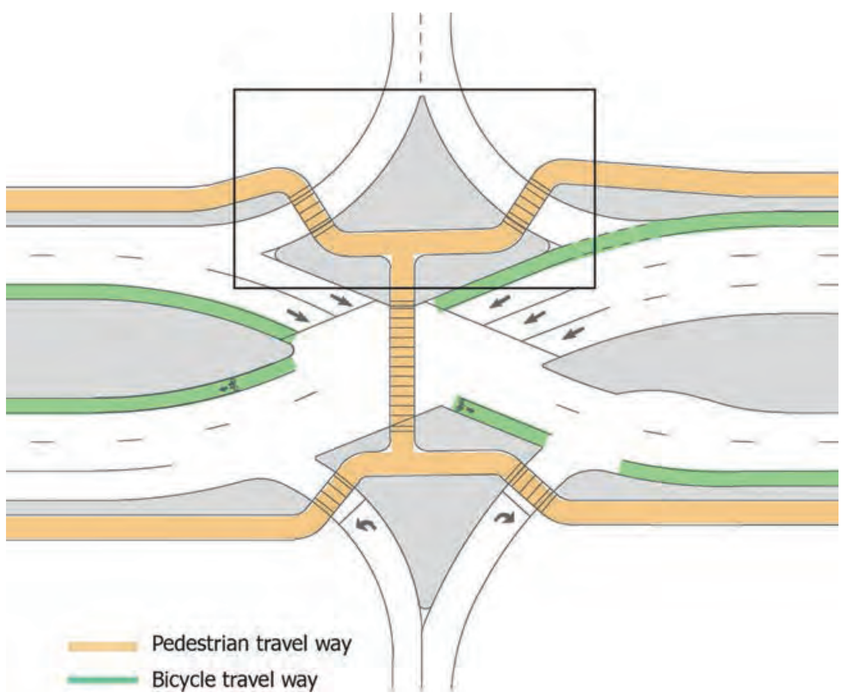

Exhibit 3-21. On-ramp free right and left turns with acceleration lanes.

Exhibit 3-22. Design flags applicable to pedestrians at DDIs.

Design Flag	Description	Exhibit
Motor Vehicle Right Turns	This flag would apply if right-turn-on-red (RTOR) were permitted.	Exhibit 3-23
Uncomfortable/Tight Walking Environment	Pre-existing bridges, abutments, and piers may constrain the total facility width between the crossovers.	Exhibit 3-24
Nonintuitive Motor Vehicle Movements	Pedestrians crossing on the outside would confront consecutive crossings with vehicle traffic arriving from the same direction.	Exhibit 3-25
Crossing Yield-Controlled or Uncontrolled Vehicle Movements	Movements to and from on- and off-ramps may be yield controlled and therefore create additional stress and safety concerns for pedestrians.	Exhibit 3-26
Indirect Paths	Outer crossing designs should still allow for pedestrian crossing of the mainline.	Exhibit 3-27
Executing Unusual Movements	In most local contexts, pedestrians do not expect to cross into the mainline median to continue moving along the mainline road.	Exhibit 3-28
Multilane Crossings	Depending on the lane configuration, pedestrians may cross multiple lanes either when crossing an on- or off-ramp or when crossing into the median.	Exhibit 3-29
Motor Vehicle Left Turns	This flag would apply if left-turn-on-red were permitted.	Exhibit 3-30
Sight Distance for Gap Acceptance Movements	At yield-controlled movements, vertical and horizontal alignments should allow for proper sight distance to pedestrian crossings.	Exhibit 3-31
Grade Change	Vertical curves on bridges may create challenges for pedestrians with mobility challenges or those carrying or pushing objects.	Exhibit 3-32

- **On-ramp movements**—If free-flow movements are provided for motorists to access freeway on-ramps, then an uncontrolled diverging conflict point is introduced between bicyclists and motorists (essentially a "right hook" opportunity). This is closely related to safety concerns with turning motorists crossing bicycle paths and should be treated as such for bicyclists in the design flag assessment.
- **Bicycle clearance time**—An approaching bicyclist must judge if there is enough time to clear the intersection before a phase change. Usually, there are two options for bicyclists to assist in this decision.
  1. If a pedestrian signal is present with a countdown, the bicyclist may get a better idea of when a signal phase is about to transition. Note that this is not the design intent of countdown timers, but they may be useful to the bicyclists. The decision to cross may lead to a bicyclist still being in the intersection when the phase changes.

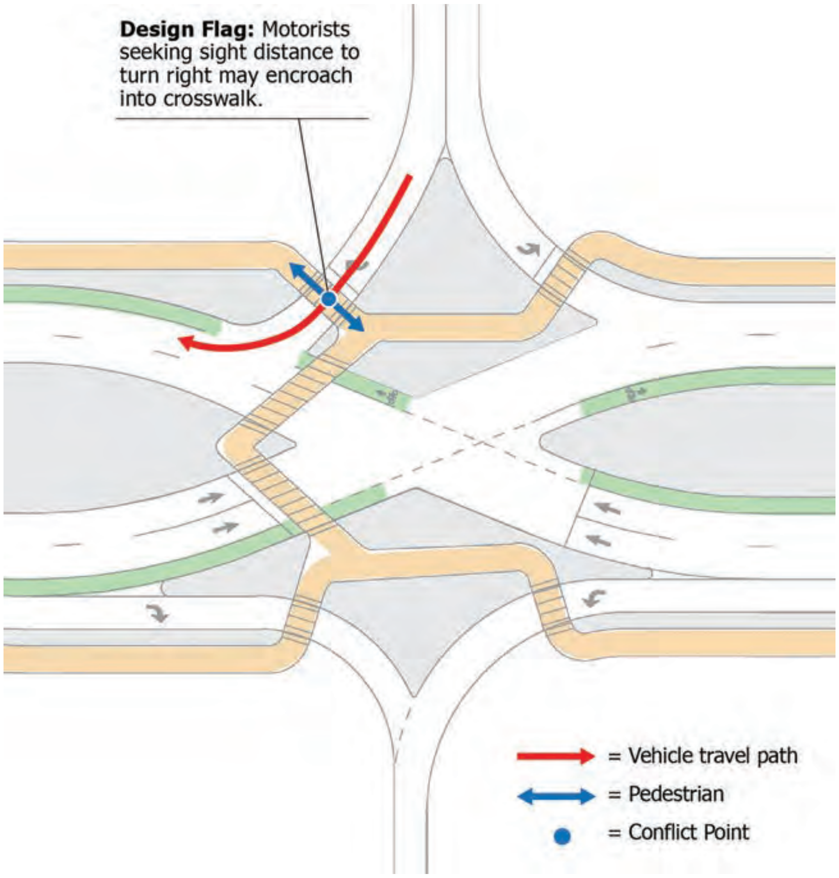

Exhibit 3-23. Motor vehicle right turns design flag.

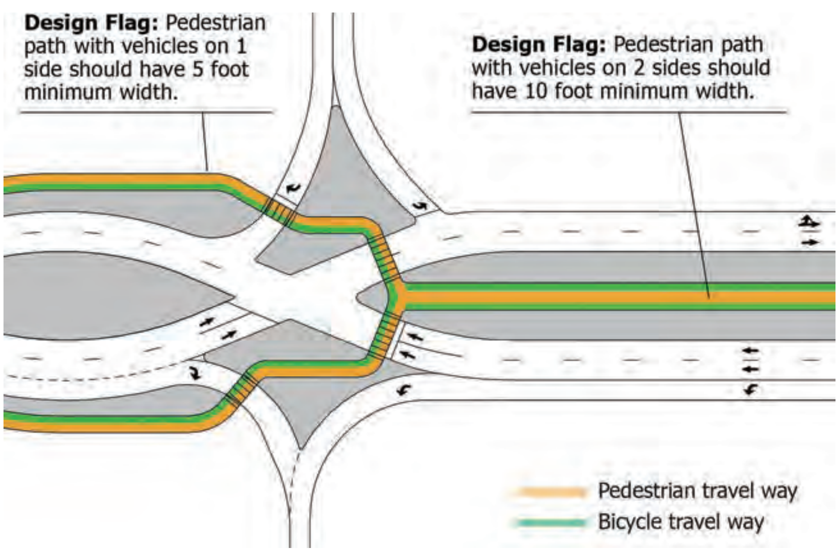

Exhibit 3-24. Uncomfortable/tight walking environment design flag.

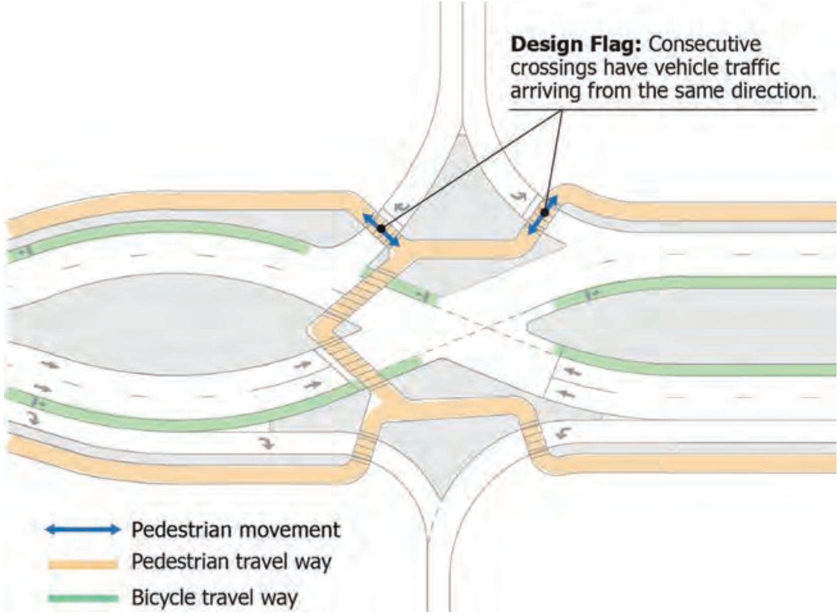

Exhibit 3-25. Nonintuitive motor vehicle movements design flag.

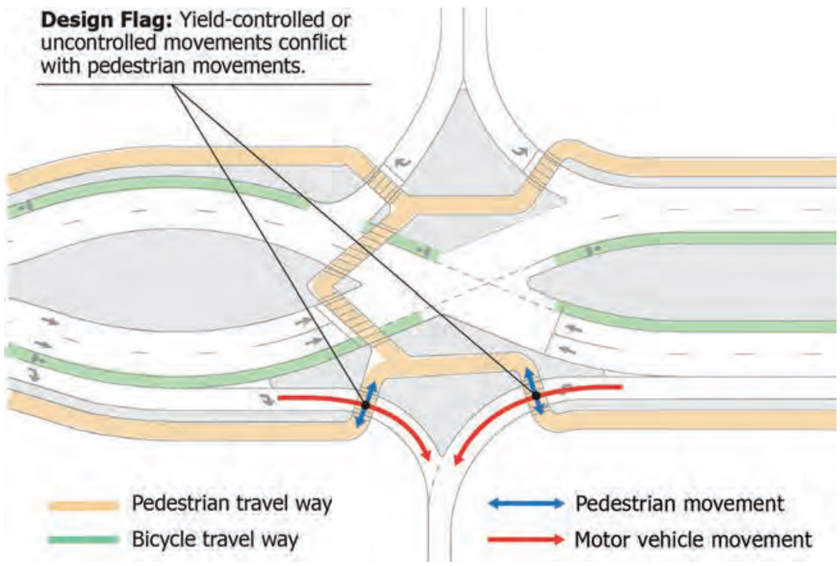

Exhibit 3-26. Crossing yield-controlled or uncontrolled vehicle movements design flag.

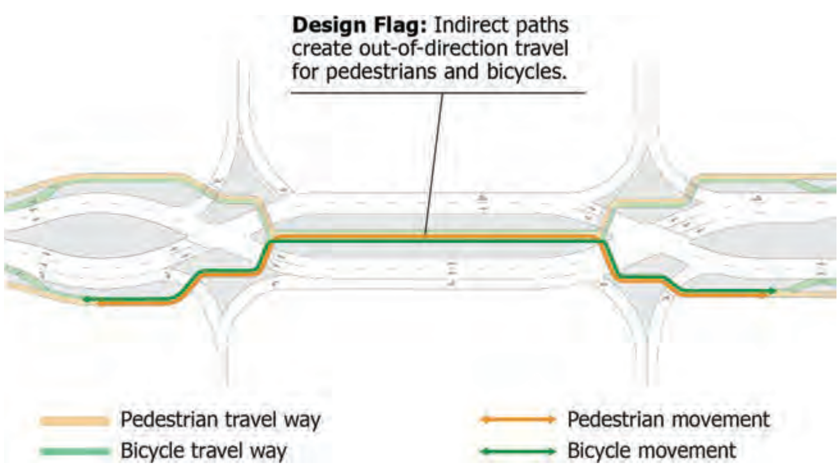

Exhibit 3-27. Indirect path design flag.

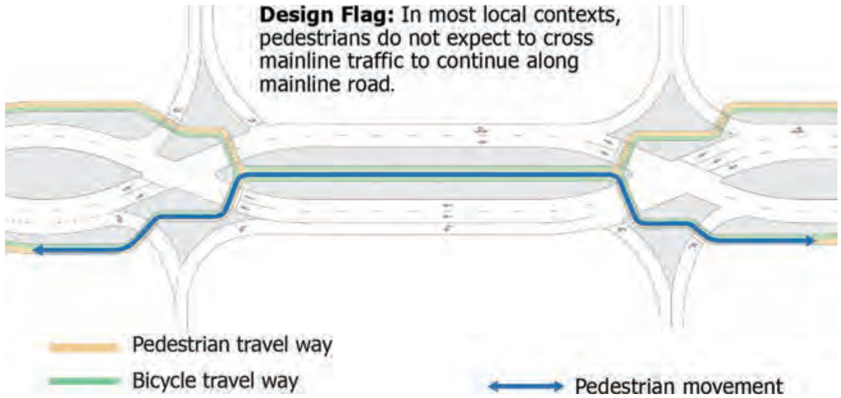

Exhibit 3-28. Executing unusual movements design flag.

2. At many signals, a bicyclist will only be able to rely on the yellow clearance phase for vehicular traffic. This yellow clearance phase is designed just for drivers and generally does not exceed 5 seconds. This clearance time is almost always too short for bicyclists to clear the intersections. The disparity is exacerbated as clearance lengths increase.

When signal heads are placed upstream of the intersection, bicyclists have no indication of whether the signal phase has changed once they have passed the signal heads.

In consideration of the bicyclist conflict points at DDIs and the key safety challenges that accompany them, Exhibit 3-33 presents the design flags that are most likely applicable to bicyclists at DDIs.

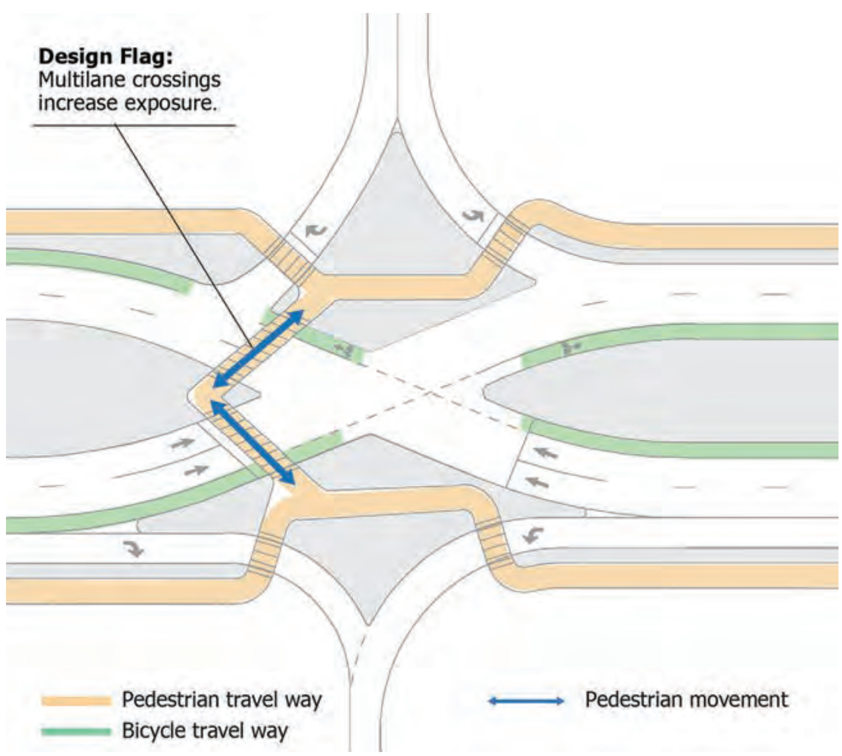

Exhibit 3-29. Multilane crossings design flag.

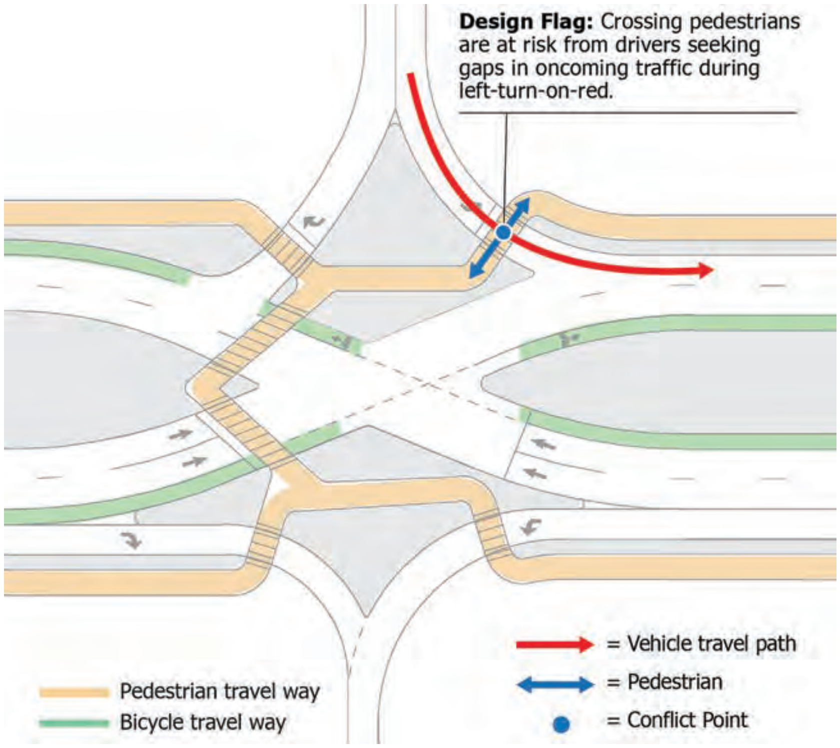

Exhibit 3-30. Motor vehicle left turns design flag.

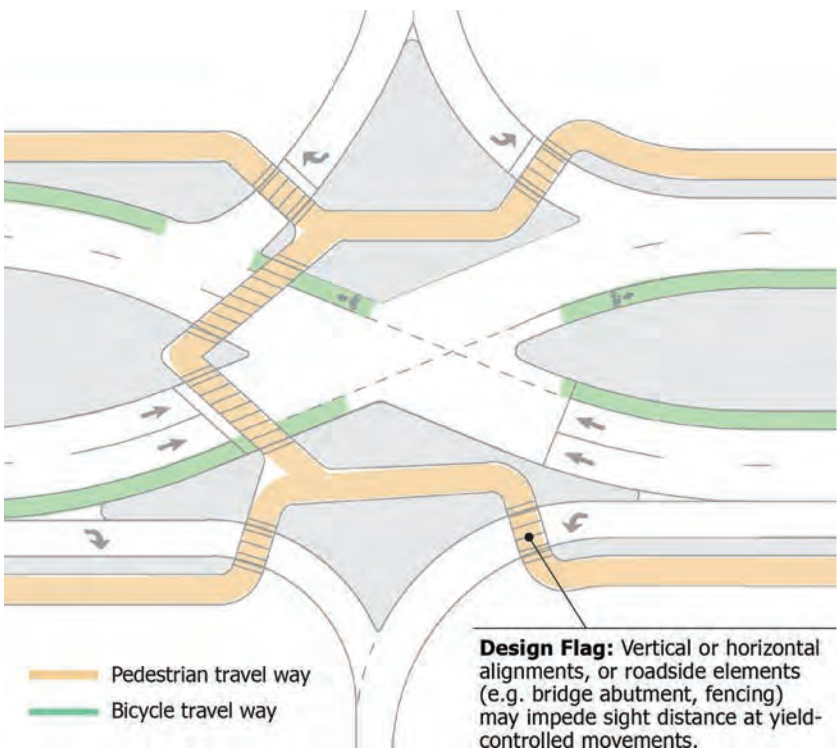

Exhibit 3-31. Sight distance for gap acceptance movements design flag.

Exhibit 3-32. Grade change design flag.

Exhibit 3-33. Design flags applicable to bicyclists at DDIs.

Design Flag	Description	Exhibit
Executing Unusual Movements	Similar to motor vehicles, bicyclists do not expect to cross to the left side of the road when crossing the DDI.	Exhibit 3-28
Multilane Crossings	Large DDIs may induce bicycles to cross a significant number of lanes at the crossover.	Exhibit 3-29
Undefined Crossings at Intersections	While not unique to DDIs, a lack of bicycle markings crossing ramp merge or diverge points may result in vehicles impeding upon the bicycle lane, particularly if RTOR is permitted.	Exhibit 3-34
Grade Change	Vertical curves on bridges may create challenges for bicycles trying to maintain speed, resulting in a large speed differential with vehicles.	Exhibit 3-32
Riding in Mixed Traffic	While not unique to DDIs, vehicle speeds near interchanges may be significant, especially if curves have large design radii.	Exhibit 3-35
Bicycle Clearance Time	Long distances between the crossover and right-turn off-ramp movement may result in conflict between bicyclists and right-turning vehicles.	Exhibit 3-36
Turning Motorists Crossing Bicycle Path	A high volume of turns onto the on-ramp may exacerbate vehicle-bicycle conflicts.	Exhibit 3-37
Riding between Travel Lanes, Lane Additions, or Lane Merges	Off-ramp designs with lane additions or downstream merges create additional stress and safety concerns for bicyclists traveling along the mainline.	Exhibit 3-38
Off-Tracking Trucks in Multilane Curves	Trucks moving through the crossover intersections may off-track into adjacent bicycle lanes.	Exhibit 3-39

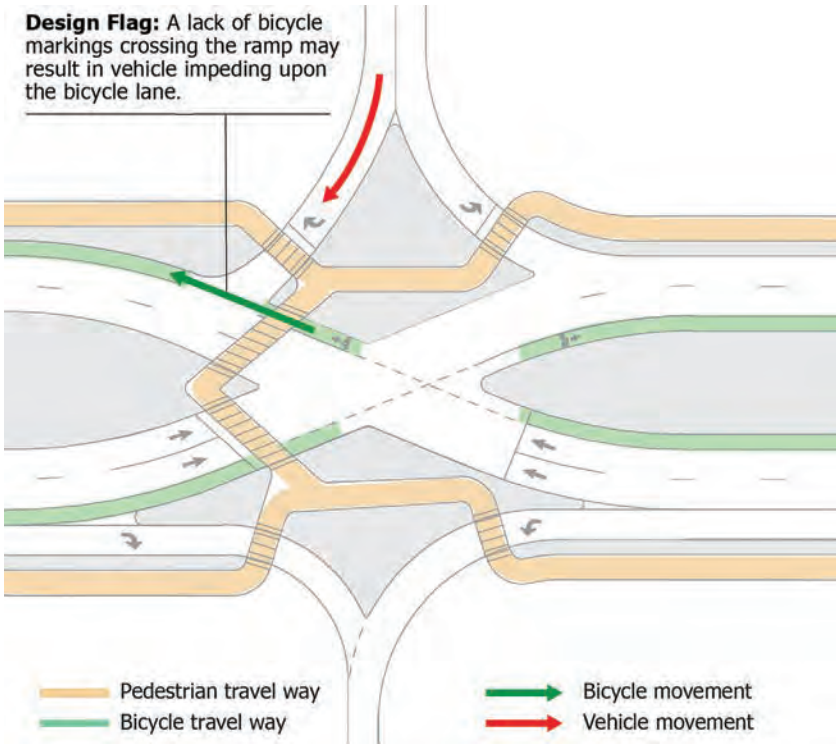

Exhibit 3-34. Undefined crossing at intersection design flag.

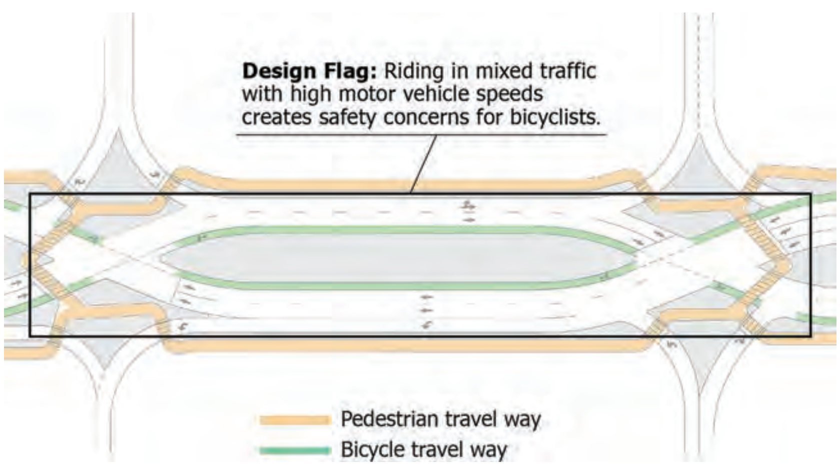

Exhibit 3-35. Riding in mixed traffic design flag.

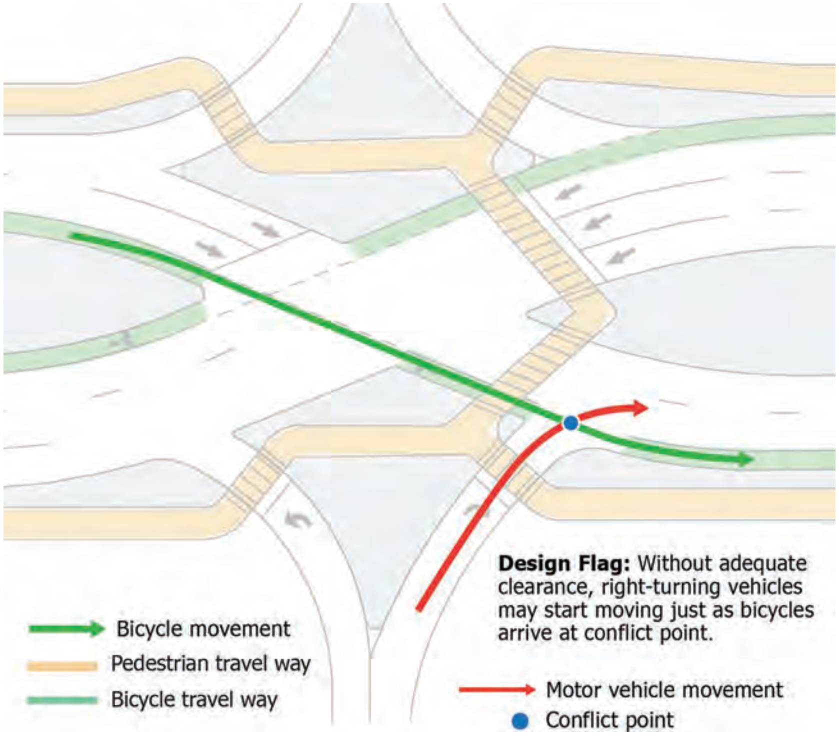

Exhibit 3-36. Bicycle clearance time design flag.

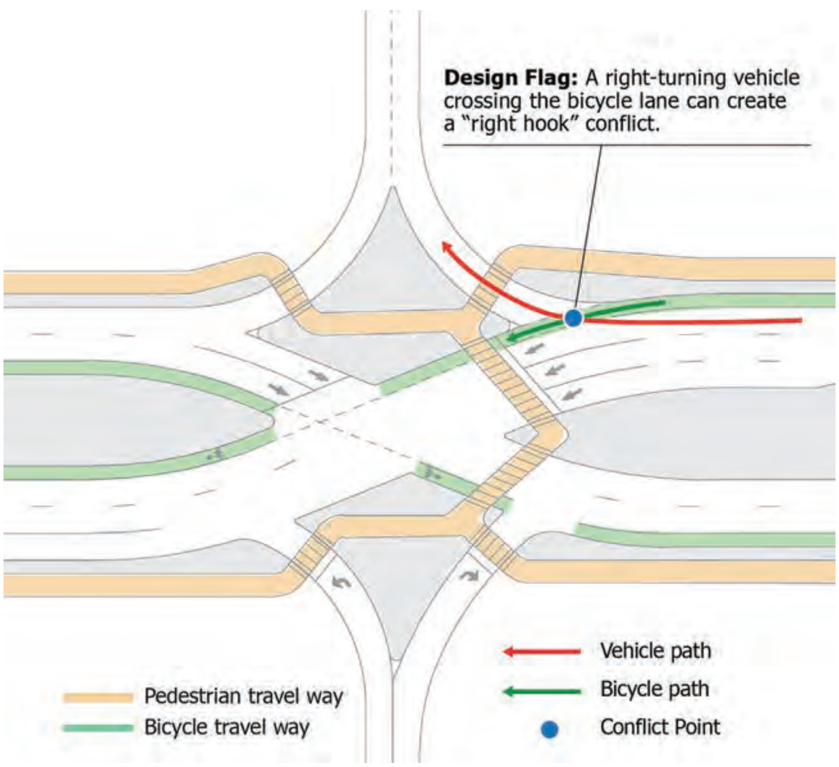

Exhibit 3-37. Turning motorist crossing bicycle path design flag.

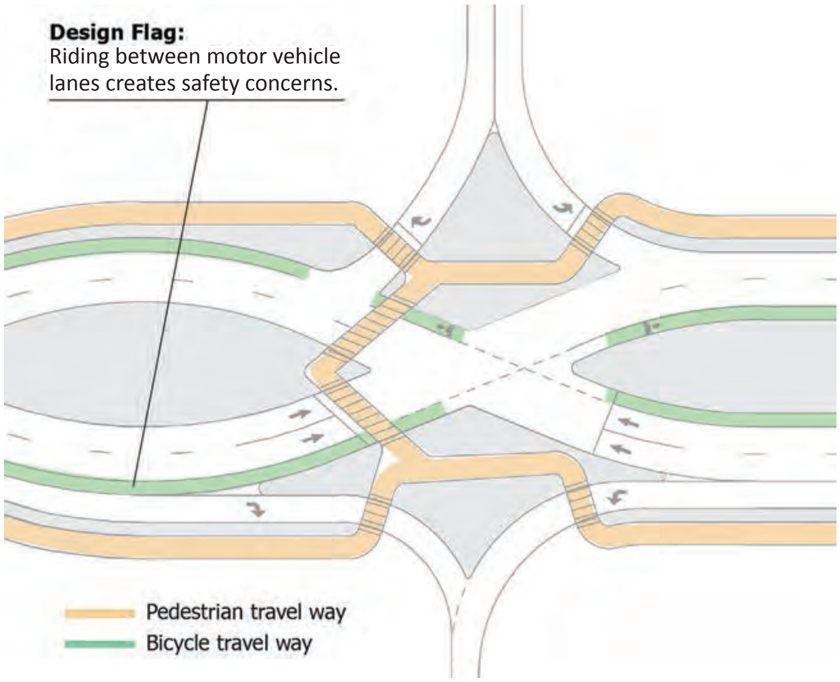

Exhibit 3-38. Riding between travel lanes, lane additions, and lane merges design flag.

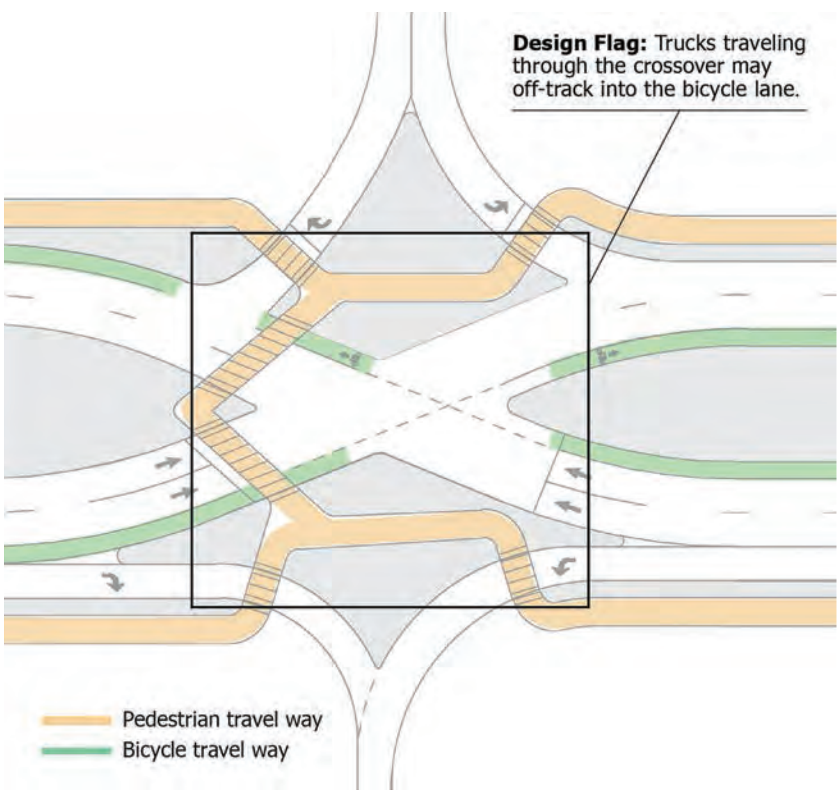

Exhibit 3-39. Off-tracking trucks in multilane curves design flag.

3.4 Intersection-Level Concepts

Three design concepts are presented in this section to offer techniques for improving pedestrian and bicycle safety and operational performance of DDIs. These concepts are not suggested as designs to be replicated as-is; rather, they illustrate the DDI options that are possible in various contexts. Note that these concepts mix design approaches. The designer must consider traffic volume and speed when matching designs and treatments to the appropriate context.

Following each concept is a discussion of the flags remaining with the given design—in other words, the flags not obviated by the design that would still need to be addressed.

The designs include the following:

- Shared-use path/inner walkway concept,
- On-street bike lane/outer walkway concept, and
- Separated bike lane/inner walkway concept.

Section 3.3 presents other key design flags that would be subject to site-specific concerns and are not obviously presented or addressed with any of the concepts presented below.

3.4.1 Shared-Use Path/Inner Walkway Concept

The first DDI concept, shown in Exhibit 3-40, includes a shared-use path located inside the median. Bicycle access to the shared-use path is provided upstream of the DDI through the use of bicycle ramps. Downstream of the DDI, ramps return bicyclists to the roadway. The concept would be appropriate for intersections where heavy vehicle movement through the crossover may result in truck off-tracking through the crossovers. The inner shared-use path allows for free-flowing left turns onto the freeway without pedestrian or bicycle conflicts.

Benefits—This design addresses the following key elements with respect to safety and comfort:

- **Nonintuitive motor vehicle movements design flag—**By providing an inner walkway, pedestrians cross motor vehicle movements in an alternating fashion. Vehicles arrive from the left at the first crossing, from the right at the next crossing, and so on. This conforms with the typical expectation.
- **Indirect path design flag**—Pedestrians and bicyclists can cross the mainline by proceeding from one side of the roadway, into the center median, and then to the opposing side of the roadway. This avoids the need for pedestrians to travel to an adjacent intersection to cross the mainline. This flag may still apply for other movements as described below.

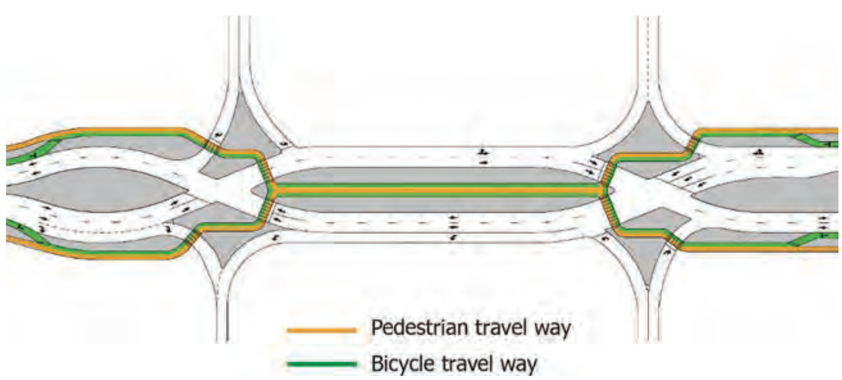

Exhibit 3-40. DDI shared-use path/inner walkway design concept.

- **Undefined crossings at intersections design flag**—All locations where pedestrians and bicyclists cross motor vehicles are marked. This will reduce the likelihood that vehicles will encroach on the crossing areas when stopped for a signal.
- **Motor vehicle left turns design flag**—The inner walkway design removes pedestrians from crossing the left turn at the off-ramp.
- **Riding in mixed traffic design flag**—This design features a bike ramp off the roadway and onto the shared-use path. Bicyclists are provided a less stressful and safer path through the interchange.
- **Bicycle clearance time design flag**—By removing bicyclists from the roadway, the bicyclists no longer must travel between the crossover intersection and the right turn from the off-ramp. This eliminates the need for additional clearance time otherwise needed for bicyclists to cover this distance.
- **Turning motorists crossing bicycle path design flag**—The bicycle ramp to the shared-use path is placed upstream of the development of the right-turn lane onto the on-ramp. This eliminates the conflict of motorists crossing the bicycle path.
- **Off-tracking trucks in multilane curves design flag**—Heavy vehicles may experience challenges maintaining their lane when traveling through the crossover intersections. By providing an off-street shared-use path for bicyclists, the users are separated in space, avoiding the potential conflict.

Challenges—Emphasizing that the design is not intended to be "ready-made," this concept leaves several design flags as described in Exhibit 3-41.

3.4.2 On-Street Bike Lane/Outer Walkway Concept

The second DDI concept, shown in Exhibit 3-42, features an outer walkway for pedestrians and on-street bicycle lanes. This concept could be implemented at locations where bridge piers or other objects in the median make an inner walkway difficult, or where local preference is to remain on the outside of the interchange. As on-street bicycle lanes are present, the design is best suited where geometric elements create a low speed environment.

Benefits—This design addresses the following key elements with respect to safety and comfort:

- **Indirect path design flag**—Pedestrians can cross the mainline by proceeding from one side of the roadway, into the center median, and then to the opposing side of the roadway. This avoids the need for pedestrians to travel to an adjacent intersection to cross the mainline.
- **Executing unusual movements design flag**—By providing an outer walkway, pedestrians desiring to continue along the mainline can do so without crossing any mainline movement. This flag still applies to bicyclists (see challenges below).
- **Undefined crossings at intersections design flag**—All locations where pedestrians and bicyclists cross motor vehicles are marked. This will reduce the likelihood that vehicles will encroach on the crossing areas when stopped for a signal.

Challenges—Emphasizing again that the design is not intended to be "ready-made," this concept leaves several design flags as described in Exhibit 3-43.

3.4.3 Separated Bike Lane/Inner Walkway Concept

The final DDI concept, shown in Exhibit 3-44, provides a separated bike lane through the intersection located within the median between the crossovers as well as an inner walkway for pedestrians. The presence of the pedestrian walkway inside the separated bike lanes provides additional separation for pedestrians from motor vehicles while moving through the median. For less confident bicyclists, the separation from both pedestrians and motor vehicles reduces stress.

Exhibit 3-41. Summary of design flags remaining with DDI shared-use path/ inner walkway design concept.

Design Flag	Description
Motor Vehicle Right Turns	DDIs tend to have high volumes of turns to and from the freeway. This design still requires pedestrians to cross the right turn from the off-ramp. This flag can be mitigated by prohibiting RTOR or by designing the curve radii to keep speeds from exceeding 25 mph. Further, the pedestrian yield point and the merge point should be separated in space.
Uncomfortable/Tight Walking Environment	Careful design of the inner walkway is necessary as the design progresses to ensure it provides adequate space for all users.
Crossing Yield-Controlled or Uncontrolled Vehicle Movements	This design has a yield-controlled right turn onto the on-ramp. Given the expected high volume of turns onto the on-ramp, the curve radii should be designed to keep vehicle speeds from exceeding 25 mph. This will mitigate the flag by increasing the likelihood of vehicles yielding to pedestrians.
Indirect Path	Users desiring to continue along the mainline may experience enough out of direction travel crossing to the median and back that the indirect path flag would apply.
Executing Unusual Movements	In most areas, DDIs are a relatively novel design. Users desiring to continue along the mainline likely do not expect to need to cross one direction of mainline traffic. Proper wayfinding design will be especially important for all users to understand how to execute their desired path.
Multilane Crossings	At the crossovers of this design, pedestrians must cross multiple lanes without refuge (the yellow flag threshold for pedestrians is 2–3 lanes).
Sight Distance for Gap Acceptance Movements	The motor vehicle right turns to the on-ramp are yield controlled and therefore require careful attention to sight distance requirements. In this design, the position of the crosswalk upstream of the center of the curve would likely provide adequate sight distance.
Grade Change	While not able to be evaluated from the plan view provided, interchanges can experience grade changes. This should be evaluated during the flag assessment process.

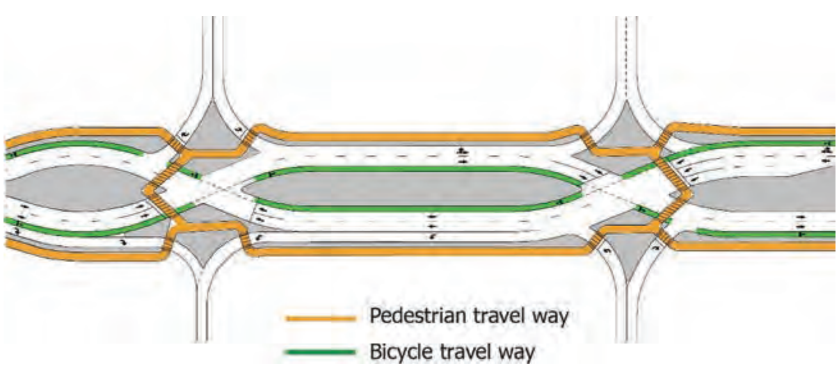

Exhibit 3-42. DDI on-street bike lane/outer walkway design concept.

Exhibit 3-43. Summary of design flags remaining with DDI on-street bike lane/ outer walkway design concept.

Design Flag	Description
Motor Vehicle Right Turns	DDIs tend to have high volumes of turns to and from the freeway. This design still requires pedestrians to cross the right turn from the off-ramp. This flag can be mitigated by prohibiting RTOR or by designing the curve radii to keep speeds from exceeding 25 mph.
Nonintuitive Motor Vehicle Movements	Shared-use path users following the outer walkway will encounter motor vehicles approaching from the same direction twice in a row. This deviates from the typical expectation of encountering vehicles from alternating directions.
Crossing Yield-Controlled or Uncontrolled Vehicle Movements	This design has a yield-controlled right turn onto the on-ramp. Given the expected high volume of turns onto the on-ramp, the curve radii should be designed to keep vehicle speeds from exceeding 25 mph. This will mitigate the flag by increasing the likelihood of vehicles yielding to pedestrians.
Executing Unusual Movements	In most areas, DDIs are a relatively novel design. Users desiring to continue along the mainline likely do not expect to need to cross one direction of mainline traffic. Proper wayfinding design will be especially important for all users to understand how to execute their desired path.
Multilane Crossings	At the crossovers of this design, pedestrians must cross multiple lanes without refuge (the yellow flag threshold for pedestrians is 2–3 lanes).
Sight Distance for Gap Acceptance Movements	The motor vehicle right turns to the on-ramp are yield controlled and therefore require careful attention to sight distance requirements. In this design, the position of the crosswalk upstream of the center of the curve would likely provide adequate sight distance.
Grade Change	While not able to be evaluated from the plan view provided, interchanges can experience grade changes. This should be evaluated during the flag assessment process.
Riding in Mixed Traffic	Given the expected high volume of vehicles on an interchange, this flag must be mitigated through vehicle speed control. Geometric design should be employed to reduce speeds below 25 mph (yellow flag threshold).
Bicycle Clearance Time	Bicyclists need sufficient time to travel through the crossover and continue through the right turn from the off-ramp. Without signal timing details, it is not possible to determine the applicability of this flag to the design.
Turning Motorists Crossing Bicycle Lanes	Vehicles turning right to the on-ramp must cross the bicycle lane, resulting in a conflict.
Riding between Travel Lanes, Lane Additions, or Lane Merges	The addition of the right-turn pocket onto the on-ramp results in bicyclists riding between the through and right-turn lanes for an extended period.
Off-Tracking Trucks in Multilane Curves	Bicycles moving through the crossover may be impeded by heavy vehicles off-tracking. Careful design of lane widths and curve radii may mitigate this issue.

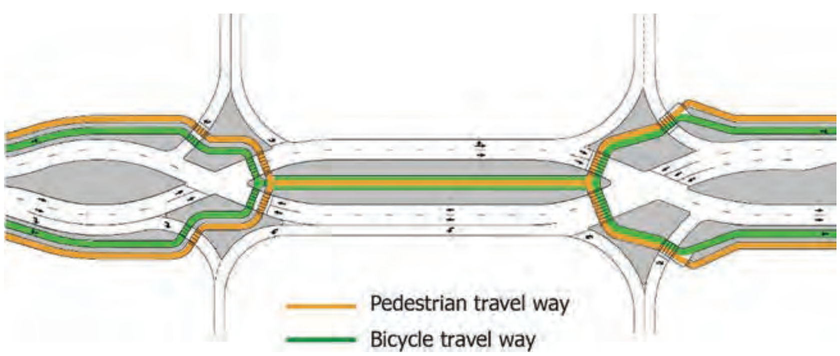

Exhibit 3-44. DDI separated bike lane/inner walkway design concept.

Benefits—This design addresses the following key elements with respect to safety and comfort:

- **Uncomfortable/tight walking environment design flag—**This design provides an exclusive path for pedestrians separate from both bicyclists and motor vehicles. By placing motor vehicles on either side of pedestrians in the inner walkway, pedestrians are further removed from motor vehicles. Care should be taken in design to ensure proper space is provided for pedestrians to move past each other without encroaching on the bicycle lanes.
- **Nonintuitive motor vehicle movements design flag—**By providing an inner walkway, pedestrians cross motor vehicle movements in an alternating fashion. Vehicles arrive from the left at the first crossing, from the right at the next crossing, and so on. This conforms with the typical expectation.
- **Indirect path design flag—**Pedestrians and bicyclists can cross the mainline by proceeding from one side of the roadway, into the center median, and then to the opposing side of the roadway. This avoids the need for pedestrians to travel to an adjacent intersection to cross the mainline. This flag may still apply for other movements as described below.
- **Undefined crossings at intersections design flag—**All locations where pedestrians and bicyclists cross motor vehicles are marked. This will reduce the likelihood that vehicles will encroach on the crossing areas when stopped for a signal.
- **Motor vehicle left turns design flag—**The inner walkway design removes pedestrians from crossing the left turn at the off-ramp.
- **Riding in mixed traffic design flag—**This design features a bike ramp off the roadway and onto the shared-use path. Bicyclists are provided a less stressful and safer path through the interchange.
- **Bicycle clearance time design flag—**By removing bicyclists from the roadway, the bicyclists no longer must travel between the crossover intersection and the right turn from the off-ramp. This eliminates the need for additional clearance time otherwise needed for bicyclists to cover this distance.
- **Turning motorists crossing bicycle path design flag—**The bicycle ramp to the shared-use path is placed upstream of the development of the right-turn lane. This eliminates the conflict of motorists crossing the bicycle path.
- **Off-tracking trucks in multilane curves design flag—**Heavy vehicles may experience challenges in maintaining their lane when traveling through the crossover intersections. By providing an off-street shared-use path for bicyclists, the users are separated in space, avoiding the potential conflict.

Challenges—Emphasizing again that the design is not intended to be “ready-made,” this concept leaves several design flags as described in Exhibit 3-45.

3.5 Detailed Design Techniques

Design flags are a means of identifying areas of an alternative that may create challenges for pedestrians or bicycles. This section addresses design responses to common DDI challenges to assist in addressing flags. This includes:

- Pedestrian phase coordination,
- Pedestrian channelization and wayfinding,
- ADA and accessibility,
- Channelized turn lanes,
- Vehicle movements from counterintuitive directions, and
- Indirect paths.

Exhibit 3-45. Summary of design flags remaining with DDI separated bike lane/ inner walkway design concept.

Design Flag	Description
Motor Vehicle Right Turns	DDIs tend to have high volumes of turns to and from the freeway. This design still requires pedestrians to cross the right turn from the off-ramp. This flag can be mitigated by prohibiting RTOR or by designing the curve radii to keep speeds from exceeding 25 mph.
Crossing Yield-Controlled or Uncontrolled Vehicle Movements	This design has a yield-controlled right turn onto the on-ramp. Given the expected high volume of turns onto the on-ramp, the curve radii should be designed to keep vehicle speeds from exceeding 25 mph. This will mitigate the flag by increasing the likelihood of vehicles yielding to pedestrians.
Indirect Path	Users desiring to continue along the mainline may experience enough out of direction travel crossing to the median and back that the indirect path flag would apply.
Executing Unusual Movements	In most areas, DDIs are a relatively novel design. Users desiring to continue along the mainline likely do not expect to need to cross one direction of mainline traffic. Proper wayfinding design will be especially important for all users to understand how to execute their desired path.
Multilane Crossings	At the crossovers of this design, pedestrians must cross multiple lanes without refuge (the yellow flag threshold for pedestrians is 2–3 lanes).
Sight Distance for Gap Acceptance Movements	The motor vehicle right turns to the on-ramp are yield controlled and therefore require careful attention to sight distance requirements. In this design, the position of the crosswalk upstream of the center of the curve would likely provide adequate sight distance.
Grade Change	While not able to be evaluated from the plan view provided, interchanges can experience grade changes. This should be evaluated during the flag assessment process.

Design techniques for specific design flags can be found in *NCHRP Research Report 948: Guide for Pedestrian and Bicycle Safety at Alternative Intersections and Interchanges* (forthcoming) (*5*).

3.5.1 Pedestrian Phase Coordination

With an inner walkway between the crossovers, the designer has the ability to time pedestrian crossings to match crossing behavior. Because the right turn onto a freeway on-ramp does not require coordination with any other phase at the DDI, the signal timing can progress the pedestrian movement across the right-turn on-ramp (if the movement is signalized) and then across the crossover movement or vice versa.

The geometry of the freeway off-ramps affects pedestrian crossing delay as well. Where an inner walkway is provided, the right-turn off-ramp and adjacent crossover crossing can operate concurrently (Exhibit 3-46). Depending on the distance between crossings and the phase length, a pedestrian may be able to cross both movements in a single signal phase. A design that keeps these crossings as close as possible would promote that sequential crossing (*6*).

Where an outer walkway is provided, the right-turn and left-turn off-ramp movements will not run concurrently (Exhibit 3-10). Thus, the distance of these crossings from one another is of less importance for pedestrian progression: pedestrians either walk slightly farther or are likely waiting for the signal phase to change (*6*).

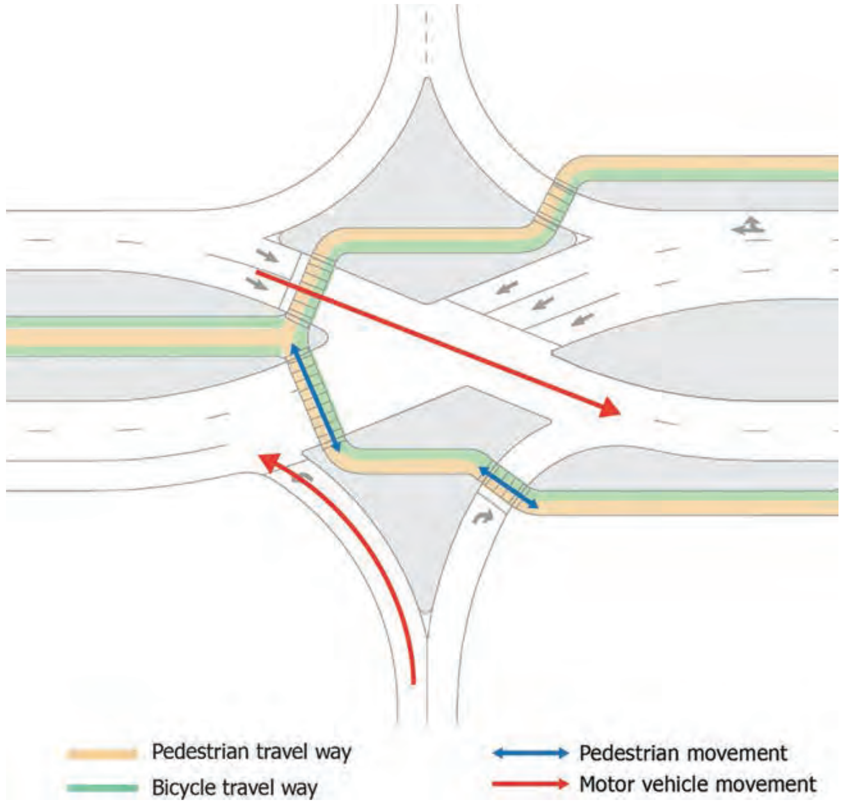

Exhibit 3-46. Back-to-back off-ramp crossings during the same signal phase.

3.5.2 Pedestrian Channelization and Wayfinding

Because the DDI crossover is unusual for drivers, human factors considerations are emphasized throughout the design process. Human factors considerations also apply to the pedestrian environment, which is different from what pedestrians are used to at conventional interchanges.

With center walkways, crossing to the center of the street is unusual compared to the typical hierarchy of street design in which pedestrian facilities are placed outside of vehicular traffic. This hierarchy is satisfied for outside walkways, but pedestrian discomfort can arise as pedestrians have to cross a freeway bridge or walk through an underpass adjacent to vehicular traffic. Depending on the design vehicle and speed of the DDI, the channelization islands separating the right- and left-turning movements can be quite large, and pedestrians need clear guidance and information on where they should and should not walk and where they should and should not cross.

Cut-through island designs can be used to provide positive guidance to pedestrians as to where walkway and crossing locations are provided. A cut-through walkway can guide the pedestrian directly to the intended crossing point and can be angled to support pedestrians in viewing oncoming vehicular traffic and potential conflicts. The channelization islands at DDIs provide the opportunity for wide walkways. The cut-through walkway should be at least 8 feet wide to comfortably accommodate pedestrians, including those with wheelchairs and other mobility devices. The actual curb ramp landing should be aligned perpendicular to the street centerline, which minimizes crossing distance and orients pedestrians to access ramps.

Exhibit 3-47. Channelization toward center crosswalk (4).

As an alternative to the cut-through design, landscaping (grass or gravel) can be used to define the boundaries of the pedestrian walkway and give pedestrians a sense of place in what can be very large channelization islands. Examples of cut-through and landscaping designs are provided in Exhibit 3-47 and Exhibit 3-48, respectively.

3.5.3 ADA and Accessibility

Accessibility was previously described in Chapter 2 in the broader contexts of considering a project's contextual environment and the ability for various users to approach a desired destination or potential opportunity for activity using highways and streets (including the sidewalks and/or bicycle lanes provided within those rights-of-way). The basic principles for accessible design can be divided into the pedestrian walkway and the pedestrian crossing location. For pedestrian walkways, the following considerations apply:

- Delineate the walkway through landscaping, curbing, or fencing to assist with wayfinding for pedestrians with visual impairments. Examples of wayfinding provisions are shown in Exhibit 3-49 and Exhibit 3-50. Note the use of fencing under the bridge structure where landscaping is more difficult to maintain.
- Provide sufficient space (length and width) and recommended slope rates for wheelchair users and other nonmotorized users, such as people pushing strollers, walking bicycles, and others.

Exhibit 3-48. Channelization toward outside crosswalk (4).

Exhibit 3-49. Example of pedestrian wayfinding provision at DDI via curbing (4).

- Construct an appropriate landing with flat slope and sufficient size at crossing points.

For pedestrian crossing locations, these additional considerations apply:

- Provide curb ramps and detectable warning surfaces at the end of curb ramp and transition to the street.
- Align the curb ramp landing to the intended crossing direction.
- Crosswalk width through the intersection should be wide enough to permit pedestrians and wheelchairs to pass without delay from opposing directions, and the medians should provide sufficient storage for all nonmotorized users to safely wait when two-stage crossings are required.
- Pedestrians with vision, mobility, or cognitive impairments may benefit from targeted outreach and additional informational material created with these specific users in mind. These outreach materials should include information on crosswalk placement and intended behavior, as well as answers to frequently asked questions. For pedestrians with visual impairments, materials need to be presented in an accessible format with a sufficient description of all features of the DDI crossing.

Exhibit 3-50. Example of pedestrian wayfinding provision at DDI using an urban fence (4).

- Provide audible speech messages to communicate directionality of traffic (from left or from right) at all crossing points. Audible speech messages should be used where spacing between accessible pedestrian signal (APS) devices is less than 10 feet or where additional narrative for the expected direction of traffic is needed (i.e., “traffic from left” or “traffic from right”).
- Provide accessible pedestrian signals with push-button locator tones at signalized crossings.
- Locate push buttons to be accessible by wheelchairs and adjacent to the crossing with a minimum separation of 10 feet.

At the DDI, locating the APS may pose a challenge on the median island for pedestrian facilities located in the center. Exhibit 3-51 shows an example of an undesirable pedestrian push-button installation with the push button for the two directions on the same pole. The lack of separation may make it difficult for pedestrians (especially those with vision disabilities) to distinguish which push button is intended for which crossing. Further, the example shown does not provide APS devices or any audible information about the crossing.

Given that the nose of the median island does not provide adequate room to allow for the pedestrian push buttons to be on separate poles and sufficiently separated, it is recommended that the pedestrian push buttons in the median be separated diagonally, as shown in Exhibit 3-52. Locating the push buttons downstream of the crosswalk provides audible separation between the APS messages and the oncoming traffic for which visually impaired pedestrians are listening.

In general, wider islands are strongly recommended to provide a true refuge area of at least 6 feet in the direction of pedestrian travel. This ensures a minimum of 2 feet between the detectable warning surfaces and adequate storage for wheelchair users.

If the two APS devices are less than 10 feet apart, speech messages with customized wording specific to the DDI are required to be played after activating the push button. During the “Wait” interval, one potential wording [for speech push-button information message, see MUTCD 4E.13, par 9 & 10 (*7*)] may be: “Wait to cross eastbound lanes Airport Road at Highway 26. Traffic coming from your left.” During the “Walk” interval, the message would be: “Eastbound lanes Airport Road; walk sign is on to cross eastbound lanes Airport Road.” An expert in

Exhibit 3-51. Undesirable use of single pole with two pedestrian push buttons, no APS, and insufficient separation of the two detectable warning surfaces (4).

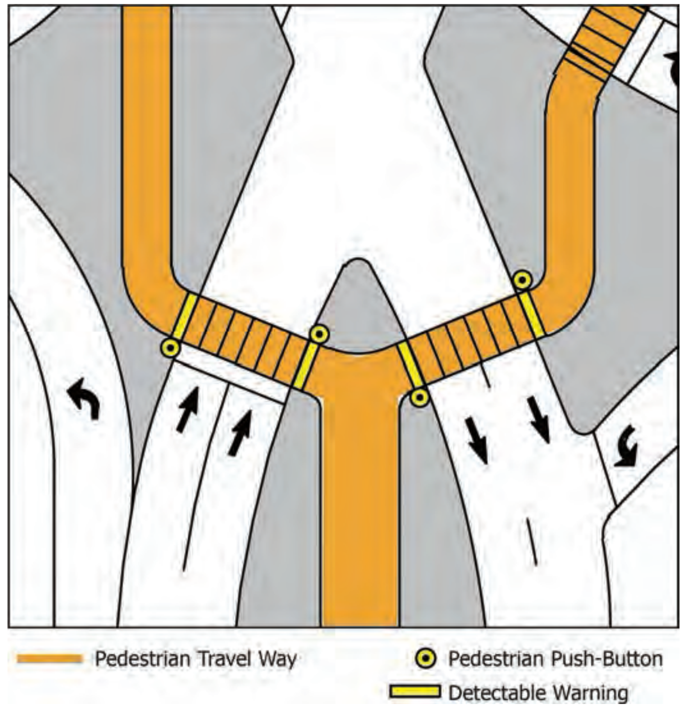

Exhibit 3-52. DDI splitter island with diagonal pedestrian signals.

accessibility installations may need to be consulted for specialized applications and signal installations at a DDI to ensure that the crossings are accessible to and usable by all pedestrians as required by ADA.

3.5.4 Turning Movements at Ramps

Channelization of all turns to and from the freeway is used to discourage wrong-way maneuvers and to move ramp terminal intersections away from the crossover intersection. Channelization, especially for unsignalized turns, could create pedestrian safety concerns due to the potential for high speeds and sight distance limitations.

Many DDI designs have been associated with upgrades to pedestrian facilities and/or shared-use paths, and best practices for the design of these facilities are still developing. Considerations include location of the pedestrian facilities (outer versus inner), unintuitive traffic directions for crossing, radius and speed of turning movements, and whether to use a form of signalization at on-ramps.

Attention to the placement, visibility, and vehicular speeds is necessary when considering the pedestrian crossing the on-ramp where speeds are higher and where there may be limited sight distance. This applies to the right-turn on-ramp regardless of the pedestrian facility selected and to the left-turn on-ramp if pedestrian facilities are placed on the outside.

Exhibit 3-53 shows one example of a left-turn crossing, viewed from the raised island and in line with one of the two crossing points for the unsignalized left turn onto the freeway. The image shows an exclusive left-turn lane approaching the crosswalk, with motor vehicles accelerating toward the freeway on-ramp. The exhibit further shows potential visibility limitations for pedestrians crossing from the bridge to exit the DDI (i.e., toward the photographer). The waiting area is obscured by a shadow in the photo, but even at other times of day, the line of sight between the waiting position and the approaching truck in the left-turn lane is

Exhibit 3-53. Example of pedestrian crossing at free-flow left onto freeway (8).

partially obstructed by the barrier wall on the bridge structure. Free-flowing vehicle movements, elevated speeds, acceleration, and insufficient sight distance can contribute to low yielding and an increased chance of conflicts at these crossing locations.

To overcome visibility and sight distance challenges, several potential treatments could be considered, including:

- Revising the left-turn geometry toward a pedestrian-focused DDI design with reduced turn radii, reduced vehicle speeds, and improved sight distances, as described above.
- Relocating the crosswalk to farther upstream in the turn-lane for improved sight distance, which may require a slightly longer crossing.
- Adding raised crosswalks or other geometric modifications to control vehicular speeds in the vicinity of the crosswalk.
- Installing signalization with standard signal heads, rectangular rapid-flashing beacons (RRFBs), or pedestrian hybrid beacons (PHBs) to alert drivers of the presence and crossing intent of a pedestrian.
- Providing a pedestrian-activated signal to supply a crossing opportunity with a steady red phase for vehicular traffic.
- Moving pedestrian facilities to inside the median (resolves left-turn movements, but right-turn movements may still need additional treatment).

While this discussion has focused on the channelized left turn to the freeway, similar considerations should be applied to channelized right-turn lanes to and from the freeway, as well as to the channelized left turn from the freeway (if yield controlled). Relative to other intersection forms, sight distance is a challenge at DDIs.

3.5.5 Vehicle Movements from Counterintuitive Directions

Regardless of whether inner or outer pedestrian facilities are provided, a unique issue with pedestrian crossings at DDIs is the propensity to look the wrong direction for gaps in traffic. One treatment that could be considered, in addition to supplemental signing and/or speech messages used with APS devices, is an embedded pavement marking, such as the one shown in Exhibit 3-54. Other marking possibilities that would be more accessible to pedestrians who cannot read English or have vision impairments could also be explored. This treatment could be helpful to pedestrians and is relatively inexpensive to install and maintain. The installation process may require that a small section of pavement is removed prior to marking installation. This provides protection against snowplows and wheel friction, which reduces the marking's maintenance needs.

Exhibit 3-54. Engraved pedestrian pavement marking—"Look Left" (4).

3.5.6 Indirect Paths

DDI design and signal phasing provide a natural time and location for pedestrian access across the mainline. Yet, some existing DDIs with outer walkways do not include provisions for pedestrians to cross the cross road at a DDI (Exhibit 3-55). If a pedestrian needs to cross the cross road, they are expected to travel to the next intersection to do so. This contradicts the design objectives to provide access, reasonable comfort, and acceptable travel time to all pedestrians. It can be expected that a person will find a desire line to cross, even if it is at the expense of safety, rather than detour to the next intersection and back for a street crossing. Crossings should be provided and can be accomplished with outer walkways. Concepts in Section 3.4.2 demonstrate how this can be reasonably achieved.

3.6 Transit

3.6.1 Buses on Cross Road

Buses operating on the cross road will benefit from the reduced number of signal phases and potentially lower delay when traveling through a DDI. In general, bus stops are not placed within interchanges unless there is transit service within the freeway corridor that stops at the interchange.

Exhibit 3-55. DDI with outer walkway and no arterial crossing opportunities.

3.6.2 Transit on Freeway

If rail transit or a busway is located within the freeway right-of-way and a station is provided at the interchange, a wider median on the cross road would allow buses on the cross road to stop directly above or below the station. This would facilitate passenger transfers, with passengers boarding and alighting directly from a median walkway with an elevator and stairs connecting the walkway to the freeway station platform. The added median width would provide room for both the elevator and stairs and for bus pullouts on the far side of the station access points to serve the bus stops.

Another transit possibility is that express bus service is provided on the freeway and transit service is also provided on the cross road, with a transfer between the two services. At a conventional diamond interchange, the typical approach would be to have the express bus service exit using the off-ramp, cross the cross road at the ramp terminal intersection, and serve a far-side stop before re-entering the freeway via the on-ramp. Because a DDI does not support through movements between off- and on-ramps, an alternative configuration would be needed. One option would be a "freeway flyer" stop where a bus-only collector-distributor road is provided adjacent to the freeway between the ramps, providing a safe location for buses to stop and serve passengers. Transfers between the freeway express and the cross road transit service would be facilitated via the inner walkway in much the same manner as described previously.

3.6.3 Light-Rail on Cross Road

Median-running light-rail can remain in the median and go "straight" at the crossover intersections. Light-rail remaining in the median would be served by a dedicated signal phase at crossover intersections. Extra clearance between the light-rail tracks and the adjacent travel lane may be required to allow for a train's dynamic envelope. Some form of positive separation may be desirable to discourage vehicles from encroaching onto the tracks when going through the curves at the crossover points.

An example of a median-running light-rail line through a DDI is shown in Exhibit 3-56. This light-rail line remains in the median through the DDI and has a dedicated (preemptive) signal phase to clear the main two crossover intersections of vehicles at both crossovers.

Geometric design considerations for a DDI with a center-running light-rail include:

- Crossover requires longer tangent length to clear rail line on straight trajectory.
- Spacing of the crossovers needs to be long enough to store the entire length of the train, unless signal phasing allows the light-rail to cross the entire DDI without stopping.

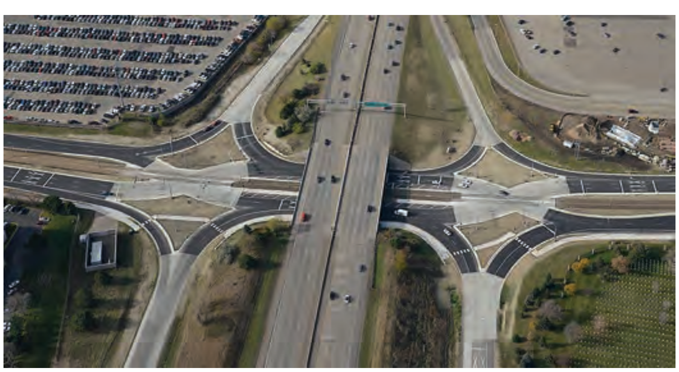

Exhibit 3-56. Aerial view of DDI with center-running light-rail at I-494 and 34th Avenue in Bloomington, Minnesota (9).

- Outer pedestrian facilities or two inner walkways (with the light-rail tracks in the middle) need to be provided.
- Pedestrian crossings of the cross road are possible, but placement of a median refuge area may be challenging due to the presence of the light-rail tracks.
- Drivers may be more likely to feel they are on the "wrong" side of the road when they see train movements to their right when between crossover intersections.

Traffic signal considerations for a DDI with center-running light-rail include:

- Additional movements to serve light-rail line through the crossover. These movements can be served in a phase concurrent with both right and left turns from the freeway.
- Signal stop bars moved further away from crossover to prevent drivers from stopping too close to the light-rail line.
- Advance pavement markings and signing alerting drivers of the rail crossing.
- Potential use of supplemental blank-out sign displaying a train graphic and message, such as "Light-Rail Crossing," when a train is approaching.

3.7 References

1. Cunningham, C., B. Schroeder, J. Hummer, C. Vaughan, C. Yeom, K. Salamati, D. Findley, J. Chang, N. Rouphail, S. Bharadwaj, C. Jagadish, K. Hovey, and M. Corwin. *Field Evaluation of Double Crossover Diamond Interchanges*. Contractor's Draft Submittal. FHWA, Project No. DTFH61-10-C-00029, 2014.
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3. Lee, K. Photo Credit.
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CHAPTER 4

Safety

Diverging diamond interchanges (DDIs), like many alternative intersection and interchange designs, offer quantifiable safety benefits compared to conventional interchange designs. This chapter provides an overview of safety principles of DDIs, followed by a summary of quantifiable safety findings. This chapter focuses on the safety aspects for motorized vehicles; refer to Chapter 3 for findings related to pedestrians and bicyclists.

4.1 Safety Principles

4.1.1 Conflict Points

The number of motor vehicle conflict points present at an intersection and volume of conflicting traffic present may serve as a surrogate measure of intersection safety. Conflict points are defined by the location where the paths of various traffic modes cross, including motor vehicle, bicycle, or pedestrian movements. Vehicle-to-vehicle conflicts are most often described as merging, diverging, or crossing, where crossing conflict points represent the greatest risk for higher severity crashes as they denote the location where severe angle collisions take place. Although traffic control devices can reduce the propensity for crashes by eliminating conflict points or controlling them through signing, signals, or pavement markings, traffic control and intersection geometry cannot completely eliminate the human error factor that contributes to collisions.

Exhibits 4-1 and 4-2 present vehicle-to-vehicle conflicts for a conventional diamond interchange and a DDI, while Exhibit 4-3 provides a direct comparison of the conflicts present at both interchanges.

Conventional diamond interchanges have 26 conflict points including off-ramp to on-ramp through movements that are typically low volume if frontage roads are not part of the ramp system. If off-ramp to on-ramp through movements are physically limited, conventional diamond interchanges have 18 conflict points. By contrast, DDIs have 14 conflict points. The reduction in conflict points is due to the unique crossover movements, which remove off-ramp to on-ramp through movements and eliminate several left-turning conflicts between the ramps and cross street. The biggest distinction is the significant decrease in crossing conflicts that typically lead to dangerous angle crashes.

4.1.2 Right Turn at Exit Ramp

Traffic between the two crossovers travels on the left side of the road, which is counter to the expectation of right-turning drivers from the freeway exit ramp. Right-turn-on-red (RTOR) operation is often desired at this movement for capacity reasons, similar to that used at conventional

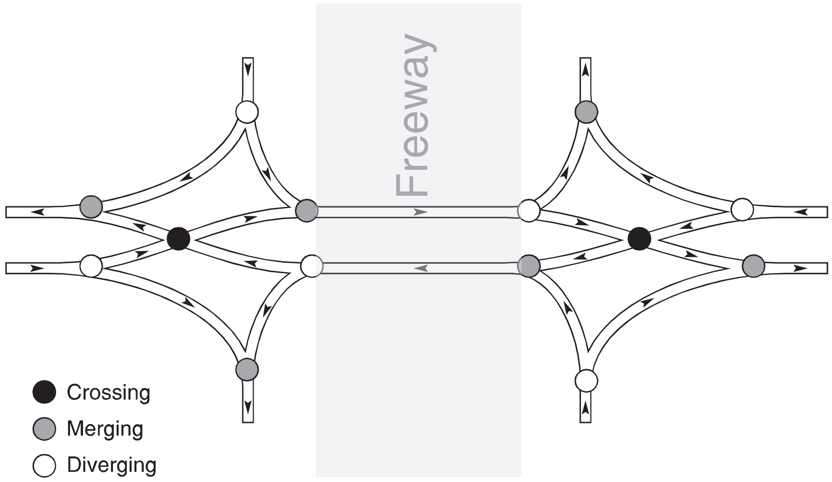


Exhibit 4-1. Conflict point diagram for DDI.

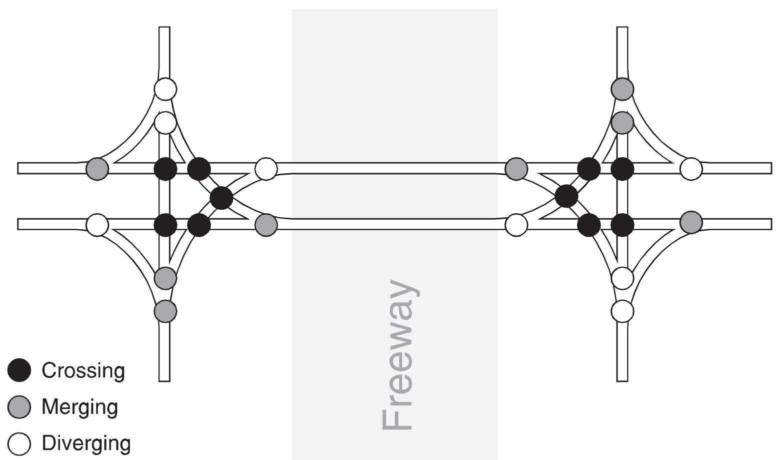


Exhibit 4-2. Conflict point diagram for conventional diamond.

Exhibit 4-3. Conflict point comparison.

Interchange Form	Crossing	Merging	Diverging	Total
Conventional diamond with ramp-to-ramp through movements	10	8	8	26
Conventional diamond without ramp-to-ramp through movements	6	6	6	18
Diverging diamond	2	6	6	14

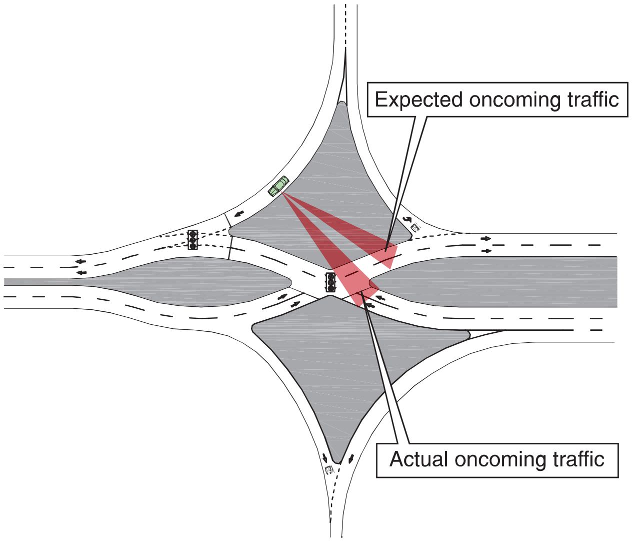


Exhibit 4-4. Oncoming traffic for the right turn at the exit ramp.

diamond interchanges. However, if RTOR operations are allowed, right-turning drivers may look on the wrong side of the road when checking for conflicting vehicles because traffic is crossed over. Intersection sight distance may also be limited by barriers or other obstacles between the crossovers. Exhibit 4-4 shows the oncoming traffic for the right turn at the exit ramp.

4.1.3 Left Turn at Exit Ramp

In states where left-turn-on-red (LTOR) operation is allowed from a one-way street to another one-way street, the unique design of the DDI allows for LTOR operations. Exhibit 4-5 shows the oncoming traffic for the left turn at the exit ramp.

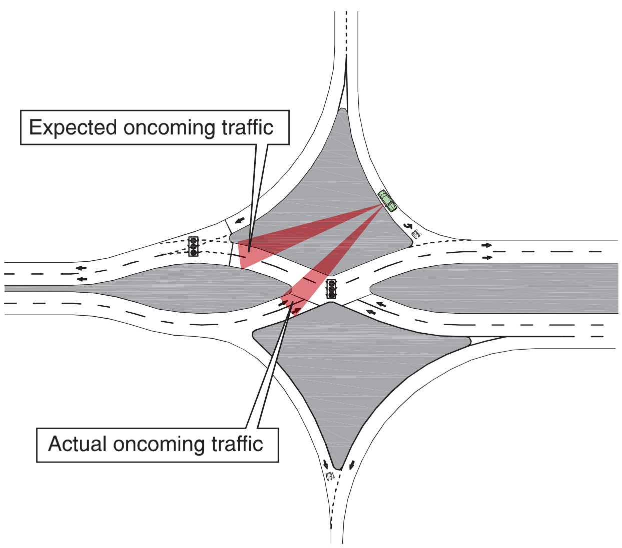


Exhibit 4-5. Oncoming traffic for the left turn at the exit ramp.

4.1.4 Wrong-way Maneuvers

At most interchanges, including conventional diamonds, wrong-way maneuver concerns are primarily related to drivers entering the freeway in the wrong direction. There is nothing inherent about the design of the DDI that would increase the likelihood of this, and the channelization of movements may decrease the likelihood of wrong-way maneuvers at freeway exit ramps. However, the crossovers on the cross street create the potential for wrong-way movements on the cross street. While early DDI research (*1*) identified a link between flat crossover angles and wrong-way maneuvers on the cross street, subsequent DDI experience has indicated other design features discussed in Chapter 6 likely play a greater role in determining the potential for wrong-way movements.

4.1.5 Incident Response Considerations

The response times of emergency responders at DDIs have been raised as a concern. Some of these concerns are summarized below:

- The barrier between travel directions and crossovers prevents passenger vehicles or emergency responders from driving on the wrong side of the road to pass or respond to broken down vehicles. This is similar to a conventional interchange with a divided arterial. In most cases, decreased delay and queuing at a DDI compared to a conventional diamond interchange mitigates the need for travel on the wrong side of the road. Long-term video monitoring efforts at seven DDIs for a 6-month period found no unusual problems in clearing crashes (*1*).
- In most cases, decreased delay and queuing at a DDI compared to a conventional diamond interchange is beneficial to emergency vehicles. The right turn on the freeway exit ramp often does not allow RTOR, causing queues to be longer than at a conventional diamond. This may impede emergency vehicles making right turns off the freeway.
- Ramp-to-ramp movements are sometimes made by emergency vehicles when congestion on the freeway does not allow passage of an emergency vehicle. The unique crossover design of a DDI does not allow through movements at the ramps, and strategies for mitigating this issue are limited.

4.2 Observed Safety Performance

The primary measure of safety performance is long-term annual average crash frequency. Crash modification factors (CMFs) based on significant samples of data from treatment and reference sites that remove bias found in most safety studies, especially regression-to-the-mean, have been developed in several studies and expanded within this guide. This section provides a summary of safety effects from early DDI implementations and surrogate measures collected at several DDIs in an FHWA study (*1*). Other safety considerations, including wrong-way maneuvers, are discussed and data is provided where possible.

4.2.1 Literature Summary

Exhibit 4-6 shows a compilation of the study summary and results of the recent DDI safety studies, which are described further in Appendix A. In summary, DDIs offer crash reduction benefits over conventional diamond interchanges. Information in the HSM indicates that road safety is affected by a change in number of lanes, lane width, shoulder width, median width, intersection skew angle, speed, traffic control type (e.g., stop, signal), and horizontal curvature. Each new interchange conversion presents unique combinations of change in most of these elements and features. The calculation of a CMF that summarizes the overall change

Exhibit 4-6. DDI safety studies, CMF values and sources.

Year of Report	Author(s)	Study Site Locations (# sites)	Study Methodology(ies)	Results
2011	V. Chilukuri et al. (*2*)	Springfield, MO (1)	Naïve Before-After	CMF – 0.54
2015	P. Edara et al. (*3*)	Missouri (6)	Empirical Bayes	**CMFs for entire interchange:** KABC – 0.374 PDO – 0.649 All – 0.592 **CMFs for ramp terminal intersections:** KABC – 0.322 PDO – 0.466 All – 0.434
2016	H. Lloyd (*4*)	Utah (5)	Empirical Bayes	**CMFs for entire interchange:** KABC – 0.43 PDO – 0.76 All – 0.64 **CMFs for ramp terminal intersections:** KABC – 0.32 PDO – 0.64 All – 0.50
2017	B. Claros et al. (*5*)	Missouri	Empirical Bayes	CMFs of 0.45 for fatal and injury, 0.686 for PDO, and 0.625 for total crashes at ramp terminal intersections.
2018	Kittelson & Associates, Inc., adapting work by Nye (*6*).	GA, ID, KS, KY, MN, MO, NC, NY, UT, VA, WY (26)	Empirical Bayes	CMF functions for each of three severity categories (i.e., FI, PDO, and all severities combined), presented in Section 4.2.2

KABC = Fatal, Disability Injury, Evident Injury, and Possible Injury Crashes
FI = Fatal and Injury
PDO = Property Damage Only Crashes

in safety associated with a specific interchange conversion describes the combined safety effect of the changes in each element and feature at that site. This "overall" (or project-level) CMF can be a reliable descriptor of the change in safety at the converted site. However, it will not be a reliable descriptor of the change in safety associated with a proposed new site unless the changes in elements and features at the converted site are a match to those at the proposed site. If one or more changes at the proposed site do not match those at the converted site, then a different project-level CMF value will be obtained for the proposed site.

4.2.2 Predicted Crash Modification Factors

A crash modification function was used to compute the predicted crash modification factor values for various combinations of the equation's input variables. The results are shown in two exhibits: Exhibit 4-7 for interchanges converted from a "before" condition with two signalized terminals and Exhibit 4-8 for interchanges converted from a "before" condition with two unsignalized terminals. Details of the equation used to derive the crash modification factors can be found in Appendix A.

Exhibit 4-7. Predicted CMF values when interchange has two signalized terminals before conversion.

Crossroad Speed Limit, mph	Change in Crossroad Through Lanes[1]	Crossroad Lane Drops[2]	CMF, FI	CMF, PDO	CMF, Total
30	2	0	0.20	0.26	0.25
		1	0.30	0.39	0.38
		2	0.45	0.59	0.58
	1	0	0.25	0.30	0.29
		1	0.38	0.46	0.44
		2	0.56	0.69	0.67
	0	0	0.32	0.35	0.34
		1	0.47	0.53	0.51
		2	0.70	0.81	0.79
35	2	0	0.28	0.38	0.36
		1	0.41	0.58	0.55
		2	0.61	0.89	0.84
	1	0	0.34	0.45	0.42
		1	0.51	0.68	0.64
		2	0.76	1.04	0.98
	0	0	0.43	0.53	0.49
		1	0.64	0.80	0.75
		2	0.96	1.21	1.14
40	2	0	0.38	0.57	0.52
		1	0.56	0.87	0.79
		2	0.83	1.32	1.22
	1	0	0.47	0.67	0.61
		1	0.70	1.02	0.93
		2	1.04	1.55	1.42
	0	0	0.59	0.78	0.71
		1	0.87	1.19	1.09
		2	1.30	1.81	1.66
45	2	0	0.51	0.86	0.75
		1	0.76	1.30	1.15
		2	1.14	1.97	1.77
	1	0	0.64	1.00	0.88
		1	0.95	1.52	1.35
		2	1.42	2.31	2.07
	0	0	0.80	1.17	1.03
		1	1.19	1.78	1.58
		2	1.77	2.70	2.41

Notes:

[1] Number of through lanes at the DDI minus the number of through lanes at the interchange before conversion (i.e., = $N_{lanes,a} - N_{lanes,b}$). Total of both travel directions.

[2] At some DDIs, the outside lane of the crossroad is dropped at the entrance ramp (i.e., the outside crossroad lane becomes a turning roadway at the ramp and continues onto the ramp). The value in the table describes the number of lanes that are dropped at the DDI. Total of both travel directions.

Exhibit 4-8. Predicted CMF values when interchange has two unsignalized terminals before conversion.

Crossroad Speed Limit, mph	Change in Crossroad Through Lanes[1]	Crossroad Lane Drops[2]	CMF, FI	CMF, PDO	CMF, Total
30	2	0	0.24	0.37	0.35
		1	0.36	0.56	0.54
		2	0.54	0.85	0.82
	1	0	0.30	0.43	0.41
		1	0.45	0.66	0.63
		2	0.67	0.99	0.96
	0	0	0.38	0.50	0.48
		1	0.56	0.77	0.73
		2	0.84	1.16	1.12
35	2	0	0.33	0.55	0.51
		1	0.49	0.84	0.78
		2	0.73	1.27	1.19
	1	0	0.41	0.64	0.59
		1	0.62	0.98	0.91
		2	0.92	1.48	1.39
	0	0	0.52	0.75	0.69
		1	0.77	1.14	1.06
		2	1.15	1.73	1.63
40	2	0	0.45	0.82	0.74
		1	0.67	1.25	1.13
		2	1.00	1.90	1.73
	1	0	0.56	0.96	0.86
		1	0.84	1.46	1.32
		2	1.25	2.21	2.02
	0	0	0.70	1.12	1.01
		1	1.05	1.70	1.55
		2	1.56	2.59	2.37
45	2	0	0.61	1.23	1.07
		1	0.92	1.86	1.64
		2	1.36	2.83	2.52
	1	0	0.77	1.43	1.26
		1	1.14	2.18	1.92
		2	1.70	3.30	2.94
	0	0	0.96	1.68	1.47
		1	1.43	2.54	2.25
		2	2.13	3.86	3.44

Notes:

[1] Number of through lanes at the DDI minus the number of through lanes at the interchange before conversion (i.e., = $N_{lanes,a} - N_{lanes,b}$). Total of both travel directions.

[2] At some DDIs, the outside lane of the crossroad is dropped at the entrance ramp (i.e., the outside crossroad lane becomes a turning roadway at the ramp and continues onto the ramp). The value in the table describes the number of lanes that are dropped at the DDI. Total of both travel directions.

The analysis results indicate that the conversion to DDI is often associated with a reduction in crashes; however, crash frequency may be increased for some combinations of higher crossroad speed limit, one or more crossroad lanes dropped at the DDI, and the existing interchange having unsignalized terminals. "Crossroad lanes dropped" refer to lanes on the outside of the crossroad that drop a freeway on-ramp. The dataset include a number of sites where lanes dropped onto entrance ramps at the DDI, but it did not include any sites where lanes dropped onto entrance ramps in the "before" condition.

The use of CMF functions was found to explain more than one-half of the systematic variability in the CMF values. However, it is believed that there is still some unexplained systematic variable in the predicted CMF values. Data for additional sites will help in this investigation by increasing the sample size. Also, some investigation of the annual average daily traffic (AADT) data provided by Nye (*6*) indicates that there may be some correlation between the CMF value and traffic volume level. However, reliable crossroad AADT data for the before period and after period was not available for all sites.

The total crash CMF model is offered to provide a general indication of the relative change in overall safety associated with interchange conversion. However, the FI CMF model and the PDO CMF model are recommended for use when quantifying the change in safety associated with a proposed conversion at a specific location. The CMFs presented in Exhibits 4-7 and 4-8 were developed from 26 DDIs from a prior ITRE study (*6*) where Nye gathered the representative crash data. Some conditions in the tables do not correspond to a condition present at any of the 26 interchanges but generally lie within the range of individual variable values within the data from the 26 interchanges.

4.3 References

1. Cunningham, C., B. Schroeder, J. Hummer, C. Vaughan, C. Yeom, K. Salamati, D. Findley, J. Chang, N. Rouphail, S. Bharadwaj, C. Jagadish, K. Hovey, and M. Corwin. *Field Evaluation of Double Crossover Diamond Interchanges.* Contractor's Draft Submittal. FHWA, Project No. DTFH61-10-C-00029, 2014.
2. Chilukuri, V., S. Siromaskul, M. Trueblood, and T. Ryan. *Diverging Diamond Interchange Performance Evaluation (I-44 & Route 13).* Report OR11.012. Organizational Results, Missouri Department of Transportation. February 2011.
3. Edara, P., C. Sun, B. R. Claros, and H. Brown. *Safety Evaluation of Diverging Diamond Interchanges in Missouri.* Report cmr 15-006. Missouri Department of Transportation, January 2015.
4. Lloyd, H. *A Comprehensive Safety Analysis of Diverging Diamond Interchanges.* MS thesis. Utah State University, Logan, UT, 2016.
5. Claros, B., P. Edara, and C. Sun. When driving on the left side is safe: Safety of the diverging diamond interchange ramp terminals. *Accident Analysis & Prevention*, Vol. 100, March 2017, pp. 133–142.
6. Nye, T. *A National Safety Evaluation for Converting a Conventional Diamond Interchange to a Diverging Diamond Interchange.* MS thesis. North Carolina State University, Raleigh, NC, 2018.

CHAPTER 5

Conceptual Operations

This chapter summarizes considerations and analysis required to develop and verify the lane configuration and phasing scheme for a diverging diamond interchange (DDI) as depicted in the flowchart in Exhibit 5-1.

The steps in this chapter will help a practitioner confirm whether a DDI is the most appropriate interchange form of the alternatives being considered, and if so, the lane configuration and signal phasing required to provide adequate capacity. This series of steps should be completed before the geometric design is complete, but can be conducted at the same time that an initial horizontal alignment is being developed.

5.1 Preliminary Operations Considerations

Because DDIs operate differently than other types of interchanges, this section describes the unique movements at a DDI as well as naming conventions for referencing them.

5.1.1 Directional Naming Conventions

Several naming conventions are introduced here to aid in discussion of movements between the DDI and adjacent intersections as illustrated in Exhibit 5-2. The following terms apply to each direction of travel:

- **Upstream Adjacent Intersection** is the last intersection a vehicle would travel through *before entering* the DDI if traveling along the cross street.
- **Inbound DDI Crossover** is the DDI intersection a vehicle would travel through upon *entering* the DDI.
- **Outbound DDI Crossover** is the DDI intersection a vehicle would travel through upon *leaving* the DDI.
- **Downstream Adjacent Intersection** is the first intersection a vehicle would travel through *upon leaving* the DDI if traveling along the cross street.

5.1.2 Operating Zones

DDIs have six types of operating zones that will be referenced throughout this guidebook. The operational effectiveness of each of these zones determines the appropriateness of a DDI. As illustrated in Exhibit 5-3, these operating zones include:

1. **Approach Zone**—the segment of the cross street between an upstream intersection and the first DDI crossover. This is often referred to as the inbound movement to the DDI.
2. **Crossover Zone**—the crossover intersection as well as the entry and exit approaches to the zone.

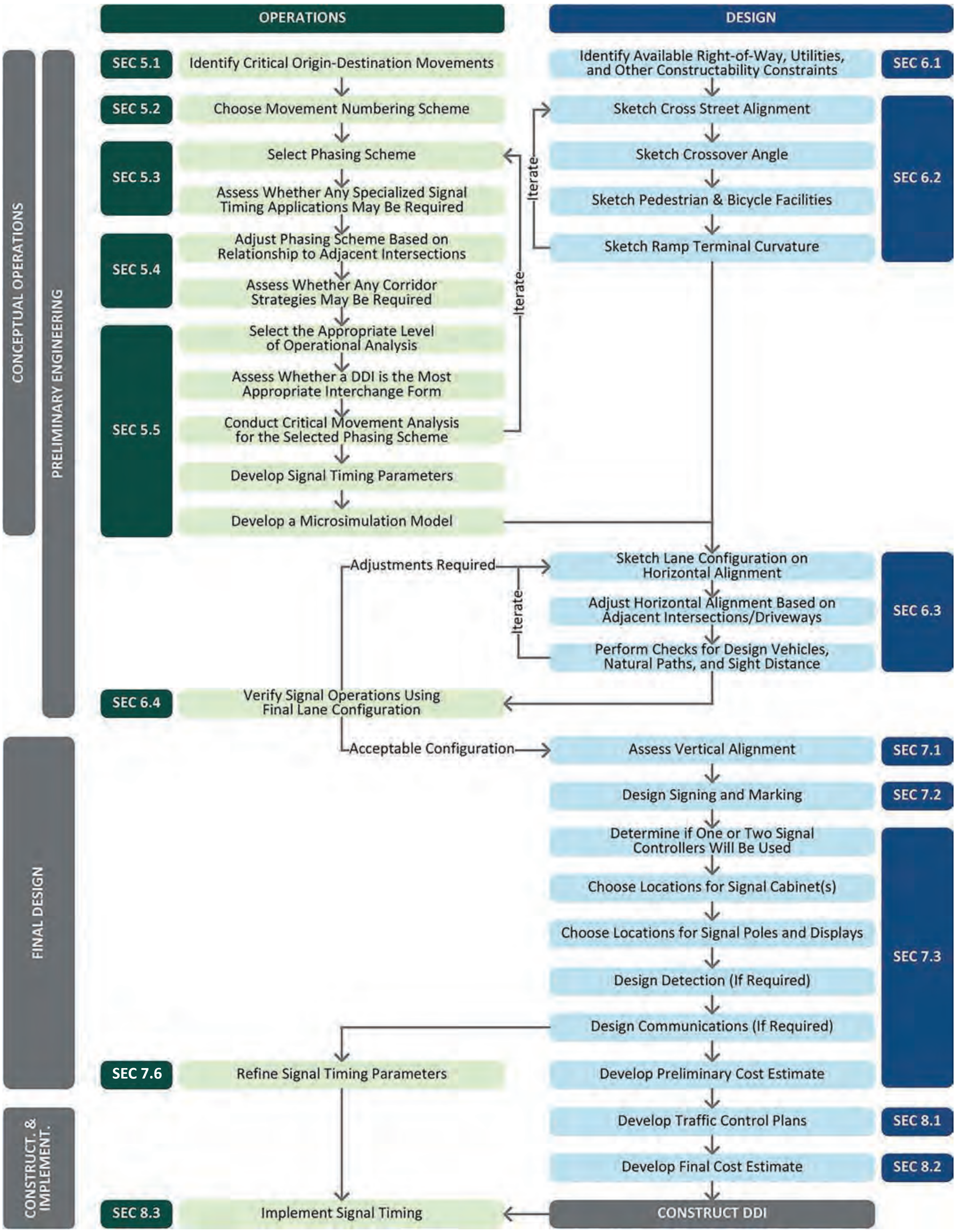


Exhibit 5-1. DDI operations and design flowchart.

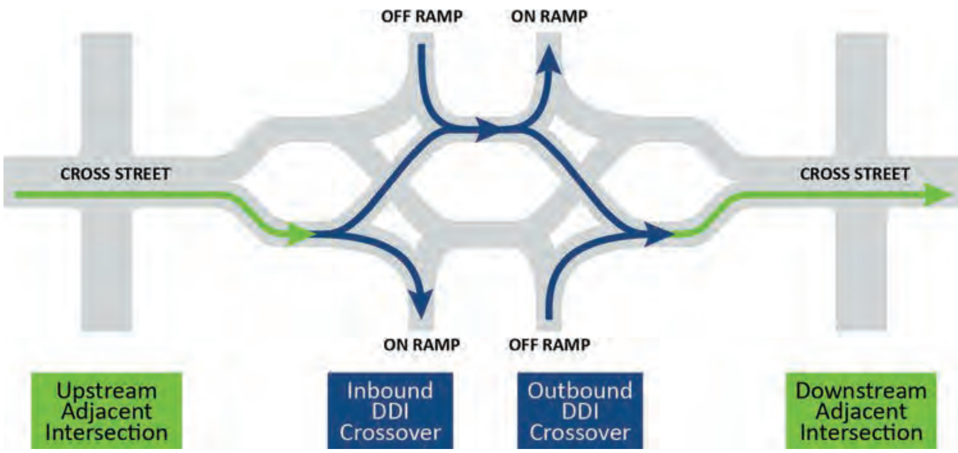


Exhibit 5-2. Directional naming conventions.

3. **Bridge Zone**—the area between the two crossovers where vehicles will drive over or under the bridge.
4. **On-Ramp Zone**—the area between the crossover and the freeway merge area.
5. **Off-Ramp Zone**—the area between the freeway diverge area and the crossover.
6. **Departure Zone**—the segment of the cross street between the second DDI crossover and a downstream intersection. This is often referred to as the outbound movement to the DDI.

By moving traffic to the left side of the street between the crossovers, left-turn movements onto the freeway do not conflict with opposing vehicle traffic (see Exhibit 5-4). As opposed to conventional diamond interchanges where left-turning vehicles are stored between the two ramp terminals, no such turn storage is required at a DDI.

5.1.3 Critical Origin-Destination Movements

Exhibit 5-5 introduces a naming convention to clearly define each of the critical origin-destination movements at a DDI. Through movements on the cross street are shown as north-bound and southbound movements. This orientation, rather than westbound and eastbound, is arbitrary for the sake of discussion in this chapter, but is how the time-space diagrams will be presented in later sections.

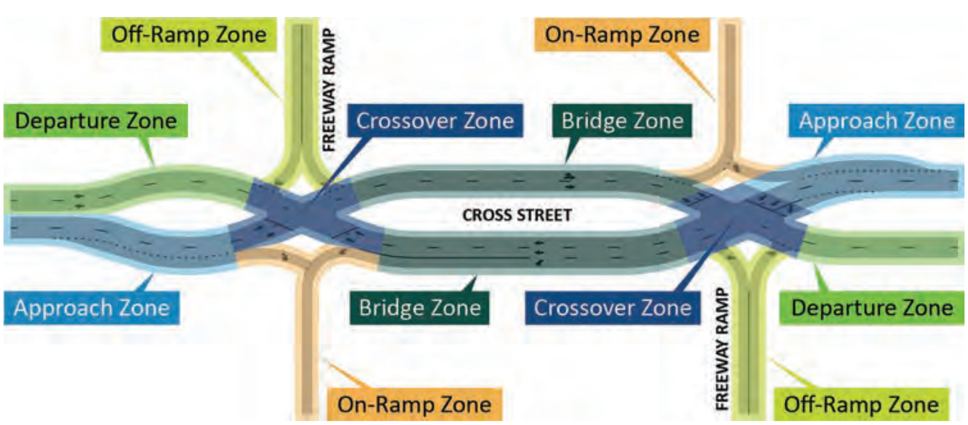


Exhibit 5-3. Operating zones.

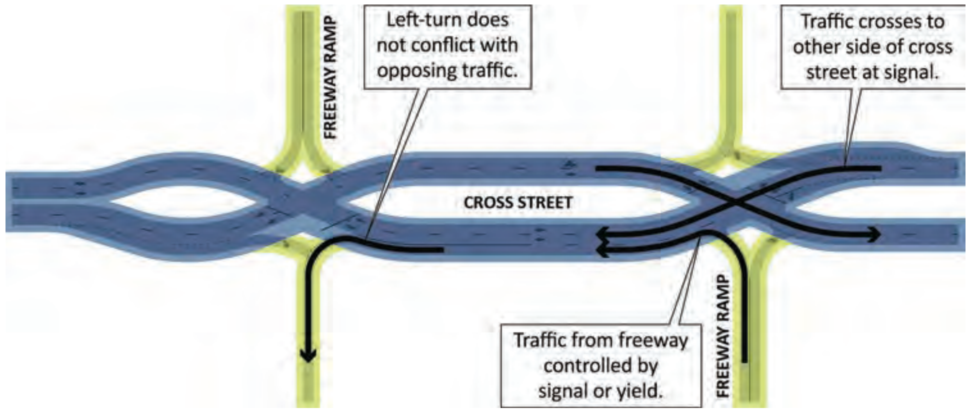


Exhibit 5-4. Key operational characteristics of a DDI.

5.2 Signal Timing Conventions

The exhibits used throughout Section 5.2 are for example purposes only. They are compiled from a variety of phasing schemes (explained in Section 5.3).

Before describing available phasing schemes in detail, this section discusses signal timing basics and conventions used throughout this guidebook. While the examples utilize phasing schemes to illustrate different concepts, details about each of the phasing schemes are not provided until Section 5.3.

5.2.1 Movement Numbering

Movements describe user actions at an intersection. Like any intersection, the movements at a DDI (both vehicular and pedestrian) should be assigned numbers that do not change with

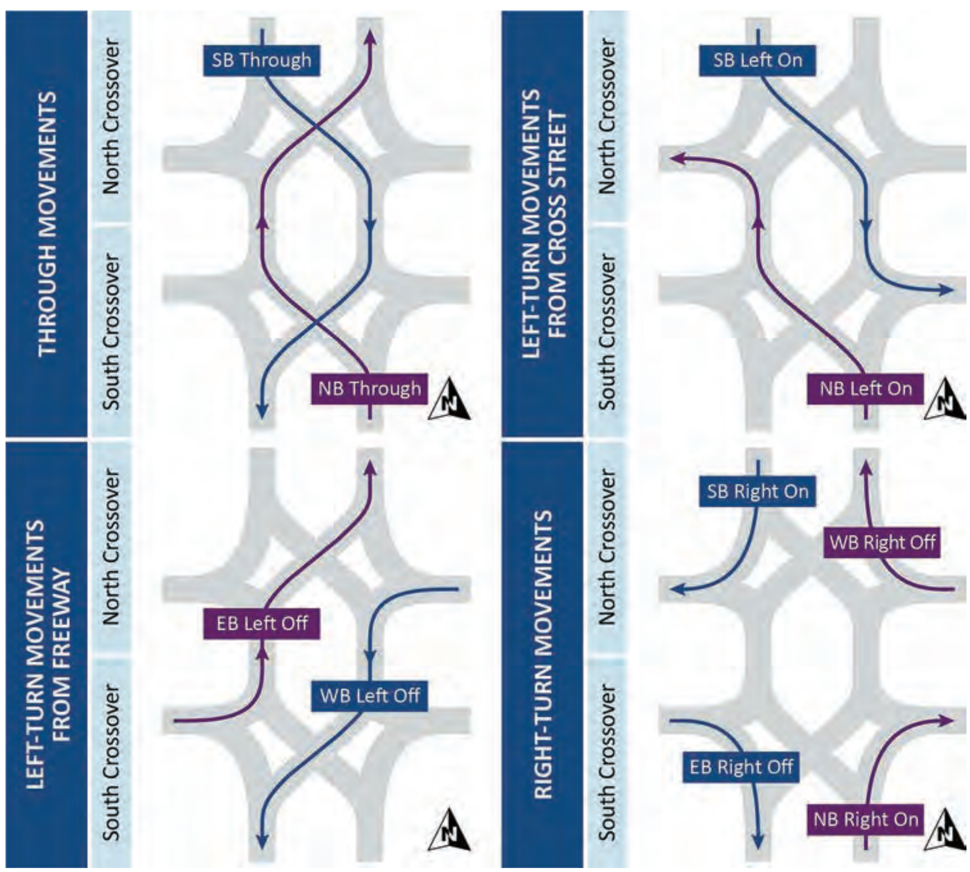


Exhibit 5-5. Naming convention for DDI movements.

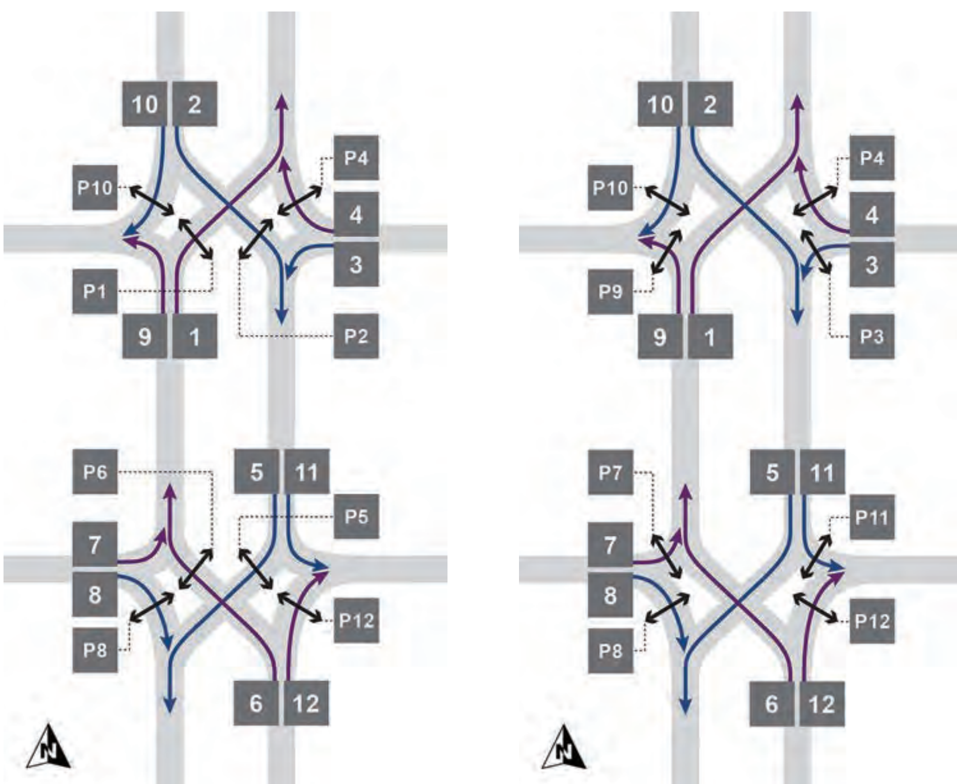
different geometric designs or signal phasing. Movements are different from both lanes and from phases. Lanes are individually striped areas containing one row of vehicles each (e.g., a through movement could be accommodated by three lanes), while phases are a timing process within the signal controller (e.g., a through and right-turn movement could be assigned to Phase 2).

At a DDI, it is common to have 12 one-way vehicular movements (six at each crossover) and eight two-way pedestrian movements (four at each crossover). Choosing a consistent numbering scheme allows for easy referencing of movements, particularly when assigning phases. Exhibit 5-6 shows two examples of movement numbering schemes that can be applied at a DDI (with different pedestrian-facility assumptions). Movement numbers are shown in the gray squares, with a P prefix indicating pedestrian movement. Note that vehicular movements that are traveling in the northbound direction or turn towards the northbound direction are depicted using purple arrows, while the vehicular movements that are traveling in the southbound direction or turn towards the southbound direction are depicted using blue arrows.

Pedestrian movements are represented with black arrows. For purposes of the operational analysis, this chapter assumes pedestrian facilities are in the median [as shown in Exhibit 5-6(a)]. For DDIs with pedestrian facilities on the outside, pedestrian movements would cross the left-turn and right-turn movements at the ramps [as shown in Exhibit 5-6(b)]. Placing pedestrians in the median or on the outside of the DDI is an important decision that should be made early, as it can affect various aspects of the geometric design and signal timing. Refer to Chapter 3 for more information about the trade-offs of placing pedestrian facilities in the median versus on the outside of the DDI.

Movement numbers in these examples are assigned as follows:

- Through movements in the approach zones are assigned numbers 2 and 6.
- Through movements between the crossovers are assigned numbers 1 and 5.



(a) Pedestrian Facility in Median **(b) Pedestrian Facility on Outside**

Exhibit 5-6. Movement numbering scheme.

- Right-turn movements from the off-ramps are assigned numbers 4 and 8.
- Left-turn movements from the off-ramps are assigned numbers 3 and 7.
- On-ramp movements are assigned numbers 9, 10, 11, and 12.
- Pedestrian movements are assigned numbers associated with the conflicting vehicular movement. For example, the pedestrian movement that conflicts with Vehicular Movement 10 is assigned number P10.

5.2.2 Phase Numbering

Phases (ϕ) allow one or more movements to be served by a traffic signal controller. Once movements have been assigned to phases, signal timing values (for parameters such as yellow change, red clearance, and minimum green) can be assigned to those phases. At a typical two-ring, eight-phase intersection, there are conventions for assigning phase numbers (e.g., major street through movements are often assigned Phases 2 and 6; minor street through movements are often assigned Phases 4 and 8). For DDIs within a single jurisdiction, phases should be assigned as consistently as possible.

Phase numbering will mostly be dictated by the phasing scheme that is chosen for the DDI. (Phasing-scheme details are summarized in Section 5.3.) There are many overlaps used in the phasing schemes to minimize lost time, particularly related to the clearance required at the crossovers (discussed in detail in Section 5.2.6.1). Overlaps allow movements to operate during more than one phase and should have their own load switches and accompanying signal timing.

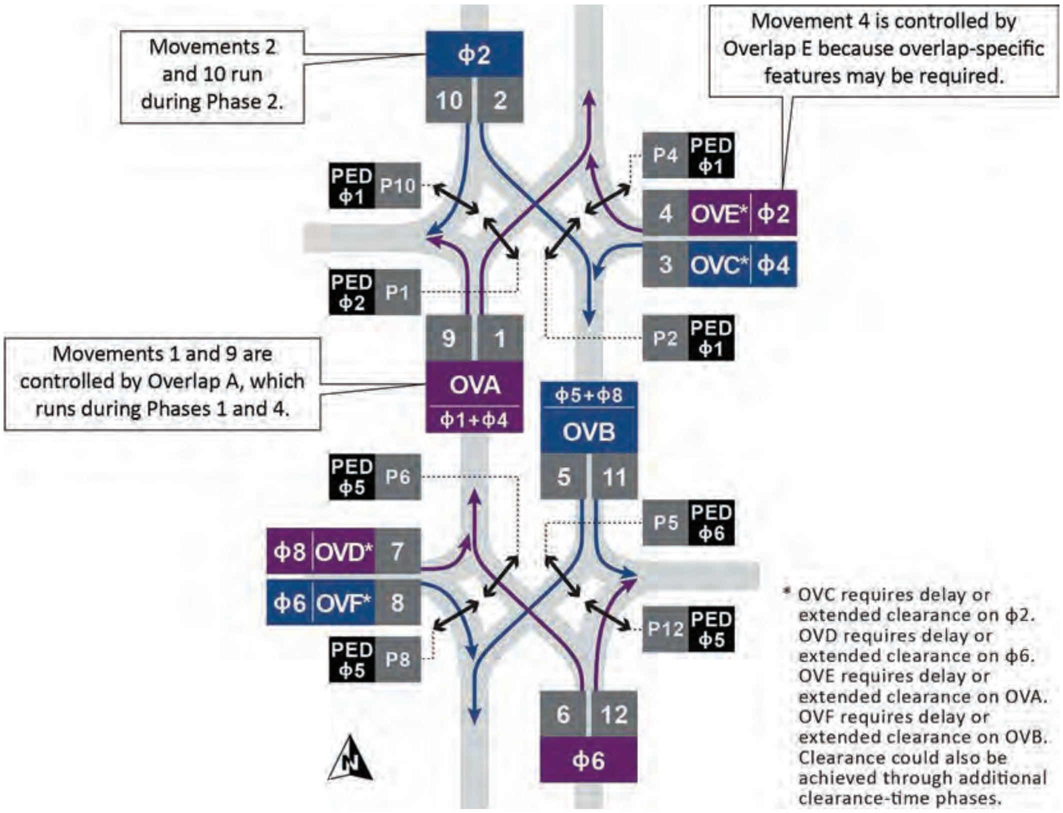
Overlap lettering can be assigned in a number of ways. However, a practitioner should attempt to assign them in a consistent manner. Phase pairs should be considered for ease of referencing [e.g., northbound through movement assigned to Overlap A (OVA), southbound through movement assigned to Overlap B (OVB)]. In this document, overlap lettering is assigned to movements in the following order:

1. Through and on-ramp movements between the crossovers.
2. Through movements in the approach zones.
3. On-ramp movements in the approach zones.
4. Off-ramp left-turn movements.
5. Off-ramp right-turn movements.

Letters are assigned starting with Overlaps A and B (OVA and OVB), moving to Overlaps C and D (OVC and OVD), and so on. Note that overlaps are not used for all movements in every phasing scheme.

Exhibit 5-7 is an example of how phases and overlaps can be assigned (using the three-critical-movement phasing scheme introduced in Section 5.3.2). The phases and overlaps are shown in purple and blue squares for vehicular phases (purple for northbound movements and blue for southbound movements), while the pedestrian phases are shown in black squares. Phase and overlap labels (purple, blue, and black squares) span the movements (gray squares) that are assigned to them. The phases that are included in the overlaps are listed next to each overlap letter. For example, in Exhibit 5-7, Movements 1 and 9 are assigned to OVA, which includes Phases 1 and 4. Movements 2 and 10 are not associated with an overlap, but are instead assigned to Phase 2.

It should be noted that some movements may not be signalized based on the design. For example, Movements 9 and 11 are often not signalized. The numbering scheme is designed to accommodate all possible signalization needs.



Note: Considerations for overlap delay and extended clearance are summarized in Section 5.2.6.1.

Exhibit 5-7. Phase and overlap assignment example (using three-critical-movement phasing scheme).

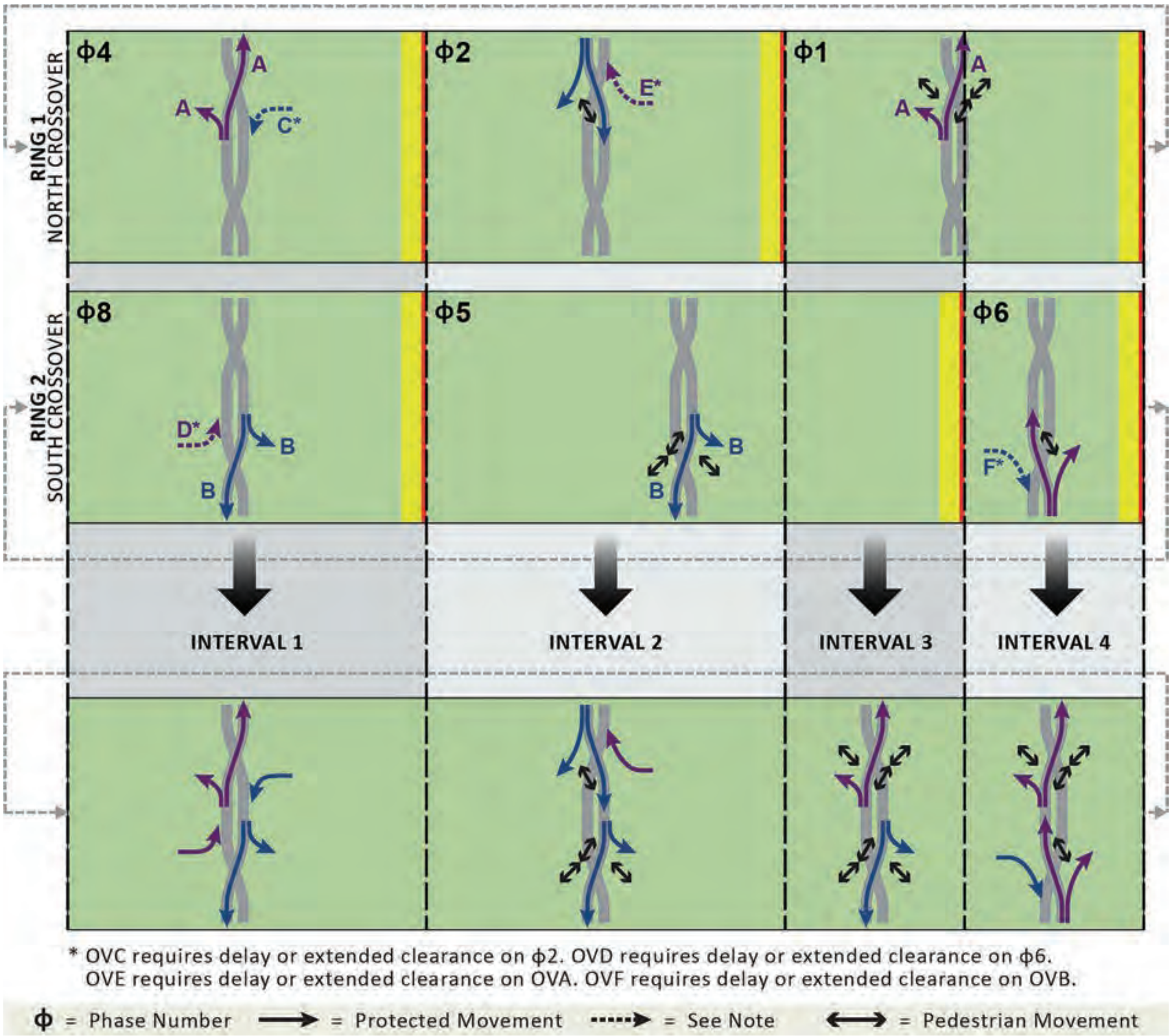
5.2.3 Phases Versus Intervals

There are multiple ways that movements at an intersection can be conveyed and represented visually. Two common ways are ring-and-barrier diagrams and interval diagrams. This guidebook will utilize ring-and-barrier diagrams because it is important that a practitioner understand how movements are programmed in the signal controller. Because interval diagrams have traditionally been utilized for explaining DDI operations, an example of the relationship between a ring-and-barrier diagram and an interval diagram is presented in Exhibit 5-8 (using the three-critical-movement phasing scheme introduced in Section 5.3.2).

Each phase shown in the ring-and-barrier diagram represents a certain amount of time. The example shown in Exhibit 5-8 has two rings but no barriers. A new interval begins each time a transition is made between phases. In Exhibit 5-8, there are transitions at the end of Phases 4 and 8, the end of Phase 2, the end of Phase 5, and the end of Phases 1 and 6. The interval diagram is an easy way to represent what is happening at a DDI. However, the diagram is unable to convey the time given to each movement, how that time can shift between phases, and the correlation between the two rings used by the controller. The remainder of this guidebook will use ring-and-barrier diagrams to explain phasing concepts.

5.2.4 Ring-and-Barrier Diagram

Ring-and-barrier diagrams are used throughout the following section to help explain the phasing schemes. For more information on reading a ring-and-barrier diagram, refer to



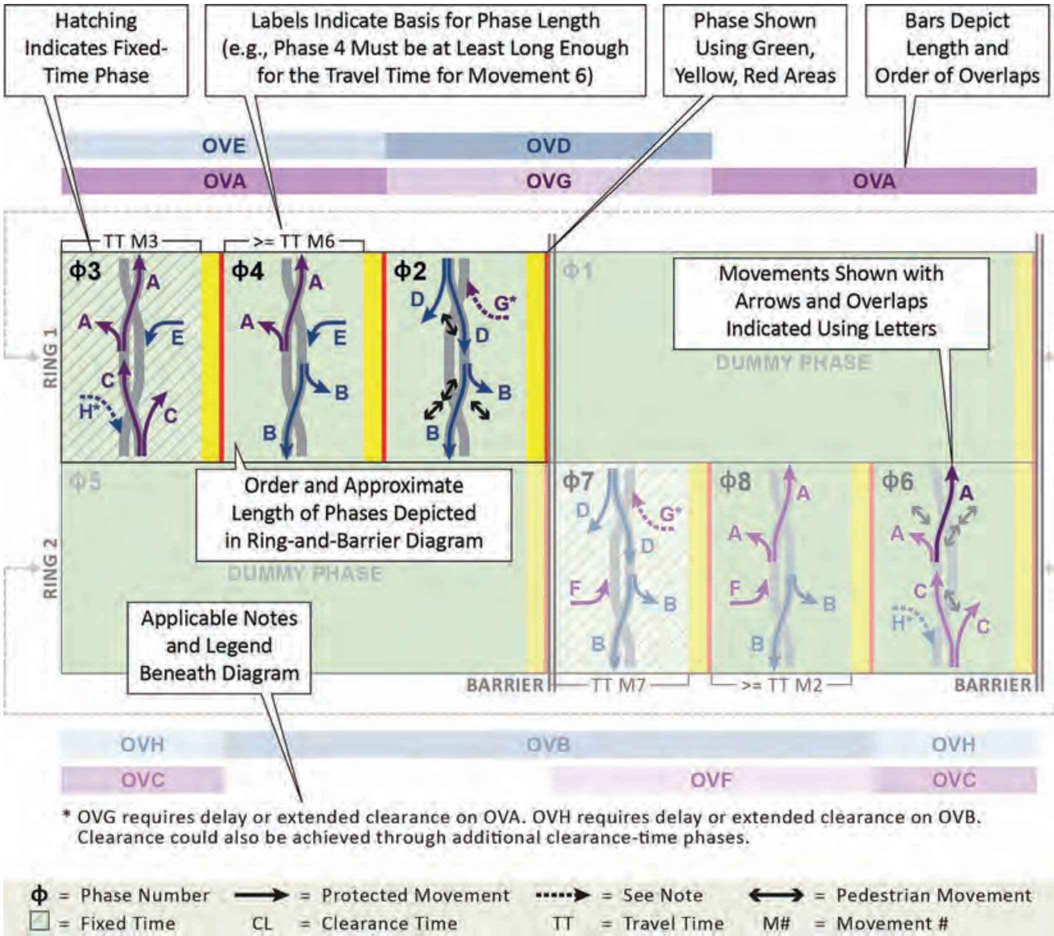
Note: Considerations for overlap delay and extended clearance are summarized in Section 5.2.6.1.

Exhibit 5-8. Relationship between ring-and-barrier diagram and interval diagram example (using three-critical-movement phasing scheme).

NCHRP Report 812: Signal Timing Manual, 2nd Edition (*1*). Some considerations for the DDI-specific ring-and-barrier diagrams are provided in Exhibit 5-9, which uses the four-critical-movement phasing scheme (Option B) for the example (introduced in Section 5.3.3).

Each phase in the ring-and-barrier diagrams is depicted using the green, yellow, and red areas; these areas not only show the phase order but also reflect their approximate duration. Small drawings of a DDI are shown in each phase area to help the reader understand the movements assigned to each phase. Hatching indicates which phases are fixed-time, and labels clarify phase-length requirements (i.e., based on travel time or clearance of a particular movement).

Movements are shown at the appropriate crossover (northern or southern) and are depicted using purple, blue, and black arrows for the northbound vehicular, southbound vehicular, and pedestrian movements, respectively. Overlaps are indicated by a letter next to the associated movement arrow, but labels are also shown above and below the traditional ring-and-barrier diagram to represent the length and order of overlaps.



Note: Considerations for overlap delay and extended clearance are summarized in Section 5.2.6.1.

Exhibit 5-9. Ring-and-barrier diagram example and conventions (using four-critical-movement phasing scheme Option B).

5.2.5 Time-Space Diagram

In addition to the phase-assignment and ring-and-barrier diagrams, each phasing scheme described in the next section has a time-space diagram that combines these two elements. For more information about reading a time-space diagram, refer to *NCHRP Report 812: Signal Timing Manual, 2nd Edition* (*1*). Some considerations for the DDI-specific time-space diagrams are provided in Exhibit 5-10, which uses the two-critical-movement phasing scheme for the example (introduced in Section 5.3.1).

Time is shown on the x-axis, and distance is shown on the y-axis. Ring-and-barrier diagrams are shown for each crossover; they convey the phase order and length and will match the larger ring-and-barrier diagram shown for each phasing scheme. Some phasing schemes use one ring for each crossover (i.e., Ring 1 for the northern crossover and Ring 2 for the southern crossover), and some phasing schemes use both rings at both crossovers.

The ring-and-barrier diagrams are separated by the distance between the crossovers. Upstream and downstream signals will use the same distance scale. The bandwidth (i.e., potential for progression) for each movement is depicted by the purple (northbound) and blue (southbound) bands. The wider the band, the more opportunity for progression between the crossovers for the indicated movement. Use of overlaps results in the bandwidth being shown over the

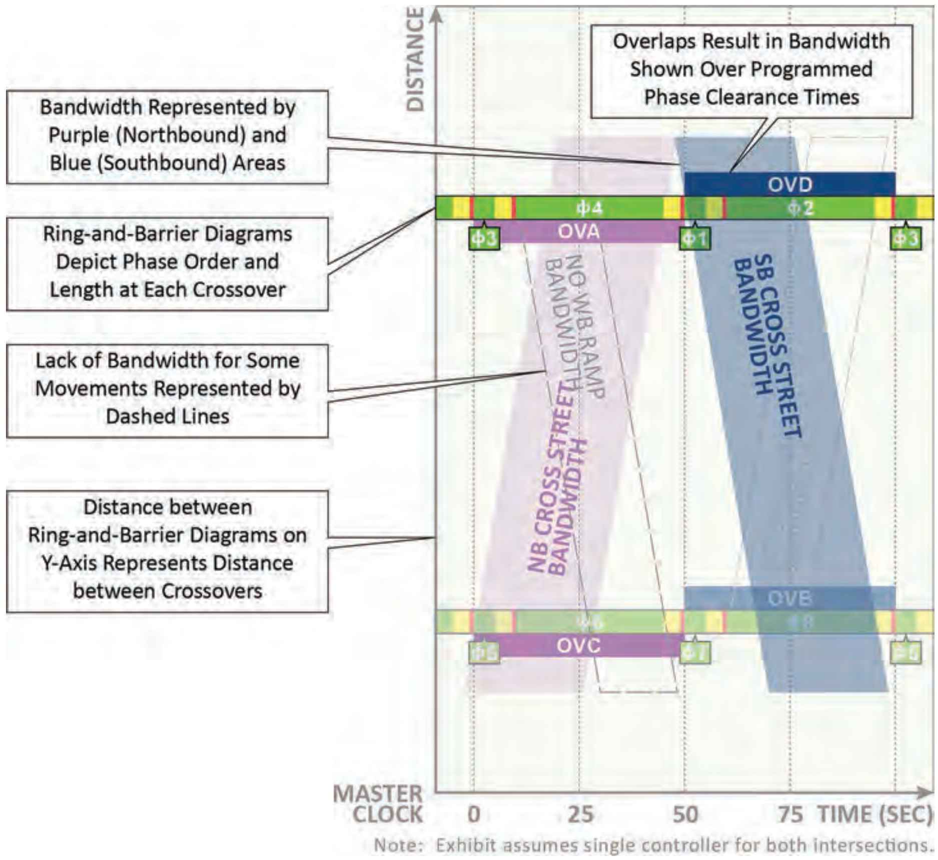


Exhibit 5-10. Time-space diagram example and conventions (using two-critical-movement phasing scheme).

programmed phase clearance times. While the two-critical-movement phasing scheme example only shows bandwidth for the cross street, other phasing schemes in Section 5.3 will depict the available bandwidth for the ramps as well.

5.2.6 Signal Timing Parameter Considerations

There are two important distances that influence signal timing at a DDI: (1) distance for a through movement to clear the conflicting off-ramp movement (clearance time) and (2) distance between the crossovers (travel time). Throughout the phasing schemes, these distances will be referenced.

5.2.6.1 Clearance Time

Much of the DDI signal timing is impacted by the distance for a through movement to clear the conflicting off-ramp movement. Unlike a conventional intersection, a through movement at a DDI has two distinct clearance times that need to be considered. The first is the time required to clear the opposing through movement at the crossover. This time is typically short because of the width of the crossover. The second is the time required to clear the conflict point with the downstream left-turn or right-turn movement from the off-ramp. This time can be significantly longer than the time required to clear the opposing through movement depending on the geometry of the DDI.

Exhibit 5-11 depicts the total clearance distance for each through movement (approaching and departing) at the crossovers. The options for accommodating the additional clearance time include:

- Using short, fixed-time phases following the through movements.
- Assigning the off-ramp movements to overlaps, in combination with overlap delay.
- Using extended clearance intervals (i.e., longer red clearance) on the through-movement phases (which is least desirable because it is perceived poorly by drivers unless there are site-specific safety concerns due to red-light running).

Bicycles generally have slower speeds and acceleration than vehicles, which can impact the time required to clear the conflicting off-ramp movement. If clearance intervals are based on vehicle characteristics, a ramp movement could receive a green indication before a cyclist has cleared the conflict area. Different traffic signal controller vendors have different options for bicycle phasing and timing parameters, but particularly if there are high bicycle volumes at a DDI, the practitioner should consider how to adjust the options above to account for bicycle characteristics.

The additional time that is required for a vehicle to clear the off-ramp movements can potentially be utilized by other nonconflicting movements, as is illustrated in Exhibit 5-12. This example makes use of a short, fixed-time phase to accommodate the additional clearance time. The exhibit shows how the northbound through movement (Movement 1 in Phase 4) requires a short clearance time to clear the crossover (shown as time “T1”) and a much longer clearance time to clear the westbound right turn (shown as time “T2”). The exhibit shows the difference between signal timing without (top diagram) and with (bottom diagram) the use of a short, fixed-time phase. The use of this short, fixed-time phase (in combination with overlaps) allows the southbound through movement (Movement 2) to utilize time that would have been lost otherwise.

5.2.6.2 Travel Time

The second important distance that impacts DDI signal timing and operations is the distance between the crossovers (depicted in Exhibit 5-13). Depending on the phasing scheme, the time to travel between the crossovers might be used to determine the length of fixed-time phases. Providing a fixed amount of time for a movement to travel the distance between the crossovers can reduce queuing and keep the space between the crossovers clear.

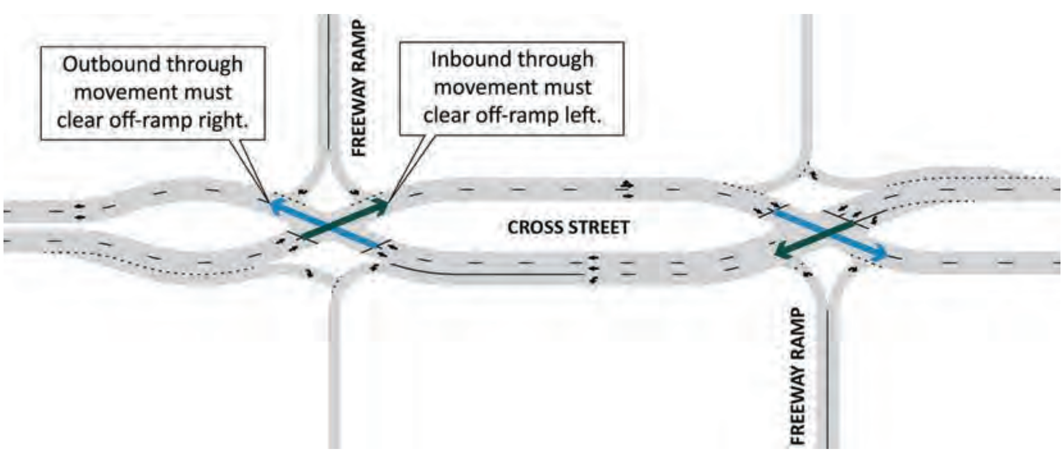
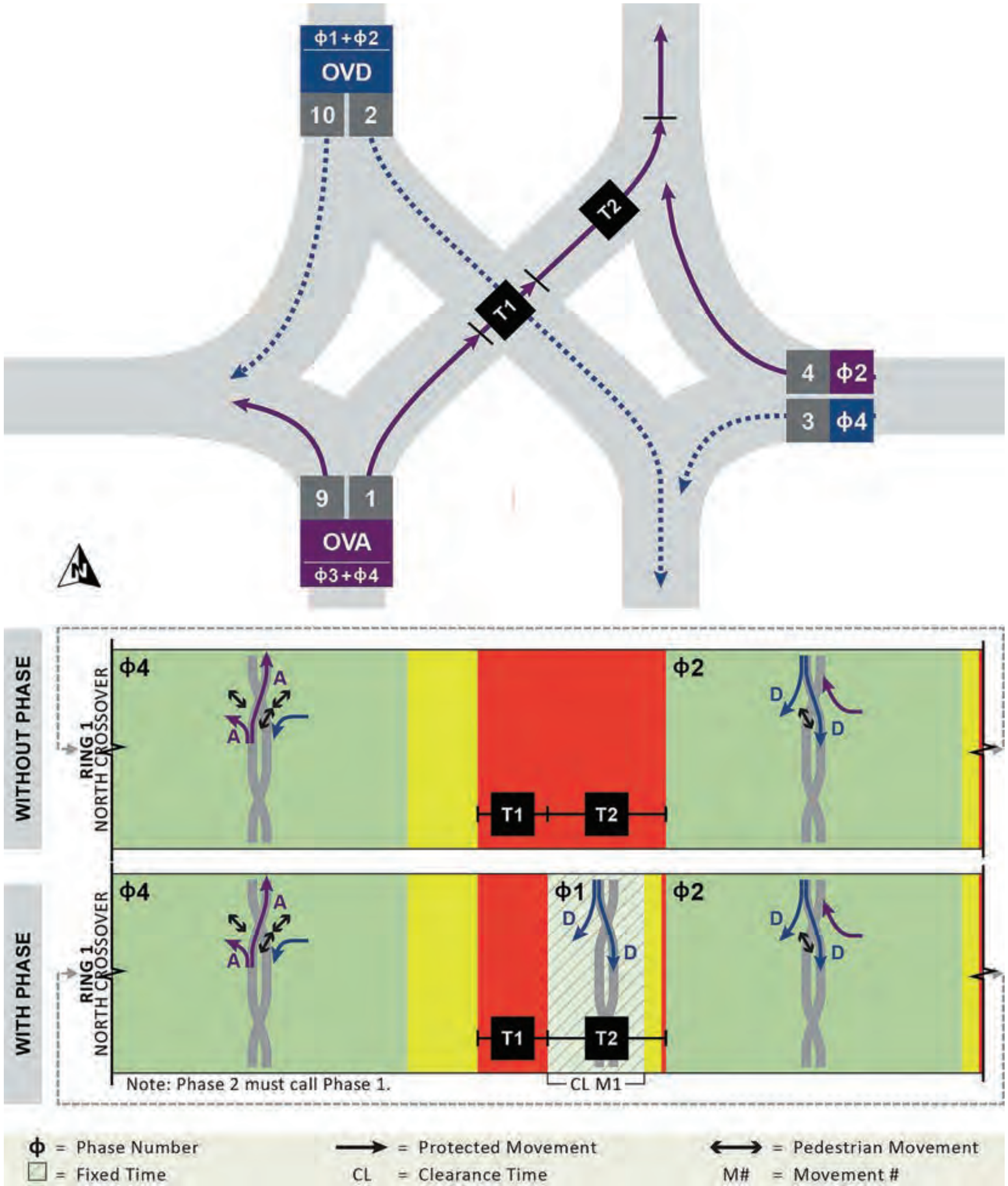


Exhibit 5-11. Through-movement clearance considerations.



Note: The rings have been drawn to focus on clearance considerations for the northbound through movement. Not all phases are shown in the ring-and-barrier diagrams.

Exhibit 5-12. Impact of crossover clearance time on signal timing.

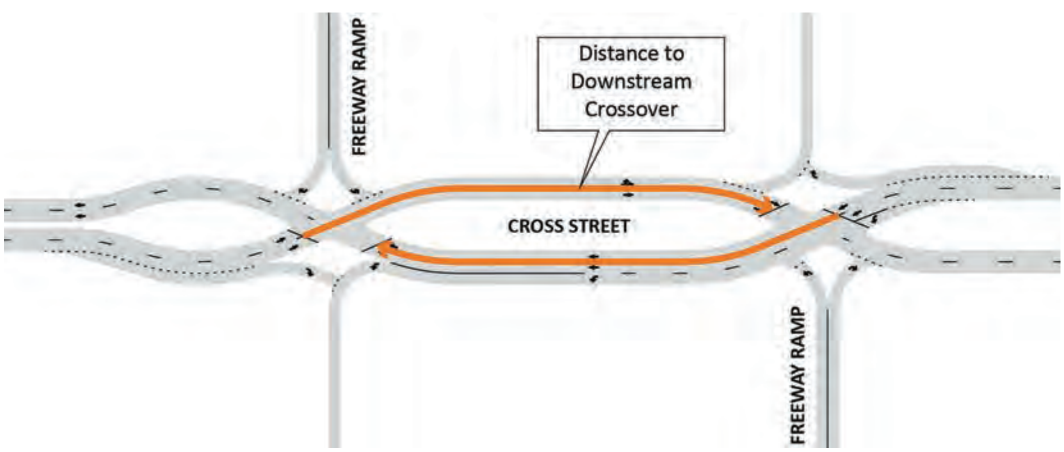


Exhibit 5-13. Travel time between crossovers considerations.

5.2.6.3 Cycle Length

The travel time from one crossover to the other is also an important factor to consider when selecting the cycle length. Conceptually, if the split for each direction could equal the travel time between crossovers and the cycle length could equal twice that value, progression could be achieved for both directions with an appropriate offset. Exhibit 5-14 illustrates this principle using the two-critical-movement phasing scheme, which is explained in more detail in Section 5.3.1.

Generally, the travel time between crossovers is too short to result in a viable cycle length, particularly at locations requiring signal timing for pedestrians and bicycles; however, it has been found at several existing DDIs that using a multiple of the travel time for splits and cycle lengths tends to provide reasonably good two-way progression. Because of this finding, a good starting point for determining the cycle length is to measure the travel time between the crossovers and then evaluate the capacity of cycle lengths that are multiples of that number.

Since speeds internal to the DDI have been found to be substantially lower than marked speed limits or design speeds, it is important to actually measure the travel time. In addition to internal DDI interactions, cycle lengths should be chosen considering adjacent intersections. More information about adjacent intersections can be found in Section 5.4.

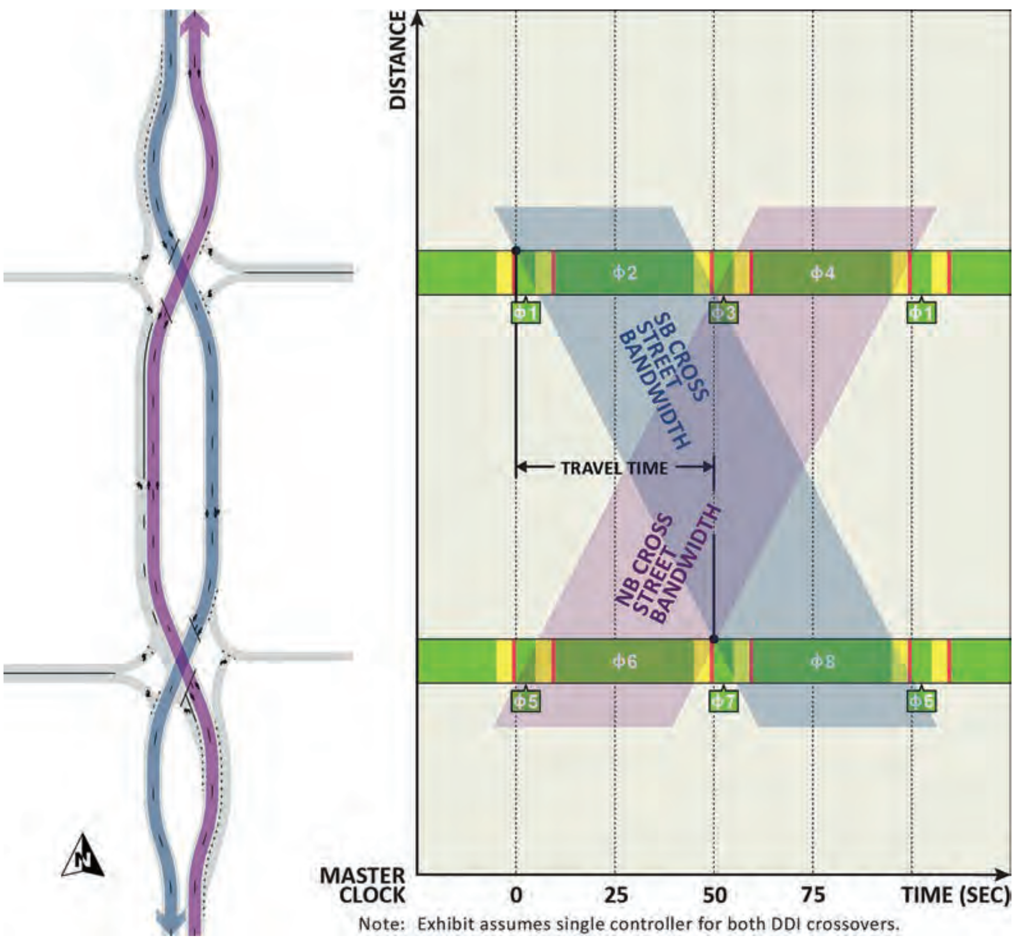


Exhibit 5-14. Relationship between splits and travel time (using two-critical-movement phasing scheme).

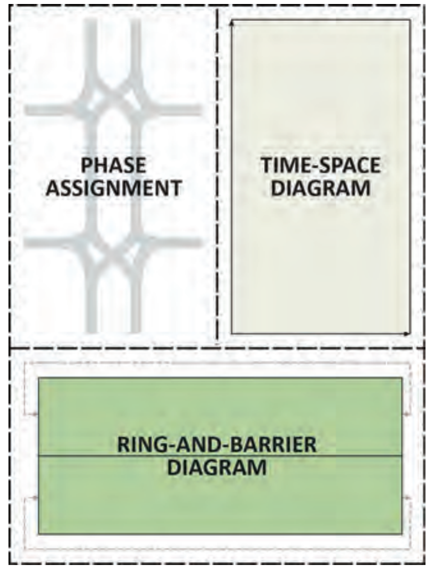


Exhibit 5-15. Phasing scheme layout.

5.2.7 Phasing Scheme Layout

Three phasing schemes will be discussed in this guidebook. Exhibit 5-15 depicts the three pieces of information provided for each phasing scheme, which were described in the previous sections—(1) phase-assignment schematic, (2) ring-and-barrier diagram, and (3) time-space diagram. Each of these pieces relates to the others. The schematic in the top left shows the assignment of movements to phases, which are then depicted in the ring-and-barrier diagram at the bottom. The ring-and-barrier diagram establishes phase order and relative timing for the phases. The ring-and-barrier diagram is then translated for each crossover in the time-space diagram in the top right, which is scaled to match the crossover distance in the phase-assignment schematic. The time-space diagram is ultimately used to identify and compare progression opportunities.

5.3 Phasing Schemes

It is important to note that the phasing schemes are presented assuming a single controller at the DDI.

The three phasing schemes discussed in this guidebook were developed to address the following critical-movement scenarios:

- **Two-critical-movement**—emphasizes progression for either the cross-street movements or the off-ramp movements and is most applicable for DDIs with one dominant movement.
- **Three-critical-movement**—emphasizes progression for the cross-street movements and the off-ramp left-turn movements and is most applicable for DDIs with one or multiple dominant movements. The three-critical-movement scheme is often the most flexible and most efficient DDI phasing option.
- **Four-critical-movement**—emphasizes progression for both the cross-street movements and the off-ramp movements and is most applicable to DDIs with low to moderate volumes, either dominant through or left-turn movements and short to medium crossover spacing. The four-critical-movement scheme tends to be less efficient and result in higher delays for DDIs that are approaching capacity, but can be a good option for metering traffic for an adjacent intersection.

As the names suggests, the phasing scheme that is selected should be based on the number of critical movements at the DDI. The critical movements will be those that an agency is choosing to prioritize, likely based on demand or other considerations. Additional guidance on selecting these schemes and a comparison of their operational performance is provided in Section 5.5. Splits in the following phasing scheme examples are for illustrative purposes only; splits should be adjusted to reflect demand.

5.3.1 Two Critical Movements

The two-critical-movement phasing scheme can either emphasize progression for the cross-street movements (depicted in Exhibit 5-16) or the off-ramp movements (depicted in Exhibit 5-17). Considerations for this phasing scheme include the following:

- The movements at the northern crossover are assigned to phases in Ring 1, and the movements at the southern crossover are assigned to phases in Ring 2. While set up for a single controller, this convention can also be used if there is a controller at each crossover.
- Because each crossover operates in an independent ring, no barriers are required. Coordination between the crossovers can be achieved through ring offset. Ring offset allows Ring 2 to be offset from Ring 1. The offset for Ring 1 will be referenced to the master clock, while the offset for Ring 2 will be the offset for Ring 1 plus a specified value. Ring offset is not available in every controller, so dummy phases may be required to achieve a similar result.
- Exhibit 5-16 depicts a scenario that prioritizes the cross-street movements. The northbound cross-street movements are given time, and then the southbound cross-street movements are given time. Depending on intersection spacing, there is little or no ramp progression with this phasing scheme.
- By changing the ring offset, the left-turn movements from the ramps can be prioritized, as shown in Exhibit 5-17. The westbound and eastbound left-turn movements are given time and can immediately proceed through the downstream crossover. Additional time could be given to the left-turn phases if there is demand. Depending on intersection spacing, there is little or no cross-street progression with this phasing scheme.
- For the two-critical-movement phasing schemes, the clearance of the through movements is accommodated using short, fixed-time phases. For example, Phase 1 allows Movements 2 and 10 (southbound through and right-turn movements from the cross street) to start before Movement 4 (westbound right-turn movement from the off-ramp). Without this fixed-time phase, the vehicles at the tail end of Movement 1 could still be traveling through the crossover when Movement 4 receives a green. To prevent the fixed-time phases from being skipped, the major phases should be assigned to call them. Note that this additional clearance time could be accommodated using overlap delay or extended clearance intervals (i.e., longer red clearance). See Section 5.2.6.1 for more information on clearance time.
- Because pedestrian movements occur in two phases, this phasing scheme results in a high probability that pedestrians will have to wait in the pedestrian island between Movements P1 and P10 at the northern crossover as well as Movements P5 and P12 at the southern crossover. Depending on pedestrian volumes, a “Not Ped” feature or other available pedestrian phasing option (such as pedestrian overlaps) could be applied to reduce the likelihood of pedestrians waiting in the island. A “Not Ped” feature would exclude the conflicting vehicle overlap only when there is a pedestrian call.

5.3.2 Three Critical Movements

The three-critical-movement phasing scheme can provide progression for the cross-street movements and the off-ramp left-turn movements (depicted in Exhibit 5-18). Considerations for this phasing scheme include the following:

- The movements at the northern crossover are assigned to phases in Ring 1, and the movements at the southern crossover are assigned to phases in Ring 2. While set up for a single controller, this convention can also be used if there is a controller at each crossover.

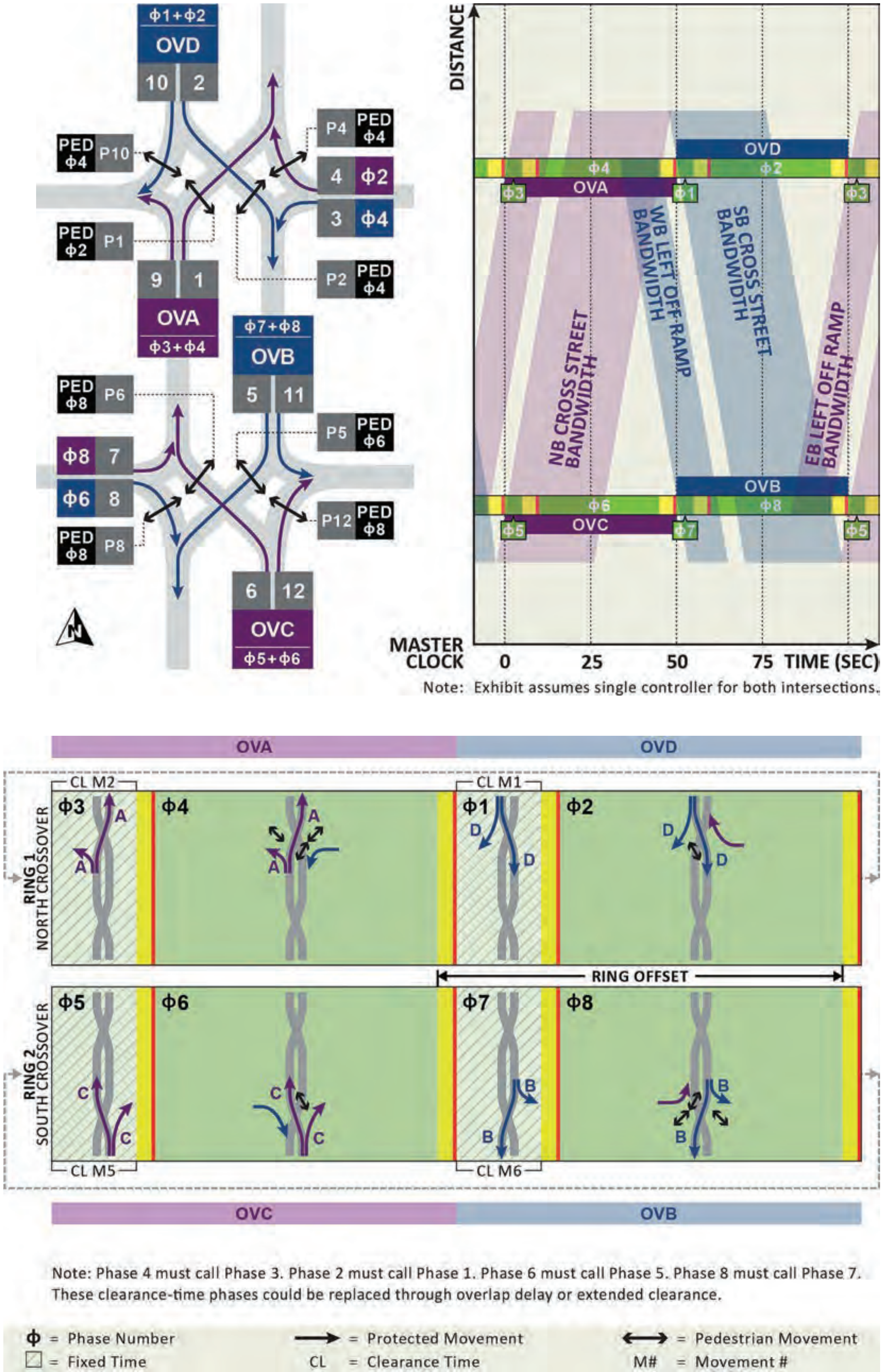


Exhibit 5-16. Two-critical-movement phasing scheme (cross-street progression).

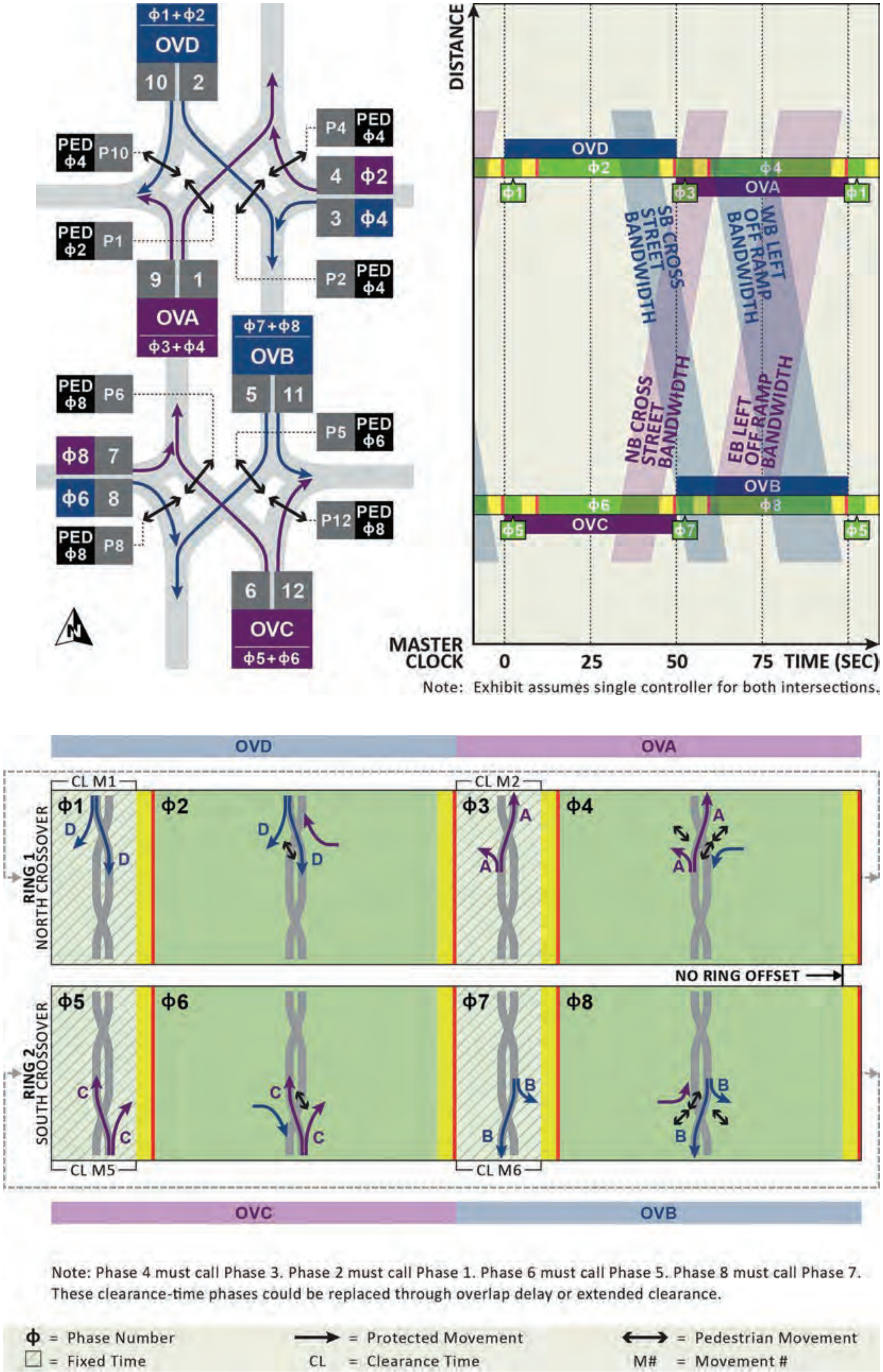


Exhibit 5-17. Two-critical-movement phasing scheme (ramp progression).

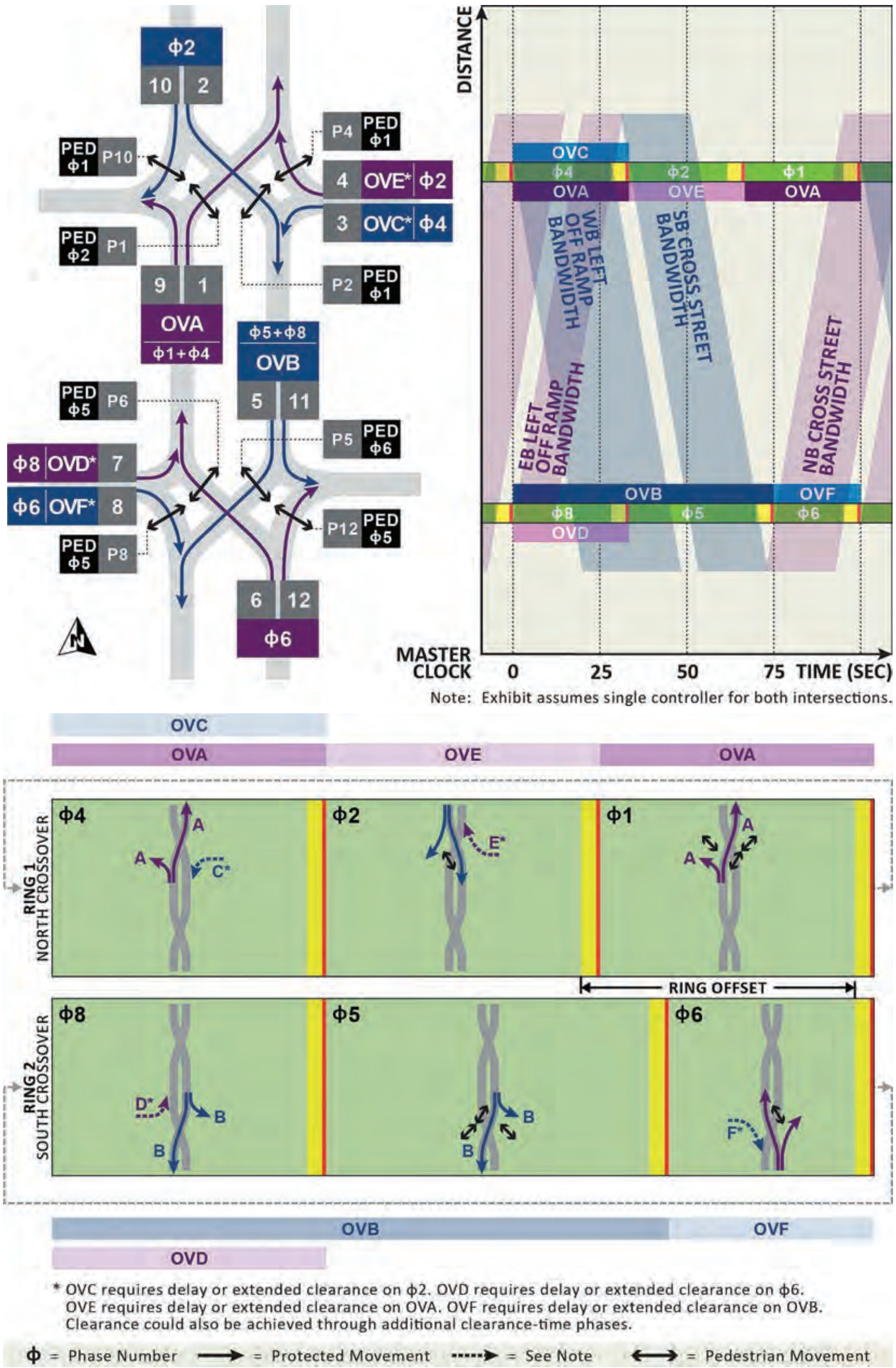


Exhibit 5-18. Three-critical-movement phasing scheme.

- Because each crossover operates in an independent ring, no barriers are required. Coordination between the crossovers can be achieved through ring offset. Ring offset allows Ring 2 to be offset from Ring 1. The offset for Ring 1 will be referenced to the master clock, while the offset for Ring 2 will be the offset for Ring 1 plus a specified value. Ring offset is not available in every controller, so dummy phases may be required to achieve a similar result.
- Exhibit 5-18 depicts a scenario that gives additional time to Phase 5, so that the southbound cross street and westbound off-ramp movements have larger progression bands.
- For the three-critical-movement phasing schemes, the clearance of the through movements is accommodated assuming the use of overlap delay. This places a specified delay on both the left-turn and right-turn movements from the off-ramps. It will allow the through movements from the cross street to clear the ramp entrance areas before the ramp movements receive a green. This additional clearance time can also be achieved through extended clearance (i.e., longer red clearance) on the phases prior to the off-ramp movements. Another alternative is to use short fixed-time phases, as was discussed in the two-critical-movement phasing scheme. See Section 5.2.6.1 for more information on clearance time.
- Because pedestrian movements occur in two phases, this phasing scheme results in a high probability that pedestrians will have to wait in the pedestrian island between Movements P1 and P10 at the northern crossover as well as Movements P5 and P12 at the southern crossover. Depending on pedestrian volumes, a "Not Ped" feature or other available pedestrian phasing option (such as pedestrian overlaps) could be applied to reduce the likelihood of pedestrians waiting in the island. A "Not Ped" feature would exclude the conflicting vehicle overlap only when there is a pedestrian call.

5.3.3 Four Critical Movements

The four-critical-movement phasing scheme can provide progression for the cross-street movements and the off-ramp left-turn movements, while also providing time for the off-ramp right-turn movements (depicted in Exhibit 5-19 and Exhibit 5-20). Considerations for this phasing scheme include the following:

- There are two options for this phasing scheme—Option A and Option B. Option A (shown in Exhibit 5-19) prioritizes the off-ramp left-turn and right-turn movements. Option B (shown in Exhibit 5-20) prioritizes the cross-street movements. Both options have phases based on travel times between the crossovers. The geometry of the crossovers and distance between them will play a critical role in the signal timing for the four-critical-movement phasing scheme.
- Unlike the two-critical-movement and three-critical-movement phasing schemes, the four-critical-movement phasing scheme does not separate the crossovers into separate rings. With Option B, the phases at the northern and southern crossovers could easily be separated into two rings, but by not separating them, the designer can easily compare Option A and Option B.
- Phases 1 and 5 are used as "dummy" phases, with no movements assigned to them. This provides consistency for numbering between the alternatives.
- For the four-critical-movement phasing schemes, the clearance of the through movements is accommodated assuming the use of overlap delay. This places a specified delay on both the left-turn and right-turn movements from the off-ramps. It will allow the through movements from the cross street to clear the ramp entrance areas before the ramp movements receive a green. This additional clearance time can also be achieved through extended clearance (i.e., longer red clearance) on the phases prior to the off-ramp movements. Another alternative is to use short, fixed-time phases, as was discussed in the two-critical-movement phasing scheme. See Section 5.2.6.1 for more information on clearance time.

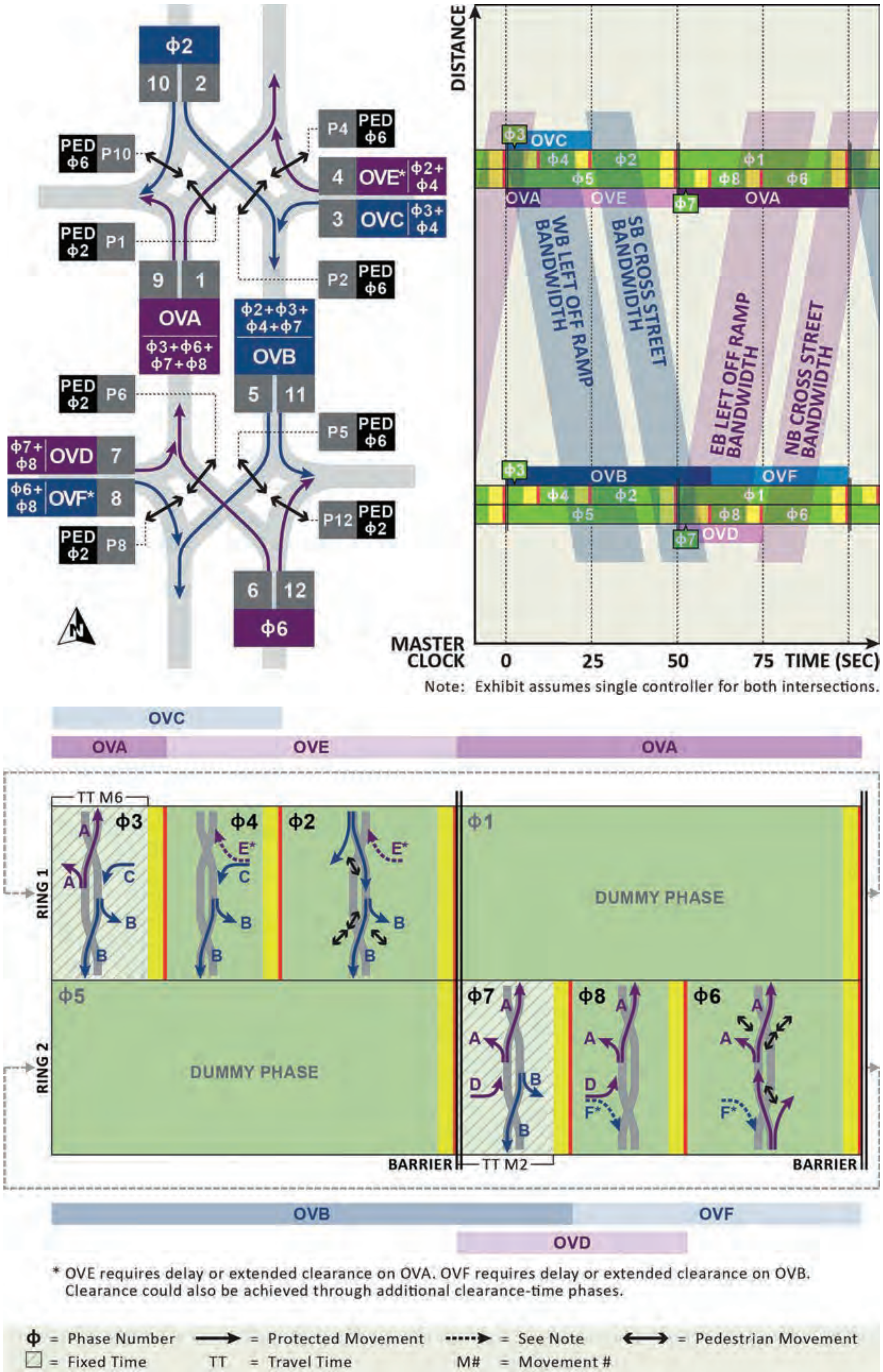


Exhibit 5-19. Four-critical-movement phasing scheme Option A.

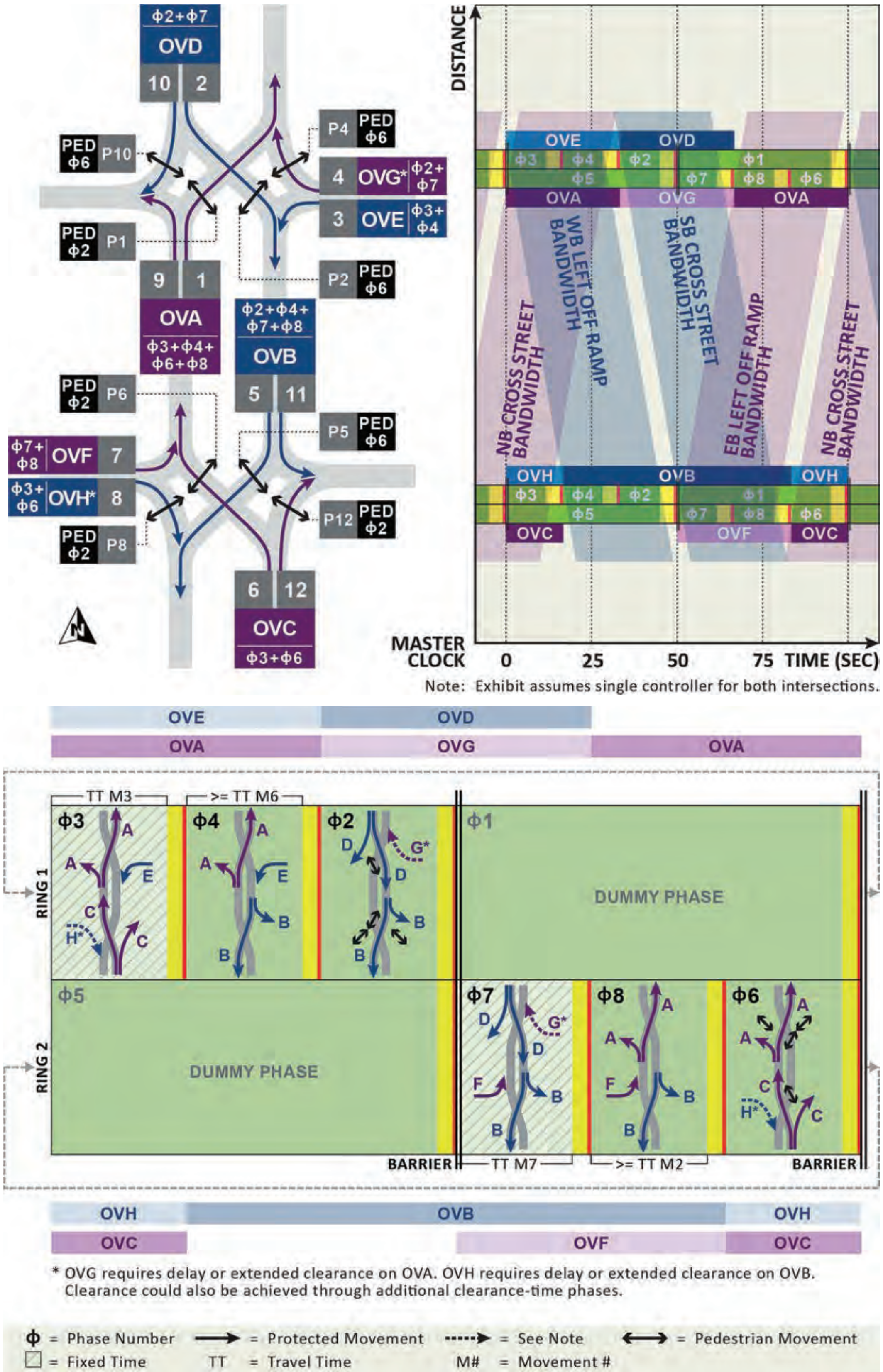


Exhibit 5-20. Four-critical-movement phasing scheme Option B.

- Both options use fixed-time travel-time phases for efficiency (unrelated to clearance for the ramps).
  - In Option A, the fixed-time phases are based on the travel time for Movements 2 and 6, which are cross-street through movements. To prevent vehicles at the tail end of those movements from getting stuck between the crossovers, these phases should be based on the time a vehicle needs to travel between the crossovers.
  - In Option B, the fixed-time phases are based on the travel time for Movements 3 and 7, which are off-ramp left-turn movements. This option will operate most efficiently if the fixed-time phases provide enough time for the off-ramp left-turn movements to travel to the downstream crossover, so that the downstream crossover turns green as the first vehicles from Movements 3 and 7 reach the intersection.
- Option B has another set of phases that, while not fixed-time, are dependent on travel time. Phases 4 and 8 should be at least long enough for Movements 2 and 6 to reach the downstream crossover. Much like the fixed-time phases in Option A, vehicles at the tail end of those movements should not get stuck between the crossovers. Depending on the time required to finish serving Movements 3 and 7 (off-ramp left-turn movements), the phases may need to be longer than the required travel time.
- Because pedestrian movements occur in two phases, this phasing scheme results in a high probability that pedestrians will have to wait in the pedestrian island between Movements P1 and P10 at the northern crossover as well as Movements P5 and P12 at the southern crossover. Depending on pedestrian volumes, a "Not Ped" feature or other available pedestrian phasing option (such as pedestrian overlaps) could be applied to reduce the likelihood of pedestrians waiting in the island. A "Not Ped" feature would exclude the conflicting vehicle overlap only when there is a pedestrian call.

5.3.4 Specialized Signal Timing Applications

The discussion in the previous section introduced three basic phasing schemes. Many variations of these schemes exist that may alter the phase sequence or duration of phases. It is expected that customization may be needed to serve site-specific needs. Examples of specialized signal timing that can enhance DDI operations for specific applications include:

- **Pre-timed control**—can be used as an alternative to the typically-recommended actuated control at DDIs.
- **Half cycle**—can be used to accommodate multiple platoons from an upstream adjacent signalized intersection.
- **Vehicle preemption ("ramp flush")**—allows both left-turn and right-turn movements from the freeway to be served concurrently to help reduce spillback onto the freeway mainline.
- **Dynamic overlap phasing**—can be used to mitigate clearance time conflicts.
- **Meter traffic at upstream adjacent signalized intersection**—can be used to minimize queue spillback into the DDI.
- **Exclusive pedestrian phase**—can be used to reduce delay for pedestrians crossing vehicular movements to and from the freeway.
- **Transit preferential treatment**—particularly for DDIs with center-running light rail or a center-running transitway.

5.3.4.1 Pre-Timed Control

Actuated signal control generally provides greater flexibility and more efficient service for roadway users, and in most cases, coordination can still be achieved between the crossovers when using actuated control. However, in some applications with two controllers, pre-timed control may be an option to maintain the time-space relationship between the intersections.

With actuated-coordinated control, minor movements can gap out or be skipped if demand is low. The extra time is often given to the coordinated movements. Depending on the phasing scheme that is chosen, there may be less added benefit for actuated control because having a movement gap out at one crossover may not greatly benefit progression at the other. A practitioner should also consider time-of-day effects. For example, pre-timed control may be advantageous during the peaks, and actuated control may be advantageous during off-peak times.

5.3.4.2 Half Cycle

Since DDI signals generally have fewer signal phases than other intersections on a given corridor, it may frequently be beneficial to run the crossovers at half of the cycle length of the cross street. (It is also possible to run multiple cycle lengths at the DDI, provided the sum of those cycle lengths equals the cycle length of the overall corridor.) Using a half cycle is particularly appealing when there are two heavy upstream movements, such as a through movement and a heavy side-street left-turn movement. If the DDI signals are running a half cycle, both movements have a chance of being progressed through the interchange. Half cycling can also be applied when the adjacent intersection uses split phasing for the side-street movements. When selecting a cycle length, it is critical to consider progression along the entire corridor. For more information about corridor considerations, refer to Section 5.4.1.

Another option is to run just one crossover at a half cycle when there is a heavy through movement and a heavy left-turn movement from one of the ramps. In that circumstance, it would be possible to progress both the upstream through movement and the off-ramp left-turn movement through the adjacent crossover. The trade-off in this case is that in every other cycle, the opposing through movement would be stopped internal to the DDI; this application works best with very directional movements.

5.3.4.3 Vehicle Preemption ("Ramp Flush")

Preemption can provide a good mechanism for alleviating excessive queuing (i.e., by "flushing" vehicles through an intersection); however, it should be used sparingly and only when a safety concern cannot be addressed by some other means. Two safety-related reasons to use preemption at a DDI include emergency vehicles and queue spillback onto the freeway.

Preemption could be used by emergency responders where traffic demand prevents acceptable emergency response times. Preemption in this case would flush vehicles through an intersection in the emergency vehicle's direction of travel, allowing emergency vehicles to respond more quickly to emergencies.

At freeway exit ramps with high demand from the left-turn or right-turn movements, preemption can be used to help flush queues that are on the verge of spilling back onto the freeway. A detector is placed on the freeway off-ramp, between the exit ramp gore and the DDI signal to detect the presence of excessive queues that have the potential to spill back onto the freeway. When the queue extends over the loop for a specified amount of time, the signal is preempted to call a dedicated phase for the left- and right-turn movements from the ramp, as illustrated in Exhibit 5-21. The placement of the queue detector is a function of observed queuing patterns and should be placed far enough upstream of the DDI as to not get triggered every cycle (i.e., greater than the average queue) but still downstream of the ramp gore on the off-ramp itself. This ramp preemption method is used regularly by several states.

While preemption is capable of alleviating excessive queuing, it should be used sparingly. It should be applied at locations where other signal timing or design strategies (e.g., longer ramps or more lanes) are infeasible. Preemption of a signal on a recurring basis could cause excessive delays and queues to form at intersections as additional phases are called or split times are increased, knocking the controller out of coordination for several cycles.

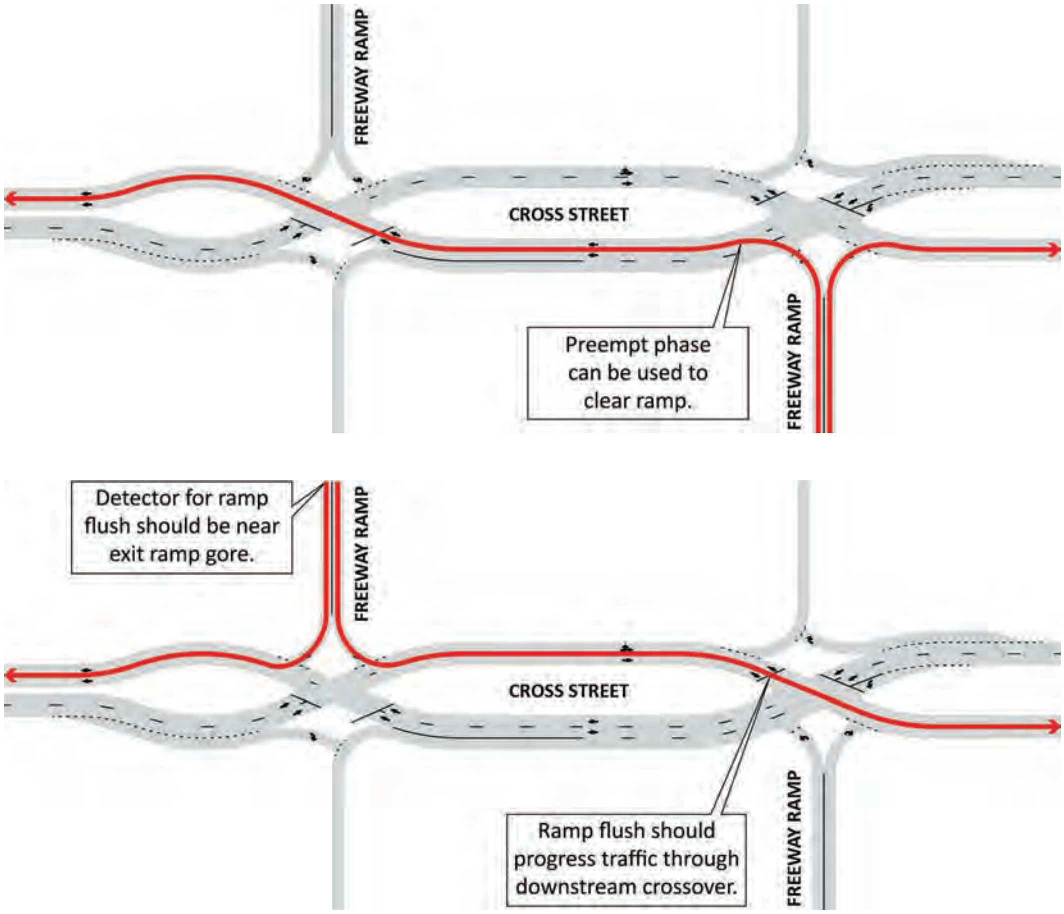


Exhibit 5-21. Ramp flush.

5.3.4.4 Dynamic Overlap Phasing

As discussed in Section 5.2.6, additional clearance time is needed at DDIs to ensure that cross-street traffic can clear conflict points with left turns and right turns from the freeway. Those clearance times are estimated based on vehicular travel times. In some cases, those assumed travel times may be too conservative, but in others they may not provide sufficient time (e.g., in the case of slow-moving vehicles). Agencies can mitigate potential conflicts through dynamic overlap phasing.

Dynamic overlap phasing uses detection to extend the overlap phases (being used for clearance) in the case of slow-moving vehicles (such as bicycles) on the cross street. In other words, if a slow-moving vehicle is detected as it approaches the conflict point, the overlap phase can extend to ensure that the phase does not end prior to the vehicle clearing the freeway merge point.

Alternatively, agencies can use supplemental signals (and stop bars) to stop cross-street traffic between the crossover and the freeway merge point. This strategy should only be applied when there is sufficient storage for one to two vehicles (per lane) without having them spill back into the crossover. It is only appropriate for DDIs with sufficient spacing between the crossover and the freeway merge point. More information about this treatment can be found in Chapter 7.

5.3.4.5 Meter Traffic at Upstream Adjacent Signalized Intersection

A downstream adjacent signalized intersection should be optimized so that throughput can be maximized with minimal queue spillback into the DDI. If spillback still occurs, the throughput of the upstream adjacent signalized intersection could be artificially reduced to match the capacity of the downstream signal. The queue that was spilling back from the downstream adjacent intersection into the outbound crossover would then be transferred to the upstream adjacent intersection. This would reduce the chance for queue spillback through the outbound DDI movement.

The upstream adjacent signalized intersection should be looked at carefully to make sure that demand starvation is not occurring at the inbound DDI crossover. The DDI crossover is expected to provide more throughput than the upstream adjacent signalized intersection. This creates an opportunity to use additional green time at the DDI to progress left- and right-turn movements from the side street at the upstream intersection.

5.3.4.6 Exclusive Pedestrian Phase

The phasing schemes presented in this chapter assume that all pedestrian movements are signalized and run concurrently with nonconflicting vehicular movements. In the phasing schemes, two pedestrian movements (one at each crossover) occur in multiple stages (i.e., pedestrians cross to an island and wait). Depending on pedestrian volumes, a “Not Ped” feature or other available pedestrian phasing option (such as pedestrian overlaps) could be applied to reduce the likelihood of pedestrians waiting in the island. However, another option to reduce pedestrian delay is an exclusive pedestrian phase. Use of an exclusive pedestrian phase would create additional delay for other roadway users, but would allow pedestrians to complete all movements during a single phase.

5.3.4.7 Transit Preferential Treatment

Some DDIs have center-running light-rail or a center-running transitway. Transit preferential treatment can be used to accommodate such arrangements. Often, an exclusive transit phase is applied that stops the cross-street vehicular movements but can allow left and right turns from the freeway ramps. Depending on traffic patterns, holding the left turns on the ramps may prevent significant queuing between the crossovers. Preferential treatment will require site-specific adjustments.

5.3.5 Understanding the Benefits and Challenges of DDI Phasing Schemes

The three basic DDI phasing schemes each have their unique benefits as well as challenges. Recommendations for which phasing scheme is most appropriate for a specific DDI depend on many factors, including DDI geometry, traffic volumes and patterns, need for specialized signal timing applications, and ultimately, agency preferences. In the sections below, dominant movements refer to those identified in Section 5.4.3.

5.3.5.1 Two-Critical-Movement Phasing Scheme Benefits and Challenges

Exhibit 5-22 summarizes the benefits and challenges of the two-critical-movement phasing scheme. In summary, the two-critical-movement phasing scheme is high efficiency and high capacity; it is simple to understand and implement, and it is adaptable to various crossover spacings. However, it has limited ability to progress multiple dominant movements. It is recommended for DDIs with high volume-to-capacity ratios and one dominant movement.

5.3.5.2 Three-Critical-Movement Phasing Scheme Benefits and Challenges

Exhibit 5-23 summarizes the benefits and challenges of the three-critical-movement phasing scheme. The three-critical-movement phasing scheme is high efficiency and high capacity; it can progress multiple dominant movements, and it is adaptable to various crossover spacings. However, it may result in internal stops for nondominant movements. It is recommended as

The three-critical-movement phasing scheme is recommended as the default when starting an analysis.

Exhibit 5-22. Benefits and challenges of the two-critical-movement phasing scheme.

	Benefits		Challenges
+	Ability to coordinate through movement on the cross-street or dominant left-turn movement from the ramps	–	Limited ability to progress multiple movements (e.g., both cross street and movements from the ramps)
+	Generally easy to understand/implement and troubleshoot in the field due to low complexity of phase assignments	–	May result in more stops internal to the DDI than other strategies
+	Minimizes lost time because of the low number of phases		
+	Highest potential capacity of the three phasing schemes		
+	Adaptable to any crossover spacing		

the default DDI phasing scheme, especially for DDIs with high volume-to-capacity ratios and multiple dominant movements.

5.3.5.3 Four-Critical-Movement Phasing Scheme Benefits and Challenges

Exhibit 5-24 summarizes the benefits and challenges of the four-critical-movement phasing scheme. The four-critical-movement phasing scheme is the least efficient phasing scheme, but is capable of progressing all movements and eliminating internal queues at the DDI. The scheme is limited in applicability to DDIs with one or more high volume-to-capacity ratio movements. It is recommended for DDIs with low to moderate volumes and short to medium crossover spacings.

5.4 System Needs

One of the most critical operational considerations in the design and implementation of a DDI is how to integrate the interchange with adjacent intersections, which requires site-specific investigation. Most DDIs are likely to be constructed in developed areas (or soon-to-be developed areas). In these cases, the cross-street portion of the DDI serves as an access route to various land uses in the vicinity of the interchange. The adjacent intersections and access

Exhibit 5-23. Benefits and challenges of the three-critical-movement phasing scheme.

	Benefits		Challenges
+	Ability to coordinate through movements on the cross-street and left-turn movements from the ramps	–	More complex than two-critical-movement phasing scheme
+	Possible to troubleshoot in the field due to the low complexity of phase assignments	–	Less efficient than two-critical-movement phasing scheme
+	Moderate lost time with only three critical phases	–	May result in stops internal to DDI for nondominant movements
+	High-capacity phasing scheme for multiple dominant movements		
+	Adaptable to any crossover spacing		

Exhibit 5-24. Benefits and challenges of the four-critical-movement phasing scheme.

Benefits	Challenges
+ Ability to progress all movements through the DDI	– Works best with balanced volumes and may be challenging with one or more dominant movements
+ Minimizes stops internal to the DDI (resulting in a better user experience)	– More difficult to understand/implement and troubleshoot in the field due to complexity of phase assignments
+ Most flexible and adaptable phasing scheme	– Highest lost time among the three phasing schemes because of the number of phases
	– Less capacity than other phasing schemes
	– Inefficient for wide crossover spacings

points may be closely spaced, resulting in significant interaction between the interchange and adjacent intersections. Adjacent intersections may also be roundabouts or have alternative intersection forms.

As with any interchange project, the practitioner should carefully consider existing land uses as well as planned and proposed developments that are expected to impact future growth of traffic through the interchange. Having a good understanding of the traffic volume levels and traffic patterns through the interchange is critical to properly design the DDI geometry and signal timing. For retrofitting existing interchanges, the practitioner should pay close attention to potential volume metering taking place for congested operations. In other words, the practitioner needs to assure that a valid estimate of the true demand at the interchange is used to design and time the DDI because the volumes served by an existing (congested) interchange may be less than those demands.

Field observations at various DDIs in the United States have shown that the observed delays and queues at a DDI are often due to queue spillback effects and capacity constraints at downstream signalized intersections (*2*). It is therefore critical that these adjacent intersections are explicitly considered prior to the design of a DDI.

There are two primary challenges of integrating a DDI into a corridor or system. The first is that the cross-street through movements cannot be processed simultaneously at the crossovers. Instead, each crossover has to process the cross-street through traffic in an alternating sequence, which impacts the ability to progress movements through the interchange in both directions. Two-way cross-street coordination at a DDI is possible, but progression opportunities will depend heavily on the phasing scheme at the DDI as well as the spacing of the adjacent intersections. The second challenge is that there are typically fewer conflicting movements at the DDI crossovers than at the adjacent intersections (e.g., left-turn movements, minor street movements requiring split phasing). This makes progression between the adjacent intersections and the DDI challenging.

Exhibits 5-25 through 5-28 are not intended to provide generalized guidance for DDI corridor performance, but rather to illustrate how to consider and evaluate DDIs in a corridor context. The specific coordination patterns and bandwidths shown will change with different sets of assumptions.

5.4.1 DDI Corridor Signal Timing

Three basic DDI phasing schemes were introduced in Section 5.3, including two critical movement, three critical movement, and four critical movement (Option A and Option B). This section discusses these phasing schemes in a corridor context. Exhibit 5-25 through Exhibit 5-28 expand the time-space diagrams for the three phasing schemes to include upstream and

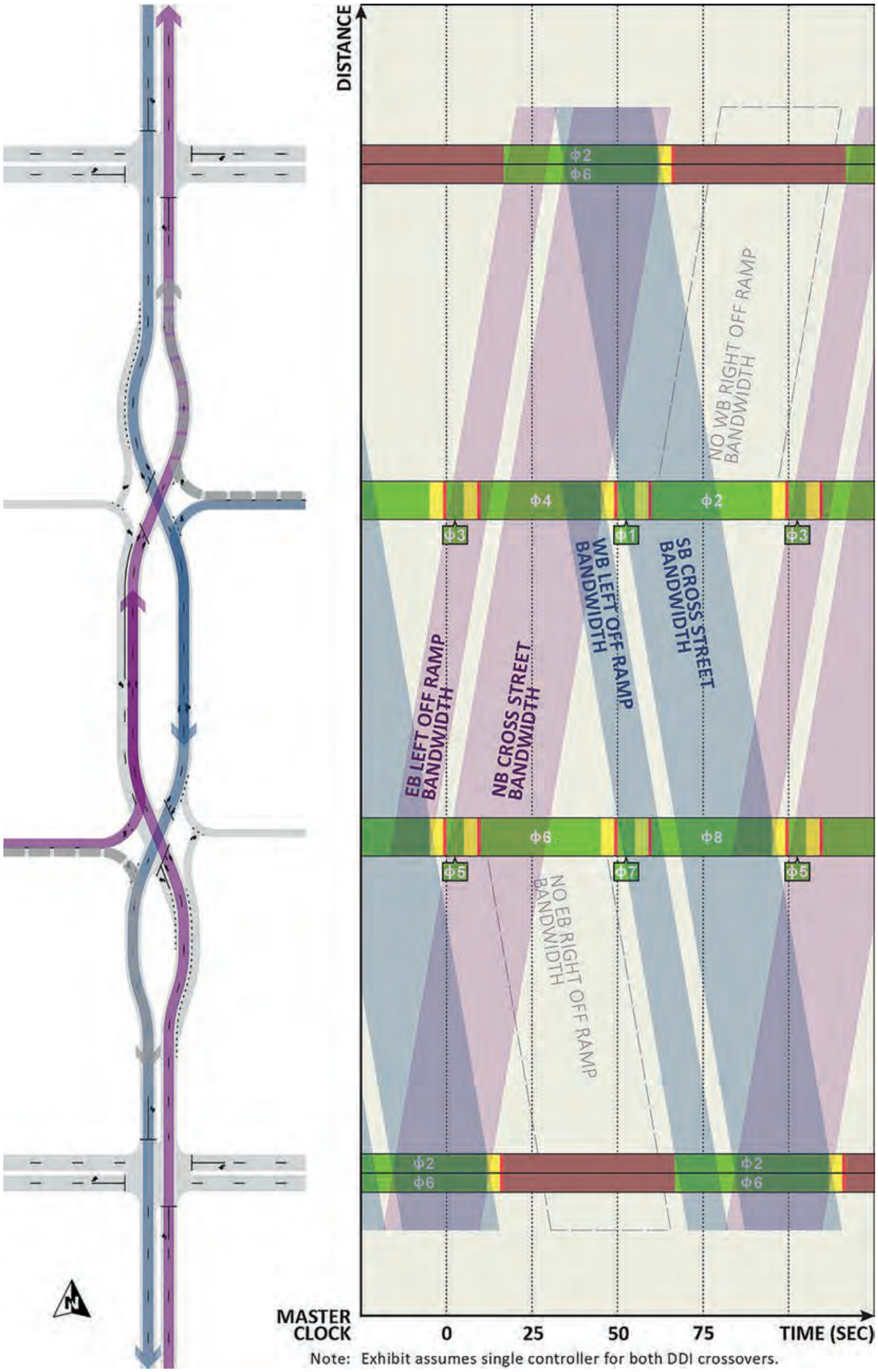


Exhibit 5-25. Two-critical-movement phasing in corridor context.

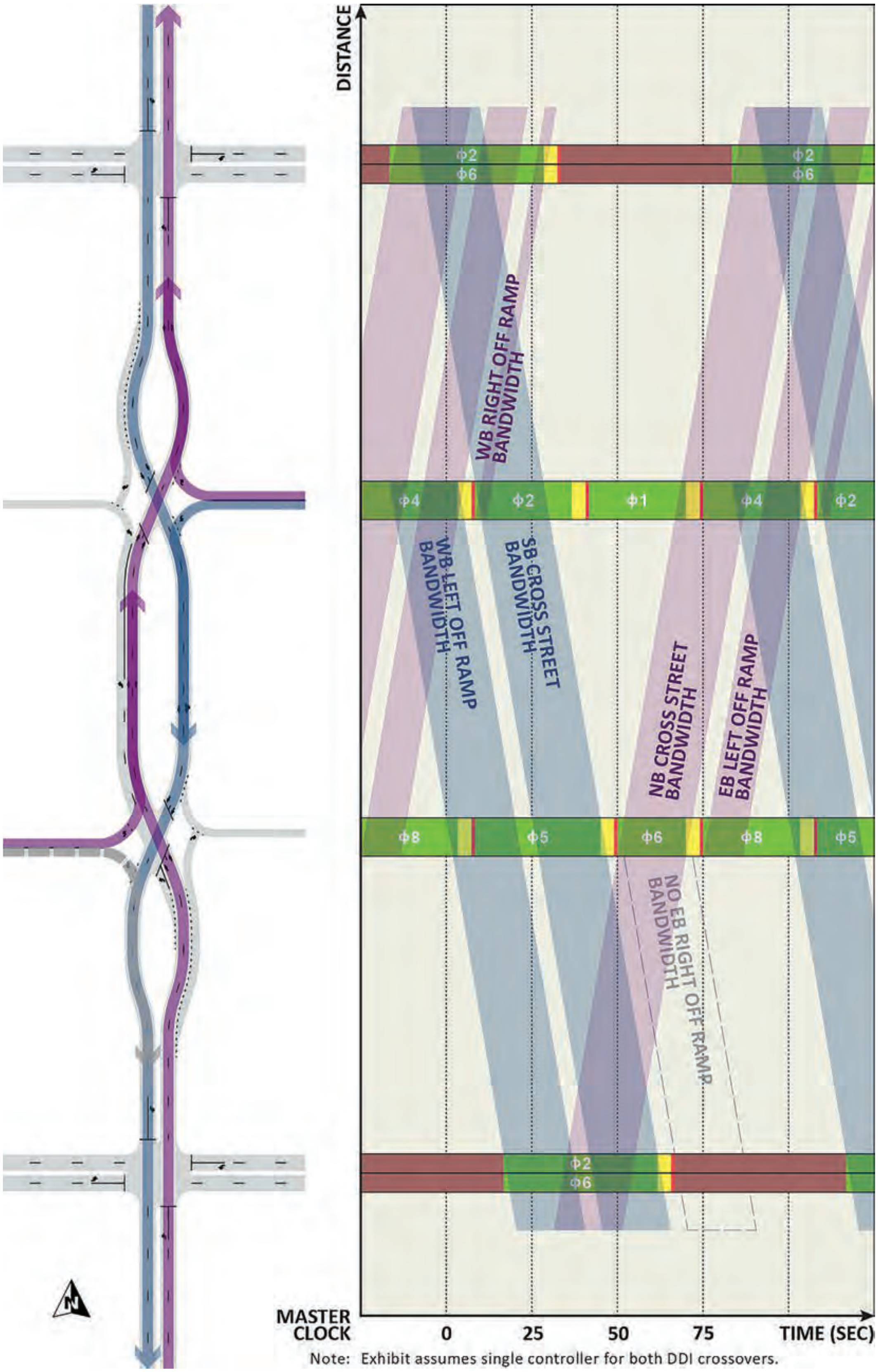


Exhibit 5-26. Three-critical-movement phasing in corridor context.

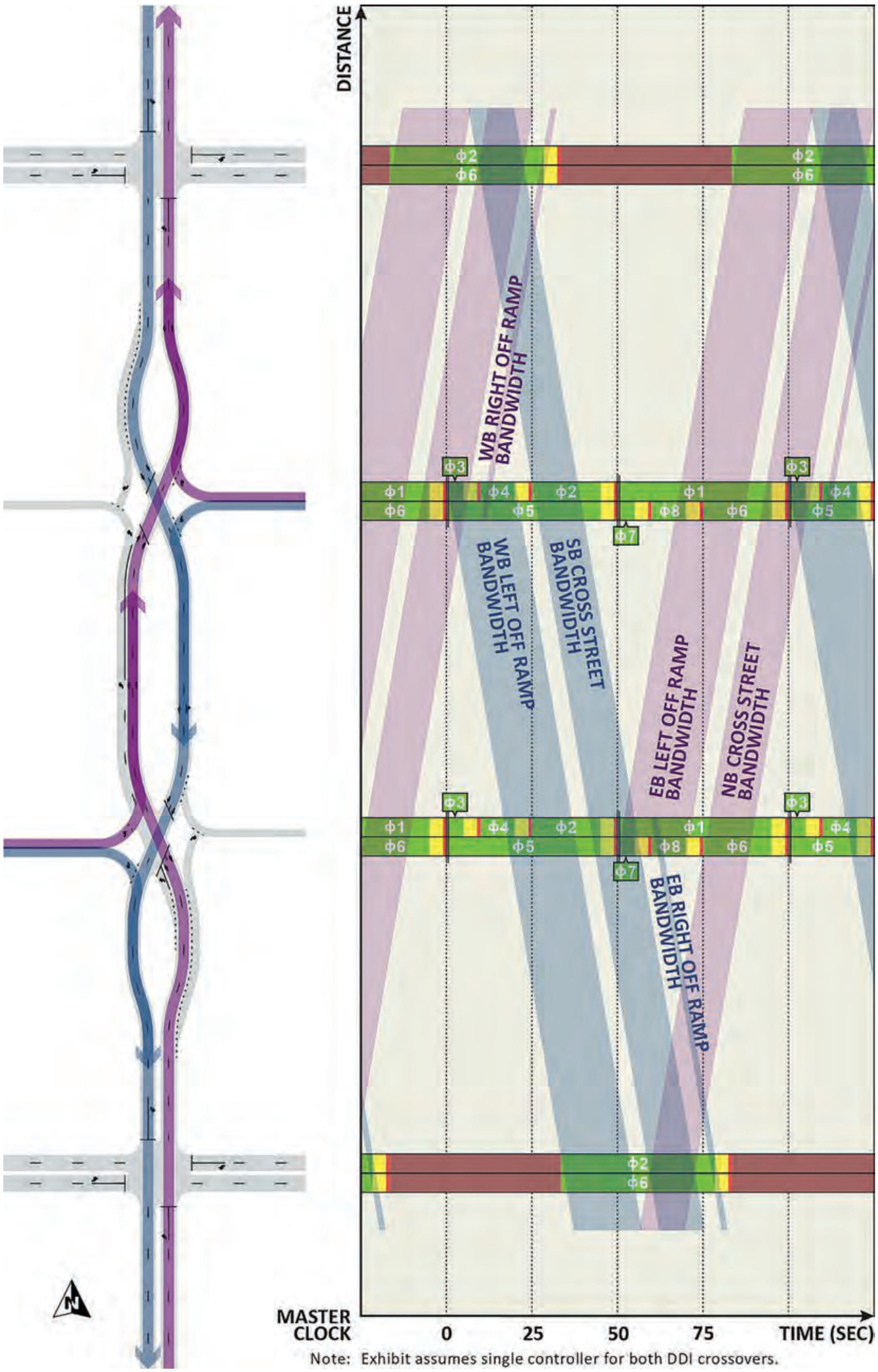


Exhibit 5-27. Four-critical-movement phasing (Option A) in corridor context.

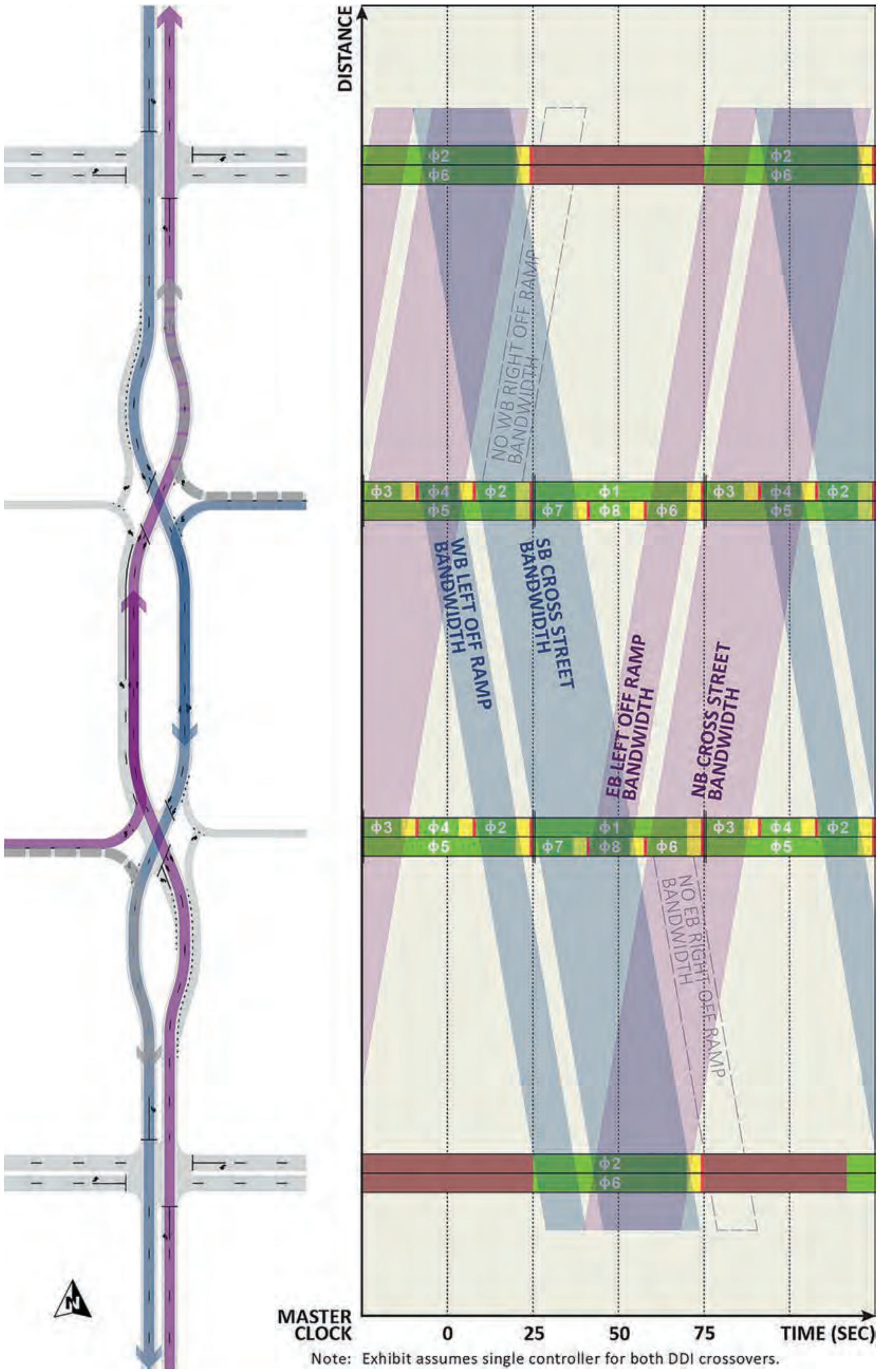


Exhibit 5-28. Four-critical-movement phasing (Option B) in corridor context.

downstream adjacent intersections. The use of time-space diagrams is strongly encouraged to visualize corridor bandwidth and properly evaluate the selected phasing scheme in a corridor context. It is important to note that these diagrams illustrate potential progression opportunities but do not illustrate queuing impacts.

When interpreting these exhibits, a practitioner should understand the various assumptions that had to be made to create them, including:

1. Splits and phase sequence at the DDI and adjacent intersections,
2. Spacing of the DDI crossovers and adjacent intersections along the cross street, and
3. Speeds along the cross street (inside and outside the DDI).

For purposes of demonstration, the upstream and downstream adjacent intersections in Exhibit 5-25 through Exhibit 5-28 use eight phases in two rings. While the offsets for the upstream and downstream intersections have been optimized for cross-street progression, the splits and phase sequence at the adjacent intersections are the same for all of the scenarios. This allows a direct comparison of the three phasing schemes.

It should be noted that, in these examples, the upstream adjacent intersection, downstream adjacent intersection, and DDI crossovers are equally spaced. This is the ideal scenario for progressing cross-street traffic and was chosen for illustrative purposes only. Other spacing scenarios will likely result in smaller bands along the corridor.

The purple (northbound) and blue (southbound) areas represent the bandwidth available based on the entire corridor (i.e., upstream and downstream adjacent intersections included). The reader may notice that the total available bandwidth is relatively similar for all three phasing schemes when considering the corridor context. However, the phasing scheme that is chosen at the DDI influences which movements receive the progression opportunities. With a limited amount of available bandwidth, an agency will have to choose priorities at the DDI.

5.4.2 Corridor Operational Considerations and Common Challenges

Building on the general coordination discussion, the following items should be considered in the process of integrating a DDI into a signal system. This section presents operational considerations for timing DDIs in a corridor context and describes some common operational challenges observed along DDI corridors. Section 5.4.4 then presents several strategies that can be employed to address these challenges.

5.4.2.1 Crossover Spacing

DDI crossover spacing is a key factor when selecting a phasing scheme. In general, shorter crossover spacing provides less queue storage internal to the DDI but also less time required to clear the interchange. Longer crossover spacing provides the ability to match the travel time between the crossovers and the upstream and downstream adjacent intersections. However, longer distances can be inefficient for clearing traffic between the crossovers.

5.4.2.2 Speed Profiles

Free-flow speeds along a corridor are limited by the geometrics of the DDI. Field studies at DDIs in the United States have shown that free-flow speeds through and between the crossovers are lower than the posted speed limit, even without interaction effects of other traffic (*2*). Free-flow speeds for the left-turn and right-turn movements are also limited by geometry. Field free-flow speeds from seven DDIs are summarized in Exhibit 5-29. The figure shows the field-observed mean speeds relative to the posted speed limit. For each observed mean speed, a range of speeds plus/minus one standard deviation is shown as well. Exhibit 5-29 suggests that the geometric design of the DDI controls the crossover free-flow speeds, independent of the speed limit.

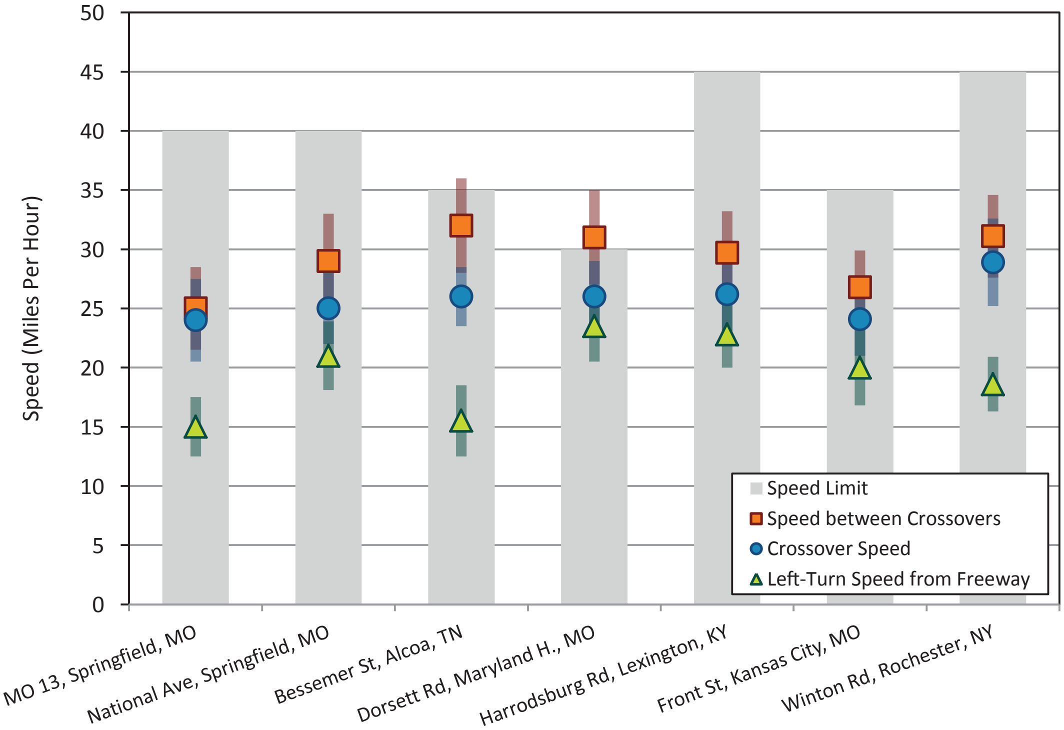
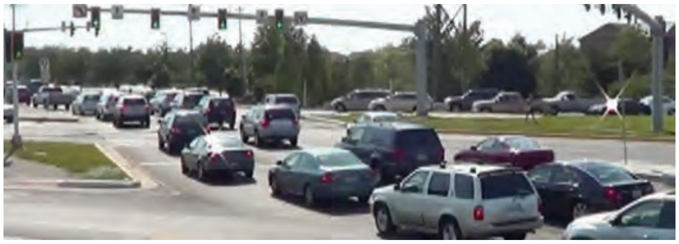


Exhibit 5-29. Field-measured speeds (mean plus/minus one standard deviation) at DDI sites.

Free-flow speeds impact the coordination speed of the DDI with adjacent intersections and potentially the capacity of traffic movements. At the same time, a traffic-calming benefit is provided that can be important for accommodating nonmotorized users. While it is unclear if DDI speeds will always be below the speed limit or if drivers will adjust over time, the speed profiles are an important consideration when evaluating a DDI in a corridor context. They are also useful for practitioners conducting simulation analyses of newly-designed facilities.

5.4.2.3 Queue Spillback

Queue spillback may occur in the departure zone downstream of a DDI. If a DDI crossover signal has a potential discharge volume that exceeds the processing capacity of the downstream adjacent signalized intersection, queues can spillback into the DDI, affecting outbound movements as shown in Exhibit 5-30 and Exhibit 5-31.



Source: *Field Evaluation of Double Crossover Diamond Interchanges* (2).

Exhibit 5-30. Queue spillback into DDI from downstream adjacent signal at Harrodsburg Road in Lexington, Kentucky.

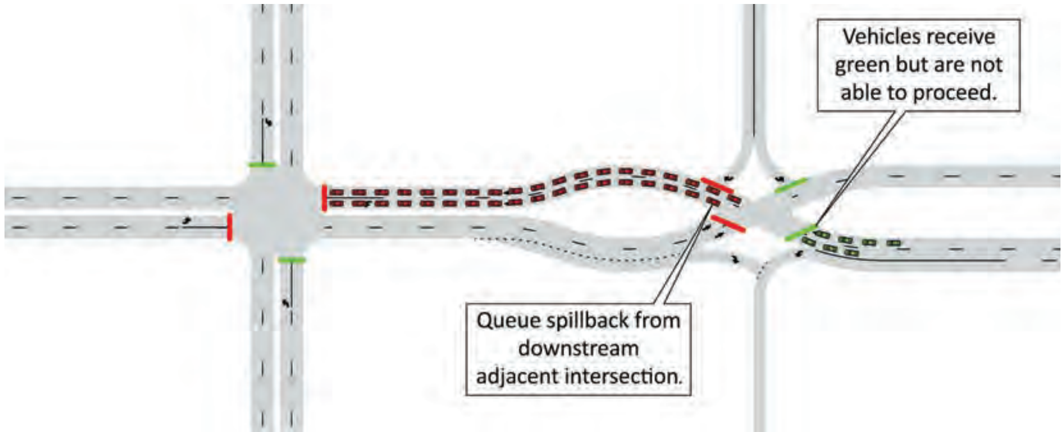


Exhibit 5-31. Queue spillback at a DDI.

5.4.2.4 Demand Starvation

Demand starvation occurs when a signal phase is green and no traffic is present. This can occur when traffic is held at an upstream adjacent signalized intersection along a corridor. Demand starvation is most likely to occur at the inbound approach to a DDI, where the capacity of the first DDI crossover may be greater than the capacity of the upstream adjacent intersection. When demand starvation occurs, the throughput of the DDI movement will be less than its capacity. Demand starvation is illustrated in Exhibit 5-32.

5.4.2.5 Lane Utilization

Interchanges often have imbalanced lane utilization because drivers making turning movements tend to pre-position in advance of the interchange. Field observations show that pre-positioning is more likely to occur at a DDI compared to a conventional diamond interchange (*2*).

Some of the lane imbalance is likely attributable to the lane configuration at the second crossover. In Exhibit 5-33, the three-lane road has a shared left-through lane at the second crossover, whereas in Exhibit 5-34, the three-lane road has an exclusive left-turn lane. The shared-lane configuration is expected to result in a mix of left-turn and through traffic in the leftmost lane at the first crossover, while the exclusive lane is expected to limit the left lane to left-turn traffic only.

Lane utilization at the first crossover may be imbalanced in both cases as a function of the amount of left-turning traffic in the traffic stream. Field observations indicate that left-

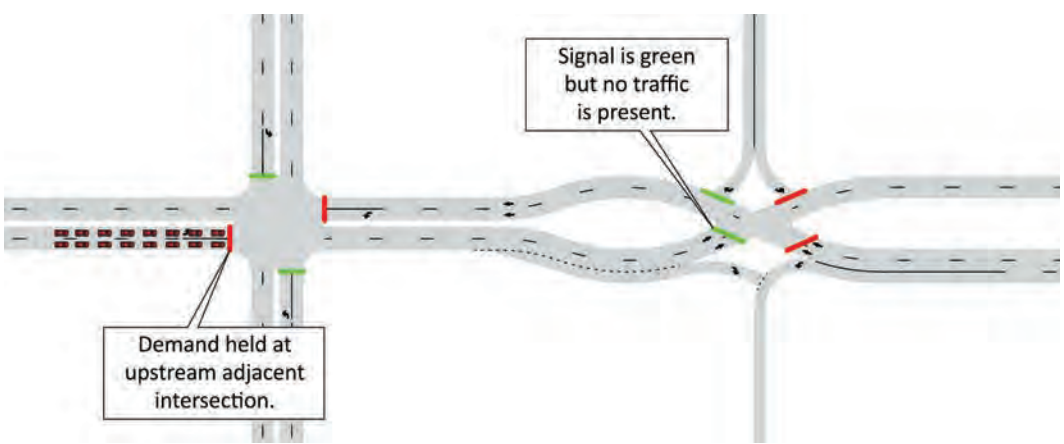


Exhibit 5-32. Demand starvation at a DDI.

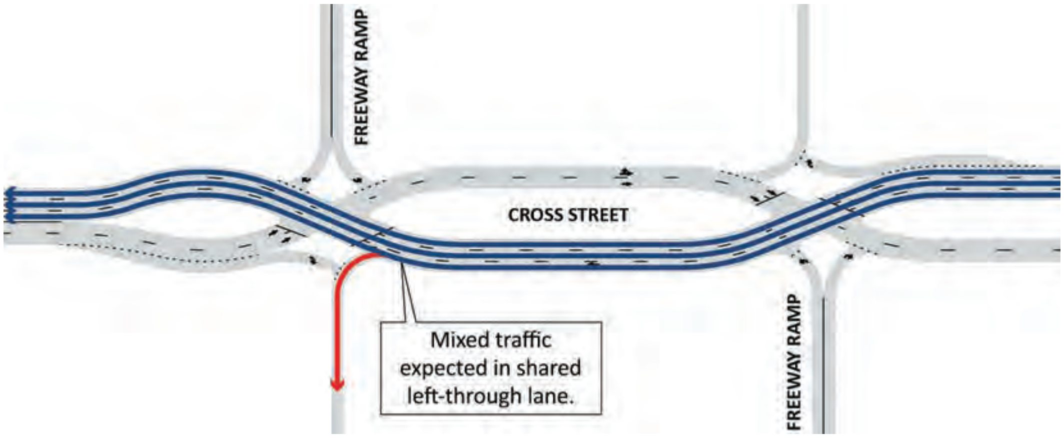


Exhibit 5-33. Shared left-through lane at a DDI.

lane utilization can be predicted by the left-turn-demand ratio (*2, 3, 4*). Lane-utilization models are integrated in the *Highway Capacity Manual* (HCM6) (*5*) analysis method for DDIs. The models predict lane utilization for the inbound movement at DDI crossovers as a function of lane geometry and the left-turn demand ratio. The reader is referred to the HCM6 for additional details on these models and how to use them.

5.4.2.6 Weaving Maneuvers

Weaving maneuvers result when an adjacent intersection is in close proximity to a DDI, as illustrated in Exhibit 5-35. Many DDIs prohibit right-turn-on-red (RTOR) maneuvers from the freeway exit ramp. This has the benefit of reducing the number of conflicts associated with weaving maneuvers. For DDIs with RTOR allowed or for DDIs with a continuous lane addition serving the right turn, weaving can significantly impact corridor operations and safety. Besides RTOR restrictions, weaving conflicts can be minimized by lengthening the distance to the adjacent intersection.

5.4.3 Assessing Signal Phasing Schemes in a Corridor Context

For any operational analysis methodology, a practitioner must first select a phasing scheme to evaluate. This section provides guidance on selecting an initial phasing scheme to test based on the concept of dominant movements. Exhibit 5-36 illustrates eight common dominant-movement schemes that exist at DDIs. Before proceeding with choosing a phasing scheme,

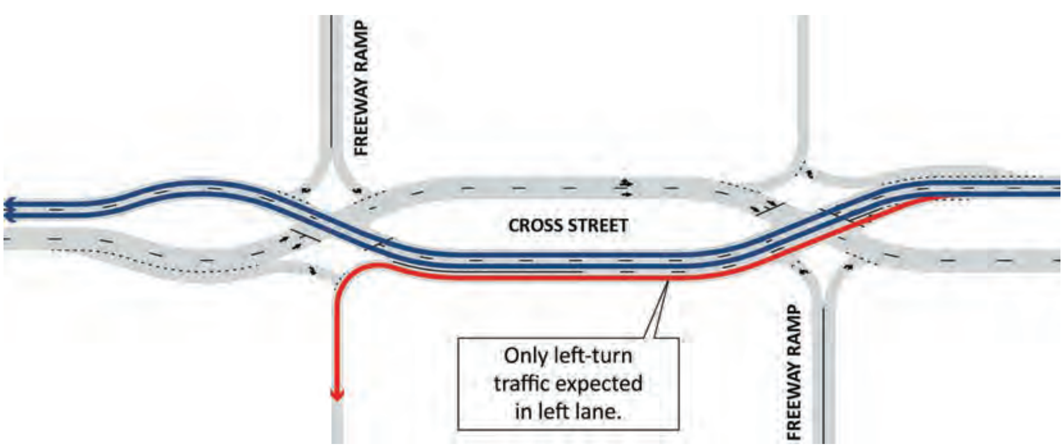


Exhibit 5-34. Left-turn-only lane at a DDI.

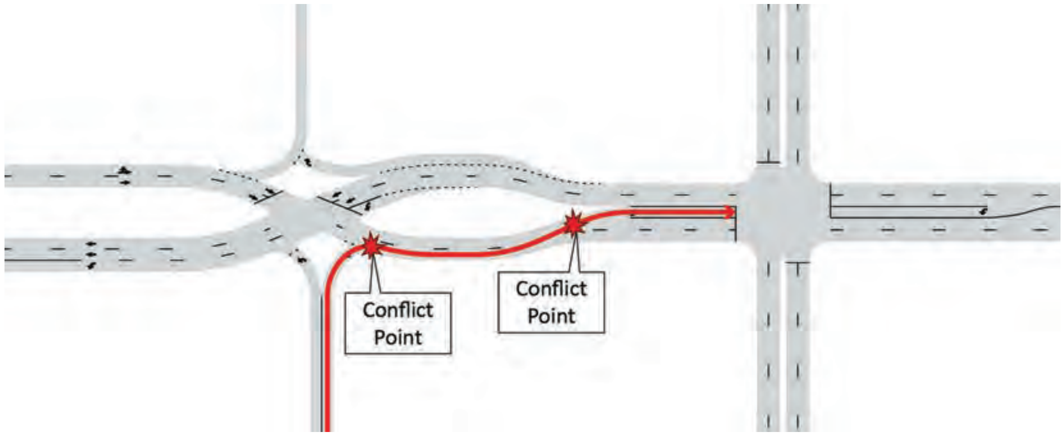


Exhibit 5-35. Weaving maneuver and conflict points for DDI right turn from freeway.

a practitioner must determine which dominant-movement patterns are likely to occur at the DDI in question, likely through a planning-level demand assessment. The dominant-movement schemes may vary based on time of day.

The various phasing schemes described in Section 5.3 can all provide acceptable performance, but how a DDI will operate under a particular phasing scheme significantly depends on the crossover spacing distance and traffic patterns. The following guidance provides information about the level of delay and queuing that might be expected when using a specific phasing scheme (i.e., two, three, or four critical movement) for a particular crossover spacing distance and set of dominant movements (i.e., one of the eight dominant-movement patterns).

Exhibit 5-37 illustrates how the movements are numbered for queuing purposes. The movements listed as potentially having significant queues are those that are anticipated to experience

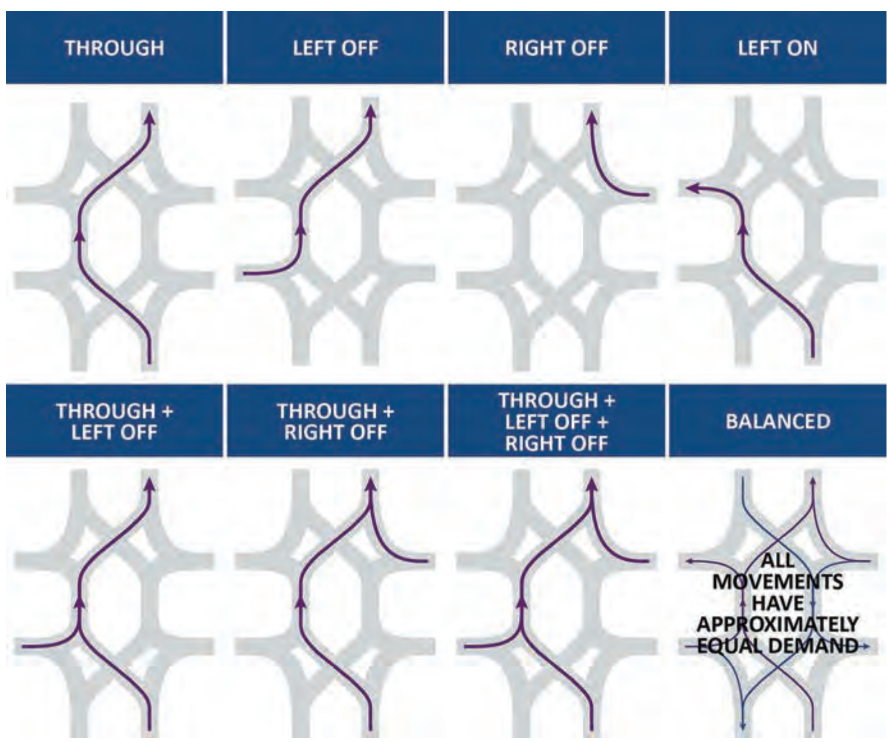


Exhibit 5-36. Dominant-movement patterns.

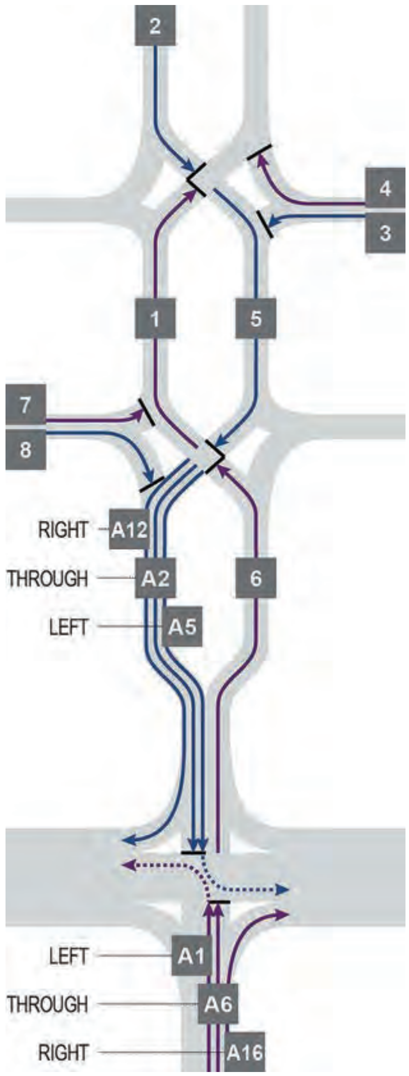


Exhibit 5-37. Significant-queue-length movement numbering.

long queues. For example, queues for Movements 1 and 5 are considered to be significant if they extend beyond the crossover spacing (300 feet, 750 feet, and 1,200 feet, respectively). A practitioner should assess the list of significant queue movements considering the site in question. If geometry makes it impossible to change the lane configuration at a ramp approach, for example, a long off-ramp queue might indicate that a different phasing scheme should be tested.

It is important to emphasize that the following tables assume that the dominant movements are at or near capacity. Clearly, a geometric modification such as a larger cross-section with additional lanes would also be likely to achieve acceptable operations. Under low to moderate volumes, any of the three phasing schemes could result in acceptable performance, although the phasing schemes could produce different results from each other. The exhibits and tables in this section are simply meant to help a practitioner choose an initial phasing scheme to test as he or she initializes an operational analysis (using the tools explained throughout the remainder of this chapter).

Note that the following tables assume the dominant movements are at or near capacity.

Exhibit 5-38, Exhibit 5-39, and Exhibit 5-40 (for crossover spacing distances of 300 feet, 750 feet, and 1,200 feet, respectively) provide a starting point for estimating the anticipated

Exhibit 5-38. Anticipated phasing-scheme queuing for a crossover spacing of 300 feet.

Heavy Demand Path(s) (Reference Exhibit 5-36)	Two-Critical-Movement Phasing		Three-Critical-Movement Phasing		Four-Critical-Movement Phasing	
	Anticip. Level of Delay	Movements that May Experience Significant Queuing	Anticip. Level of Delay	Movements that May Experience Significant Queuing	Anticip. Level of Delay	Movements that May Experience Significant Queuing
Through	Low	-	Low	-	Medium	6, A6
Left Off	Medium	1, 5, 6, 7, 8, A6	Medium	4, 7, 8	Medium	3, 4, 6, 7, 8, A6
Right Off	Low	4	Low	3, 4, 7, 8	High	3, 4, 6, 7, 8, A6
Left On	Medium	3, 4, 5	Medium	3, 4, 5	Medium	3, 4, 5, 7
Through + Left Off	Low	1, 7, 8	Low	7, 8	Medium	3, 4, 6, 7, 8, A6
Through + Right Off	Low	4	Low	3, 4, 7, 8	Medium	3, 4, 6, 7, 8, A6
Through + Left Off + Right Off	Low	1, 4, 7	Low	3, 4, 7, 8	Medium	3, 4, 6, 7, 8, A6
Balanced	Low	-	Low	-	Low	-

Exhibit 5-39. Anticipated phasing-scheme queuing for a crossover spacing of 750 feet.

Heavy Demand Path(s) (Reference Exhibit 5-36)	Two-Critical-Movement Phasing		Three-Critical-Movement Phasing		Four-Critical-Movement Phasing	
	Anticip. Level of Delay	Movements that May Experience Significant Queuing	Anticip. Level of Delay	Movements that May Experience Significant Queuing	Anticip. Level of Delay	Movements that May Experience Significant Queuing
Through	Low	-	Low	-	Medium	3, 4, 6, 7
Left Off	Low	7, 8	Low	7	Medium	3, 4, 6, 7, 8
Right Off	Low	4	Medium	3, 4, 7, 8	Medium	3, 4, 5, 7, 8
Left On	Low	-	Medium	-	Medium	3, 4
Through + Left Off	Low	7	Low	7	Medium	3, 4, 6, 7, 8, A6
Through + Right Off	Low	4	Low	3, 4, 7, 8	Medium	3, 4, 7, 8
Through + Left Off + Right Off	Low	4, 7	Low	3, 4, 7, 8	Medium	3, 4, 6, 7, 8, A6
Balanced	Low	-	Low	4, 7	Low	3, 4

Exhibit 5-40. Anticipated phasing-scheme queuing for a crossover spacing of 1,200 feet.

Heavy Demand Path(s) (Reference Exhibit 5-36)	Two-Critical-Movement Phasing		Three-Critical-Movement Phasing		Four-Critical-Movement Phasing	
	Anticip. Level of Delay	Movements that May Experience Significant Queuing	Anticip. Level of Delay	Movements that May Experience Significant Queuing	Anticip. Level of Delay	Movements that May Experience Significant Queuing
Through	Low	-	Low	-	Medium	3, 4, 6, A6
Left Off	Low	7	Low	7	High	3, 4, 6, 7, 8, A6
Right Off	Low	4	Low	4, 3	High	3, 4, 6, 8, A6
Left On	Low	-	Medium	-	High	3, 4, 6, 8, A6
Through + Left Off	Low	7	Low	7	Medium	3, 4, 6, 7, 8, A6
Through + Right Off	Low	4	Low	4	Medium	3, 4, 6, 7, 8, A6
Through + Left Off + Right Off	Low	4, 7	Low	4	Medium	3, 4, 6, 7, 8, A6
Balanced	Low	-	Low	-	Medium	3, 4, 8

delay impacts of the three phasing schemes (two, three, and four critical movements). An analyst should first use these exhibits to determine which phasing scheme(s) may be most appropriate for a given scenario. Once one or more schemes are chosen, the analyst should consider the queue interactions for critical approaches, which are also summarized in the exhibits.

The interpretation of Exhibit 5-38, Exhibit 5-39, and Exhibit 5-40 is as follows:

- **Delay rating of "low"** means that the dominant movements are readily accommodated under the given scenario. However, an analyst should still pay attention to any movements that are anticipated to experience significant queuing.
- **Delay rating of "medium"** means that the dominant movements may be accommodated under the given scenario, but operations should be evaluated carefully with the chosen operational analysis tool.
- **Delay rating of "high"** means that it will likely be difficult to accommodate the dominant movements under the given scenario. If other phasing schemes are anticipated to have lower delay for the given scenario, the analyst should consider testing them first.

5.4.4 Strategies to Improve Corridor Operations

This section discusses strategies to help with corridor operations involving a DDI. It should be noted that most of the strategies are focused on maximizing vehicle throughput at the DDI and adjacent signalized intersections.

Trade-offs between vehicles and other modes should be considered for all of the listed strategies.

Several strategies can be applied at the DDI crossovers:

- Half cycle,
- Signalized on-ramp left turn,
- Dedicated phase for concurrent off-ramp left and right turns,
- LTOR or RTOR allowed at off-ramp, and
- Dynamic overlap phasing.

Other strategies can be applied at the adjacent signalized intersections in order to influence operations at the DDI:

- Optimize timing and/or meter traffic at upstream adjacent signalized intersection,
- Alternate side-street phases at downstream adjacent signalized intersection,
- Lead/lag phasing for outbound left turns at downstream adjacent signalized intersection, and
- Eliminate phases at adjacent signalized intersection.

Additionally, one strategy can be applied at the corridor level (i.e., at the DDI crossovers and adjacent signalized intersections): Free/uncoordinated operations.

Using delay categories summarized in Exhibit 5-41, Exhibit 5-42 summarizes the change in delay that can be expected for heavy movements and DDI movements overall by applying the various strategies listed above. The results are based on a simulation-based experiment using calibrated base models of a DDI employing the three-critical-movement phasing scheme. The exhibit rows list the different strategies, while the columns list the six heavy-volume scenarios. The expected change in delay is expressed relative to base performance for the particular heavy-volume scenario using a five-point scale (summarized in Exhibit 5-41). Blank cells indicate scenarios that were not specifically evaluated. These tables should be used to prioritize strategy testing but should not be used to exclude specific strategies for particular locations. More information about each strategy is available in the following sections.

5.4.4.1 Half Cycle

Using half cycles at some intersections may provide for improved progression of off-peak traffic at the DDI by opening the green band more often. Additionally, this may help discourage red-light running at DDI intersections; because adjacent intersections are likely to require longer cycle lengths, a half cycle DDI can help reduce driver frustration due to long wait times at the crossover. Half cycling may also be useful in progressing both the through movement from the adjacent upstream signalized intersection and a heavy left-turn movement from the side street at that intersection. While this guidance only tested two cycles of equal length that summed to the overall corridor cycle length, it is also possible to run multiple cycle lengths at the DDI, provided the sum of those cycle lengths equals the cycle length of the overall corridor.

5.4.4.2 Signalized On-Ramp Left Turn

Pedestrian facilities that utilize the outside of the DDI must cross a free-flow left turn onto the entrance ramp. For pedestrians, this movement could be signalized with a dedicated pedestrian

Exhibit 5-41. Delay categories.

Symbol	Delay Category	Associated Impact on Vehicle Operations	Associated Percent Change in Delay
++	High Delay Increase	Worse Conditions	>12% Increase in Delay
+	Low Delay Increase	Moderately Worse Conditions	6% –12% Increase in Delay
o	Minimal Delay Change	Insignificant Change in Conditions	<6% Increase in Delay and <6% Decrease in Delay
-	Low Delay Decrease	Moderately Improved Conditions	6% –12% Decrease in Delay
--	High Delay Decrease	Improved Conditions	>12% Decrease in Delay
(Blank)	Not Evaluated	Not Evaluated	Not Evaluated

Exhibit 5-42 is based on the three-critical-movement phasing scheme; different results would be expected if one of the other phasing schemes was chosen.

Exhibit 5-42. Change in delay expected with various strategies and traffic patterns (based on the three-critical-movement phasing scheme).

Strategy	Low Volume		Heavy Through		Heavy Left Off		Heavy Right Off		Heavy Left On		Heavy Through + Right	
	Heavy Movement	All Movements	Heavy Movement	All Movements	Heavy Movement	All Movements	Heavy Movement	All Movements	Heavy Movement	All Movements	Heavy Movement	All Movements
Half Cycle	++	-	++	++	o	--	--	++	++	o	-	o
Signalized On-Ramp Left Turn			o	o					o	o	o	o
Dedicated Phase for Concurrent Off-Ramp Left and Right Turns					o	o	o	++			++	o
RTOR Allowed at Off-Ramp			o	-	o	o	--	--			-	o
Left-Turn-on-Red (LTOR) Allowed at Off-Ramp			-	--	o	o	--	--			o	-
LTOR & RTOR Allowed at Off-Ramp			-	--	o	+	o	--			o	--
Dynamic Overlap Phasing					o	o	-	o			o	o
Alternate Side-Street Phases at Downstream Signal			o	o	++	+	-	o			+	o
Lead/Lag Phasing for Outbound Lefts at Downstream Signal			o	o	--	o	+	o			--	-
Eliminate Phases at Adjacent Intersection					++	+	--	--	o	++	--	-
Free/Uncoordinated	++	+	++	++	++	o	++	++			++	+

++	High Delay Increase	+	Low Delay Increase	o	Minimal Delay Change	-	Low Delay Decrease	--	High Delay Decrease

phase or a beaconing device such as a pedestrian hybrid beacon (PHB) or flashing yellow beacon. To avoid creating a left-turn queue between the crossovers, the pedestrian signal could be coordinated with the DDI signal.

While not specifically a corridor improvement strategy, pedestrian signals were included here to evaluate whether this pedestrian safety treatment would result in a significant negative impact on corridor operations. The results showed that the left turns can readily be signalized to enhance pedestrian safety without negatively impacting the operations.

A practitioner should consider the impacts of shared versus exclusive lanes when evaluating this strategy. In a shared-lane scenario, the impact of queue spillback under heavy volumes could result in reduced throughput for the through movement.

5.4.4.3 Dedicated Phase for Concurrent Off-Ramp Left and Right Turns

For continuously high demand at the exit ramp during peak hours, an additional phase can be added to the time-of-day plan, which serves the left and right turns from the exit ramp. This strategy uses a similar approach as was discussed in Section 5.3.4.3, but instead of a true "ramp flush," it would use a phase to serve the ramp movements concurrently.

5.4.4.4 LTOR or RTOR Allowed at Off-Ramp

Assuming proper sight distance is provided and drivers can identify the stream of traffic with which they are merging, RTOR or LTOR can be considered. If there are sufficient gaps in the cross-street traffic, the allowance of turning on red would increase the capacity of the movement. As with any interchange and closely-spaced intersection pair (i.e., not unique to DDIs), there is the potential for a weaving maneuver as vehicles turning off of the freeway quickly maneuver over multiple lanes of traffic to turn at the adjacent intersection. Where LTOR is not legal, the use of flashing arrows could be considered.

5.4.4.5 Dynamic Overlap Phasing

Dynamic overlap phasing allows more efficient clearance of crossover through movements. Detection allows the clearance interval to be timed based on real-time vehicle information instead of estimated travel time. This can result in more time for the off-ramp movements while still providing clearance for the cross-street vehicles.

5.4.4.6 Alternate Side-Street Phases at Downstream Adjacent Signalized Intersection

The phasing scheme at an intersection adjacent to a DDI could be adjusted to provide additional capacity for the cross-street approach while only allowing one or more side-street movements every other cycle. This unusual phasing scheme could be used in a time-of-day plan when through traffic demand is high and when there is a great need for additional capacity to prevent queue spillback into the DDI.

5.4.4.7 Lead/Lag Phasing for Outbound Left Turns at Downstream Adjacent Signalized Intersection

Lead/lag phasing allows signal timers flexibility to choose when to provide the left-turn phase in a specific ring so that the maximum bandwidth can be achieved for the coordinated movement. Lead/lag phasing is being utilized much more frequently by agencies now that safety concerns with the "yellow trap" have been addressed through flashing yellow arrows and other innovations. In a DDI corridor, lead/lag phasing at the adjacent signalized intersection can help with progression of vehicle traffic to or from the DDI.

5.4.4.8 Eliminate Phases at Adjacent Signalized Intersection

For upstream and downstream adjacent intersections, additional cross-street capacity could be achieved by eliminating phases. Eliminating phases is possible through a variety of alternative intersection forms such as the Restricted Crossing U-turn (RCUT) or the Median U-turn (MUT). With fewer phases, the available capacity at the adjacent intersection can be increased to levels similar to the very efficient DDI, thereby improving overall corridor operations.

5.4.4.9 Free/Uncoordinated

In some cases, it may be more effective to allow the corridor to operate without coordination. For example, this may be beneficial during low-volume times of day. The delay results in

Exhibit 5-42 suggest that this strategy is not appropriate for any of the high-volume scenarios because it results in significant increases in delay over the corresponding base case. However, for low-volume periods this strategy can more readily adapt to changing traffic patterns and has been applied successfully at several DDIs in the United States during off-peak periods.

5.5 Operational Analysis

To support decisions regarding the choice and design of a DDI, there needs to be an appropriate level of traffic operational analysis corresponding to the stage of the project development process. This operational analysis should allow a practitioner to assess lane configurations, queues, and delay, with the ultimate goal of providing guidance to the designer. While most operational analysis focuses on motorized vehicles, final intersection configurations and associated signal timing should balance an agency's priorities (e.g., multimodal users).

The level of analysis should be consistent with available data, which could include:

- Average daily traffic (ADT),
- Future growth projections for the DDI and corridor (including traffic from planned or proposed developments adjacent to the interchange),
- Speed (posted, design, or 85th percentile),
- Weekday and weekend peak-hour turning-movement counts or demand estimates,
- Weekday and weekend off-peak turning-movement counts or demand estimates,
- Pedestrian volumes or demands,
- Bicycle volumes or demands,
- Estimates or counts of the proportion of the traffic stream composed of heavy vehicles, and
- Origin-destination (O/D) demands at the DDI and adjacent signals.

According to FHWA's "Traffic Analysis Tools" web page, several tools are available to analyze traffic operations at intersections, including the following (*6*):

- Planning-level analysis [such as critical-movement analysis (CMA) or Capacity Analysis for Planning of Junctions (CAP-X)],
- HCM6 analysis, and
- Microsimulation analysis.

One major factor distinguishing these three types of analysis is the time required to complete the evaluation. HCM6 analysis may take several times as long as a planning-level analysis, and the time required for microsimulation is typically an order of magnitude greater than HCM6 analysis. In general:

- **Planning-level tools** are useful for assessing the feasibility of a DDI and for selecting an initial number of lanes and phasing scheme.
- **An operational analysis using a deterministic method**, such as the HCM6, is useful to perform a more detailed peak-hour performance analysis and to estimate performance measures like delay, travel time, and queue lengths (*5*). HCM6 analysis may provide insight on additional geometric design and signal timing details.
- **Microsimulation** is useful for analyzing interactions between intersections and between modes to assess the overall performance in a multimodal corridor context.

5.5.1 Selecting the Appropriate Level of Analysis

Selecting the appropriate level of analysis for a DDI evaluation depends on the available input data, the desired outputs, and the available resources to conduct the analysis. As such, a DDI analysis does not differ fundamentally from any other interchange evaluation, but some DDI-specific considerations for tool selection are described below.

1. **Pre-Screening the DDI as an interchange alternative. CAP-X**, developed by FHWA, is a planning-level tool that can be used to quickly and directly compare the DDI to other (alternative) intersection and interchange forms (*7*).
2. **Determining initial lane configuration and signal parameters. CMA**, presented in *NCHRP Report 812: Signal Timing Manual, 2nd Edition*, allows for a quick evaluation of the required number of lanes at a DDI, estimation of basic signal timing parameters for the DDI, and screening for potential internal queuing issues based on minimal inputs (*1*).
3. **Estimating interchange delay and Level of Service (LOS).** The **HCM6 DDI Method** allows for estimation of interchange delays, queue lengths, and LOS using a deterministic procedure calibrated from DDI field observations in the United States (*5*).
4. **Evaluating DDI corridor and multimodal performance. Microsimulation** is ideally suited for evaluating DDIs in a corridor context, including interactions with adjacent intersections and different transportation modes. The selected microsimulation should allow sufficient flexibility and level of detail to replicate the DDI geometry and signal timing characteristics, and the analyst should consult the software user manual to assure that the tool is appropriate for modeling DDIs.

A summary of the inputs, outputs, levels of effort, and limitations is provided for each analysis tool in Exhibit 5-43.

5.5.2 Planning-Level Analysis

Two principal types of planning-level analysis apply to DDIs. CAP-X is a sketch-planning tool that can be used to compare a DDI to other intersection and interchange alternatives using volume-to-capacity ratios. CMA is a planning-level tool that is useful for comparing signal phasing options and verifying the lane configuration. Planning-level analyses can be performed by hand or software.

5.5.2.1 Advantages and Disadvantages

The key advantage of planning-level-analysis approaches is that the methods can generally be applied quickly and with minimal resources. The resulting high-level assessment of DDI performance can be helpful when determining the initial feasibility of a DDI or to explore the necessary number of lanes. However, a key disadvantage of these methods is that the simplifications and assumptions are not appropriate for every situation.

As a general rule, results from a planning-level analysis can be used to determine the next step. For example, if a planning-level analysis shows a volume-to-capacity ratio of 1.3 for a DDI, it is unlikely that a more detailed operational analysis would show such a design to work satisfactorily. Similarly, if the planning-level analysis shows a peak-hour volume-to-capacity ratio of 0.3, it is likely that the number of lanes could be reduced in the design. For any planning-level results that are close to a given volume-to-capacity threshold, a more detailed operational analysis should be performed.

5.5.2.2 CAP-X

CAP-X, developed by FHWA, is a tool that can be used to evaluate different types of innovative junction designs (eight intersections, five interchanges, and three roundabouts) using given peak-flow volumes (*7*). Exhibit 5-44 is a screen capture from the CAP-X spreadsheet (*7*). Note that CAP-X refers to the DDI as a double-crossover diamond, or DCD.

Exhibit 5-43. Comparison of DDI analysis tools.

Analysis Tool	Level of Analysis	Required Inputs	Available Outputs	Level of Effort	Limitations
CAP-X	Pre-screening the DDI as an interchange alternative	▪ Number of lanes ▪ Hourly TMCs[1]	▪ V/C[2] ratios ▪ Comparison to other designs	Low	▪ No delay and LOS ▪ No queues ▪ No signal timing ▪ No corridor effects ▪ No multimodal ▪ No lane utilization
Critical-movement analysis	Determining initial lane configuration and signal parameters	▪ Number of lanes ▪ Hourly TMCs	▪ V/C ratios ▪ Cycle lengths ▪ Queue check	Low	▪ No delay and LOS ▪ No corridor effects ▪ No multimodal
HCM6 DDI method	Estimating interchange delay and LOS	▪ Number of lanes ▪ Hourly TMCs ▪ Signal timing	▪ V/C ratios ▪ Delay and LOS ▪ Queues	Moderate	▪ No corridor effects ▪ No multimodal ▪ No signal timing optimization guidance[3]
Micro-simulation	Evaluating DDI corridor and multimodal performance	▪ Number of lanes ▪ Corridor O/D[4] volumes ▪ Signal timing ▪ Corridor data ▪ Ped/bike data	▪ Delay and LOS ▪ Queues ▪ Corridor performance ▪ Multimodal	High	▪ No signal timing optimization guidance[5]

[1] TMCs = turning-movement counts
[2] V/C = volume-to-capacity
[3] While the HCM6 does not contain any optimization routines, commercial implementations of the methods may provide optimization capabilities. Practitioners should ensure that optimization functions accurately reflect DDI operations.
[4] O/D = origin-destination
[5] Some microsimulation tools offer built-in optimization while others work in exchange with macro-level tools to provide optimization capabilities. Practitioners should ensure that optimization functions accurately reflect DDI operations.

The intersections and interchanges are evaluated using critical-lane-volume summation. Implemented in a spreadsheet workbook, CAP-X is a simple and cost-effective sketch-planning tool that can help users focus on the most appropriate intersection/interchange forms for a particular location, prior to conducting a more demanding traffic simulation. CAP-X is not sensitive to signal timing, and as such, cannot be used to compare and contrast different DDI phasing schemes. For an alternative planning method that is sensitive to phasing schemes, refer to Section 5.5.1.

The inputs for the CAP-X methodology include turning-movement counts at both crossovers, heavy-vehicle percentages, and the number of lanes at each point where two movements cross (the two crossovers, the two off-ramp right-turn entry points from the freeway, and the two off-ramp left-turn entry points from the freeway). The method further allows for an estimation of impacts from a future-year growth rate. The outputs for a DDI are the approximate volume-to-capacity ratio at each of the six crossing points. A practitioner should pay special attention to the capacity assumptions used in the spreadsheet; they may not be appropriate in every situation.

5.5.2.3 Critical-Movement Analysis

CMA is a planning-level methodology that can be used to identify the critical movements at a DDI and approximate the required cycle length. The example in this section assumes both

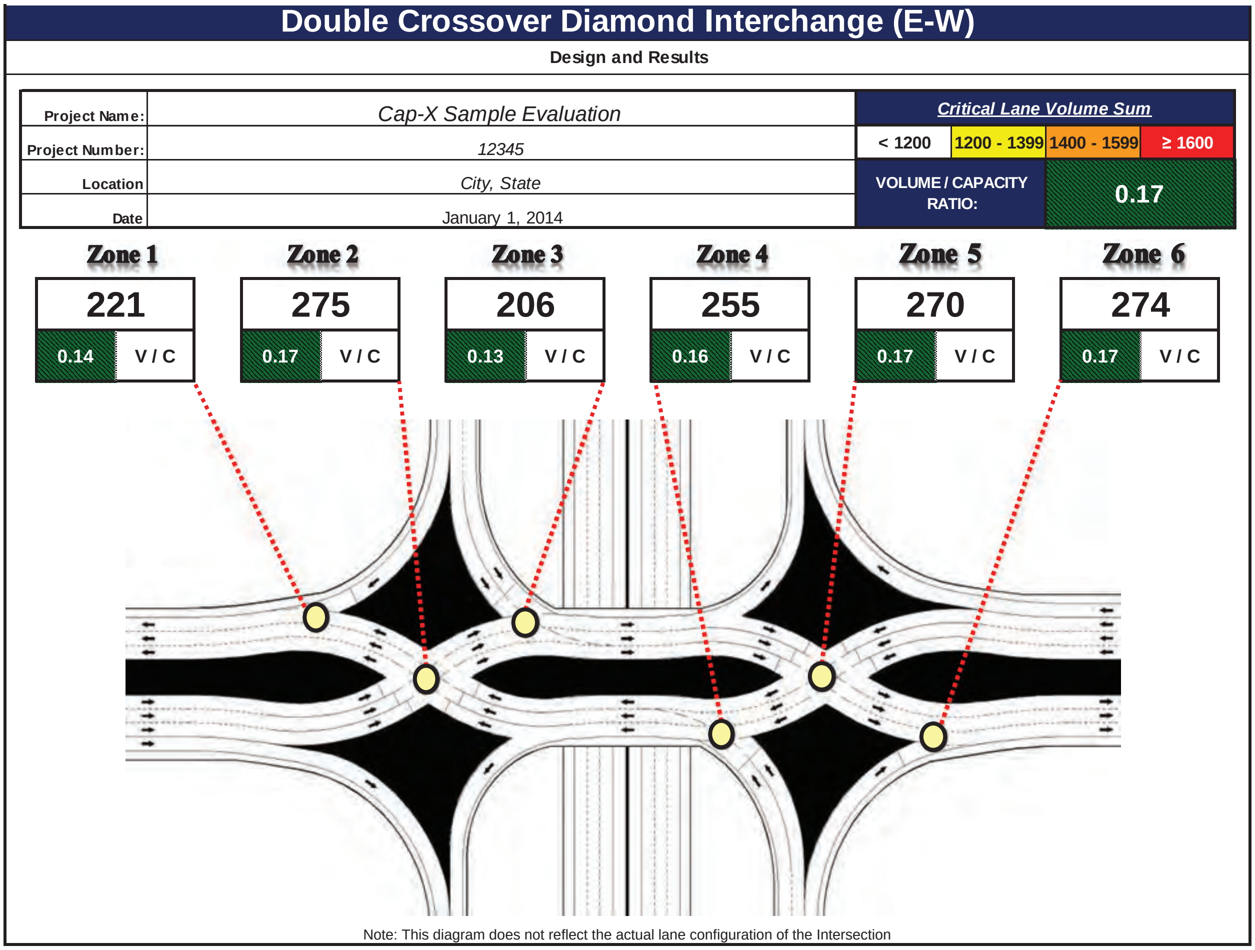


Exhibit 5-44. CAP-X planning-level tool screen capture.

off-ramp movements are signalized; free-flow movements should be treated differently. For more information on applying CMA, refer to *NCHRP Report 812: Signal Timing Manual, 2nd Edition* (*1*).

Note that volumes have generally been distributed evenly across the lanes, with the exception of the northbound and southbound left-turn movements. Even distribution is used for example purposes only, and an analyst should determine an appropriate distribution based on travel patterns.

This section explains the application of CMA for a DDI using two examples. In the first example (illustrated in Exhibit 5-45, Exhibit 5-46, and Exhibit 5-49), there is one lane for the westbound and eastbound left-turn movements from the freeway. In the second example (illustrated in Exhibit 5-47, Exhibit 5-48, and Exhibit 5-50), there are two lanes for these movements. Exhibit 5-45 and Exhibit 5-47 depict the volumes and assumed lane configuration for each example. Exhibit 5-46 and Exhibit 5-48 depict the identification of the critical volume for each phase, and Exhibit 5-49 and Exhibit 5-50 summarize the critical volume for the entire interchange.

Once practitioners have calculated the critical volume, they can use it to approximate the required cycle length using the equation below for estimated cycle length based on critical volume. Exhibit 5-51 uses the equation below to illustrate the volumes that can be accommodated under different cycle lengths for an eight-phase intersection (*1*). The two DDI examples assume the two-critical-movement phasing scheme is being used (with fixed-time phases for clearance). Capacity will vary depending on the headway and phasing scheme that is selected, so a practitioner should apply the equation using site-specific values.

$$Cycle\ Length\,(Sec) = \frac{3600 \times Lost\ Time\ Per\ Cycle\,(Sec)}{3600 - (Max\ Number\ of\ Vehicles\ Per\ Hour \times Headway\,(Sec))}$$

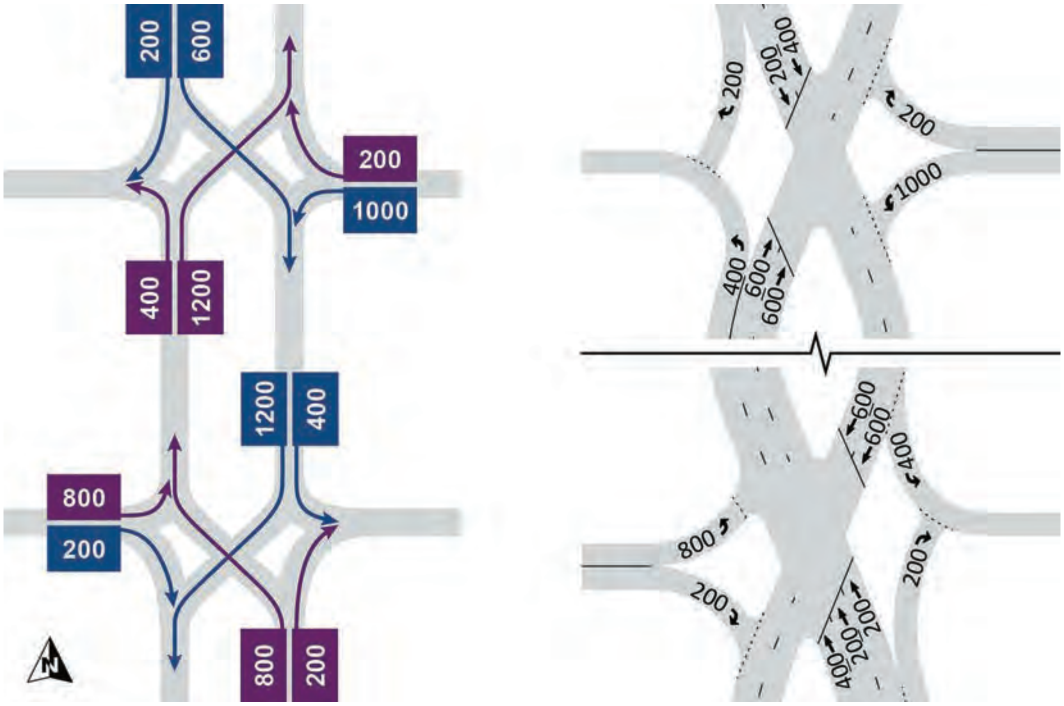


Exhibit 5-45. CMA volumes.

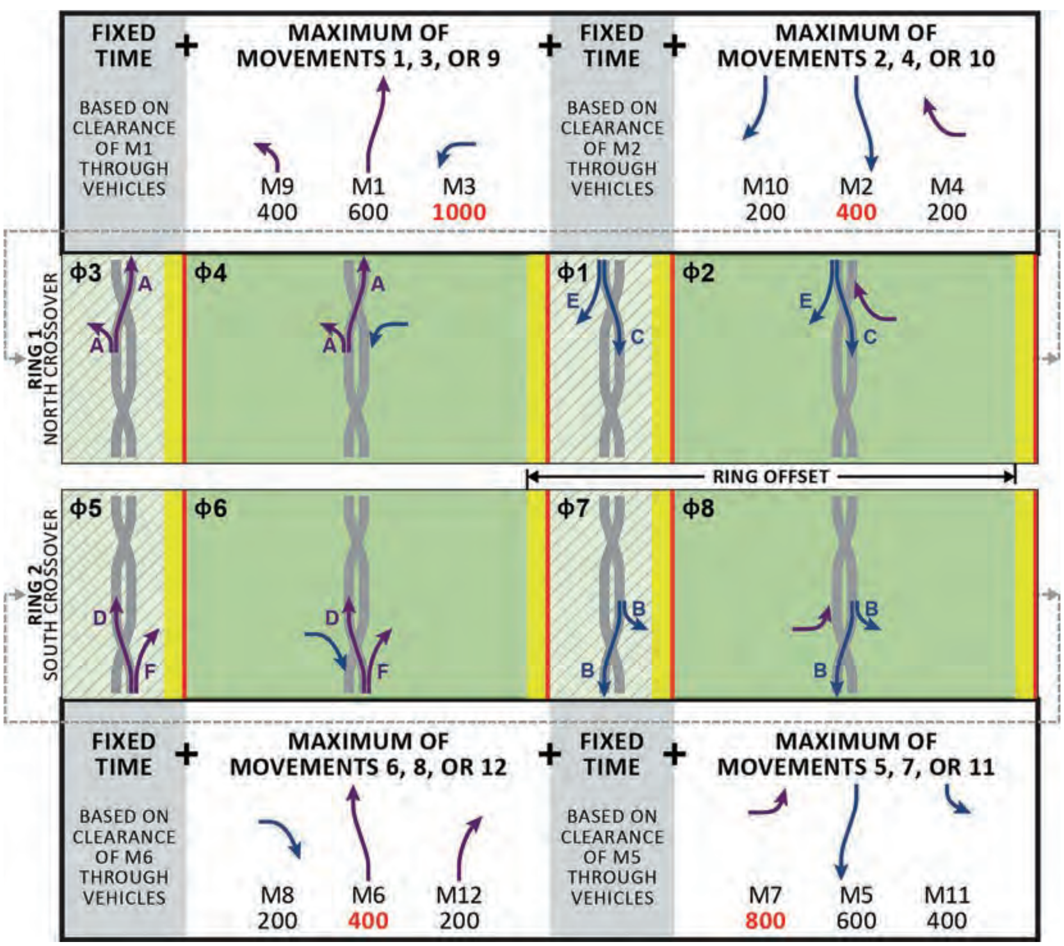


Exhibit 5-46. CMA analysis.

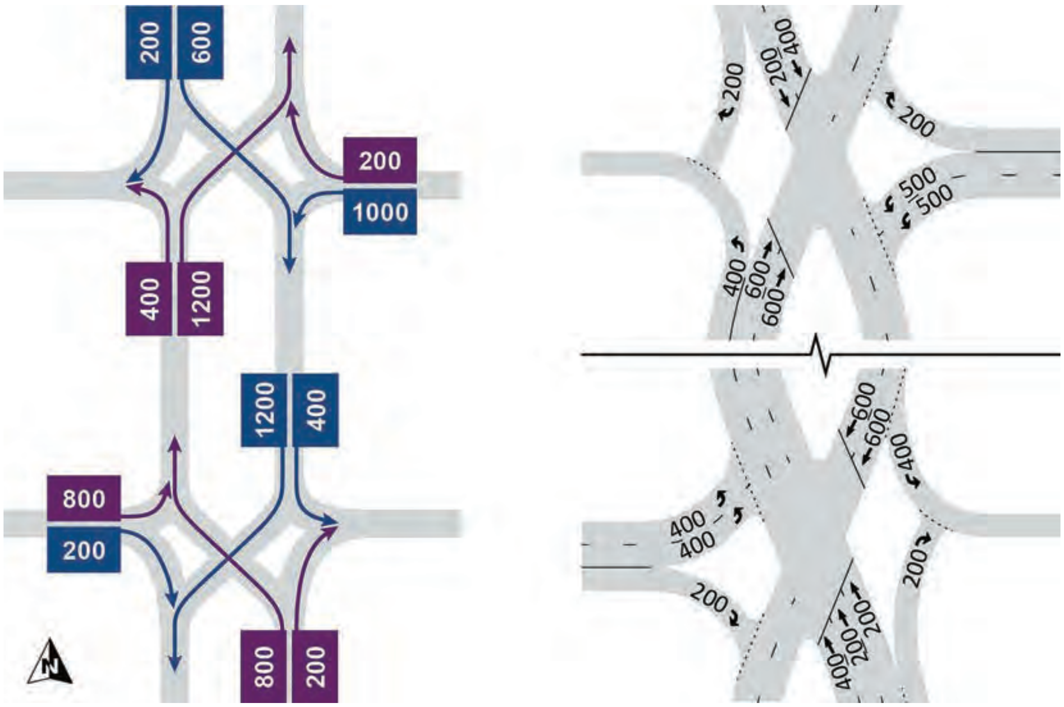


Exhibit 5-47. CMA volumes with revised lane configuration.

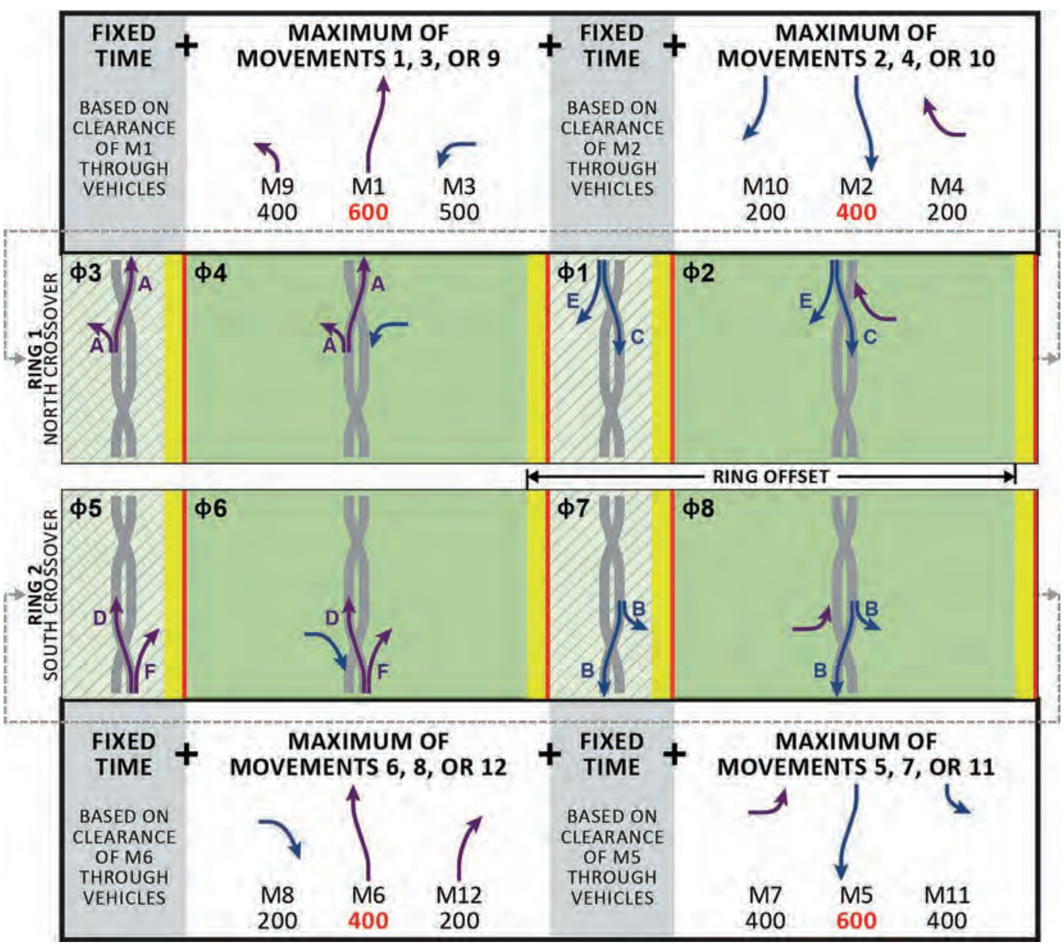


Exhibit 5-48. CMA analysis with revised lane configuration.

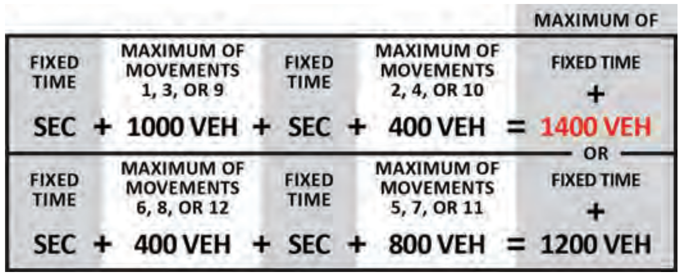


Exhibit 5-49. CMA calculations.

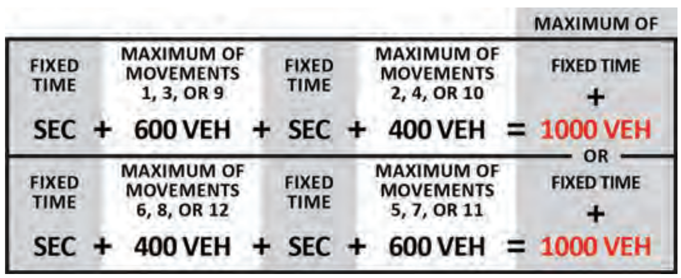


Exhibit 5-50. CMA calculations with revised lane configuration.

Exhibit 5-51. Estimated cycle lengths based on critical volume (eight-phase intersection).

Cycle Length (Seconds)	Number of Cycles Per Hour	Lost Time Per Cycle (Seconds)[1]	Effective Green Time Per Cycle (Seconds)	Number of Vehicles Per Cycle[2]	Maximum Number of Vehicles Per Hour[2]
60	60	20	40	16	933
70	51	20	50	19	1000
80	45	20	60	23	1050
90	40	20	70	27	1089
100	36	20	80	31	1120
110	33	20	90	35	1145
120	30	20	100	39	1167

[1] This lost time assumes that the intersection is operating with eight phases (four in each ring) with 5 seconds of lost time per phase. The lost time will be less at an intersection with fewer phases.

[2] The number of vehicles that can be accommodated under the various cycle lengths was calculated assuming a flow rate of 1,400 vehicles per hour which correlates to a headway of approximately 2.5 seconds per vehicle, which is generally conservative for urban/suburban environments.

Source: *NCHRP Report 812: Signal Timing Manual, 2nd Edition* (1)

Using Exhibit 5-51, a practitioner can identify that the critical volume in the first example (1,400 vehicles) requires a cycle length greater than 120 seconds. By adding a second lane for the off-ramp left-turn movements, the critical volume can be reduced in the second example (1,000 vehicles), requiring a shorter cycle length of approximately 70 seconds. Note that these cycle lengths depend heavily on the lost time and vehicle headways assumed at the DDI.

The second step of a CMA for a DDI should be assessing the potential queues between the crossovers, using the equation below for vehicle queue length. Assuming that the lane configuration from the second example is chosen (i.e., two lanes for the off-ramp left-turn movements), a cycle length of 70 seconds should be able to accommodate demand.

$$\mathit{Vehicle\ Queue}\ (\mathit{Feet}) = \left(\frac{\mathit{Critical\ Queued\ Volume}}{\mathit{Number\ of\ Cycles\ Per\ Hour}}\right) * \mathit{Vehicle\ Length}\ (\mathit{Feet})$$

With the two-critical-movement phasing scheme, there is the potential for the off-ramp left-turn movements to queue at the downstream crossover during Phases 4 and 8. In this example, the westbound left-turn movement from the off-ramp is heavier (500 vehicles), so it will dictate the required queue distance.

With a cycle length of 70 seconds, there are 51 cycles per hour. Assuming an even distribution of traffic throughout the peak hour, there would be approximately 10 vehicles queued every cycle (= 500 vehicles/51 cycles per hour). Assuming a vehicle length of 25 feet, the crossovers should be at least 250 feet apart to mitigate queues.

5.5.3 HCM6 DDI Method

HCM6 analysis tools are deterministic (similar to planning-level-analysis tools) but provide more detailed performance measures (i.e., delay, travel time, and queue lengths) at a lane-group level, as opposed to an overall intersection level. HCM6 analysis is performed using software, but individual calculations can be checked by hand.

An HCM procedure specifically for DDIs is included in the *Highway Capacity Manual* 6th edition as part of Chapter 23: Ramp Terminals and Alternative Intersections (*5*). Because the chapter contains analytical methods for evaluating several intersection and interchange forms, the chapter and methodology are well-suited for a direct comparison of the DDI with other interchange or intersection forms.

5.5.3.1 Advantages and Disadvantages

One of the advantages of this operational-level analysis is that it balances detail with reasonable data input needs and analysis resource requirements. The HCM6 method provides more detailed output (i.e., delay, travel time, and queue estimates) than the planning-level methods, while allowing for more customization and consideration of geometric variability and signal timing details. At the same time, its methods are typically applied more quickly than a resource-intensive simulation analysis.

The deterministic analysis framework of the HCM6 methodology offers consistency in performance estimation across practitioners and interchange options. While the HCM6 has limitations, it does provide the consistency that agencies need for evaluating different alternatives. The HCM6 DDI method includes several specific algorithms to reflect the operational characteristics of DDIs, including:

- Estimation of saturation flow rates specific to DDIs.
- Prediction of DDI lane utilization.

- Calculation of internal DDI queue lengths.
- Analysis of unsignalized turning movements at DDIs.
- Consideration of unique attributes of DDI signal timing in the performance estimation, such as demand starvation and other adjustments to the effective green time.

Disadvantages of the HCM6 analysis of DDIs include a limited scope of applicable geometry and a lack of focus on network and system effects, including the interaction of the DDI with the freeway facility it serves. Other operational characteristics of a DDI not handled by the existing HCM6 methodology and potentially requiring simulation-based analysis include:

- Queuing on the links between the two crossover signals.
- Demand starvation at signalized approaches leaving the DDI.
- Queue blockage of on-ramp left-turn movements in shared lanes.
- Impact of reverse curves on speed patterns and progression.
- Estimation of pedestrian or bicycle LOS.
- The effect of pedestrian and bicycle activity on vehicles.
- The interaction between freeway and arterial traffic if queues from one facility impact operations on the other.

Rather than replicating details of the methodology itself here, the reader is referred to the HCM6 for additional information (*5*). The method can be integrated with the HCM6 method on urban street facilities, which allows the HCM6 to evaluate a DDI in a corridor context.

5.5.4 Microsimulation

Microsimulation tools employ a series of algorithms for car following, lane changing, and other parameters to model the movements and interaction of individual vehicles on a sub-second interval basis. Most simulation algorithms are stochastic in nature, meaning that they include one or more random variables and distribution of variables, rather than a fixed deterministic input (e.g., vehicle speed). For the evaluation of DDIs, simulation tools have been the primary analysis tool, as many tools are not able to directly account for the unique geometry and signal timing of this interchange form. While other planning and operational tools have become available and can be highly useful in alternative selection and design refinement, simulation remains inherently suited for DDI analysis. Microsimulation analysis is performed exclusively using software.

A variety of simulation tools are available to model and evaluate DDIs. All microsimulation tools vary in user interface and available features. Among the more critical features that are required to accurately model a DDI is the ability to replicate the crossover geometry and accurately code the DDI signal timing sequence. The analyst should further review the list of calibration factors and validation parameters described in Section 5.5.4.2 to assure that the selected tool can adequately provide these.

5.5.4.1 Advantages and Disadvantages

Simulation tools allow for flexible customization and configuration of geometry, signal timing, and other operational parameters. This allows for a direct estimation of DDI performance, rather than approximating certain effects through equations that may have been derived based on only a few sites. Using simulation, a DDI can be evaluated as part of a broader network of intersections, including the interaction between the cross street and the freeway. Many simulation tools further allow the modeling and evaluation of different modes of transportation (e.g., pedestrian, bicycles, and transit) and their interaction with vehicular traffic. In addition, simulation provides visualization of traffic patterns and street geometry, which can be an invaluable asset for communicating the DDI to a nontechnical stakeholder audience.

The greatest disadvantage of simulation is the increased resource requirements, as every DDI model needs to be built and configured. Specifically, proper calibration and validation of the simulation model is needed to assure that the predicted operations adequately reflect conditions at the DDI. For a proposed site, guidance in the literature can help with the calibration process, some of which is also summarized below (*8*).

In addition, not all microsimulation tools have the ability to optimize traffic signal timing, which is critical to obtain good signal operations and coordination for the DDI and surrounding intersections. As such, simulation may be used in conjunction with a signal timing and optimization tool to obtain signal timing parameters for the network. That optimization tool needs to be able to accommodate the DDI-specific geometry and signal configuration, but otherwise, the practitioner can follow the normal timing and optimization process used for other intersections and interchanges.

The practitioner needs to understand the many unique operational attributes of a DDI (e.g., saturation flow rate, speed profiles, and lost time) as well as how to replicate those in simulation. This lack of consistency in output can be an important limitation of simulation (i.e., different results from different practitioners), especially for DDIs with estimated performance close to a defined threshold. In this case, a deterministic analysis method could be used in combination with simulation to further inform the decision-making process.

5.5.4.2 Calibration Factors

Practitioners use calibration to adjust models prior to construction so that the predicted outcome is as accurate as possible. Each simulation tool has many calibration factors, ranging from demand inputs to speed settings to signal timing parameters. The discussion that follows is not intended to be an exhaustive or complete list for simulation calibration, but highlights specific calibration settings that have proven necessary to adequately replicate DDI operations. All typical calibration steps should be followed. The key calibration factors for DDIs include:

- O/D demands at the DDI and adjacent signals that are based on field data,
- Look-back distances from route decision points to control lane positioning,
- Field-measured free-flow speeds through the DDI, as well as geometrically-constrained free-flow speeds at the crossover and for turning movements, and
- DDI-specific phasing schemes as obtained from field controller settings or design plans at the DDI and adjacent signals.

5.5.4.2.1 Origin-Destination Demands. Interchange O/D route percentages are no different at a DDI than at a conventional interchange but are important for accurately representing operations at a DDI. O/D routes should be drawn through the entire interchange and adjacent signalized intersections.

5.5.4.2.2 Look-Back Distances. The look-back distance is the distance upstream from a diverge point at which simulated vehicles are affected and initiate any necessary lane changes. In field observations of DDIs, drivers were observed to pre-position themselves well in advance of the DDI for downstream turning movements (*2*). This phenomenon was especially pronounced for left-turning movements from the cross street to the freeway, and lane utilization was impacted at the inbound DDI crossover. Consequently, the look-back distance for these movements should be specified in a way that it extends through the inbound DDI crossover (as shown in Exhibit 5-52).

5.5.4.2.3 Free-Flow Speeds. As shown earlier in this chapter, speeds at DDI crossovers were observed to be below the free-flow speeds on tangent sections of the cross street. It is therefore recommended that the analyst use speed-reduction zones to control free-flow speeds at

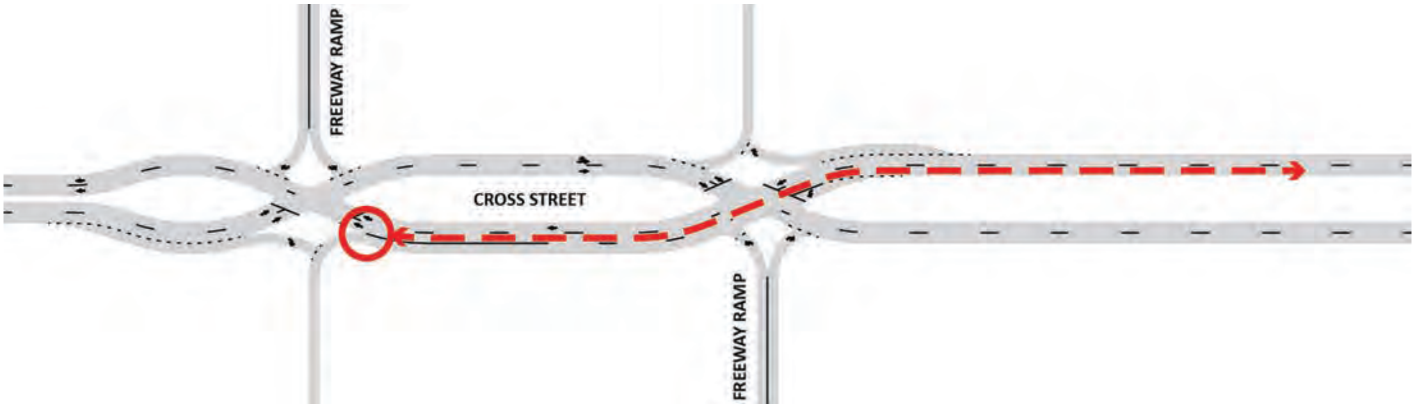


Exhibit 5-52. Simulation look-back distance.

crossovers and turns. The speed distributions should be modeled as normal distributions with the mean and standard deviation estimated from field data or adapted from the discussion in Section 5.4.2. Exhibit 5-53 shows the placement of reduced-speed areas for modeling slower speeds at turns and crossovers.

5.5.4.2.4 Phasing Schemes. To accurately model signalized control of a DDI, a practitioner needs to have a clear understanding of the phasing scheme so he or she can confirm whether the scheme can be represented accurately in the chosen simulator. The selected tool should employ signal control logic that is flexible enough to allow modeling of all three DDI phasing schemes (and their variations) introduced in Section 5.3. Because the phasing schemes can be implemented in either one or two controllers, the simulator should also be able to model either configuration.

5.5.4.3 Validation Parameters

Validation allows practitioners to refine models to reflect existing conditions. This section explains targets that can be used to validate models against conditions at constructed DDIs. Similar to the prior section on calibration, the discussion that follows is not intended to be an exhaustive or complete list for validation but rather to highlight specific measures that have proven useful for quantifying and validating DDI operations. Other validation steps and factors

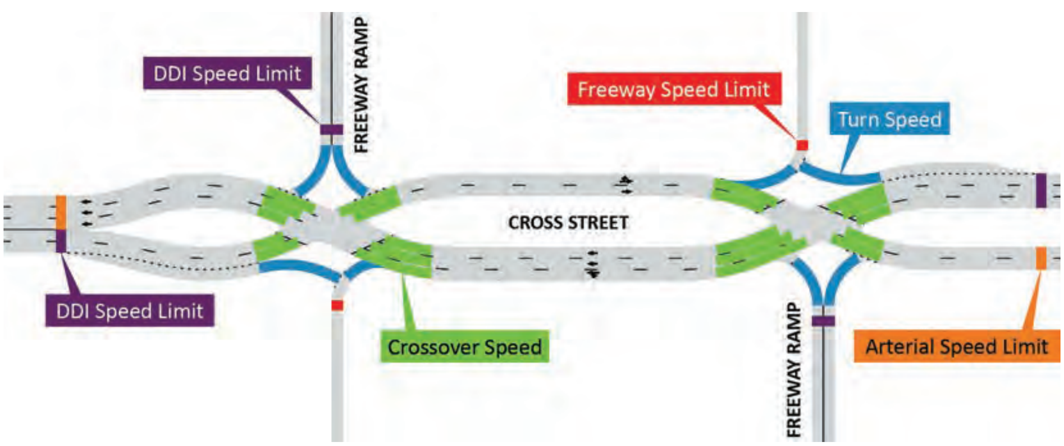


Exhibit 5-53. Simulation speed settings.

should be followed as well. Three key validation parameters recommended in the literature for accurately modeling DDIs include (*8*):

1. Interchange travel times for the through movements (between the crossovers) and left-turn movements (to and from the freeway).
2. Route travel times for through movements (through the DDI and adjacent signals) and left-turn movements (to and from the freeway through the adjacent signals).
3. Comparison of average and 95th percentile queue lengths (estimated from maximum queue lengths on a per cycle basis).

5.5.4.3.1 Travel Times. The interchange travel time includes the two DDI crossover signals and any queues immediately upstream of the DDI. The route travel time segments include, at a minimum, the adjacent signalized intersections upstream and downstream of the DDI. For left-turn routes, the travel time segments start or end at the freeway exit ramp or entrance ramp, respectively. Travel time data can be collected in a variety of ways (e.g., floating-car technique).

5.5.4.3.2 Queue Lengths. For queue measurements, cycle-by-cycle queues can be observed through manual observations in the field on a per lane basis. Detailed operational study protocols are documented in *Field Evaluation of Double Crossover Diamond Interchanges* (*2*).

5.6 References

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CHAPTER 6

Geometric Design

6.1 Overview

Chapter 6 introduces the objectives, principles, and performance checks that guide the geometric design process to evaluate and design a diverging diamond interchange (DDI). This chapter emphasizes context-sensitive and cost-sensitive design as well as the iterative nature of performance checks to refine horizontal and vertical designs. The performance checks support Intersection Control Evaluation (ICE) activities and guide practitioners in evaluating and optimizing DDIs for a given project context.

6.1.1 Integrating with ICE Activities

ICE is often evaluated in two to three stages; at a minimum, the general geometric design considerations for DDIs should begin at the earliest stages. ICE activities can occur during broad system planning efforts, corridor evaluations, and interchange planning and design studies. During this time, constrained locations or other design implementation issues could screen a DDI in favor of other interchange forms more adaptive to the environment. Staged ICE activities can parallel the general project development stages with evaluations increasing in levels of detail until an alternative is selected for final design. Geometric design details and evaluations should increase commensurate with the level of detail of staged ICE activities. The principles and concepts noted in this chapter can support any stage of ICE activities.

6.1.2 Optimizing for Project Context and User Type

DDI configurations should be based on conducting applicable geometric performance evaluations on an absolute basis while comparing and assessing how that performance relates to each user. Performance evaluations are described in Section 6.7. Project context is set by land use types and dictates the associated uses for a given environment. DDI configurations should be based on each user and vehicle type, providing design configurations that optimize the quality of service for each user. Users are described in Section 6.4.5.

6.1.3 Considering Each Project Development Stage

As described in Chapter 2, interchange evaluations may vary depending on the stage of the project development process with geometric performance checks for a DDI being necessary at each project development stage. However, the level of detail and analysis conducted at each stage will vary. Conducting planning-level geometric design checks, commensurate with planning-level traffic operations evaluations, can support early ICE activities. In general, geometric evaluations and details should correspond with ICE stages, as geometric design is advanced with increasing detail at later levels of project development.

Addressing geometric design fundamentals (such as including tangent segments between reverse curves) and considering DDI-specific design features help guide project decision making. Understanding DDI-specific features, such as crossover fundamentals for path alignment and speed management, results in better assessment of footprint impacts. This supports planning and design decisions when comparing interchange forms and ramp terminal intersection control. Considering design vehicles and generalized treatments to establish the alignments approaching the crossover at initial stages leads to better and optimized interchange configurations at later project development stages.

6.2 Principles and Objectives

A DDI is fundamentally a diamond interchange with uniquely designed ramp terminal intersections that create crossover intersections. Ramp terminal intersection treatments for left and right turns are based on intersection design principles that are generally like other diamond interchange forms. Ramp terminal intersection planning and design should follow the same intersection design and channelization principles that consider lane configurations, design users, design vehicles, oversized/overweight trucks, speed management, path alignment, and sight distance values.

In the past, it was common to design DDIs to include highly curvilinear left- and right-turn movements to and from the entrance and exit ramps at the ramp terminal intersections. In some cases, these movements were established as yield control or free-flow. These design features have sometimes been copied and applied in locations inconsistent with a new project's context. However, in contemporary DDI designs, the land use context and user types should dictate whether an interchange should include rural or urban characteristics to appropriately serve each anticipated user.

As with any interchange form, there are design considerations and configuration trade-offs to develop interchange forms and features consistent with the project context. Performance-based evaluations support flexible design applications to meet project needs for a given location and project condition.

Contemporary roadway geometric planning and design considers and appropriately integrates nonmotorized and motorized users. This is also true for DDIs. Vulnerable users and persons with vision or mobility disabilities require special design considerations including providing space and guidance for nonmotorized users and appropriate features for pedestrians with vision or mobility disabilities. Similarly, the full range of motorized users should be integrated into design configurations, as anticipated for a given interchange location.

Information about designing for each user and vehicle type is presented in subsequent sections, and additional detail is presented in Chapter 3. Exhibit 6-1 presents prominent features of the DDI.

6.2.1 DDI Planning and Design User Considerations

A DDI should be customized to serve the range of intended users at a given location. DDI configurations should be based first on specifically considering each user and vehicle type and providing design configurations that optimize the quality of service for each user. Vulnerable users and persons with vision or mobility disabilities require special design considerations, and these users should be considered and integrated at the earliest planning and design stages. Providing space and guidance for nonmotorized users and appropriate features for pedestrians with vision or mobility disabilities affects design details for other users and should be included as integral to the DDI configuration versus being added later in design.

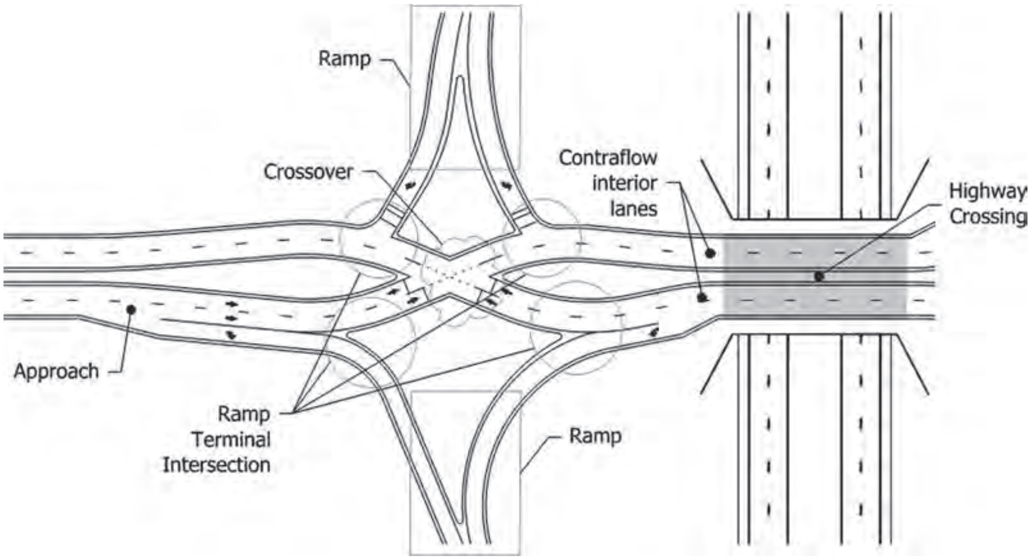

Exhibit 6-1. Prominent DDI features.

Similarly, the full range of motorized users should be integrated into design configurations, as anticipated for a given interchange location. A DDI configuration may emphasize and serve pedestrians and bicyclists by creating lower speed environments. Oversized/overweight trucks may dictate specific design configurations, while overall higher speeds may be applicable in rural or undeveloped environments. DDI design, refinement, and evaluations is a performance-based process based on first identifying the range of users and user types and then conducting applicable geometric performance evaluations—comparing and assessing how that performance relates to each user.

6.2.1.1 Pedestrians

Pedestrians have a range of abilities such as walking speed, stamina, and judgment of vehicular approach speed and distance. Young and older pedestrians may have more difficulty judging vehicle speed and crossing distances. This can affect ramp terminal intersection design and traffic control. As a high-capacity diamond form (akin to tight or single point diamonds), DDIs are commonly used in high-traffic volume environments. Whether in low- or high-volume locations, DDI design features should specifically optimize pedestrian quality of service (i.e., minimize crossing distances and reduce motor vehicle speeds) if pedestrian facilities are expected at the opening year or in the future.

DDIs can include pedestrian facilities and navigational needs that are different than those for other diamond interchange forms. There should be special consideration in helping individuals with vision disabilities and other special users navigate the features leading to and through a DDI. This can include wayfinding through the interchange, locating crossing locations, aligning with the crosswalk direction, and directional guidance on islands. Principles from *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook* are applicable to DDIs at channelized right- and left-turn locations (*1*).

6.2.1.2 Bicyclists

Bicyclists have a range of abilities and comfort levels. DDI crossovers transpose the roadway such that a bicycle lane on the outside approaching the crossover becomes on the inside between crossovers. This could put the bicyclist between the travel lane and raised barrier in some DDI configurations. This could affect the quality of experience, and the needs of various users should be integrated into early DDI planning. Similar to considering pedestrians, design features should specifically optimize bicyclists' quality of service.

6.2.1.3 Buses

Bus (school and transit) accommodation is not expected to have significant influences on DDI planning and design. Buses are variable in size (i.e., length overall, wheelbase, turning radius, and tail swing). The variability of school and transit vehicles in practice may lead to swept paths and tracking needs that differ from those for standard vehicles in vehicle path modeling software. Transit stops at DDIs may be affected by left- and right-turning movement design and proximity to the crossover compared to conventional diamond forms. There may be special considerations of near- and far-side stop locations and how placement and form (e.g., curbside or pull outs) could influence or be influenced by pedestrian and bicycle facility design in the DDI. Additional considerations are presented in Chapter 3.

6.2.1.4 Passenger Cars

Like other users, automobile drivers have a range of skill and confidence levels. As with any interchange form, there should be special consideration of human factors including the needs of older drivers. Fundamental principles for interchange and intersection design apply to DDIs. These topics include entry view angles, navigation and signing, and other considerations such as increased complexity of DDIs associated with curvilinear roadways and other horizontal alignment transition needs for approaching and departing the DDI.

6.2.1.5 Trucks

Interchanges commonly serve large numbers of trucks, and the range of vehicle types can vary significantly. DDIs have special truck service needs associated with vehicle tracking and the impacts of speeds associated with the crossover design. There could be special implications of speed management for approaching a DDI to transition drivers from higher speed approaches to relatively lower speeds through the crossovers. The design configuration established has implications and resulting impacts to operating speeds, safety performance, and other user needs.

Standard trucks are those that are typically allowed access to the roadway system without special permits. Standard trucks could include single-unit vehicles or other tractor trailer units that could be as large as WB-67 or similar. Oversized/overweight trucks are those that typically require permits for travel on the roadway system.

Planners and designers should identify the number of expected vehicles by volume and type and consider the trade-off considerations in serving these vehicles. Special attention should be placed on accessing the specific vehicle specifications to accurately model the turning paths through the curvilinear roadway alignments. DDI interchanges do not typically allow through off-ramp to on-ramp movements for directing an over-height vehicle to bypass an undercrossing. This would be a planning and design consideration unique to DDIs that should be addressed in ICE activities.

6.2.2 Project Type

The two following project types should be considered for DDIs, and within each type of project, the project land use context may impact the limitations and design constraints.

1. New facilities
2. Reconstructing existing interchanges

New facilities often have the most opportunity to include geometric design values and dimensions with the fewest restrictions. Planning and designing a new DDI facility provide the means of integrating the DDI within the adjacent roadway network and establishing adjacent access points. Overall project value and benefit (versus "cost") are common evaluation considerations. There can be more flexibility in better serving each anticipated design user through appropriate features and design choices when constructing new facilities.

Reconstructing existing interchanges increases the difficulty in DDI planning and design. In rural or suburban areas with limited adjacent land development, there can be more flexibility in locating the crossover and ramp terminal intersections to match existing entrance and exit ramp alignments. The relative lack of constraints could provide more flexibility to develop configurations that use more of the existing roadways and bridges.

However, in constrained locations (commonly, developed urban conditions) with adjacent public and private accesses and developed land or other constraints in proximity, there could be any number of design trade-offs to optimize a DDI at that location. In some cases, the physical challenges at the DDI to attain proper ramp terminal intersections and roadway approaches may mean the DDI is not a preferred solution at that location.

6.2.3 Project Context

Land use context influences the intended project outcomes and associated project performance. For example, a DDI in an urban location may necessitate slower design configurations and emphasize pedestrians and bicyclists, while a rural highway application may emphasize oversized/overweight trucks.

Reconstructing an existing interchange to a DDI may create significant challenges to optimize a configuration at a given location. In these locations, a less than ideal DDI could lead to increased safety and operational performance over a "no-build" alternative or other interchange forms.

For rural locations, right-of-way (ROW) is likely less constrained by adjacent land uses. Compared to urban locations, the presence of pedestrians and/or bicycles could be lower, and the roadway speeds approaching the crossover may be relatively higher. The turning movements at the ramp terminal intersections may more commonly be free or yield controlled.

Finally, the design objectives for any interchange can be different and depend upon the surrounding environment and project context. At urban locations, ROW footprint, access management in the vicinity of the interchange, and pedestrian and bicycle considerations will likely influence design configurations. Fundamental design principles and configurations that support target performance apply to DDIs as they would to any other interchange form.

Exhibit 6-2 summarizes potentially differing considerations between urban and rural locations. The descriptors are generalized and not rigid. Land use context is not binary, and DDI planning and design should consider the potential continuum of land use context and customize the design features based on serving anticipated users.

6.2.4 DDI Performance Considerations

DDI design and refinement is an iterative process. In addition to the information shared in this section, the configuration may be influenced by efforts to attain operational performance targets. DDIs have unique attributes compared to other diamond forms. Evaluating and assessing DDI performance includes specific performance considerations of the unique features. These are described in more detail in Section 6.7.

Exhibit 6-2. Urban and rural considerations.

Urban and Rural Considerations		
Design Considerations	*Urban*	*Rural*
Crossroad Speed	Low to moderate 25 mph to 35 mph	Moderate to high 35 mph to 55 mph
Crossover Speed	20 mph to 30 mph	30 mph to 35 mph
Design Vehicle	Lower percentage of total traffic. Limited oversized/overweight.	Higher percentage of total traffic. Some oversized/overweight.
Pedestrians and Bicycles	High likelihood for each user. Could influence traffic control.	Fewer of each user. Less influence on traffic control.
Crossover and Ramp Terminal Intersection Design	Consolidated with smaller radii. Lower speed features. Less right-turn-on-red.	Consolidated with larger radii. More opportunities for yield or right-turn-on-red.
Traffic Volume	High volumes. Multiple peaks. Omni-directional patterns.	Moderate volumes. Fewer peaks. Directional patterns.

As noted previously, a DDI is a diamond interchange and generally includes the same design considerations as those for other high-capacity forms such as the single point and tight diamond. Traditional interchange forms have relatively simple cross street horizontal alignments, commonly tangents or flat curves. Because of this relatively simple alignment, the emphasis is on the ramp terminal intersection details.

A DDI requires a change in mindset in order to recognize the unique features that impact the design approach, such as:

- Cross street horizontal geometry,
- Alignment elements (tangents and curves), and
- Surrounding environments and project context.

The DDI cross street horizontal geometry has two (sometimes unique and different) horizontal alignments for each direction. Attaining DDI design configurations that meet target operations and safety performance often results in greater distances between ramps/crossovers compared to single point and tight diamond forms. There can be a tendency among practitioners to try and adapt a DDI to a location by compromising the horizontal alignment features.

There must be special consideration of DDI alignment elements (tangents and curves) that create a smooth transition entering, traveling through, and exiting the DDI. Horizontal alignment fundamentals of avoiding back-to-back reverse curves and considering curve radii that reflect desired speed transitions to and from the interchange continue to apply to DDIs.

6.2.5 Crossover and Ramp Terminal Intersection Definitions

Interchange ramps have two "terminals": the entrance and exit ramp terminal on the highway and the ramp terminal intersections on the crossroad. A DDI ramp terminal intersection is distinct from other forms in that attaining the contraflow requires a "crossover." This is separate from the ramp terminal intersection function of serving left- and right-turning vehicles to and from the entrance and exit ramps. The crossover function and design affect and are affected by the ramp terminal intersection turning movements. For the purpose of this chapter, the DDI ramp terminal intersection describes the features separately.

The DDI crossover is the intersection proper that supports the crossroad contraflow configuration that distinguishes the DDI from other diamond forms. The ramp terminal intersection represents the intersection features that support turning movements to and from the exit or entrance ramp proper. As with any intersection, DDI ramp terminal intersections (left- and right-turning) and crossover design should be as consolidated as possible to avoid a series of isolated turning and crossing locations.

Exhibit 6-3 displays the key features of the ramp, the crossover, and the ramp terminal intersection.

DDI crossover and ramp terminal intersection design follows the principles of intersection design to keep the intersection compact while separating conflicting movements. A DDI differs from other diamond forms in that the crossover location and design set the foundation for the ramp terminal intersection configuration. Contrary to some oversimplified characterizations, a DDI is not just "two, two-phased signals." Optimizing traffic flow at a DDI is directly affected by the geometric attributes of the crossover and ramp terminal intersection designs.

In constrained DDI locations or DDIs with a skew between the highway and cross street, it can be challenging to keep the ramp terminal intersection elements (left and right turns to and from the cross street) consolidated with the crossover location. Spread intersections result in inefficient signal timing and increased signing to address the various movements. To the extent possible, the DDI should result in ramp terminal treatments in the vicinity of the crossover proper.

Exhibit 6-4 depicts the concept of consolidating the ramp terminal intersection elements.

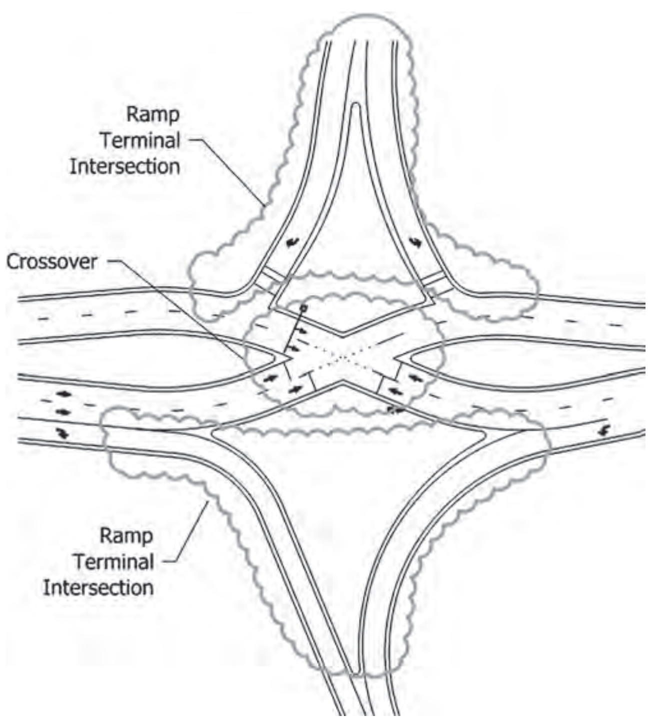

Exhibit 6-3. Key DDI features: ramp, crossover and ramp terminal intersections.

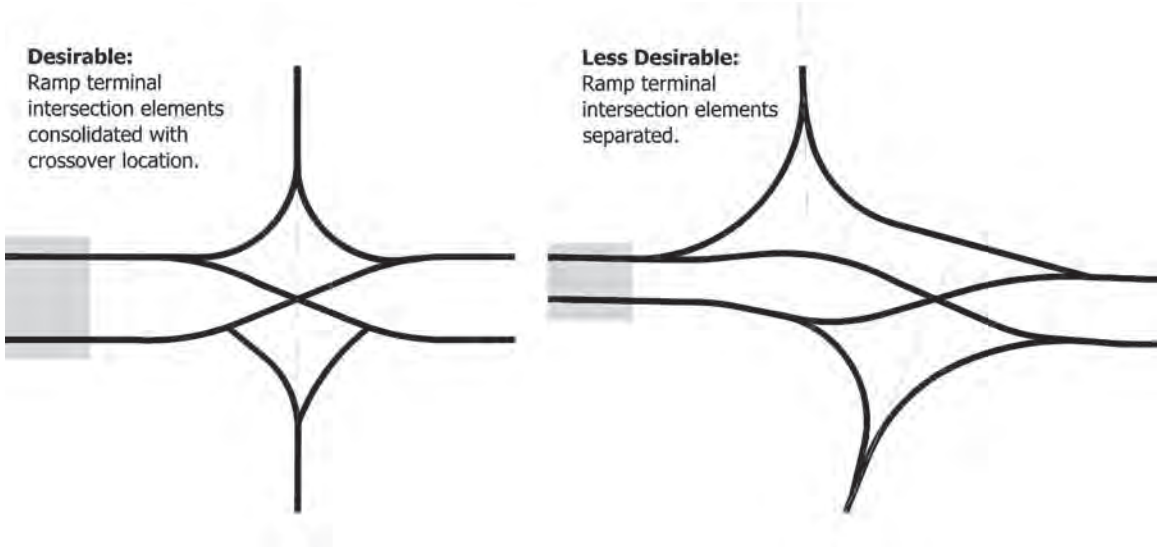

Exhibit 6-4. Consolidating the ramp terminal intersection.

6.3 Project Constraints

When considering a DDI, there are many project constraints that can influence the geometric design of this type of interchange. Understanding the unique constraints, how those may influence design decisions, and identifying solutions to minimize overall impacts to adjacent areas can help a practitioner prioritize decisions and trade-offs. The following sections provide guidance and consideration for the following items:

- Overall footprint,
- Indirect impacts,
- Adapting to site constraints,
- Constraints at the crossover and ramp terminal intersections,
- Matching to an existing highway crossing, and
- Existing ramp locations.

6.3.1 Overall Footprint

Project constraints influence most projects. A common metric in conducting ICE is the relative footprint between alternatives. A DDI will generally occupy a larger footprint than other high-capacity diamond forms (single point and tight diamond). Like a roundabout where capacity is added at the intersection allowing for narrower roadways, a DDI crossover creates a high-capacity configuration that can reduce the overall number of lanes. Like roundabout ramp terminal intersections, this creates the opportunity to retain existing overcrossing bridges (in retrofits) or less overall construction than other interchange forms.

The design features that may increase the overall footprint of a DDI are:

- Crossover proper,
- Ramp terminal intersection/crossover spacing widths, and
- Curvature required to transition to and from the crossover.

However, DDI crossovers require special attention, and the transition to, through, and departing them requires thoughtful horizontal geometry to attain desired absolute speeds and limited speed differences between successive geometric elements. The crossover proper takes up more longitudinal and cross-sectional space than a conventional signalized intersection. Avoiding horizontal curves on cross street overpasses or underpasses means the crossovers will be spaced farther apart than in single point or tight diamond ramps, contributing to a larger footprint.

The horizontal geometry of the DDI leads to ramp/crossover spacing widths that are typically greater than single point and tight diamond forms. In total, the overall cross-sectional and longitudinal impact of the DDI can lead to larger than expected footprints compared to other high-capacity diamond interchanges.

Exhibit 6-5 conceptually presents three high-capacity diamond interchange forms (tight, single point, and DDI), allowing for a comparison of the generalized forms.

6.3.2 Indirect Impacts

As with other interchange forms, the constraints can be influenced beyond the physical footprint. This might include how access management needs associated with the crossover and ramp terminal intersections affect or are affected by adjacent access. A DDI crossover and ramp terminal intersection could be deemed “too close” to an adjacent public or private driveway access. A DDI may have more “capacity” than the first signalized intersections adjacent to the interchange. This means the DDI could potentially serve more interchanging traffic than a downstream intersection might serve, resulting in queuing beyond adjacent accesses or even back to the DDI.

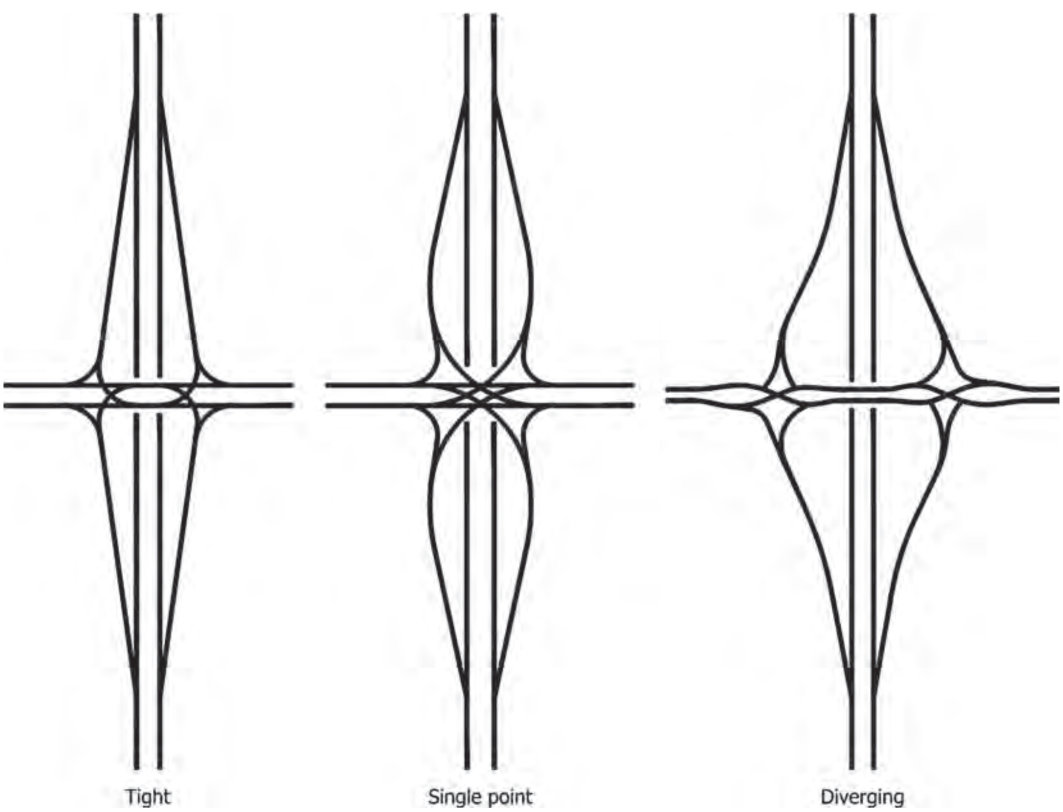

Exhibit 6-5. High-capacity diamond interchange forms.

6.3.3 Adapting to Site Constraints

Compared to traditional diamond interchanges, DDIs have special considerations in the roadway approaches and in developing optimal crossover geometry for a given location. Understanding and considering constraints begins in early concept development and evaluation. If a DDI has been determined to be a feasible alternative in early evaluations, there should be few surprises as subsequent preliminary engineering activities identify ROW and environmental permitting requirements.

ROW impacts are a common constraint with DDIs in relation to developing appropriate crossover design and the roadway approaches to the crossovers. ROW can be affected by the location of the crossover and by the associated width of the horizontal geometry of the crossover proper. ROW footprints can be longitudinal and narrow or more compact and wider. Longitudinal ROW impacts might be associated with narrower ROW and associated curvature needed for appropriate transitions to and from the crossover. Wider ROW on roadway approaches can simplify transitions to and from the crossover and reduce the longitudinal distance of the affected area.

Site constraints can include:

- Constraints at the crossover and ramp terminal intersections,
- Matching to an existing highway crossing, and
- Existing ramp locations.

6.3.4 Constraints at the Crossover and Ramp Terminal Intersections

A common project type for DDIs is reconstructing an existing interchange. Constraints at these locations play a key role in determining the horizontal layout of the DDI to minimize cost and other impacts. Available ROW and other constraints may preclude certain DDI alignments. Even in new construction situations, adjacent constraints may influence the crossover and ramp terminal intersection location, and that location and transition to and from the crossover may influence the overcrossing design.

Exhibit 6-6 depicts how constraints at crossover and ramp terminal intersection can influence planning and design decisions.

6.3.5 Matching to an Existing Highway Crossing

When reconstructing an existing interchange, the highway bridge (overcrossing or undercrossing) is a fundamental constraint. This can be related to matching the DDI crossover and

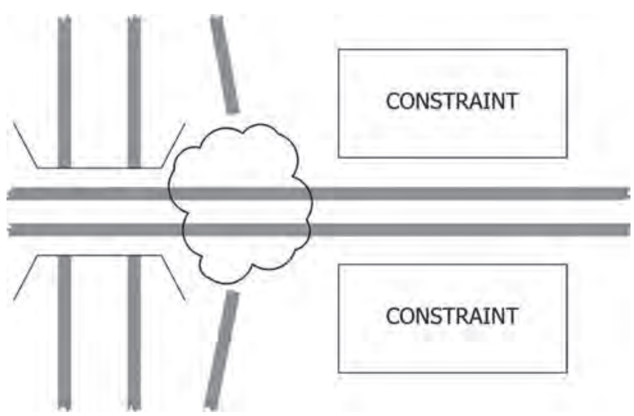

Exhibit 6-6. Constraints at crossover and ramp terminal intersections.

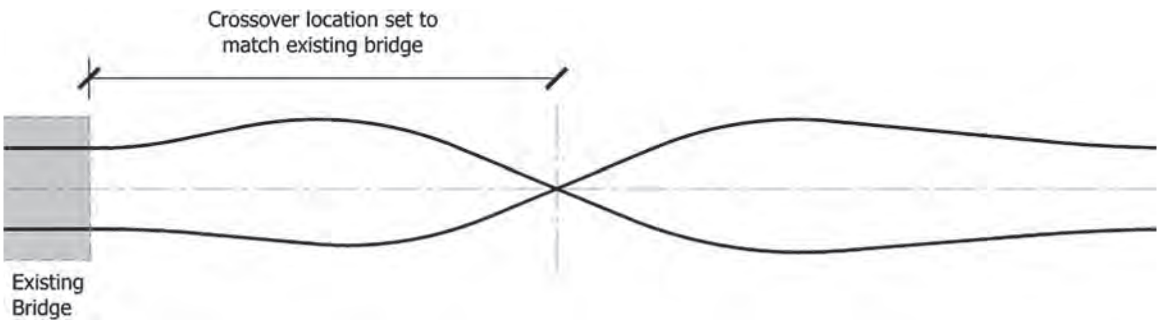

Exhibit 6-7. Matching the existing highway crossing.

ramp terminal intersection elements or to integrating the existing overcrossing during construction while building new bridges. Integrating an existing highway overcrossing creates a fixed location to which crossover planning and design must match. An overcrossing and undercrossing have different effects on how pedestrians and bicyclists are served, and those constraints could influence planning and design decisions.

Because the crossover is a special consideration in DDI configurations, locating the crossover is a key consideration of matching to an existing highway crossing. Later sections of this chapter will present a variety of factors that influence where and how to locate the crossover.

Exhibit 6-7 depicts how matching to an existing highway crossing can influence where the crossover and ramp terminal intersection are located.

6.3.5.1 Matching to an Existing Undercrossing

In a location where a crossroad passes under an existing highway, one of the most critical considerations is to assess the available space between columns, walls, or other constraints to verify if there is adequate space to serve motorized and nonmotorized users.

Clear span bridges (with no center columns) increase the flexibility of developing the roadways and pedestrian paths compared to multispan bridges that provide separate portals in which to pass the roadways and pedestrian facilities.

Exhibit 6-8 depicts a cross section of a single-span bridge and contraflow traffic patterns at the highway crossing.

Two-span configurations (with center columns) must be able to provide space to develop the roadway median but may not have enough space to include a pedestrian walkway because of the center columns. In these cases, pedestrian walkways will need to be on the outside of each roadway. Bridge configurations without existing sidewalks or sufficient room for the roadway and the pedestrian walkways may require cutting back, retaining the sloped abutment fill between the roadways and the approach bent and relocating the pedestrian walkways to this recovered space. Exhibit 6-9 depicts the cross section of two-span configurations.

Exhibit 6-10 shows a wall built to retain a sloped abutment fill and install a sidewalk at a DDI in Maryland Heights, Missouri.

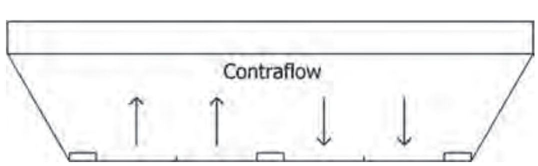

Exhibit 6-8. Single-span bridge.

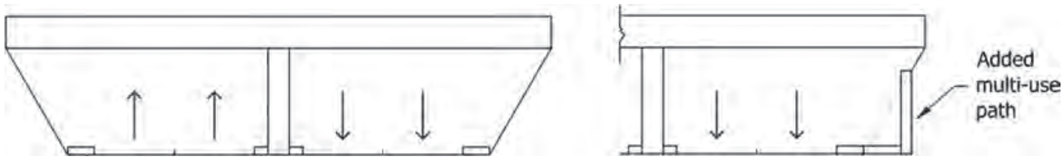

Exhibit 6-9. Two-span bridge configurations with modification for multiuse path.

Four-span bridges create the opportunity to place pedestrian walkways under the first and fourth span; however, in some four-span configurations there may not be enough room to place pedestrian facilities. Bridge configurations without space for the sidewalks because of abutment fill slopes may require cutting back and retaining the sloped abutment fill between the columns and the approach bent.

Exhibit 6-11 depicts a four-span bridge and how the sloped abutment fill might be modified to serve pedestrians and bicyclists.

Matching to an existing undercrossing typically means the crossover and the ramp terminal intersections must be located a sufficient distance away from the existing bridge constraints to be able to match the available cross section width under the highway. Attaining acceptable crossover and associated ramp terminal intersection designs guide where those intersections will be located. Locating the crossover and ramp terminal intersection could influence the alignment of the ramp proper.

Exhibit 6-12 depicts how realigning a ramp to achieve a desired crossover and ramp terminal intersection could require relocating the highway exit ramp terminal to attain an appropriate ramp configuration.

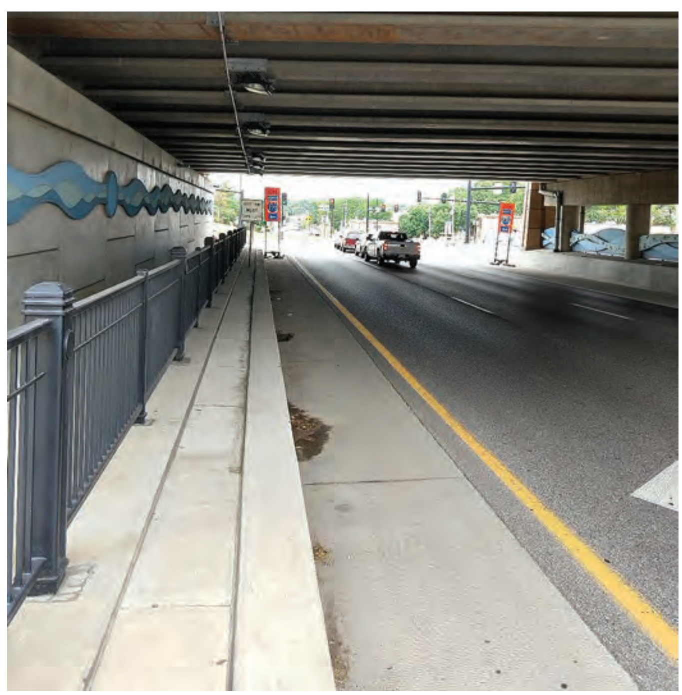

Exhibit 6-10. Example vertical wall and sidewalk (Maryland Heights, Missouri) (2).

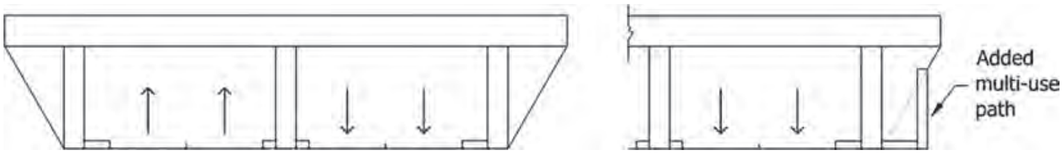

Exhibit 6-11. Four-span bridge configuration with modification for multiuse path.

6.3.5.2 Matching to an Existing Overcrossing

DDIs are often considered because they add capacity at the ramp terminal intersections and potentially allow narrower roadways that retain an existing bridge. Similar to matching an undercrossing, key considerations include assessing the width of the existing bridge and the ability to serve motorized and nonmotorized users and locating the crossover and ramp terminal intersections a sufficient distance away from the existing bridge to attain target geometry.

If there is insufficient bridge width, the existing bridge may either be widened, if the bridge type allows, or an adjacent bridge might be constructed next to the existing bridge. Depending on the location, a new bridge might be constructed on either side of the existing bridge. One benefit of this approach is that traffic will be maintained on the existing bridge while the new bridge is constructed.

Exhibit 6-13 depicts various methods in which bridges at an existing highway crossing might be modified to develop the DDI. An existing bridge could be widened or a separate bridge constructed with a wider separation between bridges.

This same approach might be used to stage construction even if the existing bridge is to be replaced. Another option is to maintain the existing bridge while new bridges are constructed on either side of the existing. This approach allows much of the DDI to be constructed on the "outside" while maintaining traffic on the existing roadway on the "inside." Another advantage of this approach is that the new bridges create a relatively wide median. As presented in the section on crossover width, the wider median creates the opportunity to use fewer horizontal curves to attain appropriate crossover geometry and could allow shorter distances between DDI crossovers and a reduced footprint.

Exhibit 6-14 depicts various ways in which bridges at an existing highway crossing might be modified to develop the DDI. An existing bridge could be replaced by symmetrical widening to two separate bridges, or the widening could occur by constructing a new bridge north or south of the existing bridge.

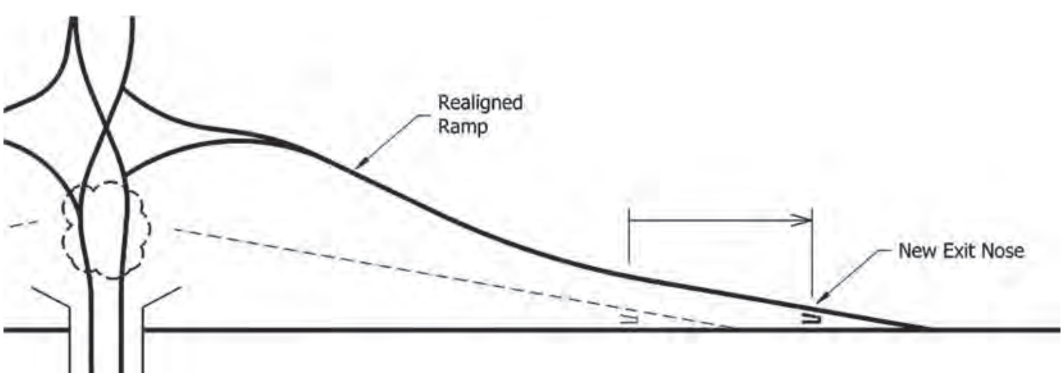

Exhibit 6-12. Realigning the ramp.

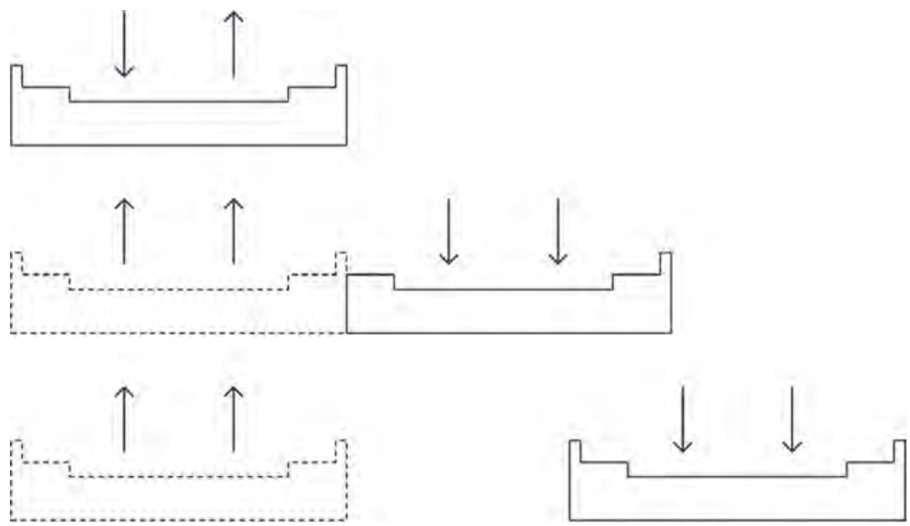

Exhibit 6-13. Options for bridges at existing highway crossings.

Exhibit 6-15 provides an example of a DDI design at Pioneer Crossing in American Fork, Utah. The general alignment of the original overcrossing was maintained, and a new alignment shifted south was used to take advantage of the available ROW.

The DDI constructed on the Glenn Highway at Muldoon Road outside Anchorage, Alaska, applied the symmetrical widening technique and constructed new bridges on either side of the existing bridge. The wide median simplified the crossover design by reducing the crossover spacing. This also allowed large portions of the roadway approaches to be constructed while maintaining traffic on the existing bridge and cross street. Exhibit 6-16 depicts this concept.

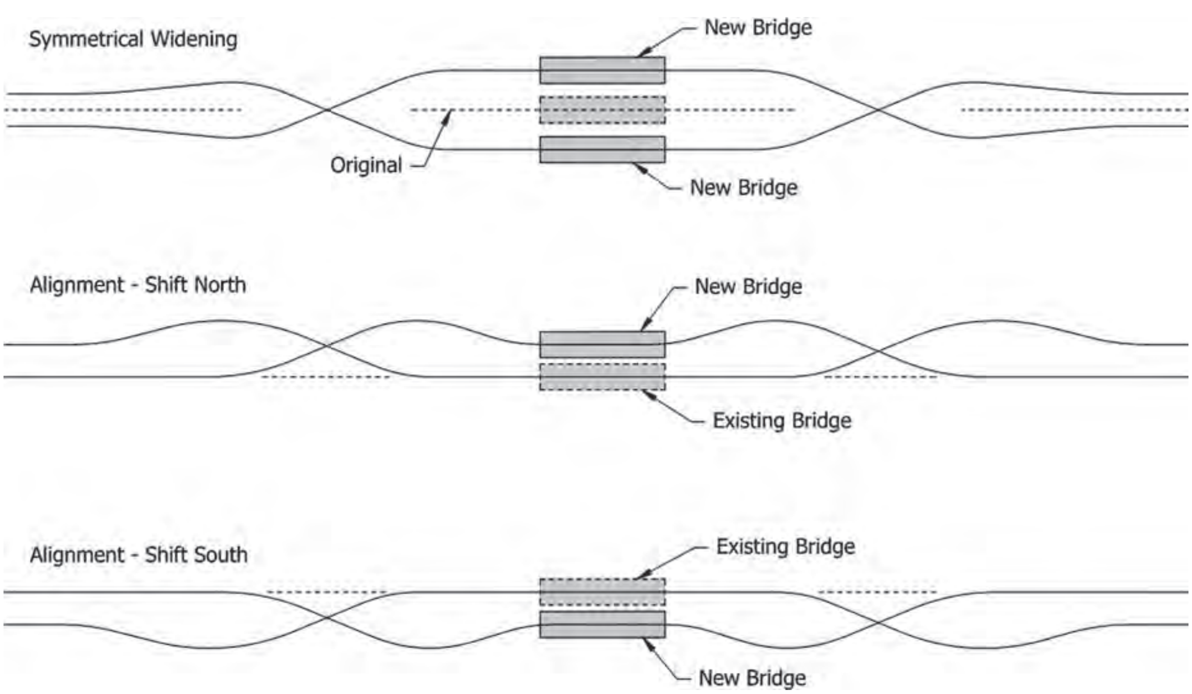

Exhibit 6-14. Options for bridges at existing highway crossings.

Exhibit 6-15. Shifted alignment south of centerline (red) (Pioneer Crossing, American Fork, Utah) (3).

6.3.6 Existing Ramp Locations

Existing ramp locations and vertical and horizontal geometry can influence DDI planning and design. It is often desirable to maintain the existing entrance and exit ramp terminal locations and to use substantial portions of existing ramp alignments. Ramp geometry and footprint dictate how much opportunity there is to adapt to possible crossover locations and the ramp terminal intersection configuration.

Depending on the ramp locations, adjacent constraints, and the desire to integrate an existing highway overcrossing, it may not be possible to create a DDI configuration that meets target operational and design performance without modifying the ramp. This could potentially result in significant ramp modifications that lead to moving the entrance or exit ramp terminal on the highway. Shifting a highway ramp terminal could increase the extents and magnitude of construction. This could lead to screening the DDI for other interchange forms.

6.4 Horizontal Alignment

The geometric design of a DDI requires balancing competing objectives. Most geometric parameters are governed by the design vehicle requirements, speed control needs, and other performance objectives. Therefore, designing a DDI requires carefully considering safety, operations,

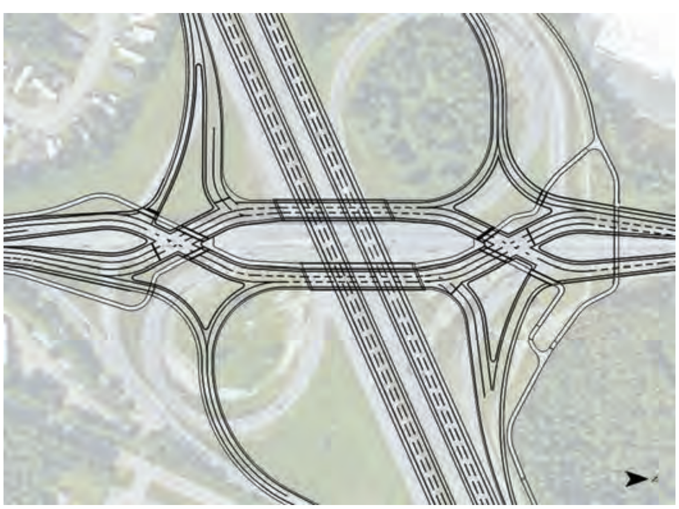

Exhibit 6-16. Symmetrical widening technique (Anchorage, Alaska) (4).

and geometric performance while accommodating the design vehicle and nonmotorized users. For new construction, it may be relatively easy to meet target objectives. In reconstruction projects, there may be an increased focus on optimizing the design configuration and considering trade-offs for a given project location and context.

The design objectives for any interchange can be different and depend upon the surrounding environment and project land use context. At urban locations, ROW footprint, access management in the vicinity of the interchange, and pedestrian and bicycle considerations will likely influence many of the project design decisions. This includes managing speeds by reducing horizontal curve and turn radii, and operating vehicle turning movements through signal control versus free or yield movements.

6.4.1 Alignment Fundamentals

A DDI is simply a diamond interchange form with special geometric attributes that use a crossover to create contraflow conditions in the interior of the interchange. DDI horizontal alignment follows fundamental design principles that create geometric design configurations that support the target user operations. The following alignment fundamentals should be considered when beginning the geometric design of a DDI:

- **Horizontal curve radii**—Horizontal curve radii should be commensurate to the anticipated or target speeds. This means curves approaching the DDI should account for the potential higher crossroad speeds compared to relatively slower speeds between the crossovers. It is not necessary to maintain the design speed of the crossroad through the crossover intersections.
- **Tangents between reverse curves**—From a functional level, tangents between reverse curves allow for appropriate superelevation transitions from one curve to the next. From a motorist perspective, tangents between curves allow drivers to read and perceive their navigation and track tasks from one geometric element to the next. As in any other horizontal alignment, tangents should be used between reverse curves unless no other option is available.
- **Tangents approaching and through the DDI—**Tangents approaching and through DDI crossovers allow the roadway geometry to be the primary guide for motorists to track to the receiving lane. A self-describing roadway reduces driver navigation workload and errors. At a DDI crossover, positive guidance can help reduce the potential for drivers to make wrong-way movements in the contraflow section.

Some early DDIs in the United States had crossovers with back-to-back reverse curves. To the extent possible, this practice should be avoided. Crossover designs without tangents or with short tangents can create conditions where vehicles at the stop bar are not aimed to their target receiving lane across the crossover. This is like "path overlap" in multilane roundabout design, in which an entry lane does not align with the proper receiving lane in the roundabout. Lane markings and lane extension lines work complementary to target geometry and are a mitigation, but not a replacement, for tangent sections that support crossover navigation.

6.4.2 Developing a DDI Layout

New construction or a site with limited constraints will create more design flexibility to optimize the configuration to meet user needs. This might include using symmetrical crossovers and crossroad alignments and a wider median on the cross street approaching the interchange area, although it is not necessary for a DDI to be symmetrical. A wider median allows for a shorter distance between crossovers.

A DDI being considered as part of reconstructing an existing interchange will create different opportunities and challenges compared to designing a new DDI interchange. Reconstructing an existing interchange at a given location may require design compromises to adapt to that site. Considering intended project outcomes and assessing project performance metrics can help optimize and select design features at a constrained location. Even in these locations, a less than ideal DDI could lead to increased safety and operational performance over a no-build alternative or other interchange forms.

6.4.3 Effect of Skew on Crossovers and Ramp Terminal Intersections

Skew between the crossroad and highway affects tight, single point, and diverging diamond interchanges. Tight and single point forms are founded on a narrow footprint with ramps tucked in close to the highway mainline. Skew and associated turning vehicle turning paths affect the operational effectiveness of the relatively tight ramp spacing.

However, the DDI has wider ramp spacing, and the skew can result in separating the crossover location from the left- and right-turning movements at the ramp terminal intersections. This can result in the intersection elements being spread out to individual elements and degrading intended traffic operations. This effect should be minimized as much as is possible to keep the ramp terminal intersections and crossover consolidated. In new or reconstruction projects, reducing or eliminating skew simplifies the crossover and ramp terminal intersection configuration.

6.4.3.1 Types of Skew

There are two kinds of skew between the highway and the cross street. Clockwise skew is where the highway is angled clockwise from the cross street. This skew affects all ramps and intersections and creates noteworthy operational effects at the exit ramps.

Counterclockwise skew is where the highway is angled counterclockwise to the cross street. This skew also affects all ramps and intersections and creates noteworthy operational effects at the entrance ramps.

Exhibit 6-17 presents the concepts of clockwise and counterclockwise skew.

Clockwise skew creates operational effects on the exit ramp by:

- Reducing the left-turn minimum radii and
- Decreasing the right-turn viewing angle.

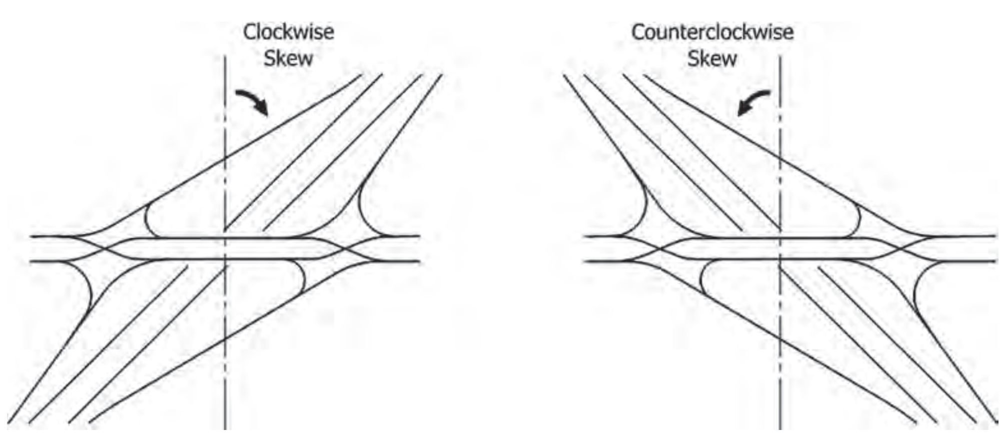

Exhibit 6-17. Clockwise and counterclockwise skew concepts.

Counterclockwise skew creates operational effects on the entrance ramp by:

- Reducing the left-turning minimum radii,
- Increasing right-turn speeds, and
- Increasing the downstream convergence angle and speed shear.

Counterclockwise skew increases the propensity for a violation of cross street route continuity (turning to stay on the designated route).

6.4.3.2 Addressing Skew at Exit Ramps

To address exit ramp operational effects associated with clockwise skew, the ramp terminal intersection could be realigned to a more perpendicular configuration. This helps facilitate left turns and increases the right-turn view angle. Realigning the ramp terminal intersection consolidates the crossover and ramp terminal intersection features and could increase the footprint.

Exhibit 6-18 shows how reducing the effects of skew can require modifying the ramp.

Attaining target ramp terminal intersection geometry and developing appropriate queue storage and deceleration to the back of the queue could increase the exit ramp length and affect the exit ramp terminal location on the highway. If the intent is to match an existing exit ramp, attaining target ramp terminal intersection geometry and queue storage could require reconstructing some or all of the existing exit ramp. Practitioners will need to assess trade-offs of maintaining the existing ramp location and attaining target ramp terminal intersection geometry. In some cases, reconstructing the ramp could be a "fatal flaw," and the DDI is screened in favor of other interchange forms.

Exhibit 6-19 shows how reducing the effects of skew could require lengthening the ramp.

6.4.3.3 Addressing Skew at Entrance Ramps

Counterclockwise skew creates operational effects to the entrance ramp that are unique compared to those for an exit ramp. At an exit ramp, drivers slow their vehicles for their turns or to come to a stop. At an entrance ramp, drivers focus on leaving the crossroad to access the higher type roadway. Opposite of exit ramps, where drivers expect to slow or stop at ramp

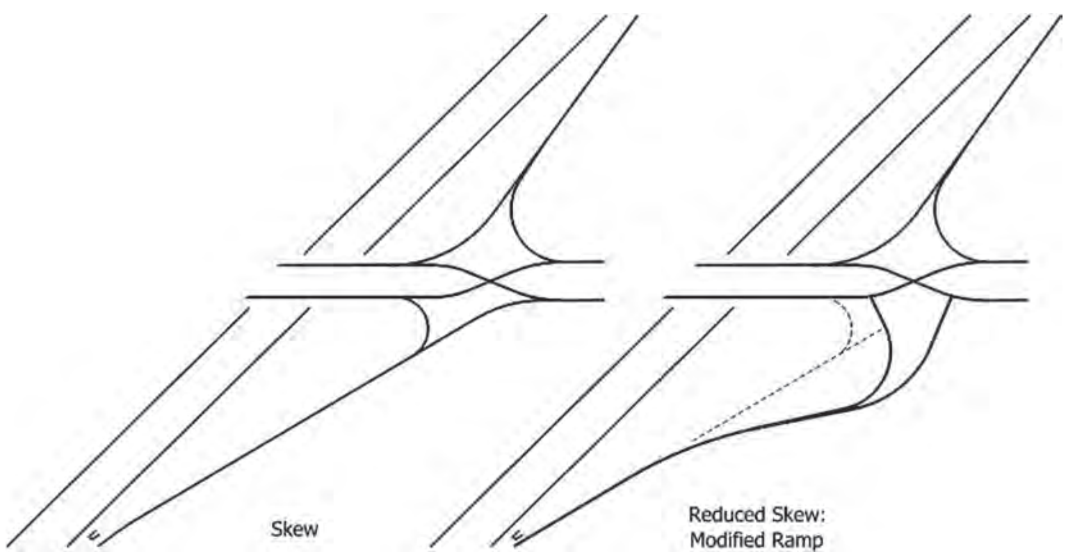

Exhibit 6-18. Modifying the ramp to reduce skew.

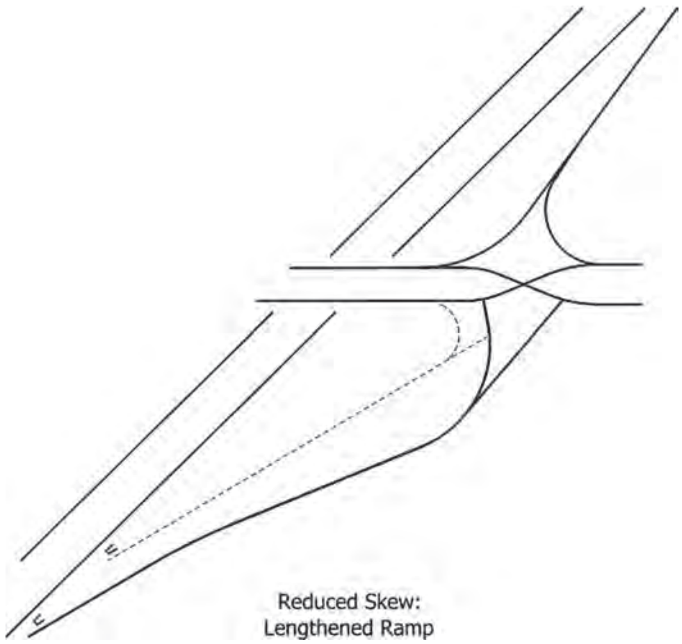

Exhibit 6-19. Lengthening the ramp to counter skew.

terminal intersections, drivers at entrance ramps have an expectation of acceleration to the higher type roadway.

As with any intersection, skew creates acute (less than 90 degrees) and obtuse (greater than 90 degrees) angles for turning traffic. At an entrance ramp, the minimum left-turn radius issues are the same as at an exit ramp: they create a turn radius that facilitates design vehicle movements. Because of the reduced radii, these movements can be some of the slowest movements at an intersection. This slow movement at an entrance ramp is where drivers wish to accelerate.

The obtuse angle for right turns to an entrance ramp creates conditions that promote higher right-turn speeds when compared to 90-degree intersections. The propensity for higher speed is amplified by driver expectation to accelerate to the higher order facility. In combination, the slower left-turning and faster right-turning create speed shear between these two movements where they converge on the entrance ramp.

It is not uncommon for designers to match the forward bearing of the left- and right-turning movements to create the alignment of the entrance ramp. The small left-turn radius creates a high convergence angle, meaning that the vehicles are aimed at each other with little separation as the paths converge to the ramp alignment. Off-setting those converging curves by a minimum of 3 to 5 feet allows the two converging movements to attain the same forward bearing before tapering to merge or lane addition.

Exhibit 6-20 shows how separating converging ramps can reduce the speed shear and convergence angle.

The minimum radius of the off- or on-ramp left turn will often be the controlling factor for the impacts to the approach alignments. Assessing the controlling minimum radii to serve design vehicles should be an early step in evaluating a DDI with a skew.

6.4.3.4 Skew and Route Continuity

Counterclockwise skew increases the propensity for a violation of cross street route continuity (turning left or right to stay on your designated route). While this can occur at nonskewed DDIs,

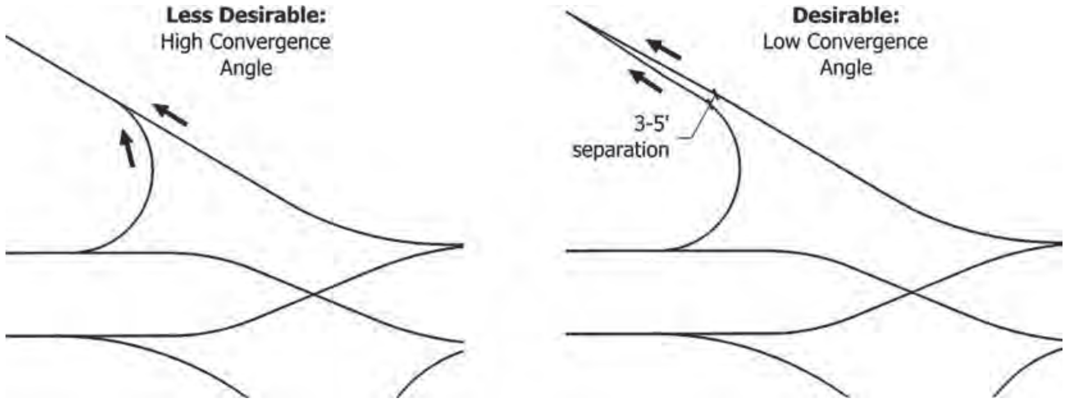

Exhibit 6-20. Separating converging ramps.

skew on counterclockwise configurations often requires right-turning drivers to travel past the crossover before initiating their turn. From a visual perspective upstream, the “straight” road leads to the right turn, while through drivers must turn to the left (to access the crossover) to stay on their designated route. To counter this effect, initiating the right-turn lane in advance of the crossover makes the accessing of the right-turn movement a deliberate deviation from the through route on the cross street.

Exhibit 6-21 shows how definitively adding the right-turn lane can maintain route continuity on the crossroad.

6.4.3.5 Examples of Skew

The DDI at Pioneer Crossing in American Fork, Utah, has a counterclockwise skew and includes some of the previously described characteristics: the left turn (with a relatively small radius) to the entrance ramp, the right turn on a tangent well beyond the right turn, a high convergence angle, and an upstream alignment of the right turn that remains essentially on the same bearing as the original cross street. The net result is that the through route curves away from the right-turn lane that traps to the entrance ramp. These features are presented to demonstrate the described geometric attributes and are not presented as a critique of the Pioneer Crossing DDI. Exhibit 6-22 shows the effect of skew at the Pioneer Crossing interchange.

6.4.4 Lane Numbers and Arrangements

Determining lane numbers and arrangement can be an iterative approach. During early interchange form assessments, such as early screening as part of intersection control evaluations, planning-level reviews might be used to screen and advance various forms for more detailed evaluations.

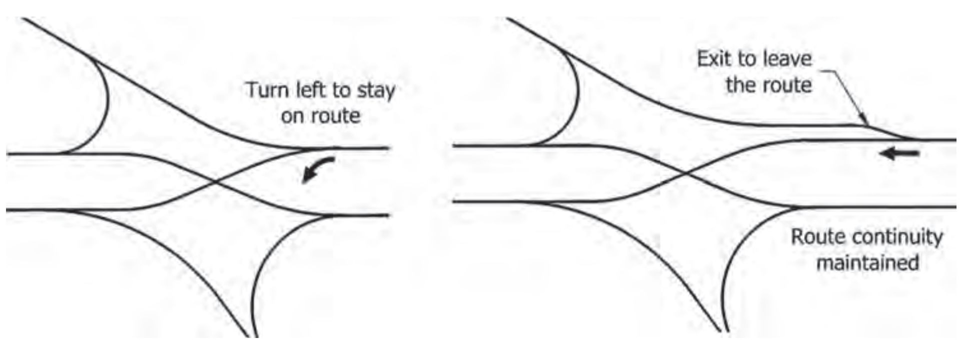

Exhibit 6-21. Maintaining route continuity.

Exhibit 6-22. Effects of skew at Pioneer Crossing interchange (American Fork, Utah) (5).

As the configurations are customized for the specific site conditions, the lane numbers and arrangements might change as more detailed traffic volumes and traffic signal timing schemes are considered in more robust evaluations than in early concept development. As project alternatives are screened and refined in later ICE or other engineering evaluations, the traffic operations evaluations become more refined to help select a preferred interchange concept that is revised and finalized, leading to final design.

Early traffic operations considerations should include assessing if left and right turns are controlled (stop, yield, or signalized) or free-flow movements. This could include replacing an exit ramp single free-flow right turn with signalized, dual right turns to promote pedestrian crossings or to reduce downstream weaving and traffic operations impacts. Early implemented DDIs often included free-flow or highly curvilinear yield control left or right turns that did not fully account for yielding driver view angles and sight lines to upstream traffic. If free-flow movements are not appropriate for a site or view angles and sight lines cannot be attained—requiring changing the ramp terminal intersection configuration—the traffic operations must be revised to match the proposed lane numbers and arrangements and geometrics.

Geometric configurations and traffic operations testing is an iterative process. Assumed traffic operations should guide corresponding ramp terminal intersection geometry, and later revisions of attainable geometrics may necessitate revised traffic operations. For example, if free right turns or right-turn-on-red (RTOR) was assumed and the appropriate geometry for either cannot be attained, the traffic operations evaluations should be revisited to ensure target traffic operations performance is attainable.

Lane numbers must not always be symmetric and can vary by direction as shown in Exhibit 6-23.

6.4.5 Design User and Type

Motorized and nonmotorized users must be evaluated in the earliest concept development. Design vehicle swept paths will affect lane widths and traffic island location and shape. Pedestrian and bicycle facilities must be considered early and as a key influence on the DDI configuration. It is not uncommon to develop potential interchange concepts early in alternatives development and evaluations; the concepts are often being generated quickly and with the pretense of not expending too many resources. At first glance, a practitioner may believe the concept is viable, but when design users and type are eventually integrated, the shortcomings of the original concept become apparent.

Exhibit 6-24 shows a horizontal functional plan that was generated quickly without considering pedestrian treatments and the influence of truck tracking. Consideration of trucks reduces

Exhibit 6-23. Example asymmetric lane numbers (Maryland Heights, Missouri) (5).

the median between the contraflow lanes and affects the pedestrian quality of experience. When pedestrian facilities and design vehicle swept paths are considered, the limitations of the initial configuration become clear. The changes to the median treatment affect pedestrian treatments that consider design vehicles. The revised crossing creates skewed pedestrian crossings, challenges in integrating detectable warning strips, and greatly decreased positive guidance for users with low vision.

Exhibit 6-25 shows an example of highly skewed pedestrian crossings that create a challenging experience for users with low vision at I-85 and Pleasant Hill Road in Duluth, Georgia.

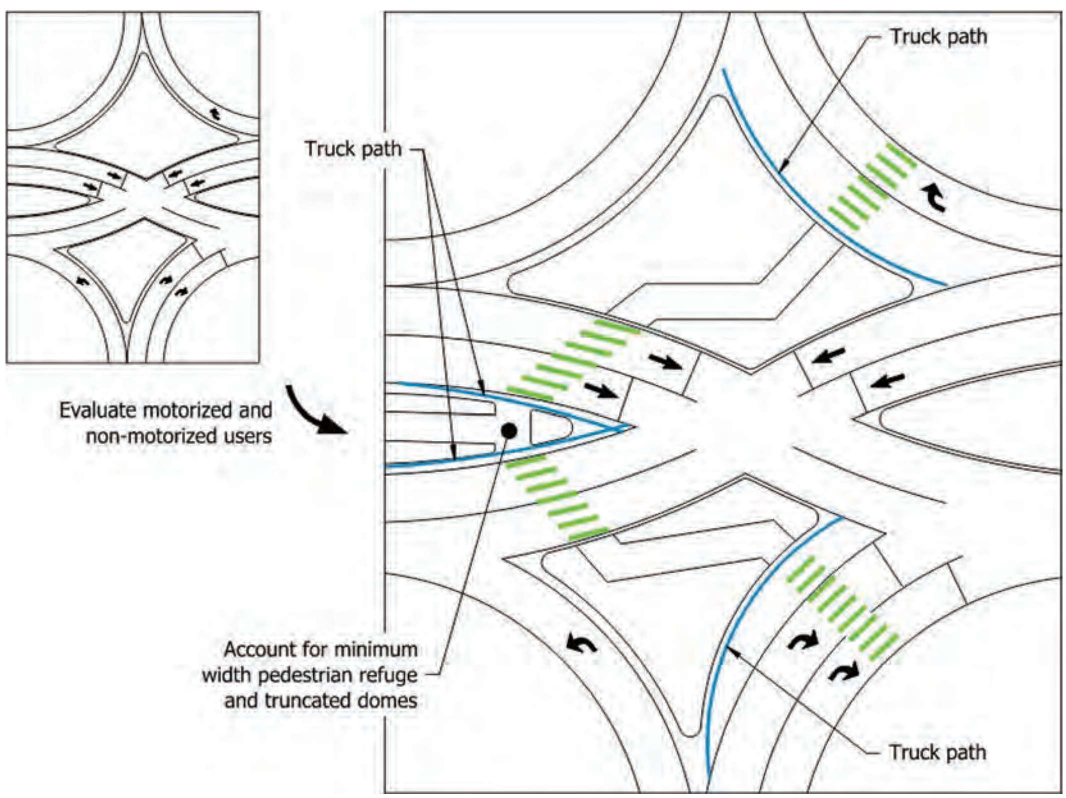

Exhibit 6-24. Example median treatments and pedestrian treatments.

Exhibit 6-25. Example of highly skewed pedestrian crossing (Duluth, Georgia) (5).

Exhibit 6-26 depicts pedestrian features that increase difficulties for users with low vision that involve locating the pedestrian push button, orienting themselves to the edge of the crossing, and then determining crossing path to reach the receiving pedestrian ramp.

Exhibit 6-27 presents design features that integrate quality pedestrian treatments. The median width and length support pedestrian crossings by including easy-to-locate push buttons, detectable warning strips at each crosswalk approach, and shorter, 90-degree crossings. These crossings help users with low vision to find the receiving ramp.

These examples emphasize how critical it is to incorporate design users in the early project concepts. Attempting to add features later for these users could result in less effective solutions than had they been considered from the start.

Exhibit 6-26. Example of pedestrian features that create difficulties for users with low vision (Duluth, Georgia) (6).

Exhibit 6-27. Example of quality pedestrian treatments (Minnesota) (6).

6.4.5.1 Design Vehicle

DDI configurations are affected by the need to accommodate the largest vehicle likely to use the interchange. Turning path requirements for this vehicle, referred to as the *design vehicle*, will dictate many of the dimensions of the DDI. Selecting the design vehicle and determining the corresponding swept paths using turning templates or a computer assisted design and drafting (CADD) -based vehicle turning path program will establish lane widths and channelization configurations.

Four key areas of the DDI are directly affected by the design vehicle: 1) through movements at the crossover, 2) left turns at the exit ramp, 3) left turns at the entrance ramp, and 4) right turns at the exit ramp. The first three areas are unique to the DDI with respect to interchange design; however, they build on concepts used for designing other street facilities such as roundabout and one-way street designs. The fourth area, right-turning vehicle paths, is not unique to DDIs.

The left turn from the crossroad to the entrance ramp is unique in a DDI. While other right-turning movements occur in other intersection forms, the same movement in a DDI does not cross an opposing lane. This makes the left-turn movement hug the left edge of traveled way and truck drivers sometimes swing wide toward the channelizing island to allow tracking as can sometimes happen with traditional right turns. Designers may consider adding additional buffer beyond the traditional vehicle swept path to account for driver error with this relatively new maneuver.

The separation of turn lanes with a vane island can allow trucks to complete turning movements without encroaching into adjacent lanes, as shown in Exhibit 6-28. Lane separation is typically provided to prevent off-tracking by heavy vehicles in turns, and the additional pavement creates the potential for emergency vehicles to pass other vehicles.

The choice of design vehicle will vary depending on the crossroad facility type and surrounding environment. Most often, state or local agencies and project stakeholders help determine the appropriate design vehicle for each site. The most common design vehicle used at DDI facilities is the WB-67. In more urbanized areas, it may be more appropriate to use smaller design vehicles, such as the WB-62 or WB-40. At a minimum, fire trucks, transit vehicles, and single-unit delivery trucks should be considered in urban areas. In rural areas, farming or other larger vehicle types may govern design vehicle needs. The need for design vehicles to travel side-by-side should be considered on a case-by-case basis and given higher priority as heavy vehicle volumes increase.

Exhibit 6-28. Vane island lane separation for heavy vehicle accommodation (3).

In some cases, it may be appropriate to consider different design vehicles for different approaches. For example, there may be oversized/overweight vehicles traveling certain routes through the interchange. These larger vehicles would need to be accounted for in the design of certain movements, with the balance of the movements designed to serve a smaller design vehicle.

Oversized vehicles may need to be considered at a DDI just like at any other interchange form. These vehicles often require a special permit to travel on the street. However, if they are expected to use the DDI, special consideration should be given to geometrics; signal height, placement, and installation; and most importantly, to the structural soundness of the facility. Dimensions for special vehicles can be established by working with local haulers or the industry or agricultural enterprises served by those vehicles. CADD-based turning path programs allow the designer to customize the electronic template for these vehicles. An example of an oversized load making a left turn onto I-44 from MO-13 in Springfield, Missouri, is provided in Exhibit 6-29.

6.4.6 Crossroad Alignment Design

The crossroad alignment considerations for DDIs are generally the same as those for other diamond forms. However, the impacts of a DDI to the crossroad alignment include transitioning vehicle speeds prior to the interchange to prepare for the lower speeds at the DDI

Exhibit 6-29. An oversized load making a left turn onto I-44 at MO-13 (Springfield, Missouri) (7).

and crossovers. There is an integral relationship between crossroad alignment and transition to and through DDI crossovers. DDI crossover-specific design considerations are presented in subsequent sections.

Unlike other interchange forms that have tangent crossroad alignments, a DDI crossroad alignment must be customized for travel direction to create a horizontal alignment that provides the transition to and from the crossover proper. This is similar to considerations of interchanges that use roundabout ramp terminal intersections in which the crossroad alignment must be created to explicitly transition to the roundabout approaches and entries. Like at roundabout ramp terminal intersections, the DDI crossroad alignment may need to be specifically tailored to attain desired performance at the crossover proper.

In addition, to appropriately transition to the crossover proper, crossroad alignments must include specific horizontal geometry to match the existing typical section while transitioning to and from the DDI crossover. Horizontal alignments supporting crossover design should be developed to consider the crossroad approach speed; this means considering horizontal curve radii commensurate to anticipated operating speeds and curve radii configurations in balance with the desired speed profile approaching and navigating the interchange.

If initial curves are to be used in advance of the crossover, the curves should have radii that support the speed transition from the higher speed approaching the interchange to the lower speed between crossovers. This means the first curve that a driver navigates in advance of the crossover (higher relative speed) would be at least as large as or larger than the curvature leading to the crossover.

Smaller curve radii may be used on the crossroad between the crossovers (lower relative speed). The transition curvature into the DDI reduces operating speeds compared to operating speeds from the crossroad approaching the DDI and smaller radii are consistent with operating speeds.

Exhibit 6-30 presents a conceptual speed profile approaching a DDI and the change in anticipated operating speed relationship associated with the crossovers.

6.4.7 Crossover Design

DDI crossovers create the crossroad contraflow through-movement operation over or under the highway. The crossover serves crossroad through movements while left and right turns to

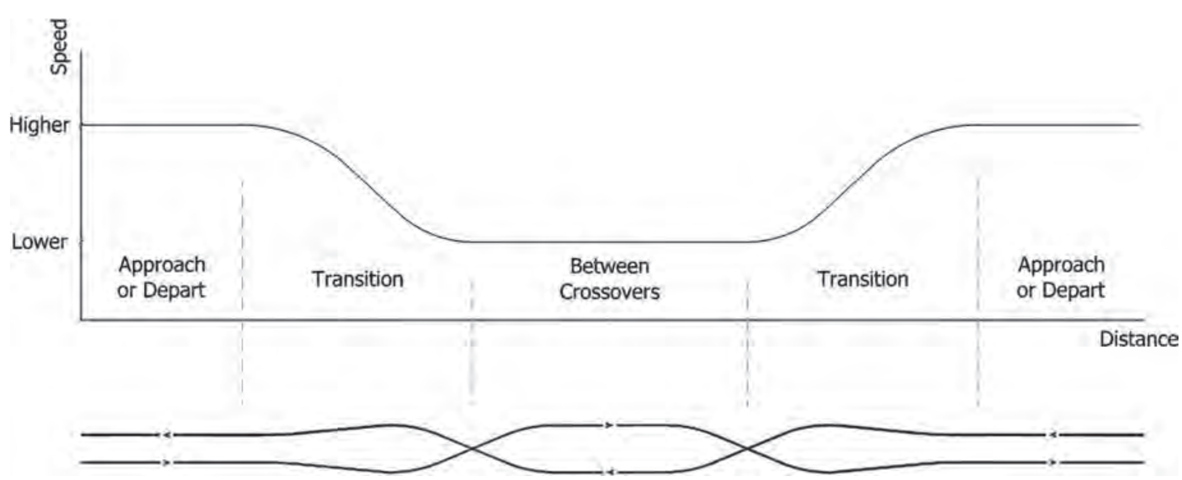

Exhibit 6-30. Conceptual speed profile.

and from the ramps are served by ramp terminal intersections. As noted previously, the ramp terminal intersections and crossover proper should be consolidated as much as possible. Consolidating intersection functions and features combines signing messaging to support navigation tasks and meets driver expectations by eliminating random, isolated turning movements.

6.4.7.1 Crossover Curvature

Crossover target speeds typically range from 20 mph to 35 mph and are influenced by horizontal curves with commensurate radii (100 feet to 400 feet). Slower crossover speeds allow designs to minimize the spacing between crossovers. Field observations at five DDI sites documented average free-flow speeds through the crossovers for inbound and outbound movements ranging from 22.3 to 31.1 mph (*8*). This corresponds to curves with radii between 180 to 350 feet. Providing curve radii values corresponding to design speeds below intended crossover operating speeds can lead to vehicles off-tracking intended travel paths and encroaching into adjacent lanes.

DDI crossover intersections are unique in that they introduce curvature for a through movement. This curvature may not meet the design speed designation of the cross street. If this is the case, it is necessary to lower the design speed through the interchange area. This is primarily a regulatory issue and not an operational or safety issue affecting the driving public. States have not reported issues with the decreased design speed through DDIs.

The curve radii approaching a crossover from the cross street (the first curve a motorist must navigate) should be at least as large as the curve radii departing the crossover (the interior curves between the crossover), so that the first curve is consistent with the transition effects into the DDI and the second curve is consistent with slower speeds in between crossovers. If different radii are used to create the crossover, the smaller radii should generally be used on the interior to reflect the lower speeds between the crossovers.

In rural or other high-speed environments approaching the DDI, speed transitions are a focus. The first curve (R1) a motorist must navigate typically may require a speed transition compared to the crossroad approach speeds in rural locations. The speed transition could involve changes in the cross section including adding raised medians and curb and gutter to reinforce the change in driving environment.

Exhibit 6-31 shows two horizontal configurations between the existing crossroad cross section and the crossover. The first configuration includes a first horizontal curve, and the second uses

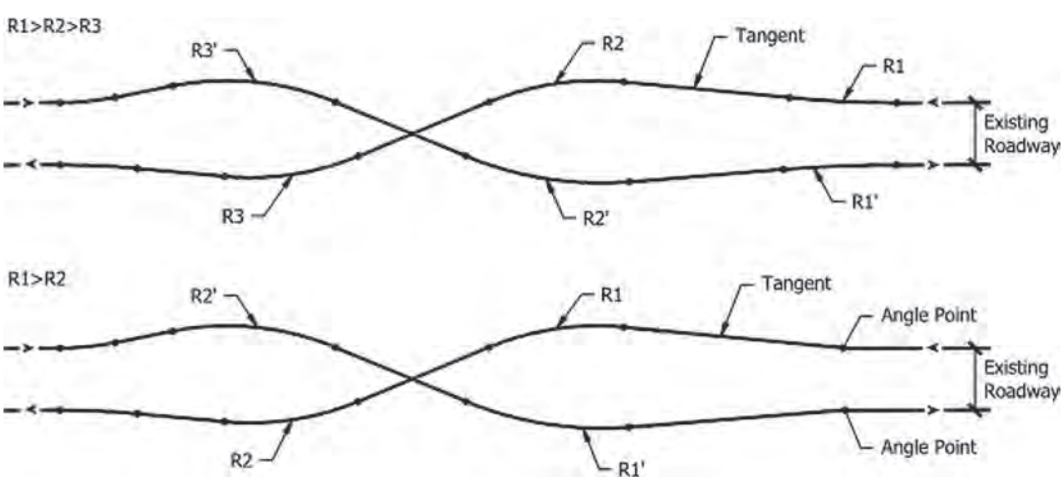

Exhibit 6-31. Horizontal configurations between existing crossroad cross section and the crossover.

an angle point. Whether a curve or angle point is used, the curve radii developed should support the speed transition relationship.

It has been common in DDI design to use a horizontal curve on the cross street to initiate the crossover configuration. However, angle points are acceptable and can help reduce overall footprint. Angle points are used at highway ramp terminal exits in high-speed environments. Highway exit ramp diverge angles typically range from 1 to 5 degrees. This corresponds to taper rates of approximately 60:1 to 12:1. Since angle points have been used successfully in high-speed environments, they may be used on the slower speed crossroad.

6.4.7.2 Crossover Spacing

Crossover spacing is affected by the width between cross street roadway centerlines and the number of reverse curves needed to attain the desired crossover. As with any horizontal alignment, tangents should be included between reverse curves. Crossover spacing (centerline to centerline) can range from 400 feet to 800 feet. The spacing range assumes 90-degree cross street crossings at the highway, and the spacing values can increase if the cross street over the highway has significant skew. The larger value is attributed to roadways with limited median widths (narrow) between cross street roadways.

- **Wider Distance**—With a wider distance between cross street roadways, as few as four reverse curves can be used. This is because the wider distance allows a single left-hand curve on the approach to the first crossover while still providing a tangent between the subsequent right-hand curve in the contraflow section between crossovers.
- **Narrower Distance**—A narrower distance between cross street roadways can result in up to eight reverse curves (each) approaching and departing the interchange. The first right-hand curve directs drivers to the right to set up the subsequent tangent and left-hand curve to the crossover. This is needed in narrow cross section areas to discourage wrong-way movements into the contraflow section.

Exhibit 6-32 presents crossover spacing with narrower and wider medians. A narrow highway crossing and narrow roadway conceptually has the longest influence area compared to a wider highway crossing and wider crossroad median.

6.4.7.3 Crossover Angle

It is desirable to provide the largest crossing angle while adapting to each site's unique conditions. Early DDI design practice targeted crossover angles of 45 degrees or greater to facilitate proper vehicle path alignment through the crossover and reduce the likelihood of wrong-way movements. Research findings from a study of seven of the first DDIs built identified a correlation between lower crossover angles and wrong-way maneuvers into opposing lanes (*8*). Since that time, there has been less emphasis on crossover angle in DDI design—it is often difficult to achieve 45 degrees in practice—and a greater focus on a range of operational and design features that are presented in Section 6.7. This includes general and DDI-specific performance categories.

Several factors influence cross angle selection:

- *Wrong-way maneuvers*—Minimizing the likelihood of a wrong-way maneuver into opposing traffic is a key consideration in DDI design. The greater the crossing angle, the more the intersection will appear conventional and support use of the crossover to attain contraflow versus a right turn to maintain typical diamond flow.
- *ROW constraints*—The surrounding environment will influence a DDI configuration. For instance, a retrofit design may be constrained by bridge abutments and built-out developments on either side of the crossover. These constraints can make it difficult for designers to maximize crossover angles.

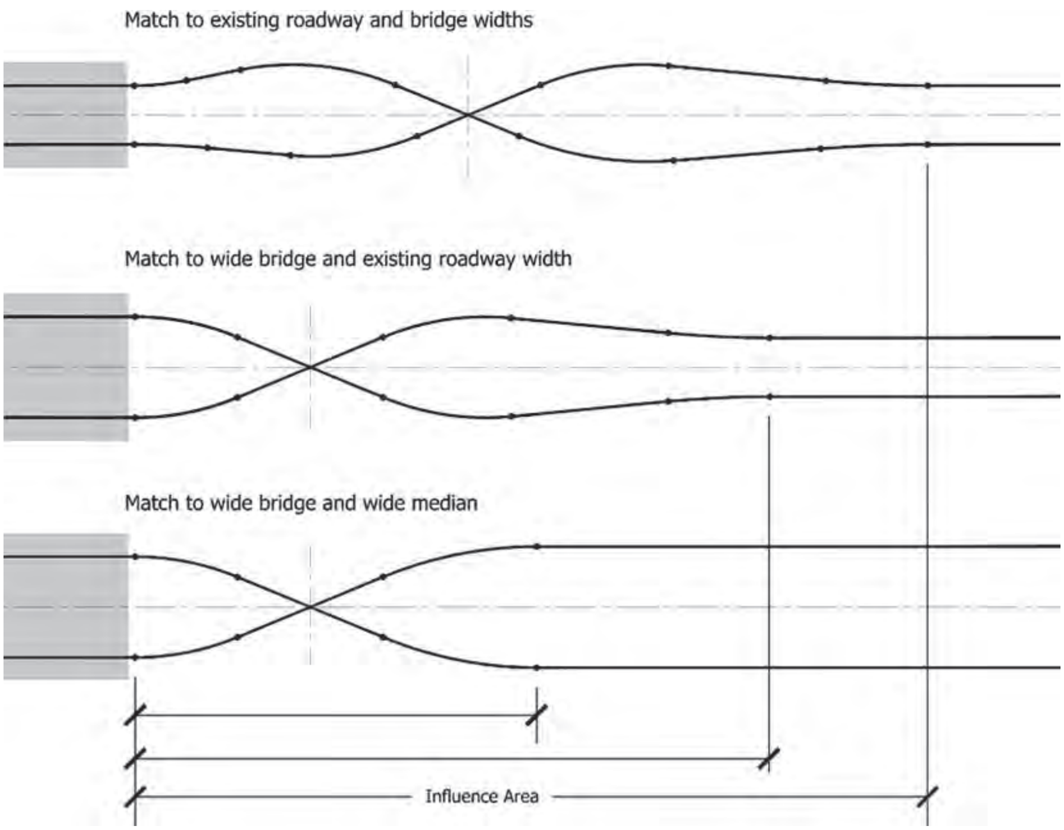

Exhibit 6-32. Crossover spacing with narrower and wider medians.

- *Driver discomfort*—Greater crossing angles require corresponding reverse curves, unless a wide median is present. Overall speed profiles approaching, navigating crossovers, and departing the interchange ideally result in speed reductions between successive movements of less than 15 to 20 mph.
- *Exposure*—As with any skewed intersection, larger crossing angles decrease the amount of time that a vehicle is exposed to conflicting traffic and reduce the potential for angle collisions if drivers disobey traffic signals.
- *Heavy vehicles*—Greater crossing angles could increase the potential for overturning unless appropriate horizontal curve radii can be provided to manage lateral acceleration. Minimizing speed reduction differences between successive geometric elements can mitigate this. DDI horizontal alignment should be based on the crossroad alignment approaching the DDI and the transition curves used to develop contraflow through the interchange. Smooth and consistent speed transitions will better serve all motor vehicles.

Commonly used treatments to supplement the crossover angle as a means of discouraging wrong-way movement at the crossovers include signing at the gore, pavement markings, and signal heads with arrows. These treatments are summarized in more detail in Chapter 7.

6.4.7.4 Using Tangents

As in any other horizontal alignment, tangents should be used between reverse curves unless no other option is available. It is ideal to have the DDI crossover proper to be two crossing tangent alignments (versus horizontal curves through the crossover). Considering each alignment separately allows the DDI to be customized to each environment. This can include adapting to different lane numbers and arrangements in each direction, accounting for various pedestrian and bicycle treatments or other site-specific conditions.

In addition to meeting fundamental horizontal geometric design principles, crossover tangents also encourage path alignment. This is the same natural path objective of multilane roundabout entry design and avoiding path overlap. The tangents direct the drivers at the stop bar approaching the crossover intersection toward the intended receiving lane departing the crossover intersection. Creating tangents approaching and departing the crossover intersection is reinforced by adjacent curb and gutter. In total, this creates self-describing roadway features through the intersection versus relying on striping to maintain lane discipline.

Exhibit 6-33 depicts a crossover intersection and demonstrates how effectively the tangent section clarifies the intended geometry with corresponding features of curb and barrier reinforcing the alignment. Striping complements these strong geometrics.

DDIs should include tangent sections if at all possible. If none are provided, curves should be of sufficient radii to match intended operating speeds. Curve radii values corresponding to design speeds below intended operating speeds can lead to vehicles off-tracking intended travel paths.

If DDIs are being considered with no tangent section throughout the intersection for all lanes, other guidance such as signing, striping, and signal head placement should be considered to aid drivers to the proper lane and provide adequate visibility to the signal heads. If back-to-back reverse curves are to be used, the horizontal curve radii provided should be commensurate with the anticipated operating speed. This means not using 100-foot radii (20 mph) if the anticipated speed profile indicates 35 mph crossover speeds (400-foot radii).

6.4.7.5 Determining Crossover Tangent Lengths

Tangents at the crossover support driver navigation and path alignment. The driver lane orientation at the stop bar is typically the location where roadway lane striping ends. Lane extension stripes are then used to provide path guidance. Striping and overhead signing are supplements to horizontal geometric alignment; roadway geometrics that promote path alignment and lane discipline should be a design objective.

The tangent length can be calculated by accounting for crossover angle, considering the amount of tangent in the vicinity of the stop bars approaching the crossover, and tangent length

Exhibit 6-33. Tangent crossover intersection at I-580 and Moana Lane (Reno, Nevada) (9).

components within the crossover and after the crossover. Basic geometry and trigonometry that consider approach widths and crossover angles can be used to compute tangent element values. In total, these elements support developing the crossover tangent lengths. Exhibit 6-34 depicts how elements from an example DDI crossover can be used to compute the tangent length.

$$Tangent\ Length = \text{“}A\text{”} + \text{“}B\text{”} + \text{“}C\text{”} + \text{“}D\text{”}$$

where

$\text{“}A\text{”} = 15' - 25'$ considers the length from the point of tangent (POT) and the intersection point as shown in Exhibit 6-34. This distance considers the stop bars placed no closer than 5 feet to the edge of travel way. The 15 to 25 feet also creates the opportunity to have a vehicle at the stop bar to be aiming to the receiving lanes beyond the crossover proper.

$$\text{“}B\text{”} = \frac{W}{\sin(crossover\ angle)} \times \sin(90 - crossover\ angle) \qquad \text{(Law of Sines)}$$

$$b = \frac{W}{\sin(crossover\ angle)} \times \sin(90 - crossover\ angle) \qquad \text{(Law of Sines)}$$

$$\text{“}C\text{”} = \sqrt{W^2 + b^2} \qquad \text{(Pythagorean Theorem)}$$

$$\text{“}D\text{”} = 10'\ minimum$$

$$W = total\ width\ (motor\ vehicle\ lanes, bicycle\ lanes, shoulders)$$

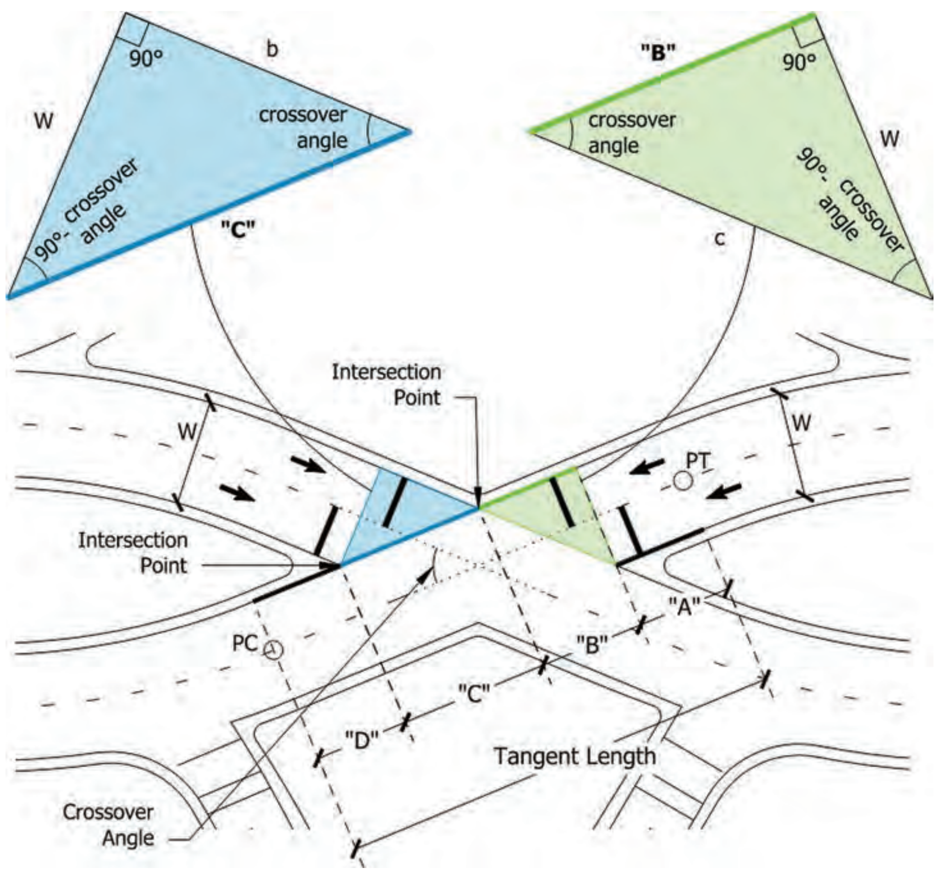

Exhibit 6-34. DDI elements and tangent length.

Examples for using this equation are shown below.

- **Example 1:** DDI with a 45 degree crossover angle and two 14-foot lanes in both directions (assumes no shoulder or bike lane)

$$W = 14' + 14' = 28'$$

$$B = \frac{W}{\sin(\textit{crossover angle})} \times \sin(90 - \textit{crossover angle})$$

$$B = \frac{28'}{\sin(45)} \times \sin(90 - 45)$$

$$B = 28'$$

$$b = 28'$$

$$C = \sqrt{W^2 + b^2}$$

$$C = \sqrt{28^2 + 28^2}$$

$$L \approx 40'$$

$$\textit{Tangent Length} = \text{“}A\text{”} + \text{“}B\text{”} + \text{“}C\text{”} + \text{“}D\text{”}$$

$$\textit{Tangent Length} = 10' + 40' + 28' + 25'$$

$$\boldsymbol{\textit{Tangent Length} = 103'}$$

- **Example 2:** DDI with a 35 degree crossover angle and two 14-foot lanes in both directions (assumes no shoulder or bike lane)

$$W = 28', B = 40', C \approx 49'$$

$$\boldsymbol{\textit{Tangent Length} = 124'}$$

- **Example 3:** DDI with a 35 degree crossover angle and three 14-foot lanes and two 4-foot shoulders in both directions

$$W = 50', B = 71.4', C \approx 87.2'$$

$$\boldsymbol{\textit{Tangent Length} = 194'}$$

The shallower the crossover angle, the larger the tangent length becomes. This is demonstrated between Examples 1 and 2. The greater number of travel lanes and shoulder or bicycle lanes in each direction, the larger the crossover intersection becomes. This is presented in Example 3. The crossover tangent length and horizontal curves are needed to transition the roadway approaches to the crossroad alignment. The horizontal alignment needs can also influence crossover width, which could influence ROW impacts.

If target lengths cannot be attained, the tangent length should be maximized within the project context and should not be less than 100 feet between back-to-back reverse curves. A method to maximize the tangent length could be to reduce the back-to-back curve radii. A small reduction in horizontal curve radii has a limited reduction in anticipated driving speeds. However, for a given set of curves with an existing tangent, simply reducing each curve radius by 50 feet results in a relatively large increase in tangent length.

As noted in the prior section, crossover width (footprint) is affected by the cross street cross section and the median width. The wider the crossover, the more simplified the horizontal alignment can be. In some cases of wider cross street medians, the crossover width can be developed within the roadway cross section width. In roadways with narrow medians, the crossover width may represent a bulge in the configuration between the approach roadway and the cross street (between crossovers). Larger median width negates the need for reverse curves (just the reverse curve of the crossover itself) on the closest side to the overcrossing bridge. Larger median widths typically increase the vista through crossovers as described in Section 6.7.2.5.

Exhibit 6-35 presents the geometric influence of narrower and wider medians.

6.4.8 Ramp Terminal Intersection

The ramp terminal intersection represents the intersection features that support turning movements to and from the exit or entrance ramp proper. The right- and left-turn lanes on DDI off-ramps tie into the crossroad to the left and right of the crossover intersection proper. While the DDI configuration is unique because of its contraflow arrangement, the ramp terminal intersection design follows intersection design principles for type of control, channelization, and adapting to the specific land use context. Each left- or right-turning movement to or from the crossroad should be configured to best serve each user and consider the vulnerability of pedestrians and bicyclists.

The first DDIs in Missouri were constructed with ramp terminal radii in the range of 100 to 175 feet, and many other states followed suit with similar dimensions. The corresponding design speeds are in the range of 20 to 25 mph. In addition, those left- and right-turn movements commonly intersected at flat angles, implying a free-flow or yield condition. Those design features were copied and included in subsequent DDI configurations regardless of the land use context. In many cases, those features create challenges for pedestrians, particularly for unsignalized movements. In addition, these conditions sometimes created weaving conditions on the crossroad from right-turning vehicles or from the left turn to the downstream left-turn lane at the adjacent ramp terminal intersection serving the entrance ramp.

Exhibit 6-36 compares two exit ramp terminal intersection configurations. The curvilinear example on the left represents legacy features of early DDIs. The more squared up version on the right reduces turning vehicle speed while maximizing the driver view angle to opposing upstream traffic.

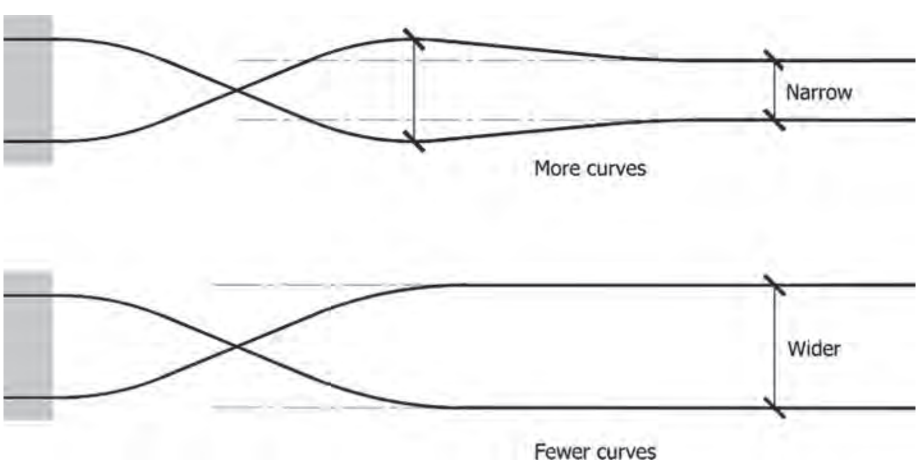

Exhibit 6-35. Geometric influence of narrower and wider medians.

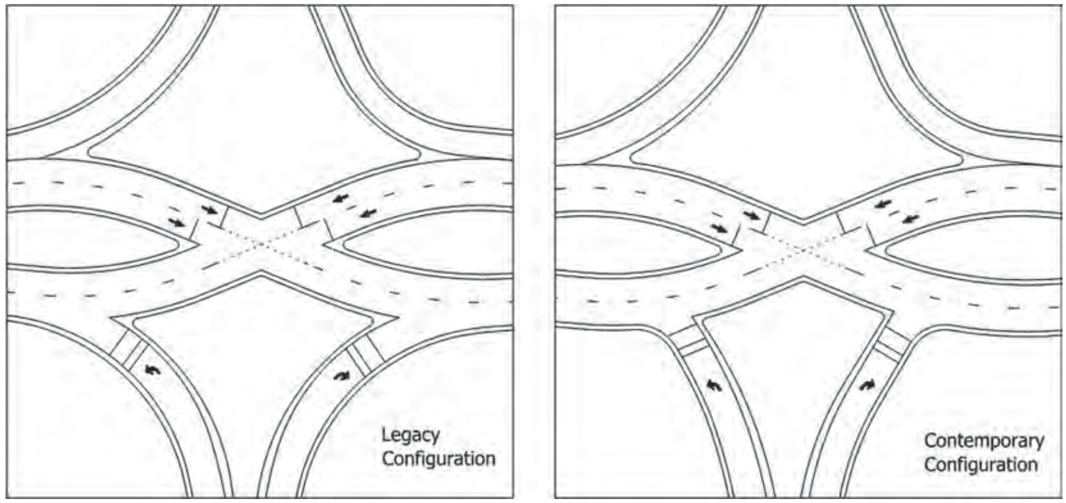

Exhibit 6-36. Comparing exit ramp terminal intersection configurations.

6.4.8.1 Intersection Design Fundamentals

DDI crossovers and ramp terminal intersections (left- and right-turning movement to and from the ramps) should follow fundamental intersection design principles including appropriate channelization that supports and reinforces intended or restricts nonintended turning movements. Intersection sight distance fundamentals (i.e., stopping and intersection sight lines) apply at each DDI movement. Other principles such as "view angle" also apply.

Intersection sight lines, stopping sight distance (SSD), or view angles should be evaluated, and intersection geometrics should be configured to meet appropriate values. If those values are not attainable, then the traffic control should be adapted accordingly. For example, if a right turn from an exit ramp does not have target sight distance, this movement might not be appropriate for a yield condition or RTOR. In this case, the geometry provided may be counter to an assumed traffic capacity need, and the DDI may not operate as intended.

There are numerous intersection planning and design considerations for any interchange form that also apply to DDIs. The following are just some of the general considerations that represent fundamental features or topics that should be included in DDI planning and design:

- Land use (urban or rural) and site context,
- Ramp terminal control (stop, yield, signal control),
- Locations and types of crosswalks and bicycle facilities,
- Distance of adjacent signals on cross street, and
- Design vehicle accommodation.

6.4.8.2 DDI-Specific Intersection Design Considerations

DDI crossovers and the contraflow operations lead to fundamental changes in driver expectations when navigating the ramp terminal intersections turning left or right from the exit ramp.

The contraflow operation creates a condition in which drivers must look to the contraflow approach compared to their expected views in a traditional diamond form. Because the crossovers create contraflow, drivers may inadvertently look at the departing traffic that has been transposed by the crossover and not see an oncoming vehicle on the other side of the crossroad. This means that there should be special attention to the approach angles at the ramp terminal intersection to maximize the ability for drivers to see conflicting traffic flows. This is shown in Exhibit 6-37.

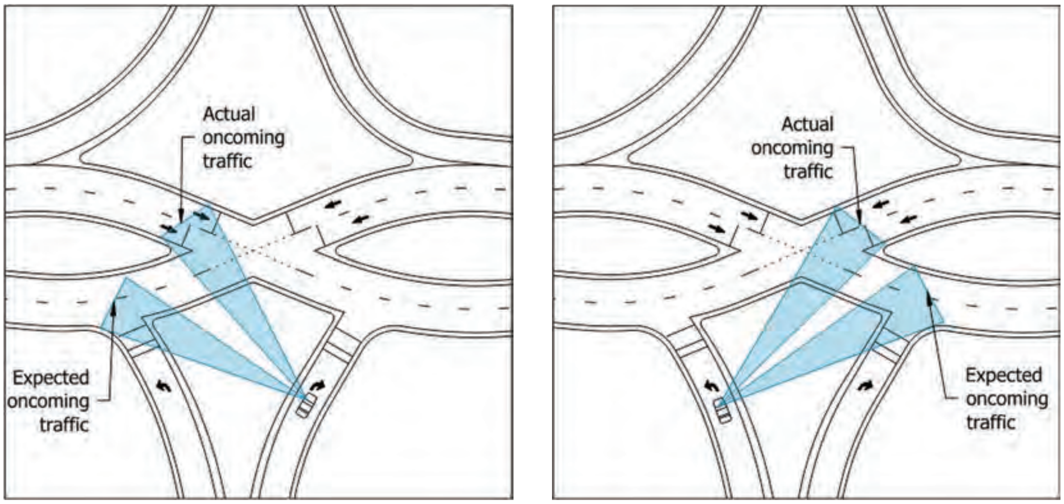

Exhibit 6-37. Alignment of exit ramp right- and left-turn movements.

The degree to which this issue exists on a site-by-site basis should be considered when selecting the control for off-ramp turning movements and traffic control. If signal control is selected, having an adequate view angle or not may determine whether to allow RTOR. For sites with limited available ROW and capacity limitations for the left or right exit ramp terminal intersection movements, glare screens have been used to assist drivers looking down the correct approach.

The angles of visibility should follow the same guidelines as conventional intersections. The intersection angle for the off-ramp right turn may be measured as the angle between the entry angle at the stop bar and the line drawn from an oncoming vehicle located at a given intersection sight distance. Guidance for designing for older drivers and pedestrians recommends using 75 degrees as a minimum intersection angle. Intersection view angle constraints should be taken into consideration when assessing whether to allow RTOR.

6.4.9 Adjacent Driveways and Intersections

DDIs have similar access management considerations compared to conventional diamonds and other service interchange forms. Raised medians automatically restrict nearby driveways to right-in/right-out. Minimizing the negative effects of adjacent access in the vicinity of the ramp terminal intersections also can lead to potential restrictions on adjacent driveways and public access points.

Like other interchange ramp terminal intersections, the type of traffic control serving right turns from the exit ramps can influence adjacent access spacing and considerations. Free-flow right turns can create downstream weaving. Signal-controlled right turns generally have less capacity, but they eliminate downstream weaving concerns while creating opportunities for signalized pedestrian crossings.

Minimum dimensions to driveways should be established based on local policy and guidance on a project-specific basis based upon traffic volumes, the number of lanes, ramp terminal intersection control, and local access management practices and standards. These operational conditions are like those of a conventional diamond interchange form. In new construction conditions, adjacent access spacing may trigger supplemental traffic operations analysis beyond the ramp terminal intersection analyses. These analysis results may help inform access management decisions and intersection spacing.

Adjacent intersection considerations are common when constructing or reconstructing existing interchange configurations and should be assessed in conjunction with the DDI. This means considering traffic flows to and from the DDI and the effects each adjacent intersection has on the DDI and the DDI effects on adjacent intersections.

From an operational perspective, DDIs often provide higher throughput than can be provided from or served by adjacent signals. Downstream operational considerations include providing appropriate lane numbers and arrangements departing the DDI to minimize queue spillback into the DDI. The crossover intersections prohibit both directions of the arterial from receiving a green indication at the same time, which creates challenges for coordination with adjacent signals. Similarly, adjacent signals with more than two phases may, in some conditions, not have the efficiency to serve the available capacity of the DDI. To the motoring public, the DDI design may appear to be ineffective when, in fact, the DDI is operating as intended.

Transportation agencies considering the DDI at locations with nearby signalized intersections and congested crossroads have made geometric and signal design modifications to nearby intersections. Some potential geometric treatments that may improve operations include:

- Closing the closest signalized intersection or converting it to unsignalized right-in/right-out control. These treatments were used at Dorsett Road in Maryland Heights, Missouri.
- Using grade separation to eliminate one or more movements at the adjacent intersection. This treatment was used at National Avenue in Springfield, Missouri, where a left turn into a hospital was modified to take a right, followed by another immediate right turn, leading to an undercrossing passing under the crossroad and accessing the hospital.
- Alternative intersection designs could potentially be used to reduce the number of necessary signal phases at adjacent intersections along the corridor. This treatment was used on Poplar Tent Road in Charlotte, North Carolina, and at several DDIs in Utah.

6.4.10 Developing a Design from the Inside Out

As noted above, a DDI follows fundamental horizontal alignment and intersection design principles. Unlike a typical diamond form, the DDI crossroad and intersection geometry is more complex. Developing an initial DDI configuration requires developing and combining many geometric elements. Designing the DDI from the “inside out” can help address seemingly minor details that form the base of the interchange configuration. The following is a suggested sequence for initially configuring a DDI: 1) Establish median width between the crossovers, 2) Locate the crossover and ramp terminal intersections, 3) Develop ramp geometry, 4) Create crossroad alignment, and 5) Performance check.

1. **Establish median width between the crossovers.** From the center of the cross street between the crossovers, work from the inside out to establish the median width between the contraflow lanes. If pedestrians are going to be directed to the median between crossovers, a quality pedestrian environment resulting in a high quality of service is as important as any other user type. This means providing adequate width for pedestrians and bicyclists who may be walking their bicycles through the walkway. Widths should consider volume and the ability of users to pass each other along the way.

   Exhibit 6-38 and Exhibit 6-39 depict two different pedestrian paths. The configuration in Exhibit 6-38 shows a relatively narrow section. If the site is to serve high pedestrian and bicycle volumes, one might consider widths that account for higher two-way flows of the two user types. The configuration in Exhibit 6-39 is at an underpass and provides a greater width for users. The extra width counters the closed-in feel between the contraflow traffic.

   The pedestrian access from the median walkway to the outside is a critical area, and enough space should be provided for appropriate refuge areas, detectable warning strips,

Exhibit 6-38. Example cross section for pedestrian path (Gwinnett County, Georgia) (6).

and appropriate curbing and guidance to support users with low vision. This may also include ensuring the median crossing locations have adequate room for traffic furniture, such as pedestrian call buttons, crosswalk signals, and illumination. This equipment should not conflict with the defined pedestrian areas.

2. **Locate the crossover and ramp terminal intersections.** From the center of the highway, work outward to locate the crossover center and ramp terminal intersections. This means considering the horizontal geometry approaching and departing the overcrossing so that appropriate alignments can be provided. The crossover location should, ideally, allow a consolidation of the crossover and the ramp terminal intersections so they are combined versus a series of separate intersection elements.

   The number of curves and providing needed tangents between reverse curves increases the overall spacing requirements between crossovers. Eliminating some reverse curves reduces driver workload and allows shorter spacing. With a wider median, the number of reverse curves between the crossovers can be minimized. Reducing the number of reverse curves to develop the crossover geometry will reduce the distance from the highway centerline to the crossovers and therefore reduce the overall distance between the crossovers.

Exhibit 6-39. Pedestrian path at an undercrossing with greater width at the MN-101 and 140th Street interchange (Rogers, Minnesota) (6).

Exhibit 6-40 compares the influence of median width on crossover location and influence area.

Tangent alignments through the crossover promote desired vehicle tracking and reduce driver workload by separating driving tasks at each curve. The tangent section between reverse curves is consistent with fundamental highway design principles. The tangent creates a self-describing alignment and allows drivers to see and prepare for the subsequent reverse curve. These principles apply to any succession of reverse curves approaching, traveling through, and departing a DDI.

With the crossover in place, the ramp terminal intersections can be located by using the crossover intersection as the basis for locating the entrance and exit ramps and the associated ramp terminal intersection. In new construction, there may be more flexibility in locating ramp terminal intersections and designing the ramp configurations based on needed lane numbers and arrangements. When adapting a DDI to existing ramps, it can become more difficult to consolidate the ramp terminal intersection.

Exhibit 6-41 shows how to use the crossover intersection location as the basis for laying out the ramp terminal intersection elements.

Exhibit 6-42 presents a crossover configuration with crossover stop bars located at the beginning of the tangent section and the subsequent reverse curve located beyond the crossover. This provides excellent path alignment and enhances positive guidance through the crossover. The entrance ramp terminal intersection aligns well with the crossover intersection. However, the exit ramp terminal intersection is offset to the left towards I-69.

Skew affects these intersection configurations, and if the crossing is skewed, special attention may be required at the ramp terminal intersections. This could be to consolidate the crossover and ramp terminal intersections and to do so while providing appropriate view angles and minimizing speed differentials between turning movements as described in Section 6.4.3.

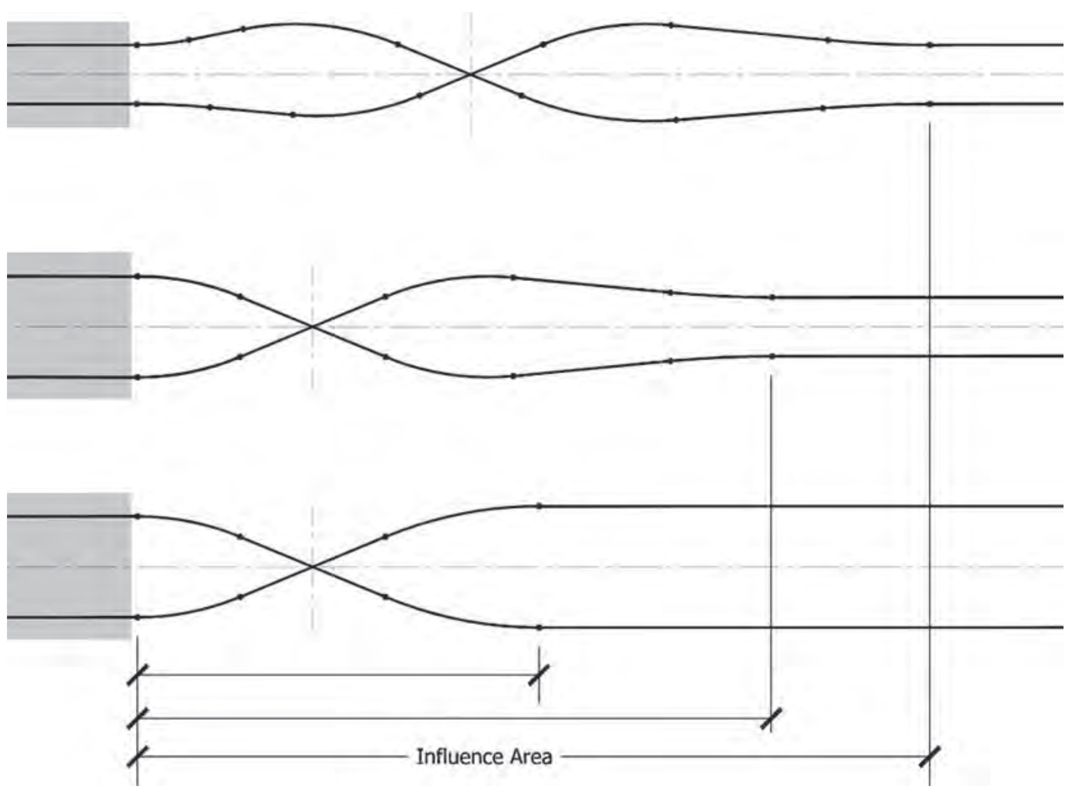

Exhibit 6-40. Influence of median width on crossover location and influence area.

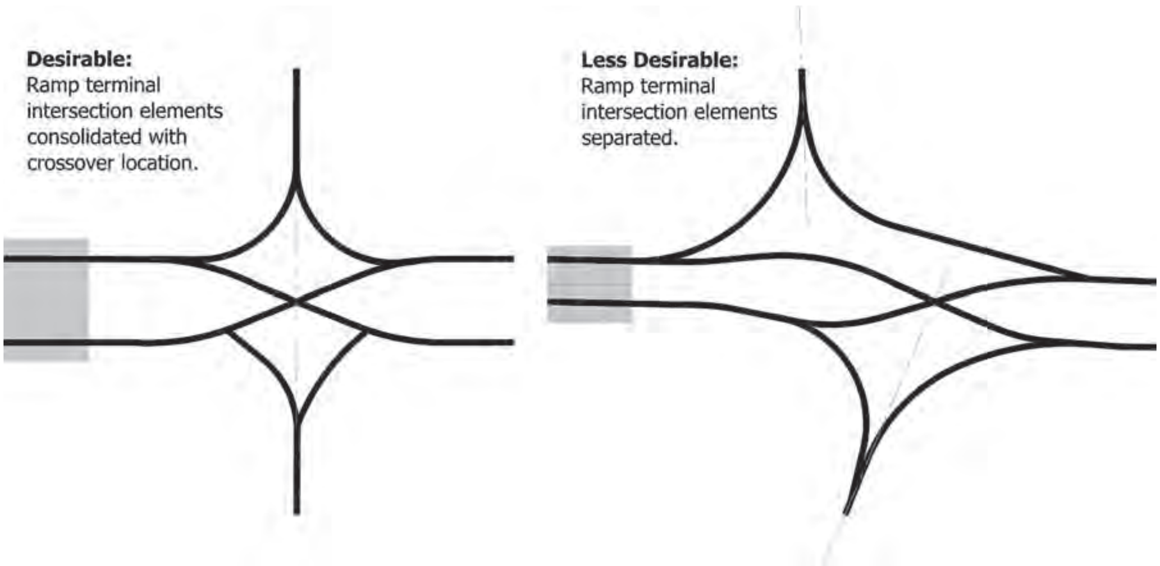

Exhibit 6-41. Crossover intersection as the basis for locating the ramp terminal intersections.

3. **Develop ramp geometry.** From the crossover and ramp terminal intersections, work outward to develop ramp geometry. On exit ramps, this means designing the ramp terminal left and right turns with appropriate lane numbers and horizontal alignment features to provide intersection sight distance and view angles. This could also mean working upstream on the ramp proper to develop the left- and right-turning lanes consistent with traffic volumes and patterns to be served.

   Exhibit 6-43 shows how ramp design must be coordinated with and integrated with lane numbers and arrangements at the ramp terminal intersection. DDI design may focus on the crossroad, but ramp geometrics that create a smooth transition from the ramp proper to the ramp terminal intersection must be established.

   On entrance ramps, this would be considering the convergence of the left- and right-turning vehicles from the cross street to provide the appropriate number of lanes and the

Exhibit 6-42. Tangent crossover configuration at I-69 and Campus Parkway interchange (Fishers, Indiana) (5).

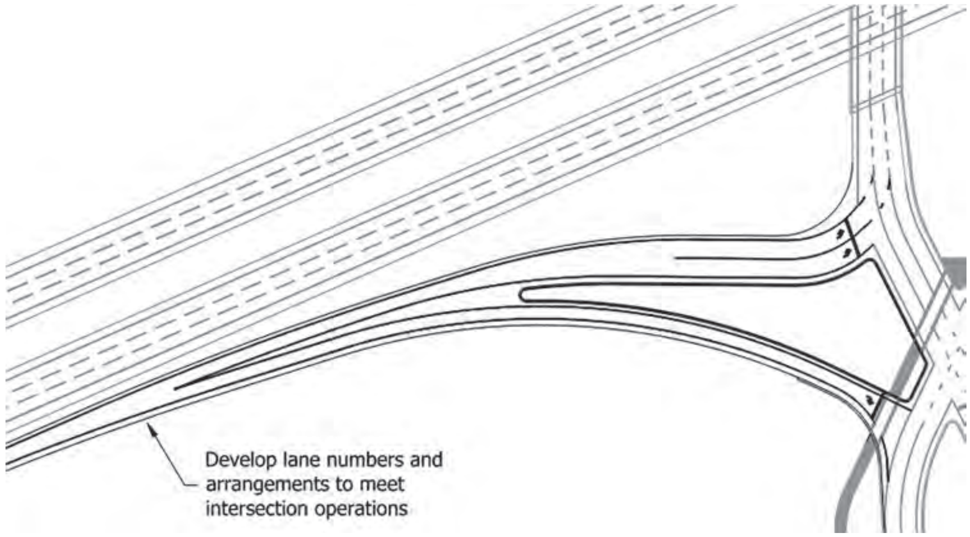

Exhibit 6-43. Ramp design and lane numbers and arrangements.

configuration of possible downstream lane drops or lane additions for high-occupancy vehicle (HOV) bypass lanes or for ramp metering queue storage. On skewed interchanges where the left-turning movement from the cross street is on an acute angle, the controlling radii may result in relatively low speeds compared to a larger radius or more acceleration distance for the right-turning vehicles from the cross street. This speed differential could be significant and may require added on-ramp length before merging the two travel streams.

Exhibit 6-44 depicts a separation of the converging left and right turns and the desirable transition to the ramp.

4. **Create crossroad alignment.** Work from the crossover and ramp terminal intersection to create transition geometry that sets up the alignment to the crossover and matches to the cross-

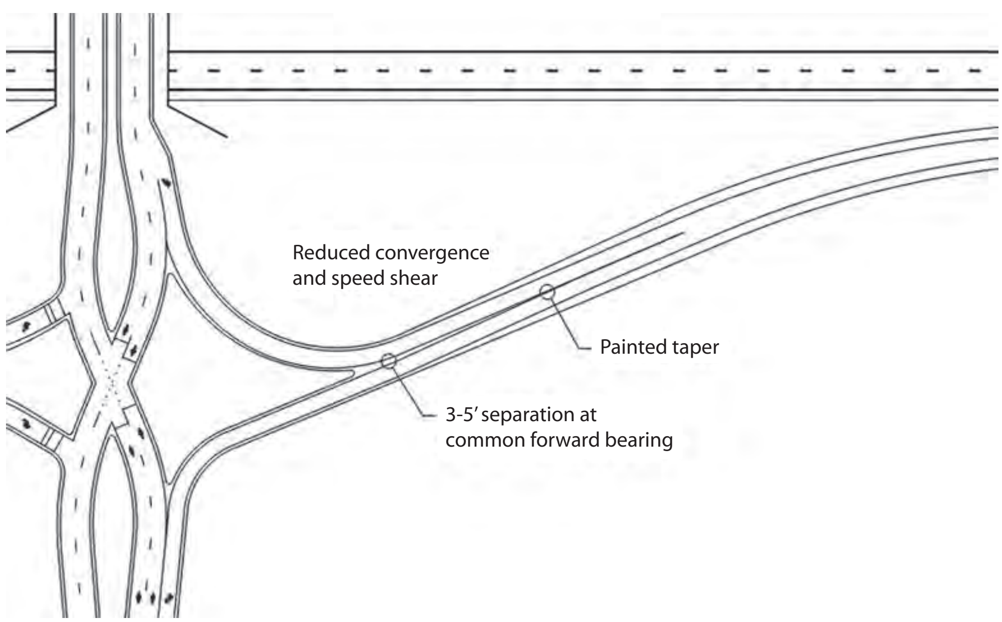

Exhibit 6-44. Separating converging left and right turns.

road typical section. This includes accounting for developing right-turn lanes to the entrance ramps to have definitive tapers to distinguish the right turn from a through movement and right-turn treatments from the exit ramps. Those right-turn treatments will vary based on the type of traffic control provided.

Reverse curves beyond the crossover intersections are often needed unless a wide median is present to provide the transition to and from the cross street typical section. Approach curves create the necessary approach angle through the crossover, and horizontal curve geometry should be established to create a smooth speed profile to, in, and through the interchange.

5. **Performance checks**. Like roundabouts, DDIs are performance based. As early concepts are developed, checking their performance should begin with the earliest draft versions. This includes general categories typical of other interchange forms. In addition, there are special considerations based on the unique attributes of the DDI. These performance checks are described in more detail in Section 6.7.

6.4.11 Performance Checks and Considerations

Like designing roundabouts, DDI design is an iterative process to optimize roadway and intersection features for each project location. Optimizing the DDI configuration is based on considering a variety of general and DDI-specific performance categories associated with the crossover design, ramp terminal intersection, and unique driver expectation issues associated with contraflow roadway. These performance checks are described in more detail in Section 6.7.

6.5 Cross Section

Cross section elements at a DDI are consistent with other service interchange forms. However, there are some features unique to the DDI that affect cross section considerations and values such as:

- **Median width**—The central walkway (noted below), the overall width between contraflow lanes, and the median width of the cross street have the most influential effects on DDI configurations. In short, the narrower the median on the crossroad or at the DDI, the more extensive the crossroad horizontal alignment to and from the crossovers becomes. The wider the separation, the more simplified the DDI design becomes.
- **Crossover design**—Because of the crossover design, through drivers must travel a curvilinear alignment to and through the crossover. The alignment is a turning roadway, and vehicle lane discipline needs to be considered. Lane widening will typically be needed from the crossroad typical section through the reverse curves of the crossover to maintain vehicle lane discipline.
- **Central walkway for pedestrians**—A central walkway between the contraflow lanes places pedestrians between two opposing travel streams. This is a unique configuration compared to other interchange forms, and pedestrian comfort and quality of service should be a focus.
- **Bicycle lanes**—Some DDIs provide bicycle lanes through the interchange. The relatively small horizontal curves increase the potential for encroachment by motor vehicles. Extra width for a painted buffer could be included in the cross section. Even with bicycle lanes, some bicyclists may not use them and will cross in the center walkway with pedestrians. Extra width might be appropriate to create ample space for these two user types and to account for being confined by a barrier and contraflow traffic.
- **Pedestrian crossing treatments—**Pedestrian crossing treatments, such as push buttons, tactile warning strips and crossing channelization to support wayfinding to the crossing and

to aim pedestrians to the receiving landing, should be integral to early concept designs. These features at the ends of the central crossing area are sometimes an afterthought leading to undesirable crossing treatments. This cross section element should be integral to DDI design.

Additional details and considerations for these unique elements of a DDI are described further in the remaining sections.

6.5.1 Overpass/Underpass Cross Section

Section 6.3.5 described considerations of matching to an existing highway crossing. Whether matching an existing cross section or developing a new DDI cross section, the cross section features influence the design configuration. DDI planning and design should consider lane widths early in concept development to fully assess possible impacts to adjacent bicycle facilities or other off-tracking considerations. Each project has a unique context in design vehicle choices, and if some off-tracking is allowed, it should be a deliberate design decision.

The interchange design will be directly affected by whether the arterial passes over or under the freeway. In most cases, DDIs with a crossroad designed as an overpass offer the most design flexibility, particularly in serving pedestrians. With a crossroad passing under the freeway, bridge abutments and columns can impede sight distances and limit roadway alignment options, particularly for retrofit projects where bridge elements are already in place.

6.5.1.1 Overpass Examples

Exhibit 6-45 provides several cross sections of DDIs with crossroad overpasses. Overpass designs can use a single, dual, or even four-span bridge structure. Overpass DDIs often use a single bridge design, as seen in Examples A through D. A single overpass is frequently the least costly overpass design option, especially for retrofit projects where there is typically an existing single-span bridge. The center crosswalk is common with an overpass as there are rarely obstructions between the two directions of travel on the cross street.

Several DDIs in Utah (including Example E) were retrofits and added lanes to the cross street by adding a parallel overpass beside an existing one. The additional lanes were needed to accommodate land use changes and increased traffic volume.

6.5.1.2 Underpass Examples

Underpass facilities tend to have less flexibility in their design. At an underpass facility, the available space between the two crossover intersections is directly affected by any components of the bridge substructure. At retrofit DDIs, this sometimes limits the locations for pedestrian facilities, and in the case where columns are in the median, limit the placement of lanes if unbalanced designs are under consideration. Underpasses can sometimes have a center pedestrian path as presented in Exhibit 6-46.

Several illustrations of crossroad underpass designs are provided in Exhibit 6-47. These show varying examples of column designs directly affecting the available space for vehicle lanes and pedestrian and bicycle facility considerations. Examples A and B provide limited space for vehicular traffic lanes. Pedestrian facilities were limited or nonexistent.

Examples C and D provide enough space for vehicular traffic and pedestrian facilities. Pedestrians were routed through the center as no columns were present in the median. Example D also provides some accommodation for bicycle lanes within the space. Examples E, F, and G each show cases of pedestrian facilities along the outside. Note the varying use of barrier

Exhibit 6-45. Examples of various overpass cross sections (*3*).

protection between vehicles and pedestrians ranging from no protection or a landscaping strip in Example E to fencing and concrete barriers used in Examples F and G, respectively.

6.5.2 Lane Width

DDI planning and design should consider lane widths early in concept development to fully assess possible impacts to adjacent bicycle facilities or other off-tracking considerations.

Exhibit 6-46. Undercrossing at the MN-101 and 140th Street interchange (Minnesota) (6).

Each project has a unique context in design vehicles and if some off-tracking is allowed, it should be a deliberate design decision.

6.5.2.1 Travel Lanes

Lane widths along the crossroad tangents typically range from 12 to 15 feet wide, depending on local design practice. The lane width is most critical in the transitions to and from the crossover. Lane widths generally should not vary unnecessarily, and widths developed in the curves approaching the crossover should be maintained for a consistent cross section through the alignment. Where necessary, lane widths should achieve their crossover lane width prior to the first curve approaching the crossover and at the end of the last curve departing the crossover. The intent would be to increase (on approach) and decrease (on departure) crossover lane widths through bridge abutments. The abutment may be a critical cross section constraint. Lane widths in longer tangent sections can be narrower if needed to reduce the overall cross section.

6.5.2.2 Turning Roadway Considerations

A crossover represents a "turning roadway," and the lane widths on the turning roadway are often widened to address issues associated with handling vehicles on curvilinear alignments. This is consistent with widening at interchange ramps or approaching and in roundabouts. Adding width to a turning roadway supports truck and large vehicle off-tracking through a curved alignment section. This applies to the geometry providing transitioning to and through the crossover, in addition to the ramp terminal intersection treatments.

There is various design guidance provided by AASHTO and other transportation agencies associated with turning roadway widths. Widths can be based on the turning radii provided and delta, the angle turned by a roadway curve. For example, considering a WB-67 design vehicle and a two-lane roadway, roadway widths on curves with a 150-foot radius curve or a 300-foot radius range from 41 feet and 32 feet, respectively. As the delta angle of curve increases beyond 15 degrees to 90 degrees, the roadway widths increase to the values that approach the higher width values.

The lane widths of the crossover and ramp movement are determined based on the design vehicle and the likelihood of multiple design vehicles being side by side. Horizontal geometrics

Exhibit 6-47. Examples of various underpass cross sections (3).

such as curve radius, crossover angle, and tangent segments at the crossover can influence lane width dimensions. Design vehicle swept paths using templates or software are useful for determining the necessary lane widths through different radius curves.

Lane widths for left- and right-turn movements at entrance and exit ramp terminal intersections may be designed using similar methods for right-turn ramp designs (entry and exit) employed at conventional interchanges. Left-turn movements entering and exiting the crossroad function in the same fashion as right-turning movements at conventional diamond interchanges. Lane widths can be increased to accommodate design vehicles at entry or exit ramps, depending on the project context.

6.5.3 Shoulder Width

DDIs are typically built with shoulders less than the width of a vehicle. Near the crossover, narrow shoulders (no more than 4 feet wide) are recommended to discourage wrong-way movements and effectively channelize vehicles. Between crossovers, shoulder width typically has considerable cost implications because shoulders are on or beneath a bridge. If a wider shoulder is desired between crossovers for snow storage or as a refuge for disabled vehicles, it should be placed to the right side of travel lanes (i.e., on the inside). Shoulders will need to be wider than 4 feet if they are designated as bicycle lanes to provide some minimal level of comfort next to the barrier. Shoulders will also need to be wider than 4 feet if it is desired for an emergency vehicle to be able to pass queued traffic.

6.5.4 Bicycle Lanes

The needs of all modes should be considered in the earliest stages of DDI design so that design decisions include, or do not preclude, high quality facilities for all users. Buffers between bicycle lanes and the travel lanes increase the quality of service for the bicyclist. However, bicycle lanes and buffers add cross section width. If separate bicycle lanes are not provided, bike and pedestrian multiuse paths must consider these two users and the cross section width should be established to reduce conflicts between these user types.

Exhibit 6-48 depicts a bicycle lane approaching the DDI crossover.

Exhibit 6-48. Bicycle lane approaching the DDI crossover at I-580 and Moana Lane (Reno, Nevada) (9).

Assessing design options for pedestrians and bicyclists is key, given the variety of pedestrian and bicycle facilities that have been used at DDIs to date. Due to the considerable amount of information on this topic, an entire chapter of this guide is devoted to it. Refer to Chapter 3 for pedestrian and bicycle design considerations.

6.5.5 Sidewalk

Sidewalk widths have a direct influence on the quality of service for pedestrians. In some cases, there may be no bike lane, and a multiuse path must be provided if the DDI is serving bicycles. This path should be designated at a minimum width of 10 feet. Pedestrians can be accommodated on the outside or within the median. However, with an underpass with multiple bridge spans, the median treatment may not be feasible since there may be insufficient median space considering the columns. Consider cross section needs for sidewalks or multiuse paths early in the concept development activities. More guidance on these facilities is provided in Chapter 3.

6.5.6 Crosswalks

Crosswalk width is commonly dictated by local or state design policies and standards. Crosswalk location to median pedestrian paths should connect in such a way that tactile warning strips and other aids to support wayfinding can be provided.

6.6 Vertical Alignment

Vertical considerations at DDIs are similar to those considered for other interchange forms. However, because of the curvilinear alignment, DDIs have special considerations that need to be reviewed and coordinated closely with the horizontal alignment. Primary considerations for vertical alignment at DDIs include:

- **Crest vertical curve on the overcrossing**—A crest vertical curve on the overcrossing could potentially mask the turning roadway alignment to the crossover. Therefore, horizontal and vertical alignments need to be coordinated closely.
- **Skew in an overcrossing**—In a typical diamond form, a left-turn movement from the crossroad to the entrance ramp occurs near the location of the companion right-turning movement to the same entrance ramp. In a DDI, the left-turn movement occurs upstream of the right-turn movement and at a location where the crossroad roadway profile is the highest. This means the left turn has a more pronounced downgrade to match the profile grade of the right-turning ramp movement. In some conditions, it may be beneficial to raise the right-turning ramp profile to better meet the left-turning movement.
- **Crosswalk visibility**—A second byproduct of the crest vertical alignment and skew angle is visibility to the crosswalk across the left-turning roadway. The relatively sharp horizontal curve to the left and bridge parapet can obscure views to a user waiting at the pedestrian crossing. As the left-turning roadway is dropping away, the crosswalk is not visible until the turn is initiated.

Exhibit 6-49 calls out some of the vertical and horizontal alignment attributes of the DDI at Pioneer Crossing in American Fork, Utah.

Exhibit 6-50 presents the influence of vertical alignment and visibility considerations at the DDI at Pioneer Crossing in American Fork, Utah. The horizontal curvature and vertical alignment coordination results in the parapet wall impeding the driver sight line to the pedestrian crossing location.

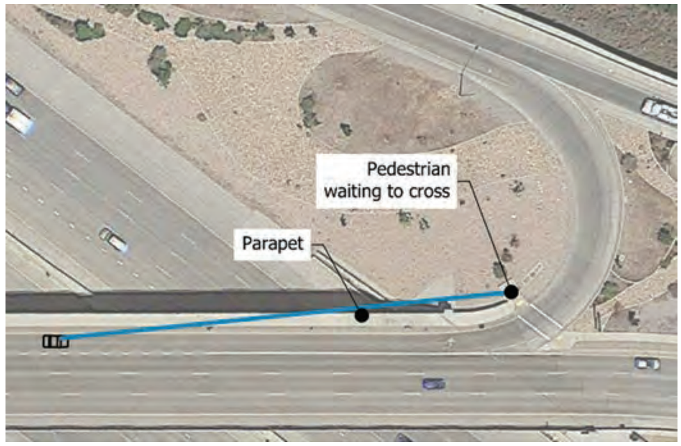

Exhibit 6-49. Vertical and horizontal alignment attributes at the Pioneer Crossing interchange (American Fork, Utah) (5).

Exhibit 6-51 presents the pedestrian crossing location at the DDI at Pioneer Crossing in American Fork, Utah.

Exhibit 6-52 presents the upstream sight line from the pedestrian crossing and the influence of the parapet wall at the DDI at Pioneer Crossing in American Fork, Utah.

6.7 Performance Checks

DDI concept design involves balancing and optimizing trade-offs associated with user performance, capacity, costs, maintenance, and construction staging, among other items. For instance, considering large design vehicles at the crossover may lead designers to contemplate larger design radii or wider lanes; however, this could promote higher speeds through the crossover for other vehicle types. Instead, to provide adequate facilities for the design vehicle while maintaining safe speeds for other motorists, designers may want to consider designs resulting in off-setting one or more of the approaches to the DDI. This method may increase street alignment radii resulting in comparatively narrower lanes to serve design vehicle off-tracking.

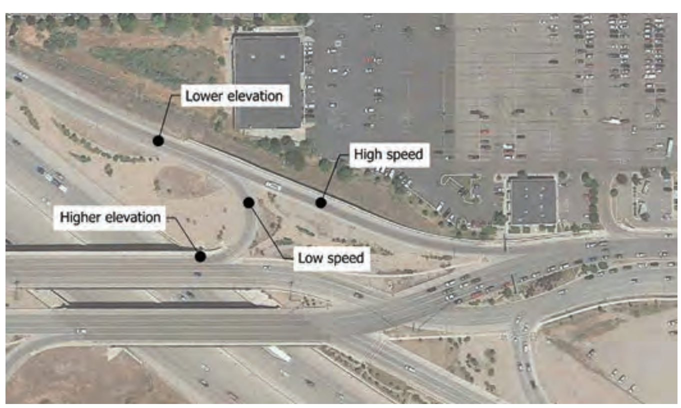

Exhibit 6-50. Vertical alignment and visibility considerations at the Pioneer Crossing interchange (American Fork, Utah) (5).

Exhibit 6-51. Pedestrian crossing location at the Pioneer Crossing interchange (American Fork, Utah) (10).

Similarly, a DDI is a high-capacity diamond interchange form. Maximizing capacity with large radii and free flow or yield control could contribute to the overall capacity. However, those movements can increase vehicle speeds and degrade the quality of service experience for pedestrians at crossing locations. Selecting multilane left or right turns controlled by signals could lead to less vehicular capacity; however, it could increase the quality of service for pedestrians by improving pedestrian crossing safety performance by reducing turning speeds and allocating signalized pedestrian crossing time.

While the previous sections provided general geometric parameters and principles related to the DDI, this section provides more specific guidance to assist designers in verifying the quality of their designs. The primary source for geometric design guidance is the AASHTO Green Book, *A Policy on Geometric Design of Highways and Streets* (*11*). This chapter augments AASHTO Green Book guidance and includes traditional roadway and intersection design fundamentals to support decisions regarding DDIs.

Exhibit 6-52. Pedestrian crossing sight line at the Pioneer Crossing interchange (American Fork, Utah) (10).

DDI planning and design is an iterative process to optimize roadway and intersection features for each project location. Optimizing the DDI configuration is based on considering a variety of general and DDI-specific performance categories associated with the crossover design, ramp terminal intersection, and unique driver expectation issues associated with contraflow roadway. These performance checks are described and summarized as follows:

- General performance categories typical of other interchange and intersection forms:
  - Verifying design users are integrated into the configuration. This specifically means accounting for pedestrians, bicyclists, and other design vehicles.
  - Stopping sight distance (SSD).
  - Intersection sight distance (ISD) (sight triangles).
  - View angle considerations: Supporting left or right turns to the cross street from the ramp terminal intersection.
- DDI-specific performance considerations and categories include:
  - Speed profile: Considering the roadway approach speeds on either side of the interchange and accounting for appropriate transition features (horizontal and cross section) to and from the interchange.
  - Approach vista: Discouraging wrong-way movements to opposing contraflow traffic by limiting sight lines on the approach to the contraflow roadway.
  - Path alignment: Assessing if the configurations appropriately direct vehicles to the receiving lanes.
  - Vista through crossover: Supporting a self-describing roadway that emphasizes contraflow through the interchange.

6.7.1 General Performance Categories

As our industry moves to performance-based evaluations, it is becoming increasingly common to conduct evaluations to help assess, evaluate, and compare concepts. Performance metrics have been integral parts of roundabout planning and design guidance since the publication of *Roundabouts: An Informational Guide, 1st Edition* (*12*). For roundabouts, this included specific categories directly associated with the specific characteristics of roundabouts.

General performance measures are described in the following sections.

6.7.1.1 Pedestrians and Bicycles

DDI planning and design begins with understanding the anticipated specific users and providing appropriate geometric features and elements that serve nonmotorized and motorized users.

In urban and suburban areas where pedestrians are expected, the configuration should be checked to assess how pedestrians are served. In cases where pedestrian use may be limited, to the extent possible, configurations should be developed to not preclude future treatments. For example, this could include ensuring that there is adequate cross section width for sidewalks and paths or that channelizing islands could be readily converted to include pedestrian features and wayfinding elements. The following represents checks to assess how nonmotorized users are integrated into design configurations:

- Minimizing the number of travel lanes to improve the simplicity and safety performance of DDI pedestrian facilities, including walkways and crossings.
- Designing for slow vehicle speeds. Wherever possible, using the smaller range of curve radii in pedestrian areas while still meeting motorized user needs. Higher speeds increase severe and fatal crashes for pedestrians.
- Providing sidewalks that are set back from roadways where possible and creating sidewalks that maximize the available width where possible to increase the quality of service. Barrier-

Exhibit 6-53. Median pedestrian crossing and pedestrian treatments at the I-580 and Moana Lane interchange (Reno, Nevada) (9).

separated pathways are increasingly common and should be accounted for in allocated cross section width dimensions.

- Providing well-defined and well-located crosswalks that include appropriate supporting features such as tactile warning strips and pedestrian call buttons.
- Considering general navigation features with a focus on visually impaired users. This includes wayfinding treatments to and through the interchange area and providing crosswalk and pedestrian ramp design details that support direction to the crossing and clear alignments to the receiving pedestrian ramps.
- Designing for integral bicycle facilities such as bicycle lanes and multiuse paths. Target configurations could include buffers from motor vehicle travel.

Exhibit 6-53 depicts the median pedestrian crossing and pedestrian treatments provided at the I-580 and Moana Lane DDI in Reno, Nevada.

Exhibit 6-54 depicts the median pedestrian crossing and pedestrian treatments provided at the MN-101 and 140th Street interchange in Rogers, Minnesota.

Exhibit 6-54. Median pedestrian crossing and pedestrian treatments (Rogers, Minnesota) (6).

6.7.1.2 Design Vehicle

The choice of design vehicle will vary depending upon the approaching roadway types and the surrounding land use characteristics. The local or state agency with jurisdiction of the associated roadways should usually be consulted to identify the design vehicle at each site. Appropriate design vehicle consideration will depend on road classification, input from jurisdictions and/or road authorities, and the surrounding environment. These users have a significant effect on interchange geometrics and should be established in the early planning and concept design stages.

Performance checks begin with documenting the underlying design vehicle assumptions and assessing if, fundamentally, the selected vehicles are appropriate for the site conditions. A second assessment is understanding the potential range of vehicle types (e.g., oversize/overweight) or special vehicles (e.g., farm implements) and the risk of those nonstandard vehicles navigating the DDI.

While some vehicles will be designed for (the agency may purposefully choose to serve trucks or other large vehicles with limited or no lane off-tracking), others may be assessed on how well they could be accommodated. "Accommodated" means assessing how the occasional vehicle could navigate the DDI and considering modifications that allow nondestructive off-tracking or lane encroachment.

Vehicle swept paths can readily be assessed using off-the-shelf software packages.

6.7.1.3 Stopping Sight Distance

SSD is the distance required by a driver to perceive and react to an object in the road and come to a complete stop without colliding with the object. SSD is a fundamental performance metric for any roadway, interchange, and intersection geometric design. As with any other intersection, DDI intersections should provide SSD on roadways and intersections. Drivers on the roadway must have the visibility to see, perceive, and react to an event and avoid a collision. SSD should be provided at every point in the DDI roadways and intersections (*11*).

The AASHTO Green Book provides an equation for calculating SSD (*11*).

$$SSD = (1.47)(V)(t) + 1.075\frac{V^2}{a}$$

where

SSD = stopping sight distance, ft;
t = perception-brake reaction time, assumed to be 2.5 s;
V = initial speed, mph; and
a = driver deceleration, assumed to be 11.2 ft/s^2.

SSD values are based on an assumed driver's eye height of 3.5 feet and an object height of 2 feet (*11*). At DDIs, SSD constraints will be most prevalent at the following locations where yield control or pedestrian crossings are provided:

- *Exit ramp left and right turns*—Drivers must be able to stop at conflicts with approaching vehicles or crossing pedestrians at the exit ramp terminal intersection.
- *Entry ramp left and right turns*—Drivers must be able to stop at pedestrian conflicts at free-flow left turns and yield-controlled right turns onto the entrance ramp. This topic is discussed in Chapter 3.

While not an SSD issue, a crest vertical curve combined with horizontal curves from the contraflow lanes approaching the crossover may result in the impending crossover intersection

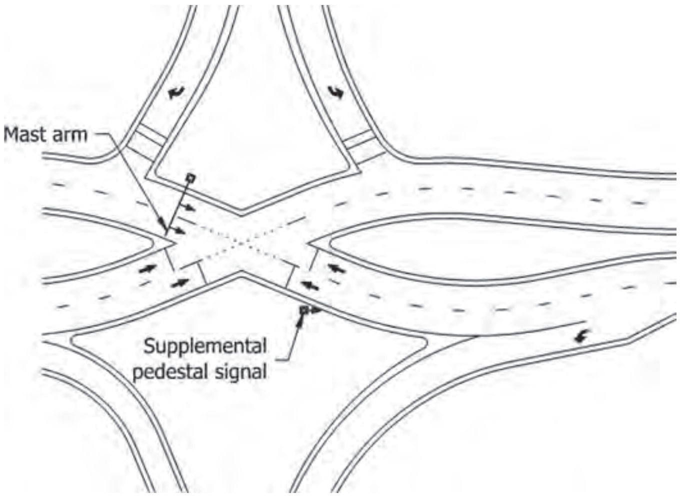

Exhibit 6-55. Example of supplemental signals.

to be out of view. Where traffic signals are not visible to oncoming drivers, advance signals can provide the necessary information to drivers regarding who has the ROW (*13*). Exhibit 6-55 and Exhibit 6-56 provide examples in which the advance signal is provided to the left of the crossroad.

6.7.1.4 Intersection Sight Distance

Intersection sight distance (ISD) is a fundamental geometric design performance metric for any intersection. Drivers on any portion of the intersection must have the visibility to see, perceive, and react to an event and avoid a collision. ISD is a contributing factor in street crashes and near collisions. As with any other intersection, DDI intersections should provide ISD. Drivers approaching or departing an intersection should have an unobstructed view of traffic control devices and sufficient length along the crossroad to safely navigate the intersection.

ISD, sometimes called "sight triangles," is the distance along a clear line of sight allowing a stopped driver from a minor approach to accept an appropriate gap in traffic when entering or crossing the major road. For a DDI, the minor approaches are the movements to and from the entrance and exit ramp terminals. ISD constraints will apply where stop- or yield-controlled movements are provided. ISD also applies to RTOR or left-turn-on-red (LTOR) at signalized

Exhibit 6-56. Example of supplemental signal (**14*****).***

Exhibit 6-57. Time gap, Case C2, left and right turn from minor approach (*11*).

Design Vehicle	Time Gap, t_g (s)
Passenger Car (PC)	8
Single-unit truck (SU)	10
Combination (Comb) truck	12

movements. As drivers cannot cross from the exit ramp to the entrance ramp (i.e., crossing the major road), only traffic on one direction of the major road is considered (*11*).

The AASHTO Green Book equation for calculating ISD is provided below (*11*).

$$ISD = (1.47)(V_{major})(t_g)$$

where

ISD = intersection sight distance, ft;
V_{major} = design speed of major road (mph); and
t_g = time gap for minor road vehicle to enter the major road(s).

The AASHTO Green Book Section 9.5.3 describes a variety of procedures to determine sight distances according to different types of traffic control (*11*). The exit ramp maneuvers represent a Case C (yield control on the minor road), maneuver 2 (left and right turns from the minor road). The left and right turns from the minor road are considered using different gap time requirements for each movement type; however, the exit ramp left turn only that conflicts with one direction of major street traffic is essentially the same as the right turn maneuver. Therefore, the requirements are the same as at a DDI. The time gap requirements based on the design vehicle are provided in Exhibit 6-57 (*11*).

Exhibit 6-58 presents ISD distance derived from the ISD equation using the time gap values for the three design vehicles. Calculations of ISD and SSD for each design vehicle are provided in Exhibit 6-59.

Exhibit 6-58. SSD and ISD calculations (Case C2) (*11*).

Design Speed (mph)	Stopping Sight Distance, SSD (ft)	Intersection Sight Distance, ISD (ft)		
		Passenger Cars (PC)	Single-Unit (SU) Truck	Combination (Comb) Truck
10	46	118	147	29
15	77	176	221	265
20	112	235	294	353
25	152	294	368	441
30	197	353	441	529
35	246	412	515	617
40	301	470	588	706
45	360	529	662	794

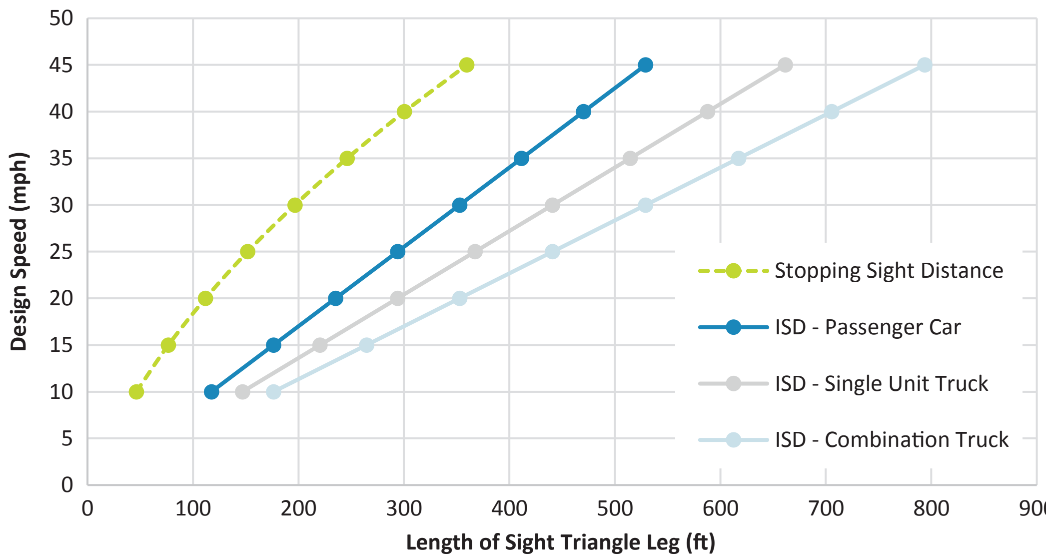

Exhibit 6-59. SSD and ISD for yield-controlled left and right turns (11).

RTOR or LTOR is an available traffic control strategy at a DDI ramp terminal intersection. Because of the curvilinear alignment to develop the crossovers, designers must work deliberately to configure left- and right-turning movements so that drivers have a view angle to upstream conflicting traffic. The view angle must be provided to the contraflow condition of the DDI, and this is different than typical driver expectations at a conventional interchange.

Target view angles should be 90 degrees and no less than 75 degrees to account for older drivers and pedestrians (*15*). The view angle can be defined as the angle between the alignment of the right-turning vehicle and the tangent of the crossover. The performance of the targeted view angle should also measure the angle between the alignment of the right-turning vehicle and the line drawn from the right-turning vehicle to the oncoming vehicle at the ISD. If the values are not acceptable, the ramp terminal intersection should be modified and optimized with other crossover features.

Exhibit 6-60 demonstrates how right-turn view angles can affect ISD. In this example, left- and right-turn movements have been modified to increase visibility to upstream conflicting

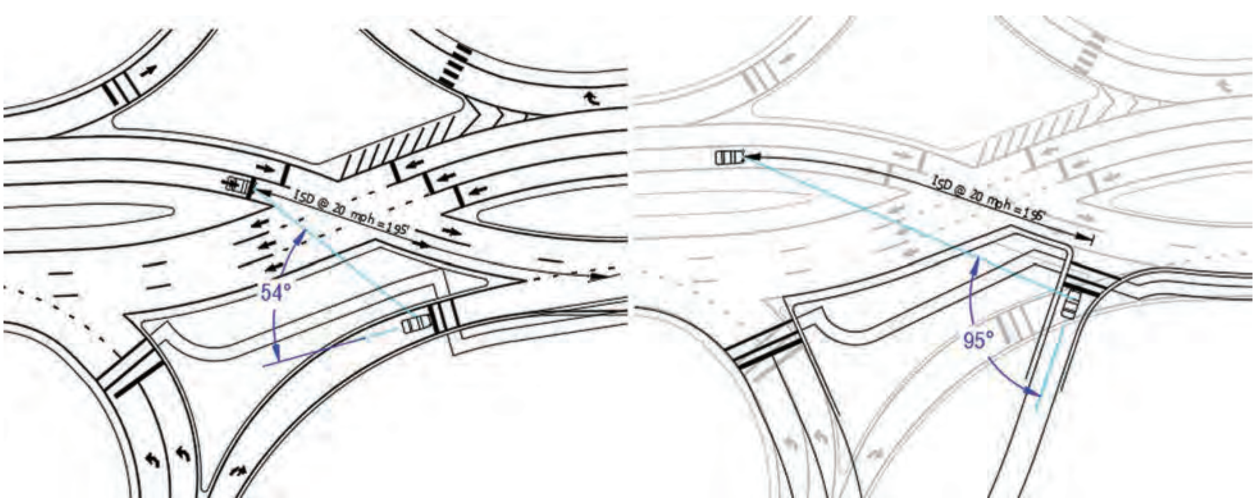

Exhibit 6-60. View angles and ISD.

traffic. Exhibit 6-60 demonstrates that consolidating the ramp terminal intersections so the left and right turns are approximately centered on the crossover intersection proper improves DDI performance. The following discussion supports performance checks for left- and right-turning vehicles.

RTOR or LTOR should not be allowed if ISD values to the correct direction of travel (oncoming contraflow) cannot be attained. The view angle influences sight line dimensions, and design checks are based on considering the view angle to the upstream conflicting traffic. Designers must evaluate left- and right-turn view angles, and LTOR or RTOR should only be allowed if ISD values are attained. Since ISD values are smaller as design speed is reduced on the major roadway, smaller radii and slower speeds from the crossovers are a way to attain sight distance. This is an example of how to use an iterative, performance-based approach to modify interchange geometrics to meet operational and safety performance objectives.

Median barrier between contraflow lanes between the crossovers can block driver sight lines. The barrier can truncate the needed line of sight even if the ramp terminal intersections have acceptable view angles. If median barriers are used, a performance check would be to verify the barrier does not impede ISD. To attain ISD, the end of the median barrier wall could be truncated or the wall height reduced to provide enough sight distance. If ISD values cannot be attained and speed on the crossroad cannot be reduced to meet ISD needs, RTOR should not be allowed.

Exhibit 6-61 demonstrates the lack of sight distance caused by median barrier walls along crossroads under and over a limited access facility.

6.7.2 DDI-Specific Performance Categories

DDIs include unique qualities and characteristics that can be evaluated to assess, evaluate, and compare alternatives. The following sections describe DDI-specific performance categories.

6.7.2.1 Speed-Radius Relationship

The relationship between horizontal curvature and travel speed is documented in the AASHTO Green Book. Typically, the equation is used to determine a curve radius given a specific superelevation rate. By using the equation, assuming a superelevation rate of ±0.02 and solving for speed, the predicted speed associated with minimum radii can be determined using the equations provided below (*11*).

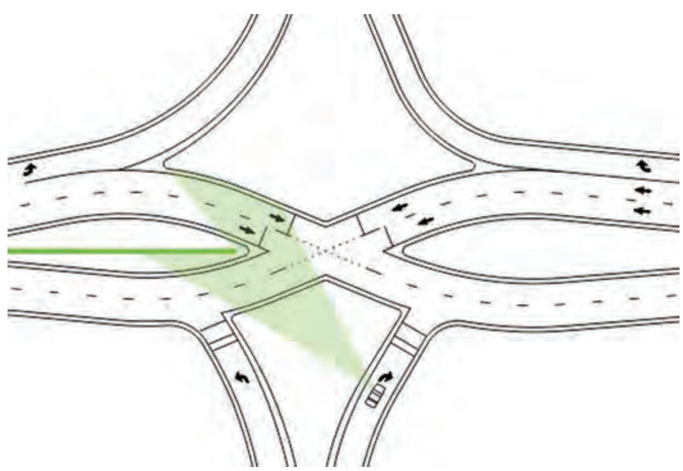

Exhibit 6-61. Median barriers blocking ISD for exit ramp right turns.

$$V = 3.4415R^{0.3861}, \textit{ for } e = +0.02$$

$$V = 3.4614R^{0.3673}, \textit{ for } e = -0.02$$

where

V = predicted speed, mph;
R = radius of curve, ft; and
e = superelevation, ft/ft.

Using the equations, the speed-radius relationships can be plotted to estimate speeds for a given radius and horizontal curve orientation (left or right) considering ±0.02 superelevation. This allows rapid assessments of predicted speed as various curve radii are being evaluated to transition to and through the DDI.

The DDI geometric influence area is a low speed environment, and superelevation beyond the normal or reverse crown is not necessary. Superelevation in speed transitions from the crossroad to the initial DDI transition alignment should be considered on a site-specific basis. The overall intent is to create a low speed environment, and superelevation should reflect transition needs approaching the DDI.

Speed reduction and smooth transition are goals in approaching a DDI. Considering crossroad speed (e.g., 45 mph) and approximate speed for the slowest horizontal curve (e.g., 25 mph), one can select an intermediate speed in the transition (e.g., 30 mph). In this example, the first curve radius in the transition could be approximately 300 feet.

This approach can be used to assess the performance of the transition speeds and radii approaching the DDI. Similarly, the speed-curve equation and graph can support performance evaluations to assess the speed transition needs between horizontal curves transitioning through the crossover. Exhibit 6-62 provides a quick reference for the speed-curve relationship for the superelevation rate (*12*).

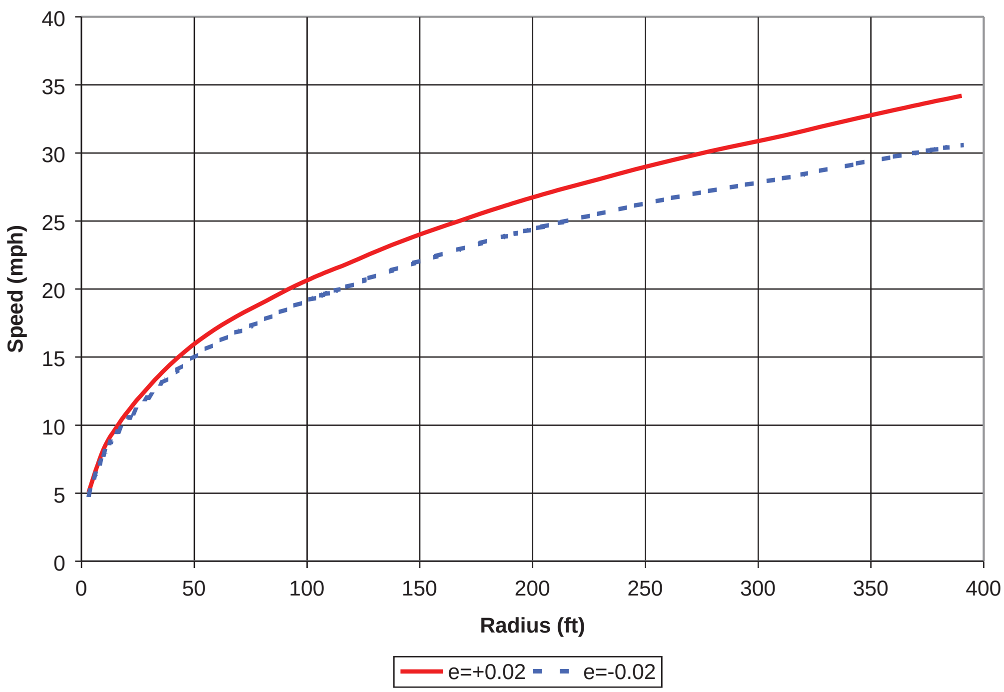

***Exhibit 6-62. Speed-curve relationship for superelevation rate* (12).**

6.7.2.2 Speed Profile and Speed Checks

Designers can use speed curvature relationships to create initial DDI concepts and then subsequently assess and refine the configurations.

- **Speed Profile:** The speed profile represents a holistic view of intended speed performance to and through a DDI. This concept can be used in at least three ways:
  1. To estimate speed relationships to and through the DDI and establish corresponding horizontal curve radii for the transition between the crossover and crossroad speed.
  2. To estimate the transition length to attain speed reductions between the crossroad and the crossover proper.
  3. To assess the specific horizontal curve radii and speed relationships of the crossover curves to meet the speed profile concepts.

Exhibit 6-63 presents a conceptual speed profile approaching a DDI and the change in anticipated operating speed relationship associated with the crossovers.

The transition distance between the crossroad speed and the crossover can be estimated using freeway exit ramp deceleration as a model. The AASHTO Green Book presents various deceleration distances between the exit speed and the ramp controlling curve. These distances can approximate the interchange's geometric influence area. In rural or urban areas where speed differentials may be substantial, the distances could guide the location of potential speed transition treatments (*11*).

Exhibit 6-64 presents deceleration/transition length considerations based on various crossroad and first crossover curve speeds.

- **Crossover Speed Checks:** Considering the speed profile in more detail, the lowest speeds should be between and through the crossover proper. Crossover target speeds typically range from 20 mph to 35 mph that correspond to horizontal curves with commensurate radii of 100 feet to 400 feet, respectively. This concept can be used at least two ways:
  1. To develop the initial horizontal alignment by selecting the horizontal curve radii that will result in the target speed profile relationship. This means selecting specific radii that will result in target speeds consistent with the transition from higher to lower speeds. Tangents should be provided between all horizontal curves unless there are no other design options.

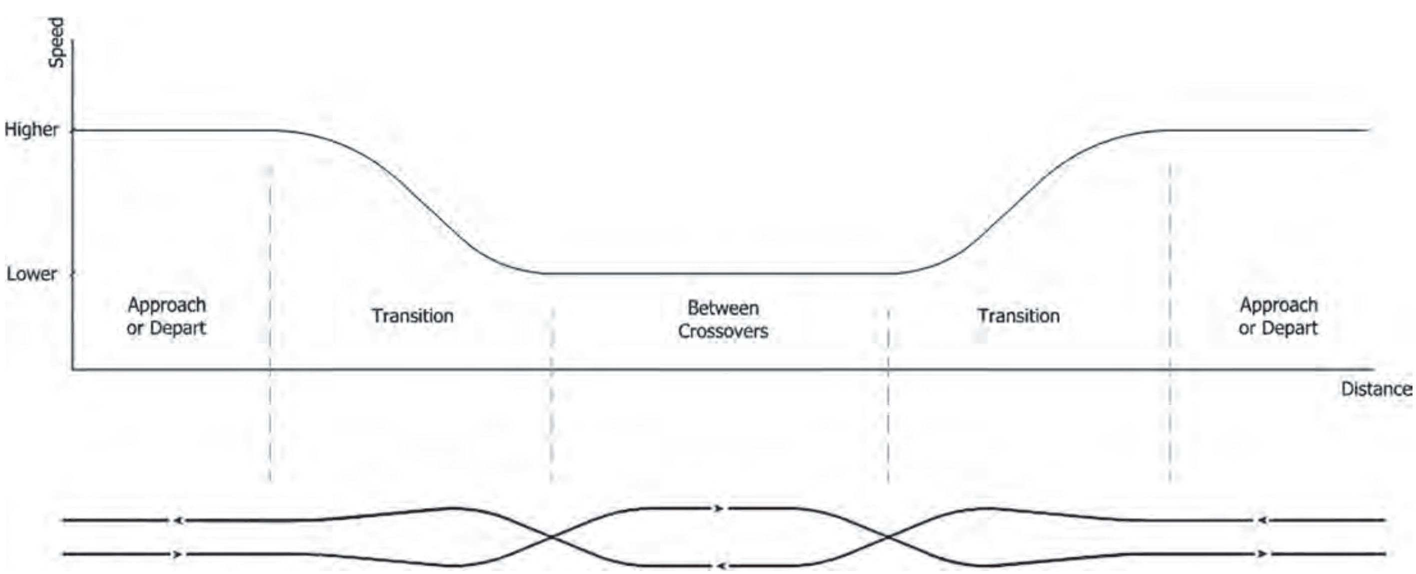

Exhibit 6-63. Conceptual speed profile approaching a DDI.

Exhibit 6-64. Deceleration/transition length considerations (*11*).

Deceleration/Transition Lengths (ft)					
		Crossroad Speed (mph)			
		65	55	45	35
First Crossover Curve Speed	45	490	340	--	--
	35	580	440	285	--
	30	620	470	316	185
	25	645	500	355	235

Exit ramp deceleration values adapted from AASHTO Green Book (*11*)

The design goal is a smooth and flowing alignment with proportionate curve lengths to avoid the appearance of kinks in the alignments.

2. To check the performance of the alignments as the DDI is refined and finalized. This could include reducing crossover speeds to attain ISD values as described previously or adapting the horizontal configurations to meet site constraints.

Exhibit 6-65 conceptually presents target design speed and horizontal curve radii relationships.

Speed consistency between the various movements and geometric elements at specific locations within the DDI is a primary DDI design goal. This means low speed differential between turning and through movements or converging travel streams. This also means low speed differentials between successive geometric design elements (i.e., curve 1 to curve 2 to curve 3 to curve 4, etc.) regardless of whether the profile speeds are decreasing or increasing.

Relative speeds between conflicting traffic streams and between consecutive geometric elements should be minimized such that the maximum speed differential between movements should

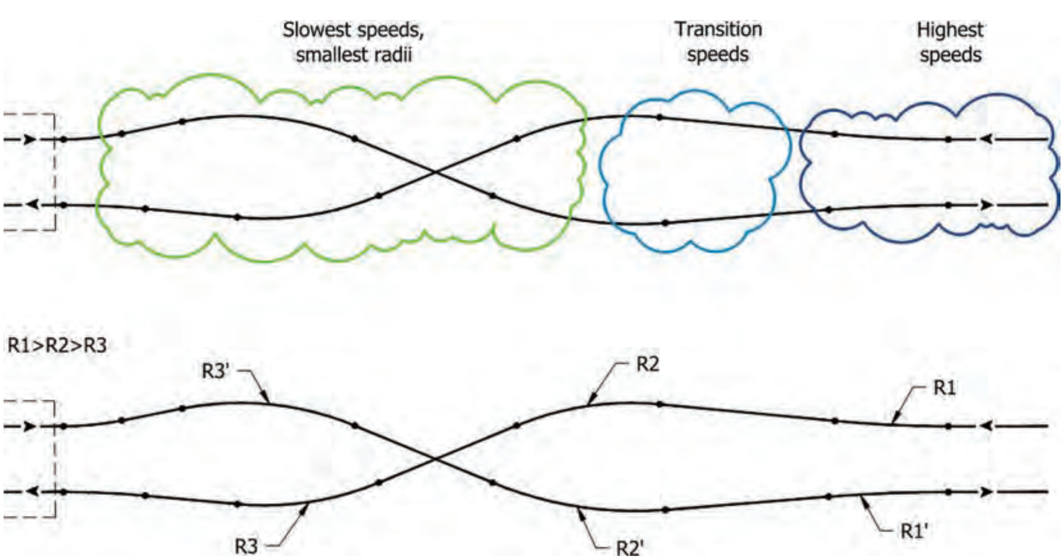

Exhibit 6-65. Target design speed and horizontal curve radii relationships.

be no more than approximately 10 to 15 mph (15 to 25 km/h) (*12*). As with other design elements, speed consistency should be balanced with other objectives in establishing a design. Conducting performance checks allows the user to optimize design and performance objectives for a given project context.

6.7.2.3 Approach Vista

Approach vista describes how much of the conflicting movement is within a direct path for a driver approaching the crossover. The crossover geometry and islands can help discourage wrong-way movements into the conflicting approach. Exhibit 6-66 shows example geometry and corresponding approach vistas for the left through lane side. The goal would be to create a terminal vista to opposing, contraflow lanes.

The entrance ramp terminal intersection may include features that fully block, partially block, or do not block direct views to the conflicting movement. Some transportation agencies use barriers at the ramp terminal intersection islands to obstruct views to the contraflow lanes. This application is called an "eyebrow" by some agencies. Creating a terminal vista allows drivers approaching the approach vista to focus on the immediate roadway and transition alignment to the crossover. Minimizing a direct view of the contraflow lane should begin in early concept development.

A terminal vista can generally be achieved as an outcome of designing an adequate tangent length and crossover angle for the crossover intersection. As configurations are refined and advanced, the approach vista should be revisited along with these other performance categories.

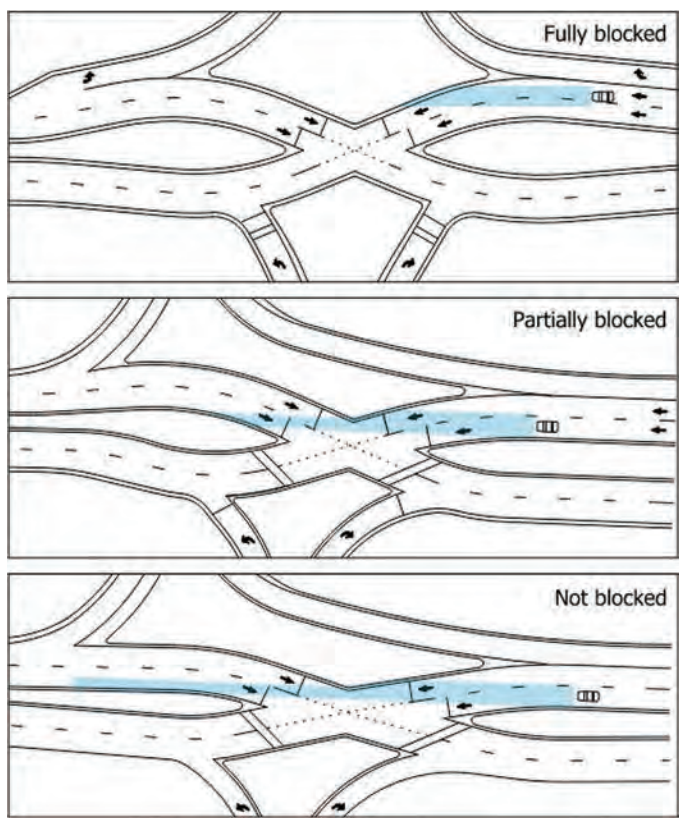

Exhibit 6-66. Three examples of terminal vistas.

Exhibit 6-67. Approach vista at a DDI (Reno, Nevada) (9).

Exhibit 6-66 presents three examples of terminal vistas where the terminal vista is fully blocked, partially blocked, or not blocked.

Exhibit 6-67 presents an example of an approach vista at a DDI. The traffic island at the ramp terminal intersection provides full blockage to the contraflow travel lanes. However, with no vertical features, there are unimpeded sight lines through the traffic island. A traffic barrier can be used to specifically block lines of sight through the traffic island.

Exhibit 6-68 depicts the application of a barrier placed on a traffic island to impede driver sight lines.

Exhibit 6-69 presents a range of examples of barriers and traffic islands to reduce sight lines. Approach vista is most critical approaching a DDI since driver approach speeds are typically higher and drivers are adapting to the change of workload and driving navigation tasks compared to the crossroad. However, approach vista can apply between crossovers. While entry sight lines are most critical at the transition into the DDI, sight line considerations apply between crossovers from the contraflow lanes.

Exhibit 6-70 presents the approach vista from the contraflow lanes to the crossroad approach departing the DDI. Visually, there is a large disparity between the driver's forward view directly

Exhibit 6-68. Barrier application to impede driver sight lines (9).

Exhibit 6-69. Examples of barriers and traffic islands to reduce sight lines (3).

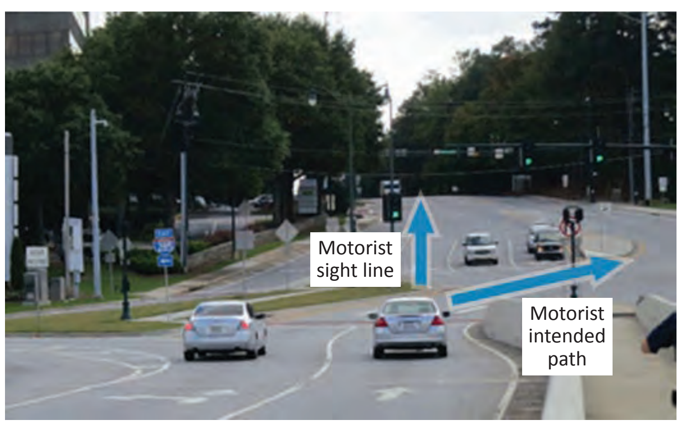

Exhibit 6-70. Approach vista from the contraflow lanes to the crossroad approach (Atlanta, Georgia) (6).

ahead versus the path they must navigate to the right. The exhibit shows the motorist sight line focuses on the oncoming traffic stream while the actual path needed to navigate the crossover is out of sight to the far right.

6.7.2.4 Path Alignment

Desired path alignment at crossovers is based on geometric alignments that direct vehicles to the receiving lanes. It is the geometrics that should provide the most dominant guidance, while striping and lane extension markings in the crossover intersection proper complement the foundational horizontal alignment feature.

If used, reverse curves between crossovers should include enough tangent length between curves to provide a direct alignment. A lack of tangents between reverse curves or indirect path alignments can lead to vehicle path overlap, or even worse, inadvertently guide motorists into opposing traffic. Path alignment supports lane discipline for tractor trailer vehicles, and the trailer can track behind the cab in the tangent section.

Through drivers do not expect to make alignment changes when passing through an intersection. Curve radii in the middle of the crossover movements place the point of curvature or tangent in the intersection where drivers do not typically turn. Back-to-back reverse curves with no tangent compound the violation of driver expectation. This is especially true for vehicles at rest behind the stop bar waiting for a green light when drivers need to continue to the left before the impending right-hand curve to maintain lane discipline.

Exhibit 6-71 shows the orientation of vehicles at a stop bar waiting for a green indication. Each vehicle is not directed to the receiving lane beyond the crossover and must navigate back-to-back reverse curves through the intersection. This creates the potential for lane departures or deceleration in the through movement (on green) as drivers slow to maintain lane discipline. Path alignment issues are easy to observe in the earliest concept development. This exhibit demonstrates the value of applying tangent sections at crossovers and between reverse curves.

Path alignment can be checked by assessing the forward alignment and vehicle path at the stop bar. Path alignment should be integral to early concepts, and the alignment should be evaluated as concepts are refined and advanced. Path alignment can be measured by drawing

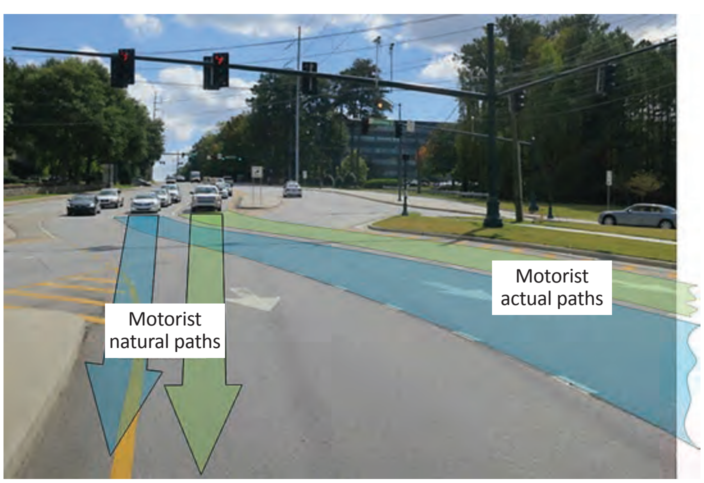

Exhibit 6-71. Orientation of vehicles at the stop bar (6).

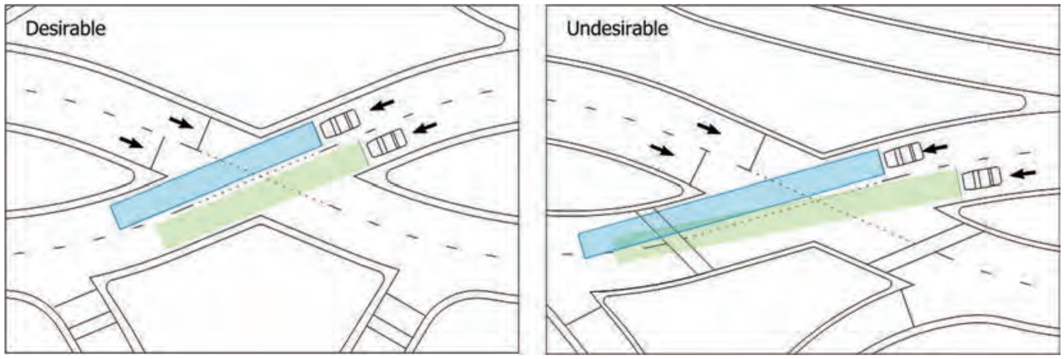

Exhibit 6-72. Vehicle paths through a crossover.

a perpendicular line extending from the center of the stop bar to determine the line representing ideal path alignment. This represents the direction to which a driver is oriented when stopped at or proceeding through the intersection. This may be different than the curvilinear alignment provided to navigate the crossover; that line can be projected to assess the natural path.

The natural path checks can include comparing the identifying angle between the crossover tangent and the natural path of a vehicle stopped at the stop bar. The angle measured from this ideal path alignment line and the crossover tangent line represents how much the natural path of the geometry will guide drivers into other lanes. With ideal path alignment, there is no angle between these two lines. Alternative configurations can be compared to those with no path overlap ranking higher than those with measurable angles.

Providing tangents and eliminating path overlap support freight movements through the DDI. Exhibit 6-72 and Exhibit 6-73 show vehicle paths through a crossover. Tangents and path alignment help support lane discipline for tractor trailer vehicles, as shown in Exhibit 6-73.

Crossover intersections should be designed so that a driver can proceed straight from the stop bar (i.e., not turn the steering wheel) and reach the receiving lane downstream of the crossover rather than an adjacent lane. Exhibit 6-74 shows a DDI where the vehicle paths

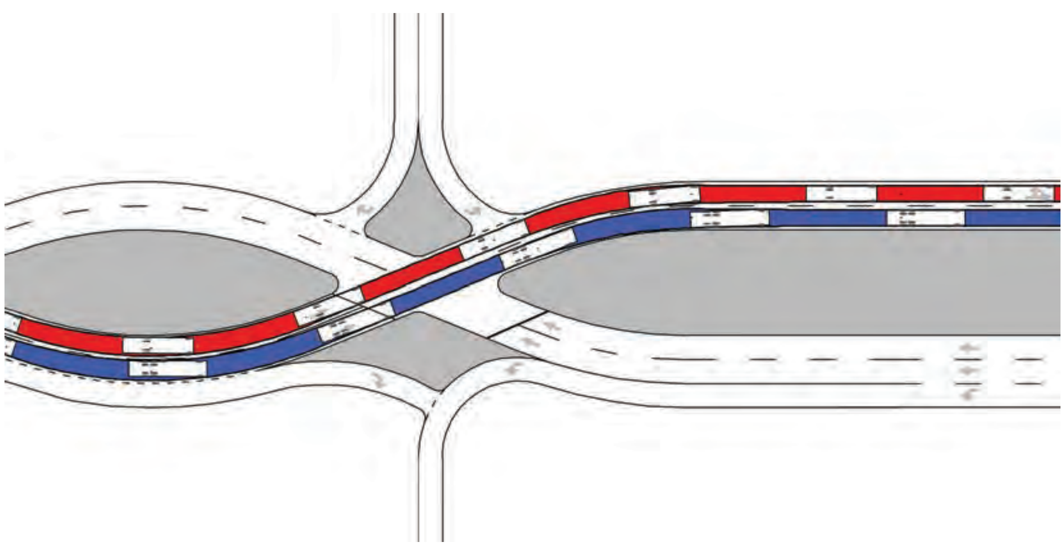

Exhibit 6-73. Truck paths through a crossover.

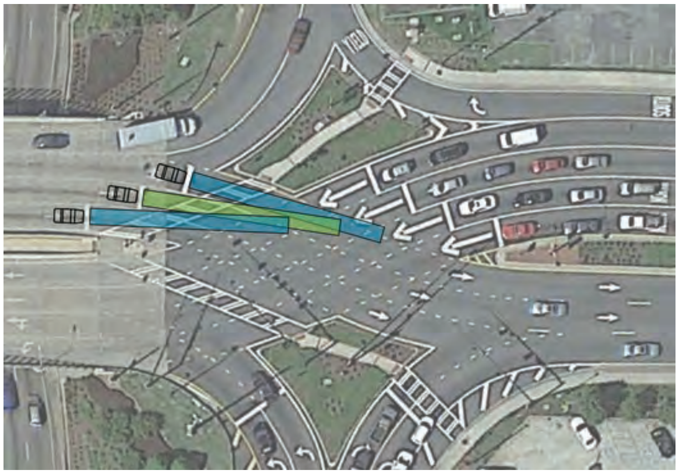

Exhibit 6-74. Crossover intersection with path overlap (3).

overlap. A similar issue can exist at multilane roundabout entries, and research at roundabouts found that entries with path overlap experienced a higher rate of sideswipe crashes than entries with proper path alignment (*12*).

6.7.2.5 Vista Through Crossover

Vista through crossover helps describe the amount of the continued roadway that a driver can see to enforce the crossover and discourage wrong-way movements. Exhibit 6-75 depicts the vista through the crossover. The more drivers can see of the roadway before them, the more prepared they are in their navigation tasks. Vista through the crossover can help drivers see potential downstream queues and other roadway features.

The nominal length of the vista through crossover is measured by drawing a line tangent to the center of the outermost approach lane line and the edge of traveled way and extending the line to the view to the edge of the roadway. Median width between crossovers has a direct influence on the available distance provided. Wider medians provide longer vistas.

In comparing geometric configurations or refining DDI geometric features, those that maximize vista through the crossover in balance with other performance metrics should

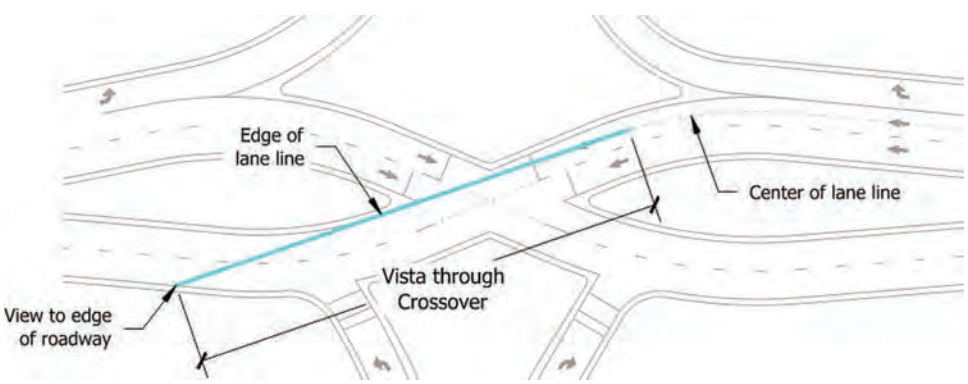

Exhibit 6-75. Vista through crossover.

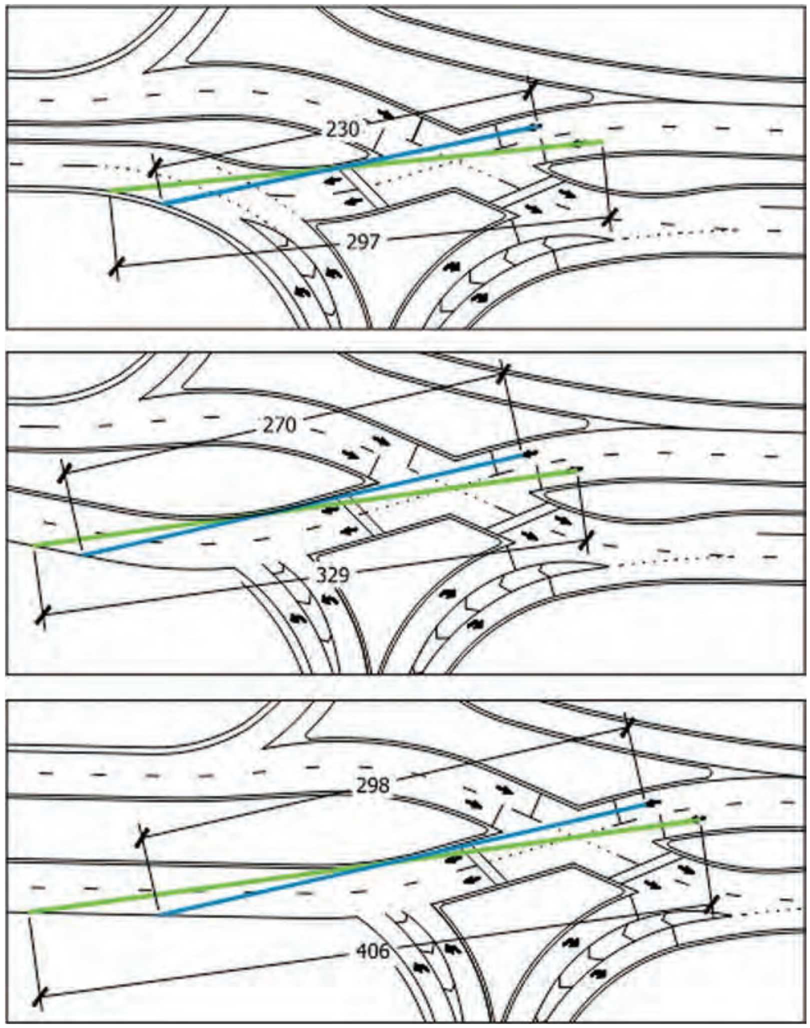

Exhibit 6-76. Median effects of vista through crossover.

rate higher than configurations with shorter vistas. Exhibit 6-76 presents three DDI configurations with various median shapes and widths as might be expected in developing and refining a DDI for a given location. Those forms with wider medians provide longer vistas through the crossover.

6.8 References

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CHAPTER 7

Traffic Control Devices and Illumination Applications

This chapter provides guidance on the use and installation of traffic control devices at a diverging diamond interchange (DDI) to inform, guide, and control various traffic modes such as motorists, pedestrians, and bicycles. Details are provided on various elements of signing, pavement marking, traffic control signals, and lighting. Where appropriate, several key issues that may arise during the design of traffic control plans are discussed, as well as the trade-offs and any potential solutions that could be considered to mitigate challenges that arise.

The *Manual on Uniform Traffic Control Devices* (MUTCD) remains the primary source for guidance and standards related to traffic control devices (*1*). This chapter is intended to augment and interpret existing MUTCD language for application to DDIs. The MUTCD (or its state-level equivalent) should be the primary source for traffic control device guidance, with this chapter providing supplemental information related to the DDI.

7.1 Traffic Control Device Design Principles and Approach

The key objective for the application of traffic control devices—signing, pavement markings, and signalization—is to provide guidance to drivers, pedestrians, and bicyclists on how to act and how to travel through an intersection or interchange. The use of consistent and clear traffic control devices enhances driver understanding and expectancy of the interchange they are about to traverse. With the unique geometric configuration of the DDI, traffic control devices need to be applied and implemented carefully to assure that drivers understand what behavior is expected from them.

In applying traffic control devices to a DDI, there are four primary objectives and messages that are conveyed to motorists and other travel modes:

1. **Priority** describes which movement has the right-of-way (ROW) at a crossing or conflict point. Priority is controlled through signalization or regulatory signage (e.g., a yield sign), as well as supplemented with pavement markings where appropriate (e.g., a stop line). If necessary, advanced warning signs may be geared at informing drivers of an upcoming conflict point and priority control.
2. **Directional guidance** informs drivers about upcoming turning movements and reduces the likelihood of movements against the intended direction of traffic (i.e., at the crossover). Directional guidance is provided through signing and pavement markings.
3. **Lane choice** communicates to drivers which lane to choose and pre-positions them to complete a specific movement such as the left turn onto the freeway. The lane choice at a DDI generally follows driver expectations to where the driver chooses the right lane to turn right and the left lane to turn left (as opposed to, for example, a cloverleaf interchange where a driver turns right to go left). Lane choice is communicated through signing and especially pavement marking.

4. **Information** about other aspects of the interchange and surrounding area is provided mostly through signage. Informational signs are not necessary at a DDI and can contribute to the visual clutter that distracts drivers from other necessary information.

This section covers traffic control device applications that are distinctive to DDIs but does not intend to be comprehensive for all possible signs and pavement markings. Proper signing, pavement marking, and signalization can be an effective aid in moving drivers through the DDI correctly. Errors can cause driver confusion, so careful attention should be paid when designing the traffic control devices for DDIs. Agencies should consult the MUTCD for further details related to placement and installation of traffic control devices (*1*).

7.2 Regulatory and Warning Signs

Regulatory signs are traffic signs intended to instruct road users on what they must or should do (or not do) under a given set of circumstances. The signs covered in this section include:

- Movement prohibition and lane control signs (R3 series);
- Signs for marking directionality around islands (R4 series); and
- "Do Not Enter," "Wrong Way," and "One Way" signs (R5 and R6 series).

7.2.1 Movement Prohibition and Lane Control Signs

Exhibit 7-1 shows the lane control signing options used at signal-controlled movements. Crossover movements consistently used "Thru Only" (R3-5A) signs. Further discussion of options for traffic control signal display is given in Section 7.5.3.

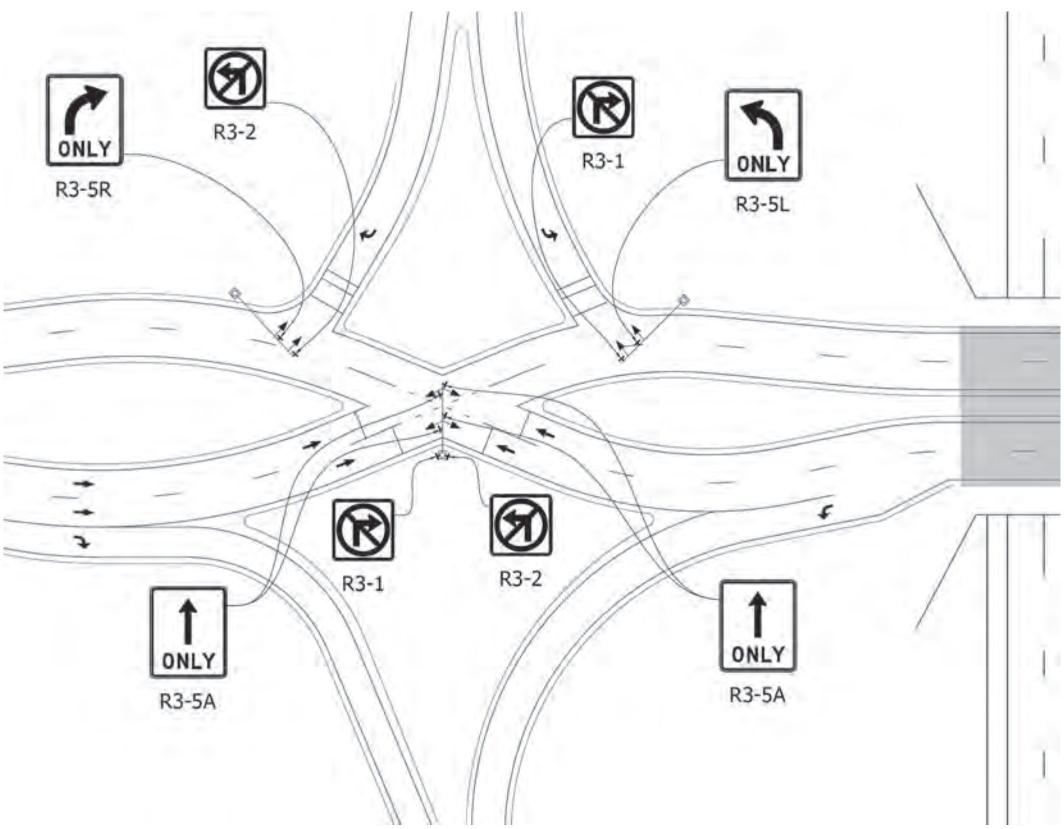


Exhibit 7-1. Lane control signing for signalized movements.

The combination "No Left Turn" and "No Right Turn" sign assembly at the crossover is consistently used at DDIs, as shown in Exhibit 7-2. The use of "No Left Turn" and "No Right Turn" signs at ramps has increased since the first DDIs opened in Missouri. Exhibit 7-2 shows yield-controlled off-ramps, but "No Left Turn" and "No Right Turn" signs are also used where off-ramp movements are signalized. Exhibit 7-3 shows a variation in which the signs at the crossover signal are mounted overhead.

"One Way" signs are sometimes used at ramp merge and diverge locations (as shown in MUTCD Figure 2B-18) if ramp entry angles are such that a vehicle might be likely to make a wrong-way movement. Good geometric design should minimize the need for these supplemental signs.

Some DDIs have also used "Do Not Enter" signs to supplement the "No Right Turn" and "No Left Turn" signs and "Stay Left "and "Stay Right" signs installed at the crossovers. "Wrong Way" signs can also be installed to supplement "Do Not Enter" signs related to the crossovers and exit ramps as shown in Exhibit 7-4. In some instances, the "Do Not Enter" sign was installed with a "One Way" sign at the exit ramp left turn. Per the MUTCD, "Wrong Way" signs are supplemental to "Do Not Enter" signs.

7.2.2 Signs for Directing Traffic Around Islands

The use of divisional islands through a DDI creates the importance of using correct signage to mark the correct path for oncoming drivers. The key signs for this purpose—"Keep Right" and "Keep Left" regulatory signs and double arrow warning signs—are shown in Exhibit 7-5.

At DDI crossovers, "Keep Right" (R4-7) and "Keep Left" (R4-8) signs are used to direct drivers to the correct receiving side of the divisional island. At the first crossover, the "Keep Left" sign

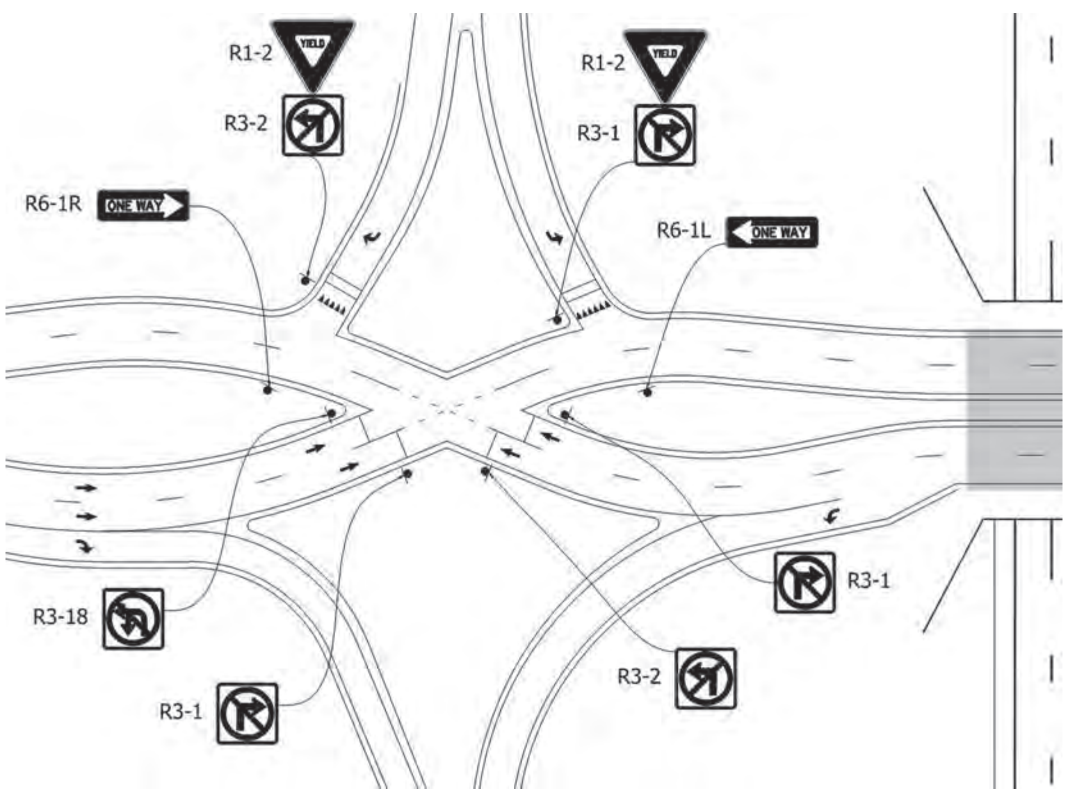


Exhibit 7-2. General use of "No Left Turn," "No Right Turn," and "One Way" signs.

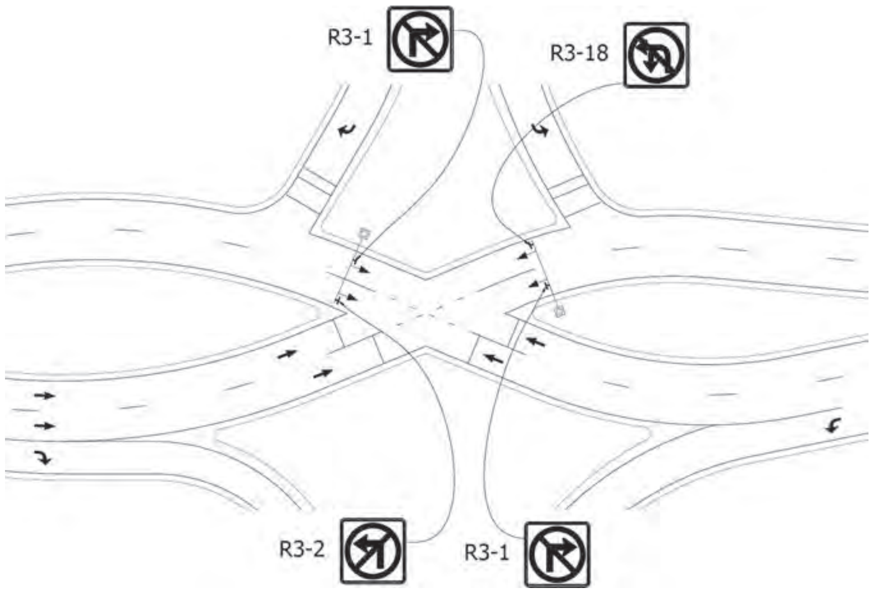


Exhibit 7-3. Overhead application of "No Left Turn" and "No Right Turn" signs.

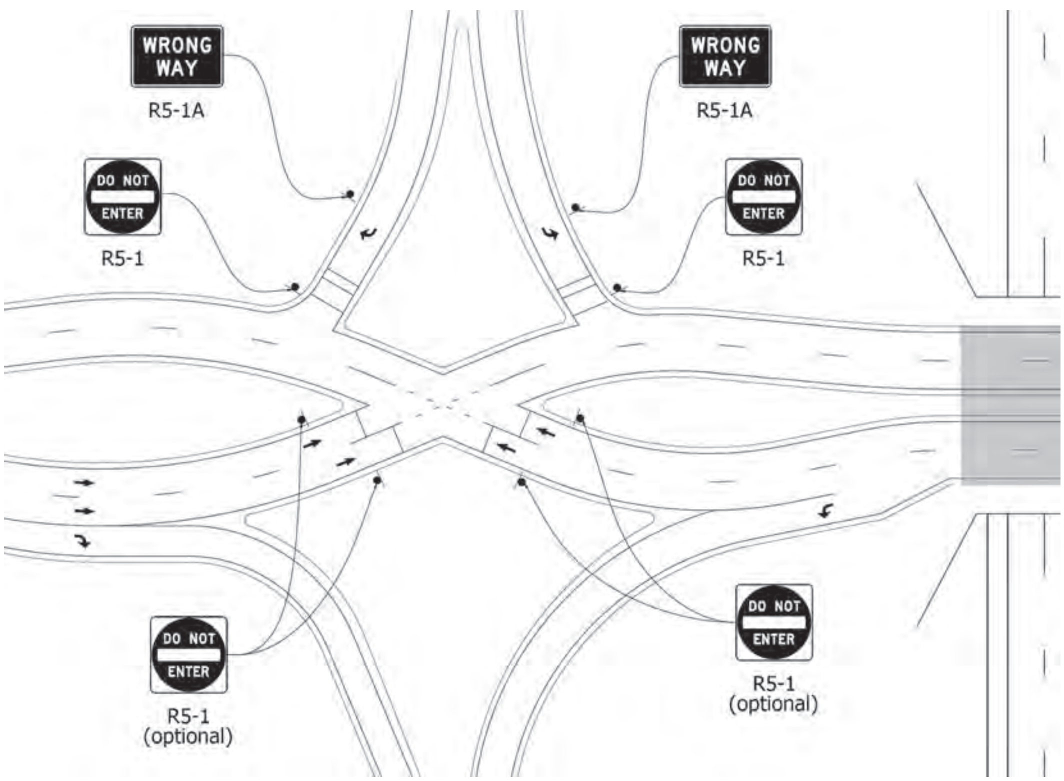


Exhibit 7-4. "Do Not Enter" and "Wrong Way" signs.

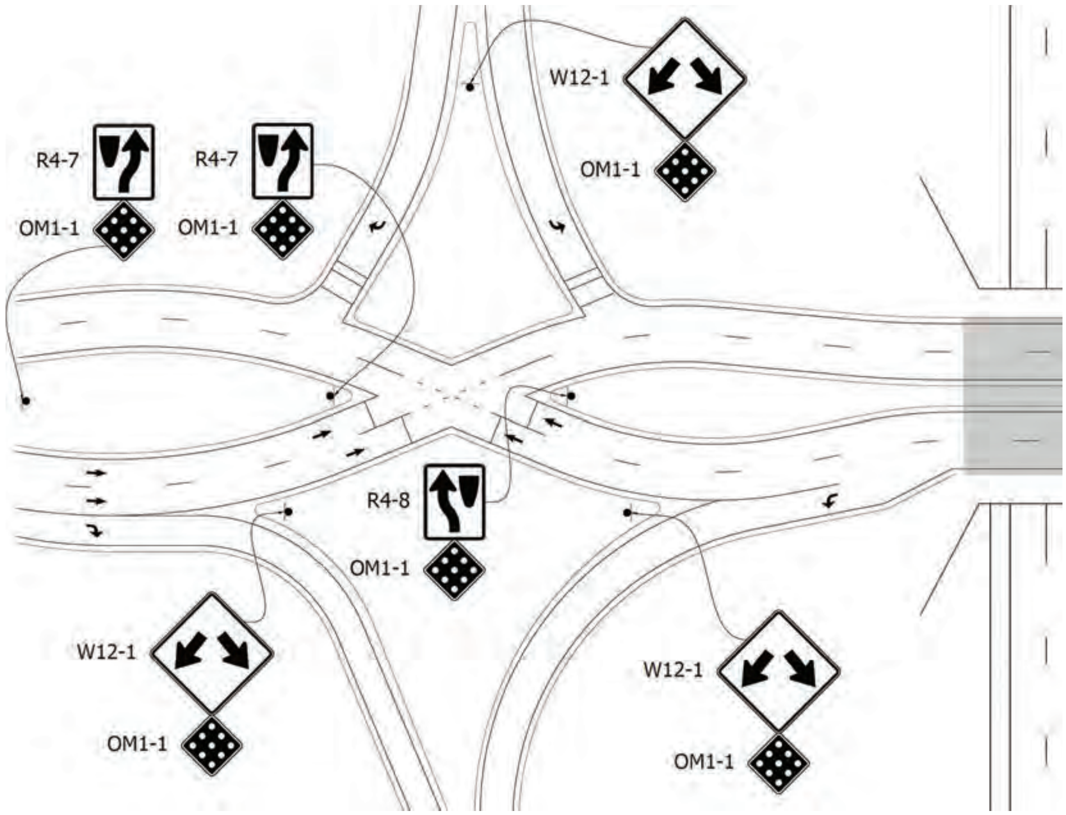


Exhibit 7-5. Signs for directing traffic around islands.

is used to direct drivers to the left side of the DDI; at the second crossover, the "Keep Right" sign is used to direct drivers back to the right side. A "Keep Right" sign may also be appropriate if the approaching roadway to the DDI is undivided and an island is added to create the DDI geometry.

For locations where a single path of traffic is split into two streams by a divisional island, the double arrow warning sign (W12-1) is used. These commonly occur in three locations on each side of a DDI:

- On the off-ramp from the freeway where the off-ramp splits into separate left-turn and right-turn lanes,
- Between the crossovers where the on-ramp diverges to the left from the arterial street, and
- In advance of the crossover where the off-ramp diverges to the right from the arterial street.

For all three signs, object marker signs can be used to supplement the governing regulatory or warning sign.

7.2.3 Advance Warning Signs

Warning signs call attention to conditions on or adjacent to a highway or street. These signs are used particularly when the condition is not obvious or cannot be seen by the motorist. The signs covered in this section include:

- Advance traffic control—Yield Ahead (W3-2) and Advance Signal Ahead (W3-3).
- Reverse Curve Ahead (W1-4).

Yield Ahead warning signs are consistently used for yield-controlled movements. Some DDIs use Advance Signal Ahead signs, and one known site uses the Reverse Curve Ahead sign.

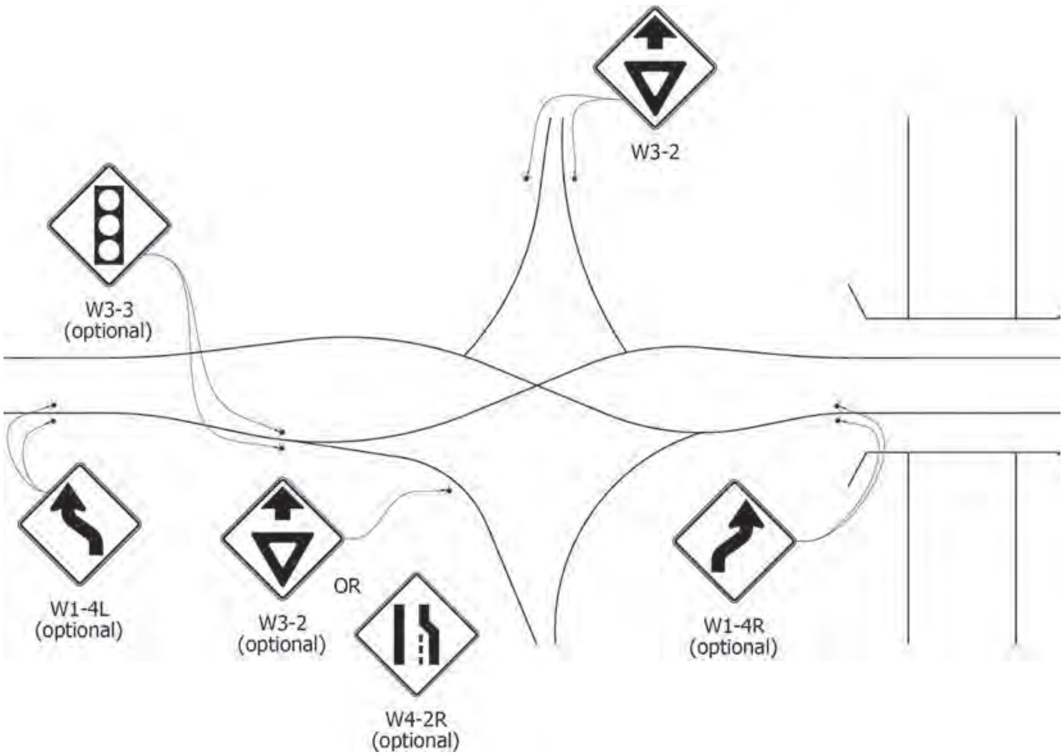


Exhibit 7-6. Advance Warning signs.

These signs are shown in Exhibit 7-6. Exhibit 7-6 assumes ramp terminals are yield-controlled, but if they are signalized Advance Signal Ahead signs could be placed on the off-ramp.

7.3 Guide Signs

Guide signs show route, street or city designations, directions, distances, services, and more. Guide signs, when used, should be located where they can be read from a proper distance to allow drivers to make safe driving decisions prior to entering the DDI. The specifics of guide sign types are not covered in this section. Instead, guide signs used along the vehicle routes from the crossroad to the limited access facility are provided, as their installation techniques and locations are unique at various sites. Overhead, lane use control sign installation techniques are also covered.

The MUTCD provides examples of guide signs that can be used at a diamond interchange with multilane approaches. These are adapted for use at a DDI as illustrated in Exhibit 7-7. The figure shows a sequence of five guide signs, labeled A through E, as follows:

- Location A, Junction Assembly—This sign is located well upstream of the DDI and is the same used at a conventional diamond interchange.
- Location B, Advance Entrance Direction signs for both freeway directions—These signs are located next in sequence and are also the same as used at a conventional diamond interchange.
- Location C, Entrance Direction sign for the first ramp—This sign is located just prior to the first crossover, where drivers must decide to take a right onto the exit ramp or continue through the crossover. Ideally, the signage provides information to drivers upstream of any queues to allow for good lane discipline through the DDI. Signage is usually provided overhead using a gantry or mast arm system; in some locations, signage is ground-mounted signage.
- Location D, Advance Turn Assembly—This sign is located just past the first crossover. The signs are most often ground-mounted where the crossroad passes over the freeway and

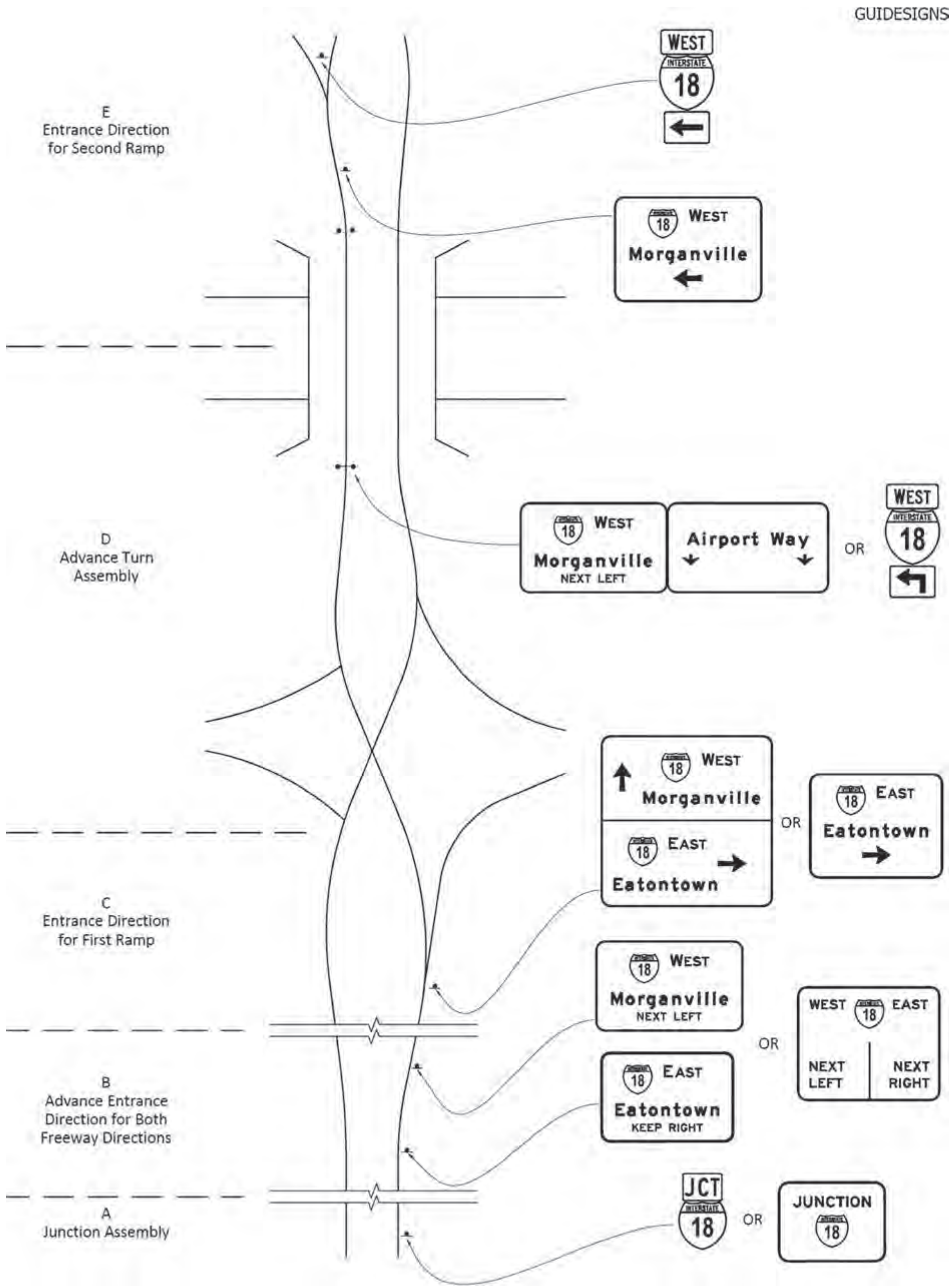


Exhibit 7-7. Typical guide sign sequence.

overhead where the crossroad passes under the freeway. The signs remind drivers about the lane assignments for merging onto the freeway, and in some cases, signage is provided for through movements as well.

- Location E, the Entrance Direction sign for the second ramp provides guide signs at the ramp diverge point—These signs remind drivers where the left-turn movement onto the freeway takes place.

7.4 Pavement Markings

In general, striping for a DDI should be standardized to maintain consistency and efficiency. Typical pavement markings for DDIs delineate the vehicle entry and exit approaches of ramps and crossovers and provide direction for bicycle and pedestrian movements when in the pavement ROW. This section discusses the application of pavement markings in the interchange influence area that are unique and may vary between sites constructed at this time.

7.4.1 Centerlines and Edge Lines

Travel on the left side of the road at a DDI creates an unusual situation for the application of longitudinal pavement markings. The MUTCD, which not does explicitly address DDIs, states that white line markings shall delineate the separation of traffic flows in the same direction or the right-hand edge of the street, and yellow line markings shall delineate the separation of traffic traveling in the opposite direction or the left-hand edge of the streets of divided highways and one-way streets or ramps. The pavement marking designs employed along the crossed-over sections of streets are quite different across states and even within states, in some cases. A pavement marking design example is provided in Exhibit 7-8 based on practices to date. This example does not reflect a standard.

The traffic driving on the left side of the road is unique to the DDI (shown in blue). At most DDIs, yellow lines have been used on the left side of travel lanes in these areas, and white lines have been used on the right side of travel lanes, as if each direction of travel is a one-way street. However, if treated as a single, two-way facility, this configuration places white, rather than yellow, lines between the two (wrong-way) directions of travel. The channelizing turn islands have three gore locations, each where a merge or diverge occurs. Most agencies choose to change pavement marking color at the gore point, as shown in Exhibit 7-8; however, some agencies have chosen to transition white pavement marking on both sides of the gore for several feet.

7.4.2 Lane Lines

As per the MUTCD, lane lines should be used at multilane approaches. For DDIs, solid lane lines are recommended to discourage lane changing in the immediate vicinity of the crossover and ramp terminal approaches, as shown in Exhibit 7-9.

There are several benefits to providing solid lane lines, including:

- Reducing the likelihood of side-swipe crashes due to last minute lane changes at an approach; and
- Discouraging lane changing immediately before crosswalks, which reduces the likelihood of multiple threat crashes between vehicles and pedestrians.

Solid lane lines may also be used on the cross street at the crossover departures. These would extend through crossover curves but not to any merge or departure maneuvers at the entry and exit ramps. The addition of solid lane lines at the departure with solid lines

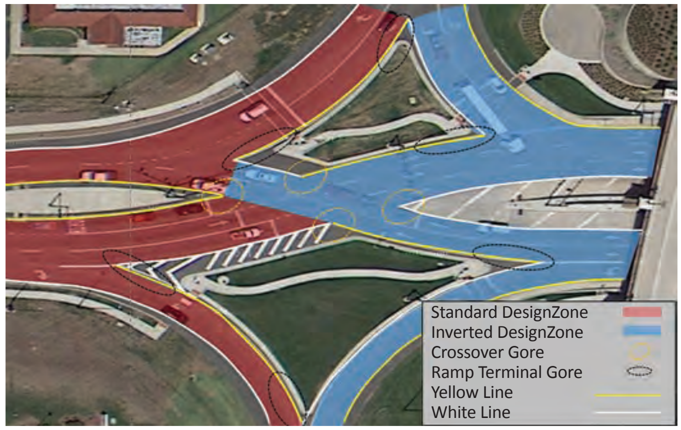


Image Source Adapted

Exhibit 7-8. Example centerline and edge line pavement markings at a DDI (2).

at the approach can discourage drivers from cutting across multiple lanes to obtain a faster path through the reverse curves of the intersection crossover.

Lane line extensions can be helpful for directing turning and crossover vehicles. Exhibit 7-9 presents lane line extensions used in the crossover to show the alignment to receiving lanes, similar to those used at many conventional intersection configurations. The aerial view shows line extensions along the outer portion of the outermost lanes in the crossover, which is not always used in design, but is recommended to provide additional channelization. Another potential location for line extensions is for dual left-turn lanes from the exit ramp, also shown in Exhibit 7-9.

Another marking treatment used prior to diverges is the dotted lane line. At DDIs, this is sometimes used to delineate an exclusive left-turn lane onto the limited access facility, as shown in Exhibit 7-10.

White channelizing lines are often used at exit and entry ramp movements with multiple lanes. Many agencies use channelizing islands, called "vane islands," to create painted islands between multiple entry lanes of a single approach. These painted islands are thought to provide additional deflection for passenger cars while accommodating the swept paths of trucks. The vane islands typically use chevron markings in the neutral area of the island. An example is provided in Exhibit 7-11.

Exhibit 7-9. Lane line markings at crossover and ramp terminal approaches (2).

Exhibit 7-10. Use of dotted lines to delineate an exclusive left-turn lane onto a limited access facility (2).

7.4.3 Lane Use Arrows

Lane use arrows, along with intersection lane control signs, provide the best opportunity to guide motorists correctly through the interchange. Standard lane use arrows should be used on each lane approaching each component intersection of the interchange, as these also provide a visual cue against wrong-way movements.

For the signalized crossover intersections, the most basic use of through pavement arrows is a standard lane use arrow as shown in Part A of Exhibit 7-12. An extension of this pavement marking use provides another standard lane use arrow in the receiving lane to provide additional guidance, as is shown in Part B. Another less frequently used option is a wrong-way arrow at the entry approach with a standard lane use arrow in the downstream receiving lane, as shown in Part C. There is no research available at the time of this writing to determine whether there is a measurable difference in performance among these methods.

7.4.4 Stop and Yield Lines

For DDIs, stop lines are used at signalized intersection approaches of crossovers and ramps and at stop-controlled exit and entry ramp movements. For unsignalized exit and entry ramp movements without dedicated receiving lanes, yield lines are used if the unsignalized movement is yield-controlled (the more typical application), and stop lines are used if the unsignalized movement is stop-controlled. The stop and yield lines define where vehicles should stop in response to the signal or regulatory sign. For multilane approaches, stop lines should be staggered, especially at ramp terminals with right-turn-on-red (RTOR) or left-turn-on-red (LTOR) operations to allow drivers to see past the vehicle in the inside lane of a multilane approach. An example of the application of staggered stop bars at a DDI is given in Exhibit 7-13.

Exhibit 7-11. Channelizing lines and vane islands at the exit ramp (2).

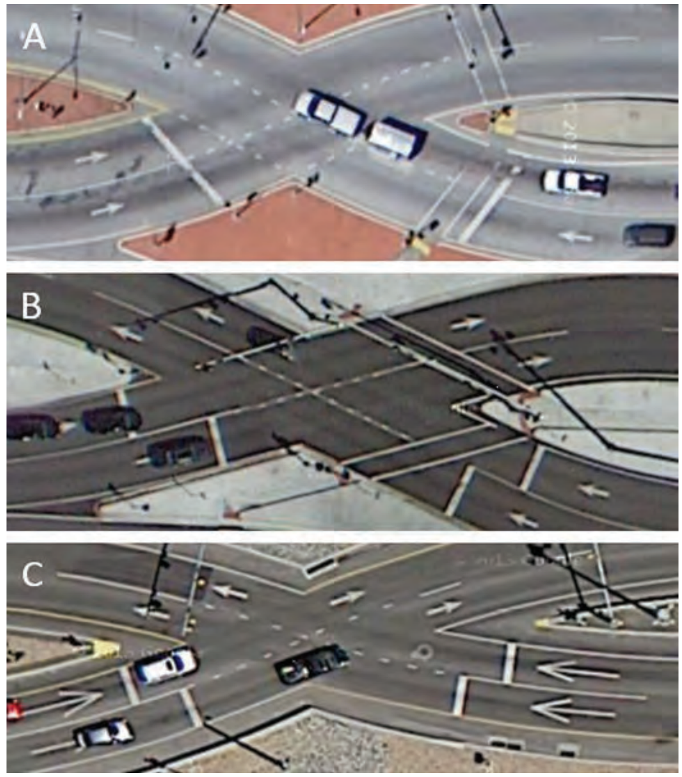


Image Source Adapted

Exhibit 7-12. Three variations of lane use arrows at the crossover intersection (2).

7.4.5 Pedestrian Crosswalk Markings

Pedestrian crosswalk markings should be installed at all pedestrian crossing locations. Crosswalk markings provide guidance to pedestrians who are navigating a DDI while also providing a visual cue to drivers of where pedestrians may be present in the street.

7.4.6 Bicycle Lanes

Guidance on the placement of bicycle lanes is provided in Chapter 3. In general, DDIs do not have unique requirements for bicycle pavement markings. Where lane line extensions are

Exhibit 7-13. Staggered stop bar locations at the intersection crossover and exit ramp terminal (2).

used to provide additional guidance through intersections for motorized vehicles, similar bicycle lane line extensions should be used to provide similar additional guidance for bicyclists.

7.5 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.

7.5.1 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 7-14 details trade-offs to consider when choosing whether to use one or two controllers.

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 trade-offs 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. Crossovers spaced closer

Exhibit 7-14. 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 (–).

together 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.

7.5.1.1 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 toward the other too soon. Use of pre-timed operations may be required to prevent early return to green; for more information, reference the section on pre-timed 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.

7.5.1.2 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.

7.5.1.3 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.

7.5.2 Signal Cabinet Details

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 and where to locate the cabinet(s).

7.5.2.1 Cabinet Equipment

Signal cabinets come in standard sizes, so there are 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 an electromechanical 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 and technicians should consider cabinet limitations prior to deciding between one and two controllers.

7.5.2.2 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 where it 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. 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 ROW so no easements or additional ROW acquisition would be required of adjacent property owners. For a DDI with only one controller, either crossover location is permissible. Exhibit 7-15 is a picture of a cabinet in this area, and Exhibit 7-16 is a graphic showing both possible locations at a DDI in this area.

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 ROW or easement (shown as an alternative location in Exhibit 7-16) and put a technician further away from being able to see all movements, but it will not impede the vision of motorists.

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.

Source: North Carolina State University

Exhibit 7-15. Signal cabinet located in a landscaped median with good visibility.

7.5.3 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 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 ROW 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.

7.5.3.1 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

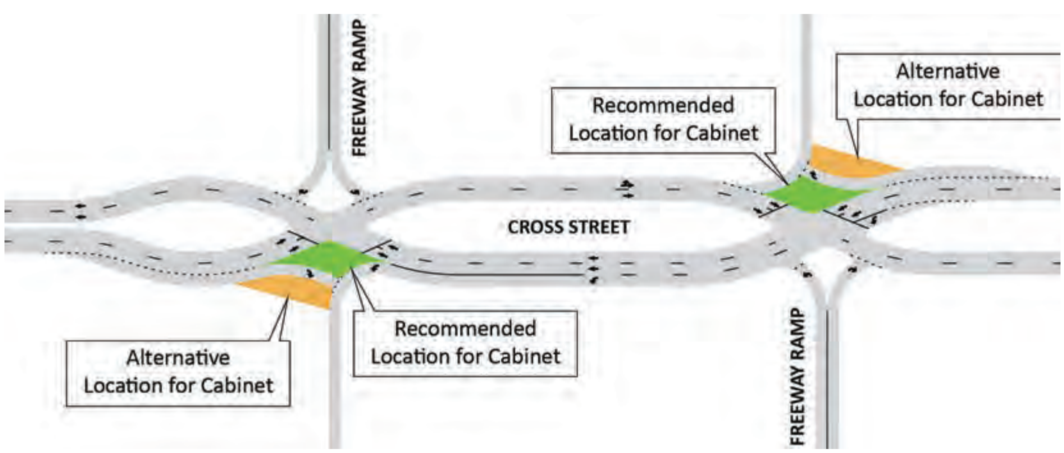


Exhibit 7-16. Recommended locations for signal cabinet(s) at a DDI.

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 7-17).

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 RTOR rule is controlled through supplemental signage, either configuration may be acceptable. Also, while most states allow RTOR, several states do not allow for LTOR. Adequate signage should supplement the signal heads to promote conformity with state laws.

7.5.3.2 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 7-18). 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 advance warning to drivers. One or more pedestal mounted signal heads in the median(s) can help with visibility on the crossover approaches.

A less common alternative strategy is to use a single mast arm with signal heads in both directions (as shown in Exhibit 7-19). 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.

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

Exhibit 7-17. Type 2 crossover signals with a Type 1 supplemental signal on left (2).

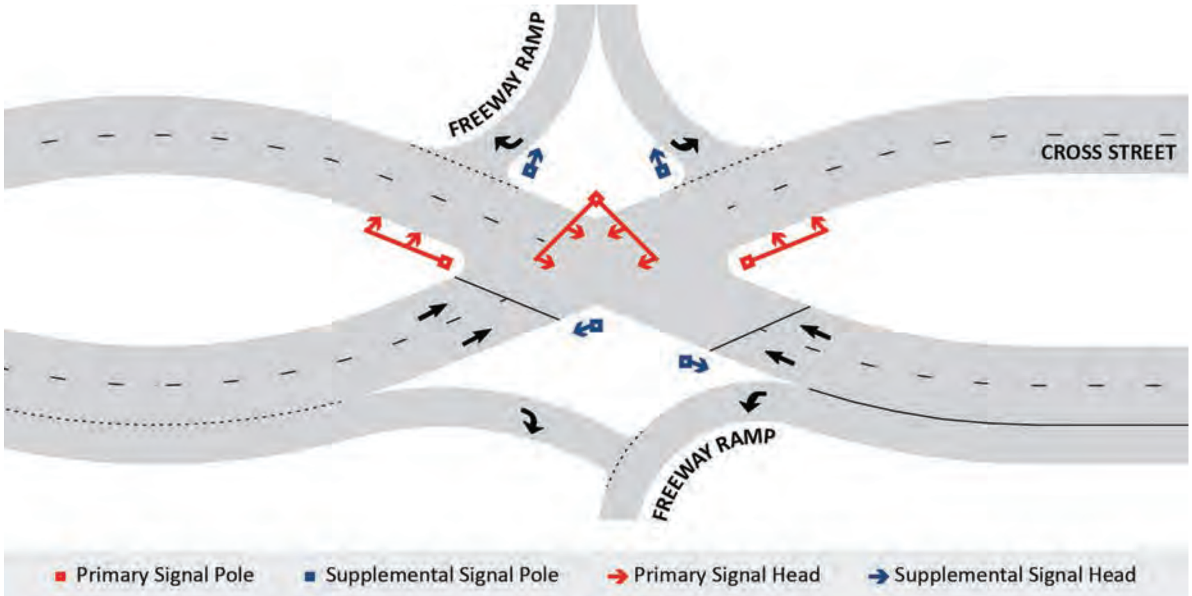


Exhibit 7-18. Option 1 for DDI signal pole and head placement.

visibility effects for an outbound DDI movement approaching the crossover is shown in Exhibit 7-20 where the presence of multiple overhead mast arms and signal heads creates visual clutter and makes it difficult to identify the appropriate signal.

7.5.3.3 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 7-21, Exhibit 7-22, and Exhibit 7-23.

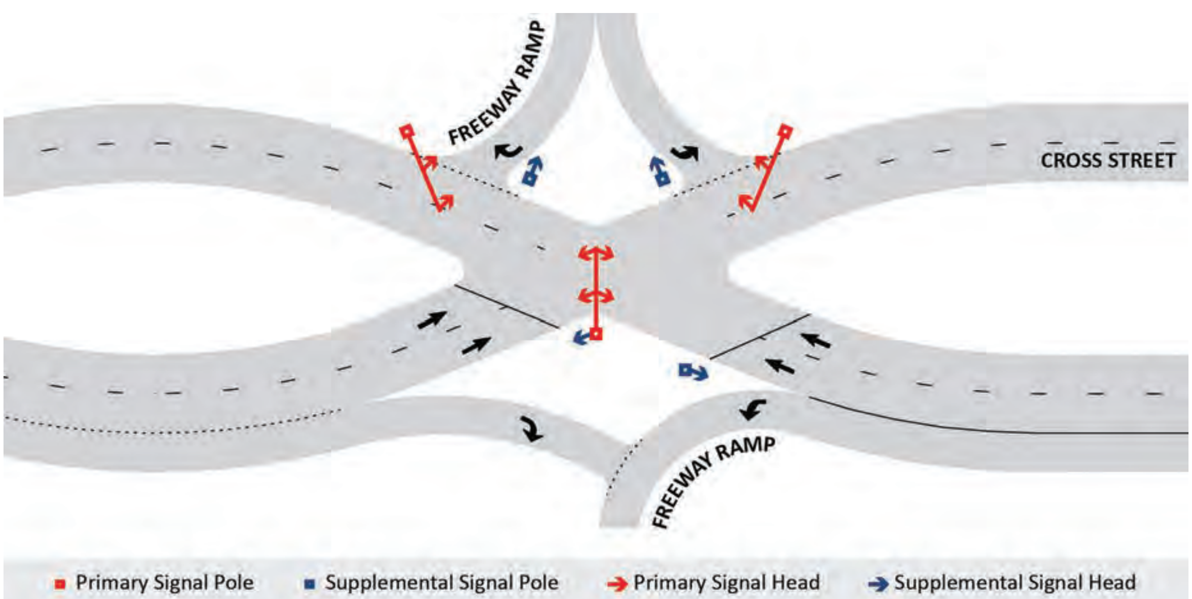


Exhibit 7-19. Option 2 for DDI signal pole and head placement.

Exhibit 7-20. ***Mast arm assembly limiting approach visibility (2).***

Image Source Adapted

Exhibit 7-21. ***Supplemental signal on right for an inbound movement at a DDI (2).***

Image Source Adapted

Exhibit 7-22. ***Supplemental signal on left for an outbound movement at a DDI (2).***

Image Source Adapted

Exhibit 7-23. ***Supplemental signal for a DDI off-ramp from freeway (2).***

For the inbound movement, the supplemental signal head is typically installed on the right-hand side of the street as illustrated in Exhibit 7-21. For the outbound movement, the supplemental signal head is typically installed on the left-hand side of the street as illustrated in Exhibit 7-22. Supplemental signals may also be required for the freeway exit ramp movements as shown in Exhibit 7-23. 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 7-23 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 7-24).

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.

7.5.3.4 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*).

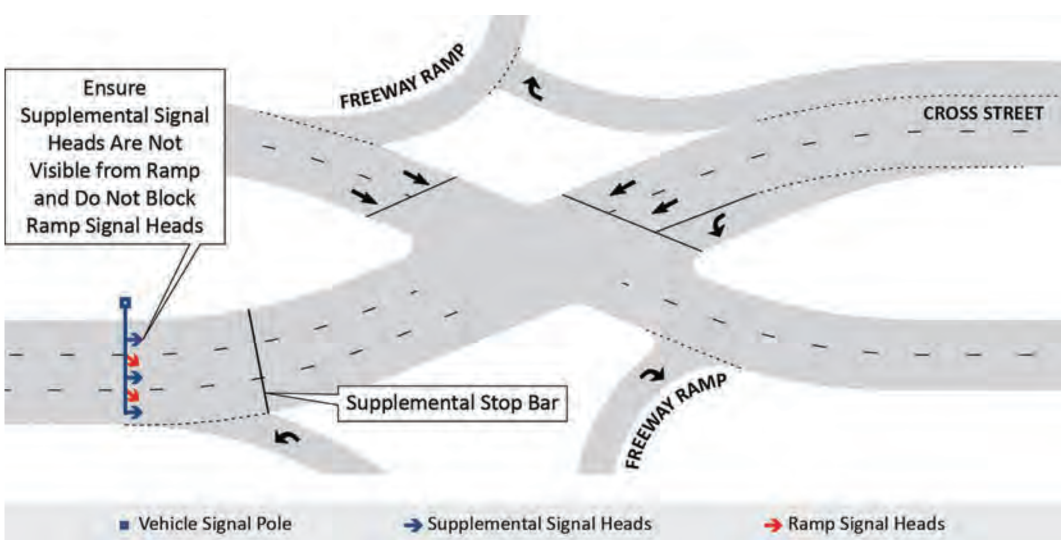


Exhibit 7-24. Use of supplemental signal for DDI inbound through movement.

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.

At the DDI, providing 10 feet of separation between the two APS devices may pose a challenge in the median island. Exhibit 7-25 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.

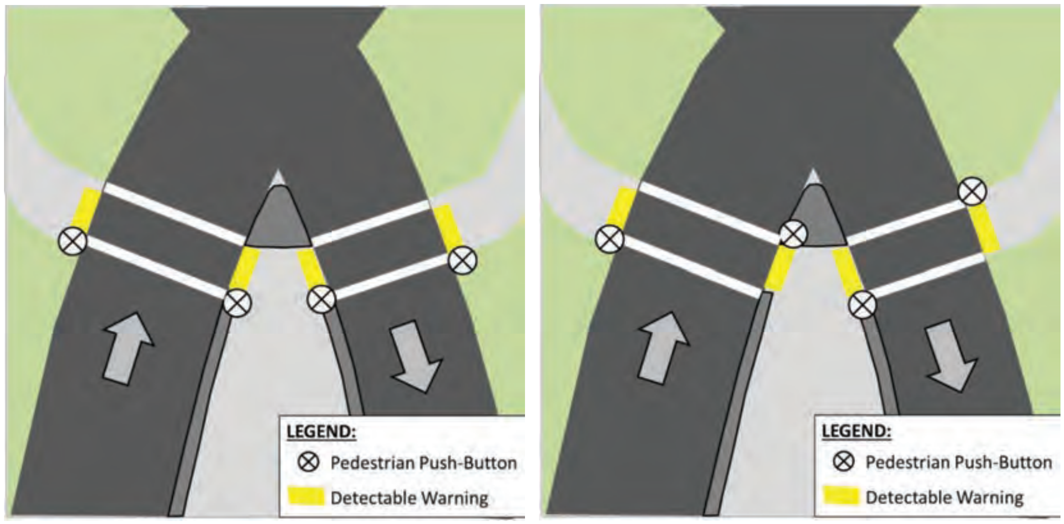
Given that the "point" of the median island does not provide adequate room to allow the pedestrian push buttons to be on separate poles, it is recommended that the poles are located on the opposite side of the waiting area where the island is generally wider. This is shown in the left illustration (*a*) of Exhibit 7-26. 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 (*b*) of Exhibit 7-26.

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 6 feet in length). This assures a minimum of 2 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

Exhibit 7-25. Undesirable use of single pole with two pedestrian push buttons, no APS, and insufficient separation of the two detectable warning surfaces (2).

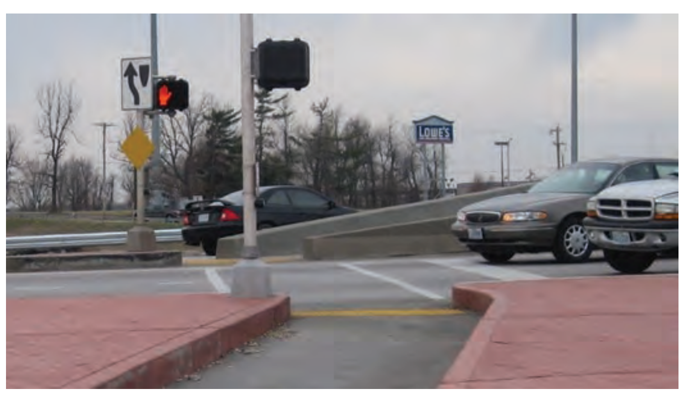


(a) Pedestrian Signals on Same Side **(b) Diagonal Pedestrian Signals**

Exhibit 7-26. DDI splitter island with pedestrian signals: (a) pedestrian signals on same side and (b) diagonal pedestrian signals.

[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 toward 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 7-27; an example of a pedestrian crossing for a left turn onto the freeway is shown in Exhibit 7-28. 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 ROW already provided in the channelization islands.



Source: *Field Evaluation of Double Crossover Diamond Interchanges* (*4*)

Exhibit 7-27. Pedestrian signal and push button on outside of crossover (pedestrian facility in median).

Source: *Field Evaluation of Double Crossover Diamond Interchanges* (*4*)

Exhibit 7-28. Pedestrian signal and push button for left turn onto freeway (pedestrian facility on outside).

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 7-29, which also shows a potential layout of pedestrian push buttons and signal heads.

7.5.3.5 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.

7.5.4 Detection

Many of the existing traffic signals at DDIs are operating as pre-timed traffic signals and are not making use of detection. However, most do still have detection installed and could

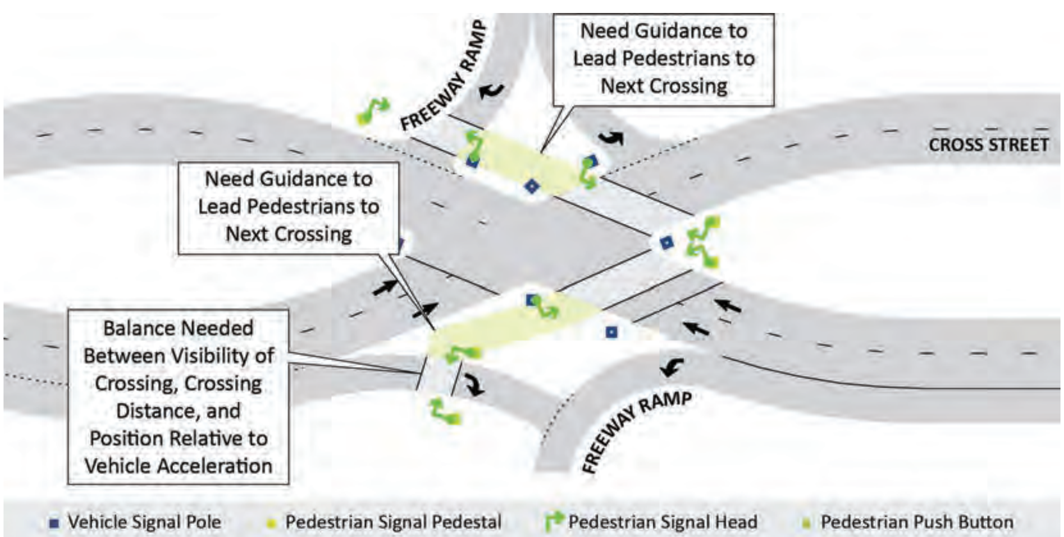


Exhibit 7-29. Pedestrian signal head placement at a DDI.

operate as fully-actuated signals if desired. One benefit of installing detection at a DDI, even if the intention is to operate it as pre-timed, 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 7.5.1, 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.

7.5.5 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, interconnected 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.

7.5.6 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.

7.6 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 6-65). 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.

7.7 Illumination

This section provides basic guidance for street lighting designers and state and local agencies regarding the design and application of street lighting. It is not intended to be a detailed guide, because lighting designs often vary depending on agency internal policies, though they should meet minimum guidelines found in various resource documents. As such, this section is provided as a resource for policy makers and the design and construction community to evaluate the need, potential benefits, and even applicable references when considering street lighting at DDIs. The AASHTO *Roadway Lighting Design Guide* (*6*) and the American National Standards Institute/Illuminating Engineering Society (ANSI/IES) *American National Standard Practice for Design and Maintenance of Roadway and Parking Facility Lighting* (*7*) offer more detailed recommendations on lighting levels and configurations at interchanges. In addition, agency-specific street lighting policies should be followed when necessary. As the DDI is a unique interchange design, agency policies regarding street lighting at these facilities may need to include specifications specific to this interchange design.

7.7.1 Complete Versus Partial Interchange Lighting Systems

AASHTO provides warrants for complete and partial interchange lighting systems (*6*). Although these warrants do not represent a requirement to provide lighting, they do provide a mechanism for designers to make sound design decisions on how to provide adequate lighting. Warrants for complete and partial interchange lighting systems are based on conditions including traffic volume, interchange spacing, adjacent light use, and night-to-day crash ratios. It is generally desirable to provide at least partial interchange lighting systems at rural DDI locations, but consideration should be given to complete interchange lighting designs. Complete interchange lighting will be desirable on bridge designs in urban and suburban areas.

Pole spacing options at DDI crossroads will be highly variable based on several factors such as:

- Type of system deployed (e.g., complete or partial),
- Types of poles being considered (e.g., high-mast poles, mast arms, post-top, etc.),
- Interchange area being considered (e.g., inbound approaches, ramps, between the crossovers, etc.),
- Surrounding environment,
- Width of the bridge(s), and
- Clear zone considerations.

At sites that are a part of a complete interchange lighting system, lighting should be used on the entry and exit ramps for continuity. If continuous freeway lighting is not provided, such as the case with partial interchange lighting systems, it is recommended that lighting be provided on the ramps to transition into the interchange given the unique design. Most often, mast arm and davit-style lighting will be used along the ramps.

When pedestrian walkways are provided along the outside of the crossroad, high-mast lighting will usually be more effective than mast arm, truss, or davit-style lighting. This provides more options for installing high-mast arms as sufficient clear zone outside the crossroad and the median are optimal. This option requires fewer poles than other methods, though their maintenance costs may be higher in some cases. An example of a complete interchange lighting system with high-mast lighting (six luminaires each) at the crossovers is provided in Exhibit 7-30. In this example, crosswalks are not present in the median, and high-mast lighting is used on the outside. If sufficient clear zone were available, it is possible to install high-mast poles in the median as well.

Sites with pedestrian facilities in the median will typically have mast arm or davit-style lighting installed along the cross street; however, it is possible to install a high mast along the outside as well, provided the poles meet applicable clear zone requirements. This pole type requires more poles than high-mast types, though they are typically easier to maintain. An example of a partial interchange lighting system is provided in Exhibit 7-31, where lighting is provided on the ramps to transition off and onto the dark, limited-access facility. The lighting at the

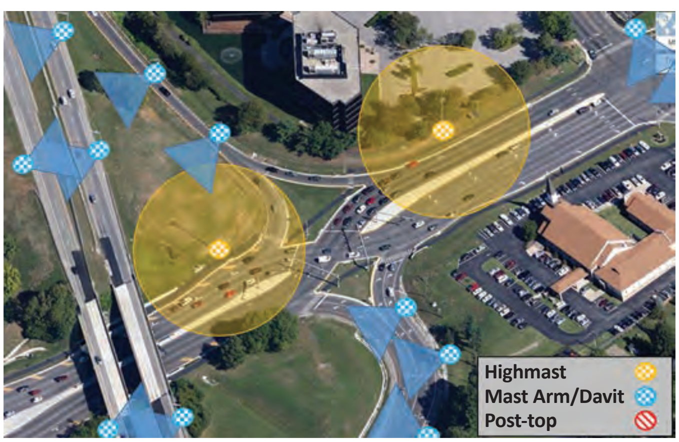


Image Source Adapted
Note: Transparent circular and triangular shapes only describe basic lighting characteristics and not necessarily the zone being lighted.

Exhibit 7-30. Continuous interchange lighting in an urban setting (2).

Image Source Adapted (*2*)
Note: Transparent circular and triangular shapes only describe basic lighting characteristics and not necessarily the zone being lighted.

Exhibit 7-31. Partial interchange lighting in a suburban setting (2). Lighting on the ramps is provided as a transition.

ramps shows key merge and diverge points at the entry and exit ramps. Post-top lighting is used along the bridge for aesthetics. An example of a partial interchange lighting system with no lighting on the ramps is provided in Exhibit 7-32.

7.7.2 Pedestrian Lighting

The lighting design for the pedestrian facilities at a DDI should follow the same considerations as at other interchanges. For arterial underpasses, these considerations include adequate illumination of the pedestrian facilities under the bridge structure, as well as lighting on pedestrian walkways and crossing points.

For center walkway locations, recessed LED lighting, as shown in Exhibit 7-33, provides an opportunity to illuminate the walkway without the need for additional street lights. Street lights may be difficult to place in a constrained ROW, and poles should not be placed within the walkway where they would form an obstacle for pedestrians. The recessed lighting feature can provide adequate illumination without introducing such obstacles, but illumination levels

Image Source Adapted (*2*)
Note: Transparent triangular shapes only describe basic lighting characteristics and not necessarily the zone being lighted.

Exhibit 7-32. Partial interchange lighting in a suburban setting (2). No lighting is provided on the ramps for transition.

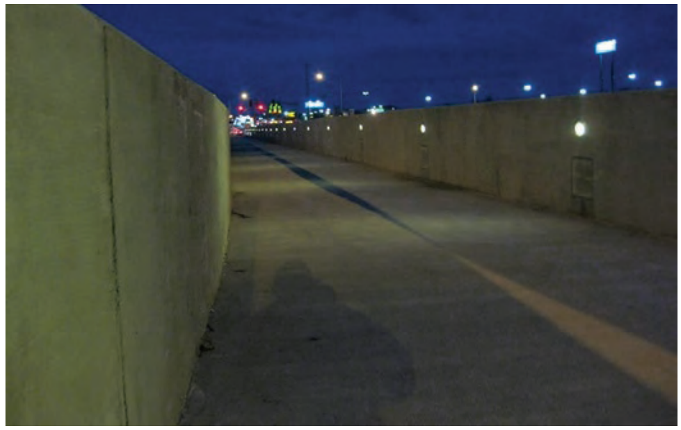


Exhibit 7-33. Recessed lighting in DDI center walkway (4).

should be checked against the appropriate federal, state, or local standards. Illumination levels of pedestrian pathways should account for low-vision users, especially in cases where ambient light may be blocked through structures or retaining walls.

7.8 Document Local Practices

This guide is intended to provide a starting point and frame of reference for many of the common issues encountered at DDIs. Each agency has specific preferences for signal design and timing parameters; documenting the local practices and preferences for DDI-specific parameters based on this guide is strongly recommended. Taking a standard approach to all DDIs operated and maintained by an agency can help 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 (*8*, *9*).

7.9 References

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6. *Roadway Lighting Design Guide,* 7th ed. AASHTO, Washington, D.C., October 2018.
7. *American National Standard Practice for Design and Maintenance of Roadway and Parking Facility Lighting*. ANSI/IES RP-8-18. American National Standards Institute, Illuminating Engineering Society, New York, 2018.
8. *Missouri's Experience with the Diverging Diamond Interchange*, MoDOT Report No. OR10- 021, Missouri Department of Transportation, Jefferson City, MO, 2010.
9. *DDI Guideline: A UDOT Guide to Diverging Diamond Interchanges*. Utah Department of Transportation, Salt Lake City, UT, June 2014.

CHAPTER 8

Construction and Implementation

This chapter provides an overview of the general considerations of constructing and maintaining a DDI. It also discusses law enforcement considerations. While there are differences in constructing, maintaining, and providing law enforcement at a DDI compared to a conventional diamond interchange, none of the differences is likely large enough to overshadow the safety and operational effects discussed in previous chapters.

8.1 Construction Staging

Implementing a DDI poses some challenges in maintaining traffic flow during construction; however, the thought processes are no different than those for other designs. The sequencing of construction can use several strategies depending on a variety of factors, including but not limited to the following:

- Is the facility an overpass or underpass?
- If the facility is an overpass, how many structures are being built and are any existing structures already in place?
- Are there nearby detour routes?
- What are the traffic demands of the facility?

Each of these factors also has significant effects on the costs of implementing a DDI design. As there are many staging options that could be considered, this section will provide some options that could be considered based on the design constraints of the site. Regardless of the staging option selected, maintenance of pedestrian and bicycle access should be an integral part of the maintenance of traffic plans.

Compared to other interchange forms, such as partial cloverleaf designs, tight diamond interchanges (TDI) and single-point diamond interchanges (SPDI), the DDI typically takes much less time to construct, particularly for upgrades of existing diamond interchanges. This is especially true if the design is a retrofit that allows for the use of the existing bridge structure. The Missouri Department of Transportation conducted a constructability analysis of a TDI and SPDI versus a DDI, and they concluded that DDI construction would last a single season and TDI or SPDI construction would last two seasons or more (*1*). This is consistent with findings from other agencies.

The primary consideration for construction staging is whether the interchange is new construction, whether additional structures are needed, or if the interchange is a true retrofit design using existing structures. Sites with retrofit designs are most common to date. Questions to consider include:

- Can the interchange be closed?
- Is the existing pavement going to be used or replaced?

- Is additional cross-section width necessary to accommodate future traffic (i.e., motor vehicles, bicycles, and pedestrians)?
- When are the best times to switch traffic between various stages of the project?

A site constructed in locations where no at-grade intersection or grade-separated interchange currently exists will cause the least disruption to traffic. A site that can be fully closed by detouring traffic to nearby intersections or interchanges provides the most efficient arrangement for construction but creates potential out-of-direction travel for users. For most agencies, DDIs will be constructed while accommodating most of the existing traffic demands already in place (*2*).

If original pavement will be used in place, switching traffic to a DDI configuration early can be accommodated. Oftentimes, simply resurfacing can facilitate the traffic switch. Switching traffic early will usually reduce the amount of temporary pavement needed during construction. Early traffic conversion can also assist by providing space for timely construction of mast-arm, lighting, and signal cabinet foundations. Considerations should be made regarding the final alignment of left-turn off-ramps and the conversion to a DDI lane configuration. If construction of the final alignment of the ramps precedes the conversion from right-hand drive to left-hand drive between the crossovers, care is needed to ensure drivers—then still on the right side of the roadway—do not mistake the off-ramp for an on-ramp.

Switching traffic later is most often done when considerable pavement replacement is necessary. The latter method is most commonly implemented and usually uses half-at-a-time construction phasing. Similar to traditional diamond interchange design considerations, portions of the available cross section must be cordoned off using raised barriers to allow construction activities to take place. Consideration is needed when determining in which stage median pedestrian facilities will be constructed if present.

Where new structures must be completed, construction with less interference to normal traffic operations is usually possible. Structures can be built in place or constructed off-site and driven in using a self-propelled modular transporter (SPMT). An example of a pre-constructed concrete girder system being driven to the site is provided in Exhibit 8-1. This technique has been used with great success for many bridge projects in Utah (*3*). Although these bridge design techniques will usually require more upfront costs, the Utah Department of Transportation (UDOT) is noticing costs decreasing as contractors become more comfortable with the technique. Recent transport and installation of a parallel bridge took less than 6 hours to complete.

Exhibit 8-1. SPMT brings superstructure to DDI location (3).

Exhibit 8-2. Construction staging using pre-cast construction methods (5).

Exhibit 8-2 shows the construction staging used at one of the UDOT sites where a prefabricated bridge was rolled into place. The middle picture shows the short transition in which the structure was installed in less than 1 day.

The staging of newly constructed bridge designs is not dependent on the technique used to build the structure. In fact, the illustration provided in Exhibit 8-2 could easily represent a more typical design that constructs the bridge in place.

Staging techniques just prior to the opening of the DDI are also dependent on whether the site is a retrofit or new construction. For retrofit designs, the entire interchange will likely need to be closed for a short period of time. A survey of expert practitioners recommends conversion to the DDI traffic pattern be completed under full closure. This is recommended, in part, to assist drivers in recognizing the lane configuration change (*4*).

In some designs, the right-turn movements on and off the limited access facility are allowed while the crossovers are tied in and striped. This is usually done in a period of 2 to 3 days over a weekend. A different tie-in method used may include one of the crossovers being closed at a time, allowing one of the left-turn movements from the limited access facility to remain in place. When the first crossover is complete, the other crossover is tied in using a similar technique. This method can be employed over a short period of time (e.g., over a weekend) as well. For designs with new structures, a common timeframe is needed for the tie-ins.

8.2 Cost Estimates

One of the primary advantages of the DDI is the reduced costs associated with the design and construction compared to those for other typical interchange designs. In fact, this is the primary reason DDIs have taken a strong foothold in the transportation community in the past 5 years. In addition, the footprint of the DDI can often fit within the existing right-of-way and on an existing bridge, making it less expensive and faster to construct compared to other interchange forms previously noted in this chapter. Structural costs are the primary driving

Exhibit 8-3. Construction cost estimates (*5*).

Interchange	Location	Open to Traffic	Construction Cost	Retrofit
Bessemer St. and US-129	Alcoa, TN	2010	$2.9 million	Yes
MO-13 and I-44	Springfield, MO	2009	$3.2 million	Yes
Winton Rd. and I-590	Rochester, NY	2012	$4.5 million	Yes
National Ave. and US-60	Springfield, MO	2012	$8.2 million	Yes
Timpanogos Hwy. and I-15	Lehi, UT	2011	$8.5 million	Yes
Mid Rivers and I-70	St. Peters, MO	2013	$14 million	No
CR-120 and Hwy 15	St. Cloud, MN	2013	$17.5 million	No
Pioneer Crossing and I-15	American Fork, UT	2010	$22 million	No

factor in how much interchanges cost, making the DDI particularly attractive if being considered as a retrofit of an existing structure.

The actual costs of designing and constructing a DDI are highly variable based on the factors described above and other site-specific elements, particularly if a design is newly constructed versus a retrofit. Construction costs at several facilities constructed to date are provided in Exhibit 8-3.

Among several retrofit DDIs constructed, costs ranged from approximately $3 million to $8.5 million. The more expensive retrofit design at National Avenue incorporated an underpass facility at the adjacent intersection, while the DDI at Timpanogos Highway added an additional bridge to the interchange.

Among several new DDIs constructed to date, costs ranged from $14 million to $22 million.

8.3 Maintenance

General maintenance considerations for a DDI are similar to those for other interchange forms, though the following should be considered:

- Lighting—High-mast systems are often more expensive to deploy yet easier to maintain as they are usually installed in locations with easy access and outside the lane lines. Maintenance is done by lowering the luminaire ring from the mast head to the base using a winch and motor, making them accessible at the ground or by using a small cherry picker. A number of DDIs have also successfully implemented davit- and post-top lighting options, which may be more familiar for maintenance crews.
- Pavement markings—Pavement markings will need to be inspected and maintained more frequently than with normal interchange designs. The unique crossover design should be well marked at all times to make sure the lanes are easily seen to help prevent path overlap. Pavement marking wear will take place much faster as the full lane widths are often used when negotiating the reverse curves.

Through expert surveys and interviews, Brown et al. developed maintenance of traffic plans for various lane closure configurations during routine maintenance (*2*).

8.4 Snow Removal

Consistent for all types of interchanges, snow removal strategies focus on systematically pushing snow to the outside of the street. Many snowplows are designed to push snow to the right. Between the crossovers, this results in snow piling in the median. For climates where the snow builds throughout the season, a plan should be in place to either allow for adequate snow storage space next to the median or to provide for removal as needed. Snow should not be regularly stored in bicycle lanes or on sidewalks.

The DDI designer needs to work collaboratively with snowplow operators to provide end treatments that delineate curb locations (i.e., surface-mounted delineators). Snowplow operators will need to become familiar with the DDI configuration and develop a sequence for plowing the different travel paths. Through lanes are typically plowed as part of a corridor.

Snow removal plans, as well as general maintenance plans, should also be developed for pedestrian and bicycle facilities. Often, these removal plans mirror current local agreements at nearby facilities. If pedestrian and bicycle facilities are located within the median, maintenance crews should be notified as the unique location may be difficult to identify under heavy snowfall.

8.5 Law Enforcement Needs

The channelization of vehicle movements at a DDI creates a relatively "self-enforcing" interchange with research showing most drivers traveling at or below the speed limit (*5*). Unlike many other alternative intersections and interchanges, there are no desired movements prohibited with signing and pavement marking alone.

Unique law enforcement needs of a DDI are primarily related to the opening period. Enforcement during this period could help drivers become familiar with the crossed-over nature of the arterial and reduce unintentional wrong-way maneuvers. Enforcement may be most beneficial during low volume, nighttime hours when there is a decreased likelihood of opposing vehicles that would naturally help drivers avoid a wrong-way maneuver.

8.6 References

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APPENDIX

Safety Details

This appendix supplements Chapter 4, Safety, to provide details of literature reviews and findings on the safety performance of diverging diamond interchanges (DDIs).

A.1 Literature Review

The primary measure of safety performance is long-term annual average crash frequency. Crash modification factors (CMFs) based on significant samples of data from treatment and reference sites that remove bias found in most safety studies, especially regression-to-the-mean, have been developed in several studies. This section provides a summary of safety effects from early DDI implementations and surrogate measures collected at several DDIs in a recent FHWA study.

A.1.1 Chilukuri et al. (2011) (*1*)

A safety evaluation was conducted in 2011 on the first DDI opened at MO-13 and I-44 in Springfield, Missouri. Crash data obtained from the Missouri Department of Transportation and the City of Springfield were analyzed for a 5-year period before the improvements and 1 year after improvements. Roadway segment crash rates were compared to determine any changes in the pre-construction and post-construction periods. The safety conclusion included the following:

- Total crashes were down by 46% in the first year of operation.
- Left-turn type crashes were eliminated and left-turn right-angle type crashes were down 72% because of how left turns are handled within the DDI (free-flow movements or yield control).
- Rear-end type crashes were down slightly. This might also be due to how left turns are handled without traffic signal controls.
- DDI post-construction crash types are similar to those for any other signalized intersection; in the review, no definite crash pattern was noticed that could lead to determining that a certain type of crash increased within a DDI.

A.1.2 Edara et al. (2015) (*2*)

Data from six DDI sites in Missouri were used to conduct a before-after evaluation in 2015. The safety evaluation consisted of three types of observational before-after evaluation methods: Naïve, empirical Bayes (EB), and Comparison Group (CG). All three methods showed that there was decreased crash frequency for all severities in locations where a DDI replaced a conventional diamond intersection.

The safety evaluation at the project-level accounts for the influence of the DDI treatment in the entire footprint of the interchange. The findings include:

- The highest crash reduction was observed for fatal and injury (FI) crashes: 63.2% (Naïve), 62.6% (EB), and 60.6% (CG).
- Property Damage Only (PDO) crashes were reduced by 33.9% (Naïve), 35.1% (EB), and 49.0% (CG).
- Total crash frequency also decreased by 41.7% (Naïve), 40.8% (EB), and 52.9% (CG).

The site-specific approach focused on the influence at the ramp terminals only. Main findings include:

- The highest crash reduction was observed for FI crashes: 64.3% (Naïve), 67.8% (EB), and 67.7% (CG).
- PDO crashes were reduced by 35.6% (Naïve), 53.4% (EB), and 47.0% (CG).
- Total crash frequency also decreased by 43.2% (Naïve), 56.6% (EB), and 53.3% (CG).

A collision type analysis revealed that the DDI, as compared to a diamond, traded high severity for lower severity crashes. While 34.3% of ramp terminal-related FI crashes in a diamond occurred due to the left-turn angle crashes with oncoming traffic, the DDI eliminated this crash type.

A.1.3 Lloyd (2016) (*3*)

Lloyd (2016) conducted a safety analysis at five locations in Utah that have been converted from traditional diamond interchanges to DDIs. The EB before-after method, using the *Highway Safety Manual* (HSM) and Interchange Safety Analysis Tool Safety Performance Functions (ISAT SPFs), was applied to the selected locations in order to provide a statistical analysis of the increase or decrease of crashes at the location since the DDI conversion.

A.1.4 Claros et al. (2017) (*4*)

Claros et al. (2017) generated CMFs for ramp terminals at DDIs in Missouri using EB evaluation. The authors obtained CMFs of 0.45 for FI crashes, 0.686 for PDO crashes, and 0.625 for total crashes.

A.1.5 Nye (2018) (*5*)

Nye (2018) examined the change in safety associated with the conversion of a conventional interchange to a DDI. For this examination, Nye compared crash records for multiyear time periods before and after the conversion at 15 interchanges. Nye analyzed the data using two before-after study methods. One method was called the Naïve Method by Nye. [However, it is more appropriately called the Volume-Corrected Method because it includes the use of annual average daily traffic (AADT) data to account for changes in traffic volume between the before and after periods.] The second method was called the Comparison-Group Method. It is used to account for changes in traffic volume, driver behavior, weather, vehicle fleet, traffic safety programs, and crash reporting threshold between the before and after periods.

A.1.6 Nye et al. (2019) (*6*)

Nye et al. built on the work of Nye (2018) and subsequently obtained data for 11 more interchanges and re-evaluated the data for all 26 sites using the Comparison-Group Method. For both the original 15-site database and the 26-site database, CMFs were computed for each site and for the combined group of sites. CMFs were also computed for specific crash types (e.g., angle, rear-end, sideswipe, all types combined), crash severity categories (e.g., FI crashes, PDO crashes, and for all crash severities combined), and for light conditions (e.g., day, night, all conditions combined).

The site-specific CMFs for FI crashes indicated that CMF values ranged from 0.193 to 1.208. Similar wide ranges were obtained for the site-specific CMFs for the other crash severity, crash types, and lighting condition categories. It is likely that some of this variation is attributable to the variation in geometric design elements and features among sites.

Given that there are a large number of geometric elements and features at an interchange that influence safety, it is almost a certainty that some of the changes at one converted site will be different from those at other sites. The range in site-specific CMF values reported by Nye et al. (2019) is likely a reflection of the differences among sites (*6*).

Information in the HSM indicates that road safety is affected by a change in number of lanes, lane width, shoulder width, median width, intersection skew angle, speed, traffic control type (i.e., stop, signal), and horizontal curvature. Each new interchange conversion represents unique combinations of change in most of these elements and features. The calculation of a CMF that summarizes the overall change in safety associated with a specific interchange conversion describes the combined safety effect of the changes in each element and feature at that site. This "overall" (or project-level) CMF can be a reliable descriptor of the change in safety at the converted site. However, it will not be a reliable descriptor of the change in safety associated with a proposed new site unless the changes in elements and features at the converted site are a match to those at the proposed site. If one or more changes at the proposed site do not match those at the converted site, then a different project-level CMF value will be obtained for the proposed site.

A.2 Crash Modification Factor Development

The objective of this section is to document the findings from a re-examination of the project-level CMFs produced by Nye et al. (2019) (*6*). The purpose of this re-examination is to determine whether the reported variation among CMF values can be explained by one or more geometric elements or features at the interchanges.

A.2.1 Data Summary

The database assembled by Nye et al. (2019) consists of data for 26 sites at which an existing interchange was converted to a DDI. One observation in the database represents one interchange site (*6*). The location of each site is identified in Exhibit A-1.

The AADT volume data listed in Exhibit A-1 are indicated by Nye (2018) to describe crossroad traffic conditions for most sites (both travel directions combined). For at least one site, the crossroad AADT was not available, and volume information for the ramps was substituted (*5*).

The AADT data were evaluated further for this re-examination. Specifically, the AADT volume was combined with the crossroad lane count and a typical ratio of peak-hour volume to AADT volume (i.e., K factor) to compute a peak-hour lane volume. This lane volume was then compared to a typical peak-hour lane volume of 700 vehicles per hour (vph). Those sites with a lane volume greatly in excess of this amount were flagged as having an unusual AADT volume. One site was found to have a peak-hour volume of 2,600 vph/lane. Eight of the 26 sites had a peak-hour volume in excess of 800 vph/lane.

As a spot check of the AADT values, the crossroad AADT volumes for the three sites in North Carolina were obtained from the North Carolina Department of Transportation (NCDOT) (*7*)

Exhibit A-1. Interchange site location, traffic volume [vehicles per day (vpd)], and lanes.

No.	Road Names	City	State	AADT (vpd), Before[1]	AADT (vpd), After[1]	Crossroad Through Lanes[2], Before[1]	Crossroad Through Lanes[2], After[1]
1	I-85/Jimmy Carter Blvd.	Atlanta	GA	53,465	58,350	4	4
2	I-85/Pleasant Hill Rd.	Duluth	GA	50,766	54,475	4	6
3	I-86/Yellowstone Ave.	Pocatello	ID	26,800	28,500	4	4
4	I-435/Roe Ave.	Overland Park	KS	42,925	37,500	4	4
5	KY 4/US-68	Lexington	KY	36,550	33,095	4	6
6	I-494/34th Ave. S	Bloomington	MN	17,300	17,750	4	4
7	I-70/Stadium Blvd.	Columbia	MO	42,247	52,452	4	4
8	US-65/East Chestnut Expy.	Springfield	MO	22,900	24,000	2	4
9	US-60/S Kansas Expy.	Springfield	MO	24,900	26,782	3	4
10	US-67/Columbia St.	Farmington	MO	12,550	12,100	2	4
11	US-65/MO-248	Branson	MO	31,800	33,150	2	3
12	I-44/Range Line Rd.	Joplin	MO	23,421	22,817	4	4
13	I-70/Mid Rivers Mall Dr.	St. Peters	MO	27,060	22,443	4	4
14	I-70/Woods Chapel Rd.	Kansas City	MO	17,412	17,676	4	4
15	I-29/Tiffany Springs Pkwy.	Kansas City	MO	19,090	20,637	3	4
16	I-77/Catawba Ave.	Cornelius	NC	25,969	27,938	4	4
17	I-85/NC-73	Concord	NC	25,643	23,460	2	5
18	I-85/Poplar Tent Rd.	Concord	NC	18,655	24,536	2	4
19	I-590/S Winton Rd.	Rochester	NY	17,716	17,464	4	4
20	I-15/St. George Blvd.	St. George	UT	36,111	36,917	4	4
21	UT-201/UT-154	Salt Lake City	UT	35,233	33,130	5	5
22	I-15/S 500 E St.	American Fork	UT	18,927	18,213	2	4
23	I-15/Timpanogos Hwy.	American Fork	UT	22,960	23,511	3	4
24	I-15/US-91	Brigham City	UT	18,483	19,000	2	2
25	I-64/US-15	Gordonsville	VA	6,700	7,000	4	4
26	I-25/College Dr.	Cheyenne	WY	13,374	11,253	4	2

Notes:
1. Before = conditions present before conversion to DDI. After = conditions present after conversion to DDI.
2. Number of lanes on the crossroad that serve vehicles traveling as a through movement. Total of both travel directions. Each lane can be traced as a continuous traffic lane through the interchange (including both crossroad ramp terminals).

and are shown in Exhibit A-2. They can be compared with those obtained from a spreadsheet prepared by Nye et al. (2019) (*6*). The volumes reported by Nye et al. are consistently higher than the crossroad AADTs obtained from the NCDOT website. It is possible that the AADTs attributed to Nye et al. may be inclusive of volumes on the ramps as well as the crossroad.

Given the uncertainty, AADT was not considered in the development of a CMF function. If crossroad AADT volume could be confirmed for all sites in Exhibit A-1, then this variable should be evaluated to determine if CMF value is a function of crossroad AADT.

Exhibit A-3 identifies several supplemental variables that were collected from Google Earth and added to the database. The site number in the first column of this table coincides with the site numbers in Exhibit A-1. The methods by which each variable was measured are listed in the table footnotes.

The variables listed in Exhibit A-3 were selected because of their documented correlation with road safety. Although not shown, several additional variables were also collected: ramp-to-ramp distance, skew angle, median type, and number of curves along the crossroad.

A.2.2 Analysis Results

Nye (2018) used both the Volume-Corrected Method and the Comparison-Group Method to compute site-specific CMFs for a 15-site database (*5*). Subsequently, Nye et al. (2019) used only the Comparison-Group Method to compute the same CMFs for a 26-site database (*6*). For both applications of the Comparison-Group Method, they used "total" crashes (i.e., all crash severities and types combined) to describe the change in safety at the comparison sites.

The use of total crashes to compute the comparison site ratio is appropriate for the evaluation of total crash frequency at the interchange conversion sites. However, the use of total crashes to evaluate specific severity categories (e.g., FI), crash types (e.g., angle), or lighting conditions (e.g., day) may not produce the most reliable CMF values. For example, a change in the reporting threshold (between the before and after evaluation periods) is likely to have a significant effect on PDO crash frequency and a small effect on FI crash frequency. Arguably, it would be more appropriate to quantify the comparison ratio using FI crash frequency when estimating a CMF for FI crashes at the conversion sites (and a ratio based on PDO crash frequency when estimating a CMF for PDO crashes). In support of this claim, Hauer (1997, p. 131) advises that when selecting the comparison group, "there should be reason to believe that the change in factors influencing safety is similar in the treatment and comparison groups" (*11*).

Nye (2018) identified a comparison group for each of the interchange conversion sites. He computed the odds ratio and its variance for the comparison group (*5*). This variance was subsequently used in the calculation of the CMF value and its standard error. Roughly speaking, a reduction of 0.03 in this variance corresponds to about a 3% increase in the CMF value.

Exhibit A-2. North Carolina AADTs.

No.	Road Names	City	State	NCDOT AADT (vpd), Before[1]	NCDOT AADT (vpd), After[1]	Nye et al. AADT (vpd), Before[1]	Nye et al. AADT (vpd), After[1]
16	I-77/Catawba Ave.	Cornelius	NC	25,969	27,938	33,000	31,500
17	I-85/NC-73	Concord	NC	25,643	23,460	52,000	47,000
18	I-85/Poplar Tent Rd.	Concord	NC	18,655	24,536	37,000	50,000

Notes:
1. Before = conditions present before conversion to DDI. After = conditions present after conversion to DDI.

Exhibit A-3. Interchange geometric elements and features.

No.	Before Control Type[1], Terminal 1	Before Control Type[1], Terminal 2	Crossroad Lane Drops[2]	Area Type	Stop Line to Stop Line Distance[3], ft	Crossroad Speed Limit, mph	Median Width[4] Before, ft	Median Width[4] After, ft
1	signal	signal	2	Urban	600	40	1	17
2	signal	signal	2	Urban	435	40	1	15
3	signal	signal	0	Urban	600	35	4	81
4	signal	signal	2	Urban	620	25	1	55
5	signal	signal	0	Urban	710	45	16	30
6	signal	signal	2	Suburban	600	35	40	64
7	signal	signal	0	Suburban	640	40	1	22
8	signal	signal	0	Suburban	375	40	16	15
9	signal	signal	1	Suburban	670	45	6	24
10	stop	stop	0	Rural	700	40	1	21
11	sig/sig	signal	0	Suburban	810	40	1	30
12	full clover	full clover	0	Suburban	750	40	8	40
13	signal	signal	2	Urban	465	35	8	33
14	signal	signal	1	Suburban	525	35	1	17
15	signal	signal	2	Suburban	325	25	16	28
16	signal	signal	1	Urban	645	30	4	36
17	stop	signal	0	Suburban	860	45	4	50
18	stop	stop	2	Rural	590	45	1	30
19	signal	signal	0	Suburban	605	45	1	12
20	signal	signal	1	Urban	760	30	4	34
21	signal	signal	0	Suburban	815	50	10	27
22	signal	stop	0	Urban	890	45	1	78
23	signal	signal	1	Suburban	710	45	1	26
24	stop	stop	1	Rural	740	30	1	23
25	signal	signal	0	Rural	1,020	30	42	45
26	stop	stop	0	Rural	613	40	1	35

Notes:

1. Traffic control type at the interchange crossroad ramp terminals before conversion to DDI (note: all DDI terminals are signalized). All interchanges have two crossroad ramp terminals. Stop = ramp approach is stop controlled; crossroad approach is uncontrolled. Full clover = no stop- or signal-controlled approaches at terminal; ramp approach may have yield control or no control.
2. At some DDIs, the outside lane of the crossroad is dropped at the entrance ramp (i.e., the outside crossroad lane becomes a turning roadway at the ramp and continues onto the ramp). The value in the table describes the number of lanes that are dropped at the DDI. Total of both travel directions.
3. Travel distance measured along the crossroad from the stop line at one crossroad ramp terminal to the stop line at the downstream terminal in a given travel direction. Distance is measured for both directions of travel, and the average value is shown in the table.
4. Median width is measured for the crossroad between the edge of traveled way for the two opposing roadbeds. It is measured between the two crossroad ramp terminals. If this width varies between the terminals, then it is measured at the widest point.

An examination of the computed variance of the odds ratio indicated that (1) it is likely biased to a value that is smaller than the true value, and (2) it includes a large random variation. These issues stem from the use of a small number of years of before data at most of the sites.

The Chi-Square distribution can be used to describe the distribution of standard deviation values. In the extreme, when there are only two samples of a population's standard deviation, it can be shown using the Chi-Square distribution that (1) the true standard deviation is likely to exceed the computed value in 68 of 100 samples and (2) the 90% confidence interval for an estimate of standard deviation is about 15 times the size of the computed standard deviation. For example, consider a site that has 3 years of before data. These data can be used to compute two odds ratio estimates. The standard deviation of these two estimates is computed as 0.10. Using the Chi-Square distribution, the 90% confidence interval of the standard deviation is 0.05 to 1.55, which is quite large. In fact, the range of the interval is 1.5 (=1.55 – 0.05), which is equal to 15 × 0.10. Moreover, there is 68% chance that the true standard deviation is larger than 0.10 (and 32% chance that it is 0.10 or less).

With an increase in the sample size, the true value of the standard deviation approaches a 50th percentile representation, and the confidence interval decreases. In general, there would need to be five or more before-years of data at each site to obtain a reasonably reliable estimate of the variance of the odds ratio.

The issue noted in the previous two paragraphs (i.e., variance of the odds ratio) has less impact on the CMF results if the analysis of the site-specific CMFs indicates that they can be combined to produce one CMF for all sites. When the data for all sites are combined, the variance of the odds ratio becomes negligibly small such that concerns about its reliability are more likely to be inconsequential. Hauer (1997, Chapter 10) describes the issues associated with variation in CMF values among sites. He also describes a procedure for combining the estimates across sites if the CMF variation is considered to be negligibly small (*11*). However, the variation in site-specific CMF values reported by Nye et al. (2019) for the interchange conversions is quite large, so the reliability of the variance of the odds ratio is a valid concern when a CMF is computed at the site-specific level (*6*).

Based on the discussion in the previous paragraphs, the Volume-Corrected Method was used for this re-examination to compute the CMF values for each site. The calculations associated with this method are described by Hauer (1997, Chapter 8) (*11*). CMFs were computed for FI, PDO, and all severities combined (i.e., total crashes). The computed CMFs and the associated standard errors are listed in Exhibit A-4.

A Chi-Square test of homogeneity was conducted to determine if the CMF values in Exhibit A-4 are sufficiently similar that their combined value could reasonably describe the change in safety at a typical interchange site. The calculations associated with this test are described by Griffin and Flowers (1997) (*10*). The calculations are also summarized in a paper by Kittelson and Associates, Inc. (2015) (*8*). The findings indicate that the hypothesis that the CMFs are equal can be rejected ($p = 0.001$); that is, there is sufficient evidence that the variation in CMF values is larger than can be explained by random variation. It is likely that there are design elements or features that vary among the conversion sites and are causing some of the variation in the computed CMF values.

A.2.3 Modeling Approach

This section describes the development of a model for predicting the CMF value as a function of a site's geometric elements and features. Separate models were developed to predict CMFs for FI crashes, PDO crashes, and all severity categories combined (i.e., total crashes).

Exhibit A-4. Computed CMF values.

No.	CMF (Std. Error) for All Severities Combined	CMF (Std. Error) for Fatal and Injury	CMF (Std. Error) for Property Damage Only
1	2.034 (0.229)	1.590 (0.254)	2.151 (0.249)
2	1.177 (0.117)	0.767 (0.114)	1.291 (0.132)
3	0.623 (0.133)	0.726 (0.226)	0.562 (0.145)
4	0.629 (0.110)	0.543 (0.164)	0.659 (0.128)
5	0.746 (0.077)	0.527 (0.101)	0.788 (0.084)
6	0.645 (0.126)	0.823 (0.249)	0.558 (0.133)
7	0.376 (0.087)	0.320 (0.111)	0.410 (0.117)
8	0.408 (0.070)	0.442 (0.126)	0.391 (0.076)
9	0.617 (0.110)	0.824 (0.225)	0.520 (0.112)
10	1.042 (0.177)	0.783 (0.255)	1.107 (0.205)
11	0.515 (0.094)	0.294 (0.095)	0.620 (0.128)
12	0.974 (0.168)	0.679 (0.295)	1.013 (0.183)
13	0.741 (0.100)	0.740 (0.176)	0.738 (0.104)
14	0.472 (0.084)	0.349 (0.127)	0.506 (0.098)
15	0.449 (0.117)	0.365 (0.186)	0.461 (0.132)
16	0.368 (0.083)	0.307 (0.134)	0.382 (0.095)
17	0.646 (0.124)	0.405 (0.141)	0.746 (0.158)
18	0.371 (0.085)	0.277 (0.123)	0.397 (0.101)
19	0.821 (0.125)	0.727 (0.141)	0.926 (0.185)
20	0.843 (0.139)	0.549 (0.159)	0.994 (0.184)
21	1.871 (0.243)	1.268 (0.252)	2.188 (0.321)
22	0.498 (0.091)	0.268 (0.085)	0.667 (0.142)
23	1.940 (0.262)	1.071 (0.229)	2.431 (0.375)
24	0.729 (0.182)	0.462 (0.248)	0.813 (0.221)
25	0.438 (0.120)	0.341 (0.167)	0.477 (0.150)
26	1.113 (0.193)	0.770 (0.277)	1.198 (0.224)

The development of the CMF model form focused on the site-specific FI CMF values. There are two reasons for this focus. The first reason relates to the variation in crash reporting threshold between and within jurisdictions. An evaluation of PDO CMFs in the database indicated a wider variation in their value relative to that for the FI CMFs. This wider variation is likely to be the result of differences in the legal reporting threshold between jurisdictions and differences in the level of adherence to this threshold within jurisdictions. The wider variation in PDO CMFs can cloud the search for association between database variables and crash frequency. In contrast, FI crashes are more consistently reported among jurisdictions, and thus the FI CMFs provide a more reliable basis for model structure development.

A second reason for focusing model development on the FI CMFs (as opposed to total crashes) is that developing models using total crashes may increase the potential for creating suboptimal formulations for the CMF functions. A suboptimal formulation will bias the model predictions at some factor levels.

Recent research indicates that the underlying causal mechanisms for FI crashes can be different from those for PDO crashes. These important differences may be missed by the analyst when a CMF model is developed using total crashes. In contrast, they are more likely to be detected (and accounted for) when separate models are developed for FI crashes and for PDO crashes. Elvik (2011) discusses the potential for biased estimates and misleading conclusions when the wrong model form is calibrated (*9*).

For this analysis, the FI CMF model was developed first, followed by the PDO CMF model. The minimal influence of reporting threshold variation on the FI CMF values ensured that this approach would provide an effective means of identifying those factors that have a true effect on safety. Once the FI CMF model was developed, the same model form was used in the development of the PDO CMF model. The retention of a variable in either the FI or PDO model was based on consideration of its regression coefficients and overall model fit [i.e., p-value, direction of effect, practical significance, Akaike information criterion (AIC) value]. As a result of this approach, the "FI CMF model" and "PDO CMF model" have a similar structure and common variables.

As a final step, the FI CMF model form was used as a starting point for the development of a total crash CMF model. The total crash CMF model was developed to provide a general indication of the relative change in overall safety associated with interchange conversion. The FI CMF model and the PDO CMF model are recommended for use when quantifying the change in safety associated with a proposed conversion at a specific location.

A.2.4 Statistical Analysis Methods

The nonlinear regression procedure (NLMIXED) in the software package SAS was used to estimate the proposed model coefficients. This procedure was used because it supports the examination of nonlinear model forms, the specification of the distribution of the dependent variable, and the assessment of fixed versus random effects for selected model variables.

A maximum likelihood criterion was used in NLMIXED to quantify the regression model coefficients and variance scale parameter. The dependent variable of the regression model is the CMF, which is asymptotic to the lognormal distribution when the CMF is based on a large number of crashes (Griffin and Flowers, 1997) (*10*). For this application, the log-likelihood function for the lognormal distribution is described by the following equations:

$$LL_i = \frac{1}{2}\left[\frac{\left[\ln(CMF_i) - \ln\left(\widehat{CMF}_i\right) + 0.5\, v/w_i\right]^2}{v/w_i} + \ln\left(\frac{v}{w_i}\right) + \ln(2\pi) + 2\ln(CMF_i)\right] \quad \text{Equation A-1}$$

with

$$w_i = \left(\frac{CMF_i}{s_i}\right)^2 \quad \text{Equation A-2}$$

where

LL_i = log likelihood for observation i;
v = predicted variance scale parameter;

w_i = weight of CMF observation i (from Equation A-2);
CMF_i = value of CMF observation i;
$\widehat{CMF}_i$ = predicted value of the CMF for observation i;
s_i = standard error of CMF observation i; and
π = 3.14159 . . .

When the weight of each CMF observation is defined using Equation A-2, the variance term v in Equation A-1 represents a scale parameter. Values of this parameter equal 1.0 when the variance in the CMFs is explained by their standard error. Values of this parameter that exceed 1.0 indicate the presence of additional variability in the CMF observations (i.e., beyond that explained by their standard error).

Each observation in the regression database represents the CMF, its standard error, and selected geometric elements and features for one interchange conversion site.

A.2.5 Model Fit Statistics

The calibrated regression model can be evaluated using a Chi-Square analysis of the observed and predicted CMF values. The Chi-Square treatment and Chi-Square homogeneity statistics in Exhibit A-5 can be used for this purpose. The Chi-Square treatment is used to determine if the treatment affects crash frequency. The Chi-Square homogeneity is used to determine if the observed treatment effect varies from the predicted effect by an amount that is more than can be explained by just random variation (i.e., that some unexplained systematic influence is likely present such that the predicted effect may not accurately describe the treatment effect associated with each observation).

To assess the level of treatment influence or homogeneity, the computed Chi-Square statistic is compared with the Chi-Square distribution for the specified degrees of freedom. If the computed Chi-Square statistic for treatment has a probability less than 0.05, then the null hypothesis that the treatment has no effect is rejected (i.e., the treatment is likely to have some effect on crash frequency). If the computed Chi-Square statistic for homogeneity is less than 0.05, then the null hypothesis that the CMF observations are equal is rejected (i.e., there is likely some unexplained systematic variation present).

A useful measure of model fit is one that relates the residual error of the predicted value to the residual error associated with the use of an overall mean value. For normally distributed data with constant variance, the coefficient of determination R^2 is commonly used for this purpose. This coefficient has a similar interpretation when the log transform of the dependent variable is normally distributed with constant variance. Under these conditions, the following equations can be used to describe model fit.

Exhibit A-5. Chi-Square analysis of regression model.

Source	Chi-Square Statistic	Degrees of Freedom
Treatment (i.e., model)	$\sum w_i[\ln(\widehat{CMF}_i)]^2$	p + 1
Homogeneity	$\sum w_i[\ln(CMF_i) - \ln(\widehat{CMF}_i)]^2$	N − p − 1
Total	$\sum w_i[\ln(CMF_i)]^2$	N

Note: p = number of regression coefficients in model; N = number of CMF observations; “1” for predicted variance scale parameter.

$$R_t^2 = 1.0 - \frac{\sum w_i \left[\ln(CMF_i) - \ln\left(\widehat{CMF}_i\right)\right]^2}{\sum w_i \left[\ln(CMF_i) - \overline{L}\right]^2}$$ Equation A-3

with

$$\overline{L} = \frac{\sum W_i \ln(CMF_i)}{\sum w_i}$$ Equation A-4

where $\overline{L}$ is the weighted average value of the natural log of the CMF; and all other variables are previously defined.

A.2.6 Predictive Model Form

The general form of the CMF model is shown in the following equation. It is shown as a regression model with a calibration coefficient for each of several variables that describe selected geometric elements and features.

$$\widehat{CMF} = \exp\left[b_0 + b_1 N_{drop} + b_2 (S_l - 30) + b_3 (N_{lanes,a} - N_{lanes,b}) + b_4 (1 - 0.5 N_{s,b}) + b_5 I_{18} + b_6 I_9\right]$$

Equation A-5

where

$\widehat{CMF}$ = predicted CMF value;
N_{drop} = number of crossroad lanes dropped at the entrance ramp; applies to the DDI design (total for both travel directions; = 0, 1, 2), lanes;
S_l = speed limit for the crossroad through the DDI, mph;
$N_{lanes,a}$ = number of crossroad through lanes at the DDI (total for both travel directions), lanes;
$N_{lanes,b}$ = number of crossroad through lanes at the interchange before the conversion (total for both travel directions), lanes;
$N_{s,b}$ = number of signalized crossroad ramp terminals at the interchange before the conversion (= 0, 1, 2);
I_{18} = indicator variable for site 18 (= 1 if site 18; 0 for other sites);
I_9 = indicator variable for site 9 (= 1 if site 9; 0 for other sites); and
b_i = calibration coefficient *i*.

This model was estimated using the site-specific CMFs listed in Exhibit A-4. Separate versions of the model were estimated for FI CMFs, PDO CMFs and total-crash CMFs. The variables found to be correlated with CMF value are listed as variables in the model. Other variables were considered for inclusion in the model but were not retained because they were not statistically significant or the effect implied by the regression coefficient was not logical. Variables considered included skew angle, median type, median width, number of curves per direction, area type, and stop-line-to-stop-line distance.

At some DDIs, the outside lane of the crossroad is dropped at the entrance ramp (i.e., the outside crossroad lane becomes a turning roadway at the ramp and continues onto the ramp). The number-of-crossroad-lanes-dropped variable N_{drop} is used to describe this characteristic. None of the interchanges present before conversion to the DDI were noted to have a crossroad lane drop. Hence, this variable also describes the change in “number of lanes dropped” associated with the interchange conversion.

The speed-limit variable S_l was obtained from Google Earth Street View. The Street View images are fairly current and coincide with the time period in which the DDI is present. Information about the crossroad speed limit before the conversion was not available.

The number-of-crossroad-through-lanes variable N_{lanes} describes the number of lanes on the crossroad that serve vehicles traveling as a through movement. Each through lane can be traced as a continuous traffic lane through the interchange (including both crossroad ramp terminals).

The number-of-signalized-crossroad-ramp-terminals-at-the-interchange-before-the-conversion variable $N_{s,b}$ describes the traffic control type at the existing interchange. After conversion to the DDI, both terminals are signalized at the interchanges studied.

A.2.7 Model Calibration

The results of the model estimation process for FI CMFs are presented in Exhibit A-6. The *p*-value for the homogeneity Chi-Square statistic is 0.114. This value is larger than 0.05, so the null hypothesis is not rejected (i.e., it is unlikely that there is any systematic variation in the CMFs that is not explained by the model). The coefficient of correlation for the log-transformed data R_t^2 is 0.69. This value indicates that the model explains about 69% of the variation in the data.

The model coefficients are provided in the bottom half of Exhibit A-6. The *t*-statistics listed in the last column indicate a test of the hypothesis that the coefficient value is equal to 0.0. Those *t*-statistics with an absolute value larger than 2.0 indicate that the hypothesis can be rejected with the probability of error in this conclusion being less than 0.05. For the one variable in which the absolute value of the *t*-statistic is smaller than 2.0, it was decided that the variable was important to the model, and its trend was found to be logical and consistent with previous research findings (even if the specific value was not known with a great deal of certainty as applied to this database). The findings from an examination of the coefficient values and the corresponding CMF predictions are documented in a subsequent subsection.

Indicator variables for sites 9 and 18 were included in the regression model. The coefficient for site 18 variable is statistically significant. Its value indicates that the CMF value at site 18 is about 88% smaller than that at the other sites, all other factors being the same. This result cannot be explained by differences in area type, median width, skew angle, and other factors in the

Exhibit A-6. Model estimation results for fatal-and-injury crashes.

Statistics	Value	Degrees of Freedom	*p*-value	
Number of observations	26	N/A	N/A	
Model Chi-Square	93.4	7	0.001	
Homogeneity Chi-Square	26.6	19	0.114	
R_t^2	0.69	N/A	N/A	
Estimated Effect of...	**Variable**	**Coefficient Value**	**Standard Error**	**t-statistic**
Intercept	b_0	-1.1529	0.166	-6.96
Crossroad lane drops at DDI (crossroad to ramp)	b_1	0.3988	0.0715	5.58
DDI speed limit	b_2	0.0619	0.0108	5.72
Changing the number of crossroad through lanes	b_3	-0.2224	0.0539	-4.13
Changing the traffic control type	b_4	0.1820	0.206	0.88
Site 18: I-85 and Poplar Tent Rd.	b_5	-1.4955	0.512	-2.93
Site 9: US-60 and S Kansas Expy.	b_6	0.00		
Variance scale parameter	v	0.9954	0.275	3.62

database. It is likely due to factors at site 18 that are different from the other jurisdictions and not represented in the database (e.g., signing, pavement condition, weather, or curve radius).

The results of the model estimation process for PDO CMFs are presented in Exhibit A-7. The *p*-value for the homogeneity Chi-Square statistic is 0.001. This value is not larger than 0.05, so the null hypothesis is rejected (i.e., it is likely that there is some systematic variation in the CMFs that is not explained by the model). The coefficient of correlation for the log-transformed data R_t^2 is 0.68. This value indicates that the model explains about 68% of the variation in the data.

The model coefficients are provided in the bottom half of Exhibit A-7. The *t*-statistics listed in the last column indicate a test of the hypothesis that the coefficient value is equal to 0.0. Those *t*-statistics with an absolute value larger than 2.0 indicate that the hypothesis can be rejected with the probability of error in this conclusion being less than 0.05. For the one variable where the absolute value of the *t*-statistic is smaller than 2.0, it was decided that the variable was important to the model, and its trend was found to be logical and consistent with previous research findings (even if the specific value was not known with a great deal of certainty as applied to this database). The findings from an examination of the coefficient values and the corresponding CMF predictions are documented in a subsequent subsection.

Indicator variables for sites 9 and 18 were included in the regression model. The coefficient for each variable is statistically significant. Its value indicates that the CMF value at site 18 is about 85% smaller than that at the other sites, all other factors being the same. Similarly, the CMF value at site 9 is about 63% smaller than that at the other sites. These results cannot be explained by differences in area type, median width, skew angle, and other factors in the database. It is likely due to factors at sites 9 and 18 that are different from the other jurisdictions and not represented in the database (e.g., signing, pavement condition, weather, or curve radius).

The results of the model estimation process for crashes of all severities combined are presented in Exhibit A-8. The *p*-value for the homogeneity Chi-Square statistic is 0.001. This

Exhibit A-7. Model estimation results for PDO crashes.

Statistics	Value	Degrees of Freedom	*p*-value	
Number of observations	26			
Treatment Chi-Square	153	8	0.001	
Homogeneity Chi-Square	78.2	18	0.001	
R_t^2	0.68			
Estimated Effect of...	**Variable**	**Coefficient Value**	**Standard Error**	**t-statistic**
Intercept	b_0	-1.0437	0.190	-5.49
Crossroad lane drops at DDI (crossroad to ramp)	b_1	0.4176	0.0852	4.90
DDI speed limit	b_2	0.0800	0.0126	6.37
Changing the number of crossroad through lanes	b_3	-0.1558	0.0590	-2.64
Changing the traffic control type	b_4	0.3591	0.197	1.82
Site 18: I-85 and Poplar Tent Rd.	b_5	-1.8691	0.512	-3.65
Site 9: US-60 and S Kansas Expy.	b_6	-1.0045	0.378	-2.65
Variance scale parameter	v	2.9144	0.805	3.62

Exhibit A-8. Model estimation results for crashes of all severities combined.

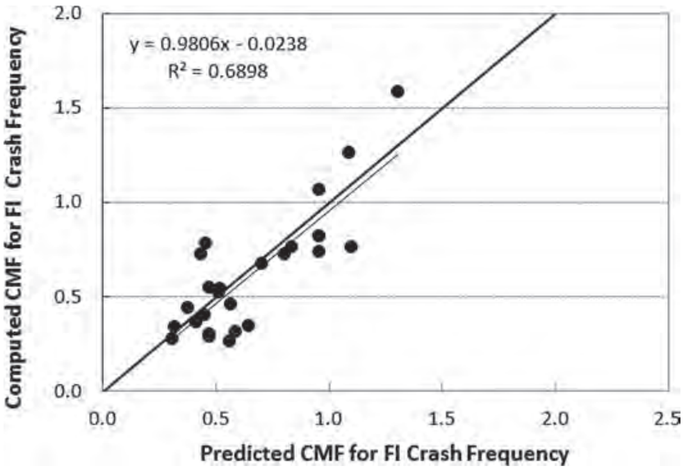
Statistics	Value	Degrees of Freedom	*p*-value	
Number of observations	26			
Treatment Chi-Square	180	8	0.001	
Homogeneity Chi-Square	83.0	18	0.001	
R_t^2	0.68			
Estimated Effect of...	**Variable**	**Coefficient Value**	**Standard Error**	**t-statistic**
Intercept	b_0	-1.0919	0.174	-6.25
Crossroad lane drops at DDI (crossroad to ramp)	b_1	0.4257	0.0808	5.27
DDI speed limit	b_2	0.0748	0.0116	6.43
Changing the number of crossroad through lanes	b_3	-0.1564	0.0558	-2.81
Changing the traffic control type	b_4	0.3538	0.185	1.91
Site 18: I-85 and Poplar Tent Rd.	b_5	-1.8330	0.480	-3.82
Site 9: US-60 and S Kansas Expy.	b_6	-0.7336	0.327	-2.24
Variance scale parameter	v	3.1097	0.860	3.61

value is not larger than 0.05, so the null hypothesis is rejected (i.e., it is likely that there is some systematic variation in the CMFs that is not explained by the model). The coefficient of correlation for the log-transformed data R_t^2 is 0.68. This value indicates that the model explains about 68% of the variation in the data.

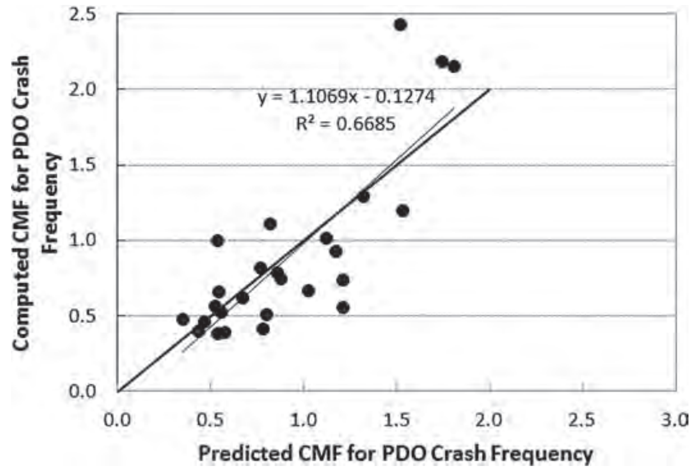
The model coefficients are provided in the bottom half of Exhibit A-8. The *t*-statistics listed in the last column indicate a test of the hypothesis that the coefficient value is equal to 0.0. Those *t*-statistics with an absolute value larger than 2.0 indicate that the hypothesis can be rejected with the probability of error in this conclusion being less than 0.05. For the one variable in which the absolute value of the *t*-statistic is smaller than 2.0, it was decided that the variable was important to the model, and its trend was found to be logical and consistent with previous research findings (even if the specific value was not known with a great deal of certainty as applied to this database). The findings from an examination of the coefficient values and the corresponding CMF predictions are documented in a subsequent subsection.

Indicator variables for sites 9 and 18 were included in the regression model. The coefficient for each variable is statistically significant. Its value indicates that the CMF value at site 18 is about 84% smaller than that at the other sites, all other factors being the same. Similarly, the CMF value at site 9 is about 52% smaller than that at the other sites. These results cannot be explained by differences in area type, median width, skew angle, and other factors in the database. It is likely due to factors at sites 9 and 18 that are different from the other jurisdictions and not represented in the database (e.g., signing, pavement condition, weather, or curve radius).

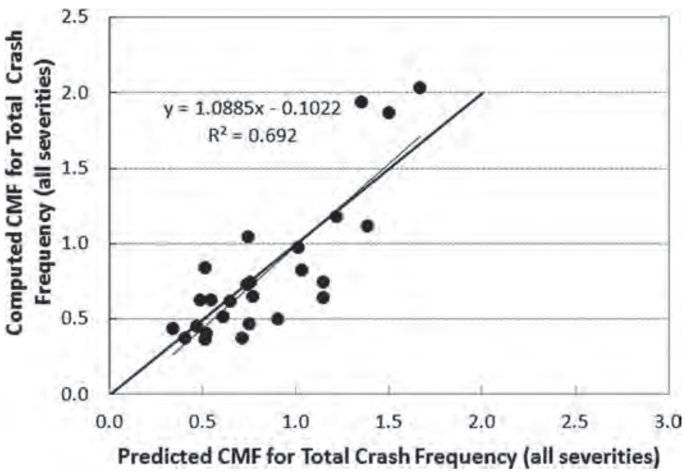
The fit of each model to the CMF data is shown in Exhibit A-9. This figure compares the predicted and reported crash frequency in the calibration database. The thick trend line shown represents a "y = x" line. A data point would lie on this line if its predicted and reported crash frequencies were equal. The shorter thin line corresponds to a best-fit linear regression model. The fact that this line is very near to the "y = x" line confirms the good fit of the predictive model (i.e., Equation A-5).



a. CMF comparison for FI CMFs.



b. CMF comparison for PDO CMFs.



c. CMF comparison for total-crash CMFs.

Exhibit A-9. Predicted versus reported CMFs.

A.2.8 Sensitivity Analysis

The coefficient values in the three preceding tables were used in Equation A-5 to compute the predicted CMF values by varying each of the equation's input variables in isolation. The results are shown in Exhibit A-10.

Exhibit A-10 is divided into four sections—one section for each of four input variables. The first section in the table lists the predicted CMF values when the number of crossroad through lanes is changed during the conversion. The values shown indicate that the addition of one through lane to the DDI reduces the FI CMF by 20%, the PDO CMF by 14%, and the total-crash CMF by 14%. This trend likely reflects the reduced density of traffic (i.e., increased vehicle spacing) as a result of the additional lane. This safety benefit from an increase in through lanes would likely be realized regardless of the form of interchange to which the location is converted. In fact, crashes would likely be reduced at the existing interchange if it were reconstructed to include additional crossroad through lanes.

The second section of Exhibit A-10 lists the predicted CMF values based on the number of crossroad lane drops at the DDI. The values shown indicate that dropping one through lane at the entrance ramp increases the FI CMF by 49%, the PDO CMF by 52%, and the total-crash CMF by 53%. This trend is likely a reflection of the increased lane-changing activity associated with a lane drop (especially a lane drop that occurs just after a horizontal curve).

Exhibit A-10. Single-factor sensitivity analysis.

Traffic Control Type before Conversion	Crossroad Speed Limit, mph	Change in Crossroad Through Lanes[1]	Crossroad Lane Drops[2]	CMF, FI	CMF, PDO	CMF, Total
Change in crossroad through lanes						
Signal	30	2	0	0.20	0.26	0.25
Signal	30	1	0	0.25	0.30	0.29
Signal	30	0	0	0.32	0.35	0.34
Number of crossroad lane drops at DDI						
Signal	30	0	0	0.32	0.35	0.34
Signal	30	0	1	0.47	0.53	0.51
Signal	30	0	2	0.70	0.81	0.79
Conversion from specific traffic control type to signalized DDI[3]						
Unsignalized	30	0	0	0.38	0.50	0.48
Signal	30	0	0	0.32	0.35	0.34
Crossroad speed limit						
Signal	25	0	0	0.23	0.24	0.23
Signal	30	0	0	0.32	0.35	0.34
Signal	35	0	0	0.43	0.53	0.49
Signal	40	0	0	0.59	0.78	0.71
Signal	45	0	0	0.80	1.17	1.03

Notes:
1. Number of through lanes at the DDI minus the number of through lanes at the interchange before conversion (i.e., = $N_{lanes,a} - N_{lanes,b}$). Total of both travel directions.
2. At some DDIs, the outside lane of the crossroad is dropped at the entrance ramp (i.e., the outside crossroad lane becomes a turning roadway at the ramp and continues onto the ramp). The value in the table describes the number of lanes that are dropped at the DDI. Total of both travel directions.
3. Traffic control type listed in column 1 corresponds to that in service at *both* crossroad ramp terminals before conversion to DDI. If one terminal is signalized and the other is unsignalized, then use Equation A-5 with $N_{s,b}$ = 1.

The third section of Exhibit A-10 lists the predicted CMF values based on a change in traffic control type as part of the conversion. The values shown indicate that converting from an unsignalized interchange to a signalized DDI increases the FI CMF by 20%, the PDO CMF by 43%, and the total-crash CMF by 42%. This trend is likely a reflection of the increase in crash rate (especially the less severe rear-end crash rate) when an unsignalized intersection is converted to signal control. This degradation in safety associated with the change in control type would likely be realized regardless of the form of interchange to which the location is converted. In fact, crashes would likely be increased at the existing interchange if its crossroad ramp terminals were converted from unsignalized to signalized control.

The last section of Exhibit A-10 lists the predicted CMF values for various crossroad speed limits. The CMF values shown indicate that interchanges with a 5 mph higher speed limit are associated with FI CMF values that are larger by 27%, PDO CMF values larger by 33%, and total-crash CMF values larger by 31%.

The CMFs in the last section of Exhibit A-10 describe the best estimate of the influence of DDI design on safety. It is noted that the total-crash CMF associated with a speed limit of 45 mph is greater than 1.0, which suggests that the conversion to a DDI with a 45-mph crossroad is likely to increase crash frequency—most notably, it will increase the PDO crash frequency. Fortunately, the FI crash frequency is likely to decrease for this speed limit.

A.2.9 Summary

This re-examination of the site-specific CMFs reported by Nye et al. (2019) led to the development of a CMF function for each of three severity categories (i.e., FI, PDO, and all severities combined) (*6*). Each function included variables that quantified the change in CMF value associated with a change in key geometric features. The analysis results indicate that the conversion to DDI is often associated with a reduction in crashes; however, crash frequency may be increased for combinations of higher crossroad speed limit, one or more crossroad lanes dropped at the DDI, and the existing interchange having unsignalized terminals.

The use of CMF functions was found to explain more than one-half of the systematic variability in the CMF values. However, it is believed that there is still some unexplained systematic variable in the predicted CMF values. Data for additional sites will help in this investigation by increasing the sample size. Also, some investigation of the AADT data provided by Nye et al. (*6*) indicates that there may be some correlation between the CMF value and traffic volume level. However, the crossroad AADT data for the before period and after period at each site will need to be obtained before this investigation can be undertaken.

The total crash CMF model is offered to provide a general indication of the relative change in overall safety associated with interchange conversion. However, the FI CMF model and the PDO CMF model are recommended for use when quantifying the change in safety associated with a proposed conversion at a specific location.

A.3 References

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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