JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Evaluation of Alternative Intersections and Interchanges

Volume II — Diverging Diamond Interchange Signal Timing

Christopher M. Day, Amanda Stevens,
James R. Sturdevant, Darcy M. Bullock

SPR-3830 • Report Number: FHWA/IN/JTRP-2015/27 • DOI: 10.5703/1288284316012

RECOMMENDED CITATION

Day, C. M., Stevens, A., Sturdevant, J. R., & Bullock, D. M. (2015). *Evaluation of alternative intersections and interchanges: Volume II—Diverging diamond interchange signal timing* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2015/27). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316012

AUTHORS

Christopher M. Day, PhD, PE
JTRP Senior Research Scientist
Lyles School of Civil Engineering, Purdue University

Amanda Stevens, PE
Indiana Department of Transportation

James R. Sturdevant, PE
Director, Traffic Management Division
Indiana Department of Transportation

Darcy M. Bullock, PhD, PE
Professor of Civil Engineering
Lyles School of Civil Engineering, Purdue University
(765) 494-5027
tarko@purdue.edu
Corresponding Author

ACKNOWLEDGMENTS

The authors wish to thank the following individuals for their valuable contributions to the research presented here: Alex Hainen (University of Alabama), Howell Li (Purdue University), Steve Lavrenz (Purdue University), Eric Miller (Indiana DOT), Jamie Mackey (Utah DOT), Matt Luker (Utah DOT), and Mark Taylor (Utah DOT). This project was made possible by funding from the Indiana Department of Transportation through the Joint Transportation Research Program co-administered by Purdue University.

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at: http://docs.lib.purdue.edu/jtrp/

NOTICE

COPYRIGHT

Print ISBN: 978-1-62260-380-0
ePUB ISBN: 978-1-62260-381-7

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2015/27		

4. Title and Subtitle	5. Report Date
Evaluation of Alternative Intersections and Interchanges: Volume 2—Diverging Diamond Interchange Signal Timing	December 2015
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Christopher M. Day, Amanda Stevens James R. Sturdevant, Darcy M. Bullock	FHWA/IN/JTRP-2015/27
9. Performing Organization Name and Address	**10. Work Unit No.**
Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051	
	11. Contract or Grant No. SPR-3830
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

This report presents findings from field studies of operations at diverging diamond interchanges (DDIs) in Salt Lake City, Utah and Fort Wayne, Indiana. These discuss optimization of signal offsets both within the DDI, and with the DDI integrated as part of an arterial corridor. Optimization of Fort Wayne, Indiana corridor comprising the DDI and three neighboring intersections yielded an annualized user benefit of $564,000, when assessing origin-destination paths both along the arterial and for movements to and from the freeway. This is the first field study of DDI offset optimization with neighboring intersections. Additionally, a pilot study was carried out in Salt Lake City on a new phasing scheme that incorporated a “holdback” phase into the signal sequence that delayed vehicles exiting the ramp in order to better coordinate their arrival at the downstream intersection, increasing the percent on green from 53% to 92%. The report concludes with a discussion of practical issues pertaining to DDI signal timing and provides a series of guidelines to assist in the design of new signal timing plans for future DDI deployments.

17. Key Words	18. Distribution Statement
diverging diamond, signal timing, link pivot offset optimization	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	40	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

ALTERNATIVE INTERSECTIONS AND INTERCHANGES: VOLUME II—DIVERGING DIAMOND INTERCHANGE SIGNAL TIMING

Introduction

Diverging diamond interchanges (DDIs) have been growing in usage over the past few years and have gained considerable attention and interest. The advantage of the DDI over a conventional diamond interchange is that DDIs eliminate the need for left turn phases at the two intersections of the diamond, while occupying roughly the same geometric footprint as the conventional diamond. At the beginning of this project, no DDIs had yet been constructed in Indiana, and there was a need to evaluate methods of signal timing for them. Also, at the beginning of this project there had not yet been any studies nationally on coordinating DDIs with neighboring intersections along an arterial. There is still relatively little guidance on phase configuration for DDIs, especially with pedestrians. This project report includes results from a field study of an existing DDI in Utah, a second field study of Indiana's first DDI in Fort Wayne (which is the first field study of optimizing signal offsets in a corridor including a DDI), a simulation comparison of DDI signal timing strategies, and guidelines for DDI phasing with pedestrians (including both interior and exterior pedestrian paths).

Findings

The Salt Lake City field study investigated operations at SR 201 and Bangerter Highway. The study looked at offset optimization within the DDI, as well as two alternative signal timing options, and demonstrated the option of prioritizing alternative movements, validated the prediction model based on high resolution data, and showed the range of possible timing options. Alternative "two-phase" and "three-phase" schemes were examined. It was found that the three-phase scheme permitted the development of a signal timing plan that could accommodate two platoons at a downstream intersection, whereas the two-phase scheme forced a choice between either of those two platoons. Implementation of the three-phase operation increased the percentage on green from 53% to 92%.

The Fort Wayne study is the first field study to examine offset optimization in a corridor incorporating a DDI. The study examined a five-intersection system around the interchange of SR 1 and I-69 in Fort Wayne, Indiana. An existing offset optimization methodology was applied to the DDI, incorporating a method for extracting the ring displacement parameter from the suggested offset adjustments. Evaluation of the timing was done using a network of Bluetooth vehicle sensors that considered not only the arterial through movements, but also origin-destination paths leading to and coming from the freeway. An estimation of user costs related to the observed travel times and their reliability showed an annualized benefit of $564,000. Full details are provided in the reprint included in Appendix B.

The instant report includes a discussion of practical issues related to DDI signal timing. The clearance phase requirements, and how to implement these in different controller types, are discussed in detail. Guidelines for signal phasing and several draft template timing plan designs have been prepared for a variety of circumstances, including both inside and outside pedestrian crossings. Finally, software modeling for optimizing timing plans are discussed.

Three strategies for cycle length selection have been identified and compared with one other using a VISSIM simulation of a DDI with two neighboring intersections under six different traffic scenarios. The study outcomes agree with the field comparison of two- and three-phase operations in Utah, in that three-phase operations improve coordination within an interchange. However, the study went further and examined overall corridor operations. When comparing overall interchange and corridor operations, a half-cycling strategy yielded the lowest user cost and the lowest average delay for most movements (although three-phase does reduce delays on the movements exiting the DDI). From this outcome, it is recommended to use a half-cycling strategy where possible. This is the current strategy used at the Fort Wayne interchange.

CONTENTS

1. PROJECT OVERVIEW 1

2. FINDINGS ON DDI SIGNAL TIMING. 1
2.1 Signal Timing at Bangerter Highway, Salt Lake City, Utah 1
2.2 Signal Timing at SR 1 and I-69, Fort Wayne, Indiana. 5

3. DDI SIGNAL PHASING AND TIMING GUIDELINES. 8
3.1 Literature Review. 8
3.2 Movements and Clearance Times. 9
3.3 Implementation in Fort Wayne 12
3.4 Accommodation of Pedestrians 13
3.5 Modeling of DDIs in Optimization Software 24
3.6 DDI Cycle Length Selection 24

4. CONCLUSIONS 34

REFERENCES 34

APPENDICES
Appendix A: Reprint of "High-Resolution Controller Data Performance Measures for Optimizing Diverging Diamond Interchanges and Outcome Assessment with Drone Video" 36
Appendix B: Reprint of "Extending Link Pivot Offset Optimization to Arterials with Single Controller Diverging Diamond Interchange" 36

LIST OF TABLES

Table Page

Table 2.1 Reductions in user costs (positive is decrease; bold is improvement). Values in thousands of US dollars 8

Table 3.1 Grouping of movements into phases at the DDI and assignment of basic phase numbers 10

Table 3.2 Explanation of draft phase designs for DDIs 25

Table 3.3 Turning movement counts by scenario. Shaded rows indicate the arterial through movements 30

Table 3.4 Average delay (s/veh) by movement for signalized DDI movements. The strategy with the lowest average delay for the movement within each scenario is highlighted in bold 33

LIST OF FIGURES

Figure	Page
Figure 2.1 SR 201 and Bangerter Highway, Salt Lake City, Utah	2
Figure 2.2 Offset optimization within the DDI	3
Figure 2.3 “2-phase” versus “3-phase” DDI operation	4
Figure 2.4 SR 1 and Interstate 69 Exit 316 interchange, Fort Wayne, Indiana, and neighboring intersections. The blue numbered boxes show the location of Bluetooth monitoring equipment	5
Figure 2.5 Prediction of conditions after offset and ring displacement adjustments for single-controller operation. Results are shown for the midday timing plan	6
Figure 2.6 Change in percent on green; 5 days before optimization versus 5 days after optimization: (a) Westbound and (b) Eastbound	7
Figure 3.1 Diverging diamond interchange. Callouts indicate the locations of vehicle-vehicle conflict points (1, 2, 3, etc.). Letters indicate vehicular movements (a, b, c, etc.)	9
Figure 3.2 Clearance distances for a DDI crossover through movement	10
Figure 3.3 DDI template scheme without pedestrians; option A: delayed overlaps	11
Figure 3.4 DDI template scheme without pedestrians; option B: clearance phases	12
Figure 3.5 SR 1 and Interstate 69 Exit 316 interchange, Fort Wayne, Indiana	13
Figure 3.6 Views from the arterial approaches on Fort Wayne DDI	14
Figure 3.7 Options for serving pedestrians in a DDI	15
Figure 3.8 DDI template scheme with inside pedestrian crossing; option A: delayed overlaps	16
Figure 3.9 DDI template scheme with inside pedestrian crossing; option B: clearance phases	17
Figure 3.10 DDI template scheme with inside pedestrian crossing, modified for 4-ring single controller; option A: delayed overlaps	18
Figure 3.11 DDI template scheme with inside pedestrian crossing, modified for 4-ring single controller; option B: clearance phases	19
Figure 3.12 DDI template scheme with outside pedestrian crossing and non-conflicting on-ramp turning movements; option A: delayed overlaps	20
Figure 3.13 DDI template scheme with outside pedestrian crossing and non-conflicting on-ramp turning movements; option B: clearance phases	21
Figure 3.14 Simplified DDI template scheme with outside pedestrian crossing and conflicting on-ramp turning movements; option A: delayed overlaps	22
Figure 3.15 Simplified DDI template scheme with outside pedestrian crossing and conflicting on-ramp turning movements; option B: clearance phases	23
Figure 3.16 Modeling of the DDI in optimization software	26
Figure 3.17 VISSIM model for comparing DDI cycle lengths	27
Figure 3.18 Westbound vehicle trajectories for different DDI cycle length strategies	28
Figure 3.19 PCDs for different DDI cycle length strategies (Westbound at Int. 2)	29
Figure 3.20 Arrivals on green by scenario and cycle length strategy, segmented by movement. The total number of arrivals on green are shown at the bottom. The strategy within each scenario having the greatest number is highlighted in bold	31
Figure 3.21 O-D paths used for user cost estimation	32
Figure 3.22 Annualized user costs for all of the O-D travel times considered for each scenario under each cycle length strategy. The strategy with the lowest total user cost is highlighted in bold. The bars show the breakdown of user cost by O-D path type	33

1. PROJECT OVERVIEW

This report summarizes the work done for a component of research project SPR-3830 that focused on signal timing at diverging diamond interchanges (DDIs). This document is provided as a second volume of the SPR-3830 report.

DDIs, also called "double crossover diamonds" (DCDs), have been growing in usage over the past few years and have gained considerable attention and interest. The advantage of the DDI over a conventional diamond interchange is that they eliminate the need for left turn phases at the two intersections of the diamond, while occupying roughly the same geometric footprint as the conventional diamond. In contrast, single-point urban interchanges (SPUIs) replace the two intersections with a single one, but are typically more difficult to construct, with overpasses in particular requiring very large bridge decks.

From a signal timing perspective, DDIs have some advantages and some disadvantages. The primary advantage is the elimination of left turn phases. In theory, this enables each of the two crossover intersections to be operated as a simple "two-phase" signal. While there are some nuances regarding the clearance times, there are indeed only two splits that have to be balanced against each other at each intersection. However, the *disadvantage* is that the two intersections have to be operated similar to what is called a "split phased" intersection. That is, the opposing through movements have to be operated sequentially rather than in parallel. This makes the task of coordinating traffic along the arterial challenging. At the time when this study was initiated, there was no literature that discussed DDI optimization along a corridor, and currently there is still rather little "practice ready" material regarding DDI timing in general. That is, there is not much guidance that a practitioner can immediately use with the tools at his or her disposal. This report aims to change this.

This report contains two contributions. One is a summary of findings from two field studies, both of which have been (or will be) presented Transportation Research Board (TRB) annual meeting (Day, Lavrenz, Stevens, Miller, & Bullock, 2016; Hainen et al., 2015). This is presented in Section 2. These studies focus on signal timing options at constructed DDIs in Utah and Indiana. The second contribution is a discussion of practical considerations and basic guidelines for signal timing at DDIs. This is presented in Section 3.

2. FINDINGS ON DDI SIGNAL TIMING

2.1 Signal Timing at Bangerter Highway, Salt Lake City, Utah[1]

In 2014, there was not yet an operational DDI that could be studied in Indiana, so the research team worked with the Utah Department of Transportation (UDOT) to conduct research at one of their constructed DDIs. The research team traveled to the site and conducted studies on site over several days, focusing on ways to improve traffic flow between the two intersections of the interchange.

Figure 2.1 shows a map of the DDI with detail of the north and south crossover intersections. The figure includes a ring diagram showing how the signal is timed using a single-controller scheme, with the north intersection operated by Ring 2 and the south intersection operated by Ring 1. The offset between the two intersections is the most important quantity that governs the relationship between movements leaving each intersection and their arrival at the next. Also importantly, the odd-numbered phases are used to provide additional clearance times for the ramp movements (as discussed in more detail in Chapter 3).

The study initially set out to find the best offset for maximizing the total amount of arrivals on green at both movements exiting the DDI. Figure 2.2 shows the results of this analysis, showing the predicted percentage on green (northbound, Figure 2.2a; southbound, Figure 2.2b) and total number of arrivals on green (northbound, Figure 2.2c; southbound, Figure 2.2d), as well as the interchange percent on green (Figure 2.2e). The objective of optimization is to choose a common *x*-axis value (offset adjustment) that maximizes the dark black "TOTAL" curve. However, this curve is a sum of the two thin-line curves that represent the vehicles from the two upstream movements coming from the other crossover intersection. As Figure 2.2a and Figure 2.2b show, it is possible to progress 100% of the vehicles from either movement, but only when *minimizing* the percent on green from the other movement. Figure 2d shows that the maximum number of arrivals on green is about the same for the "upstream thru" vehicles as for the "upstream ramp" vehicles. One could then adjust the offset to prioritize either traffic stream. This was done in the field by applying an adjustment of +30 seconds, which validated the prediction (the full details are provided in Appendix A).

Note that the optimal adjustment for maximizing arrivals on green for one particular traffic stream does not do so for the others. An adjustment of +30 maximizes the southbound "upstream ramp" traffic (Figure 2.2d), but Figure 2.2c shows that this adjustment is poor for both northbound traffic streams. In fact, the +30 adjustment *minimizes* the total intersection percent on green (Figure 2.2e). Similar outcomes result from other potential adjustments, such as +55 to maximize the northbound thru traffic. The result is that the overall percent on green curve is relatively flat (Figure 2.2e). The maximum interchange percent on green is reached with an offset adjustment of +0, meaning that the original offset was "optimal" in terms of maximizing total intersection percent on green. However, a view of Figure 2.2a and Figure 2.2b shows that this results in sub-optimal performance on all four individual traffic streams. Of course, it is often challenging to obtain

[1]This work was also partly supported by Pooled Fund Study TPF-5(258) on signal performance measures.

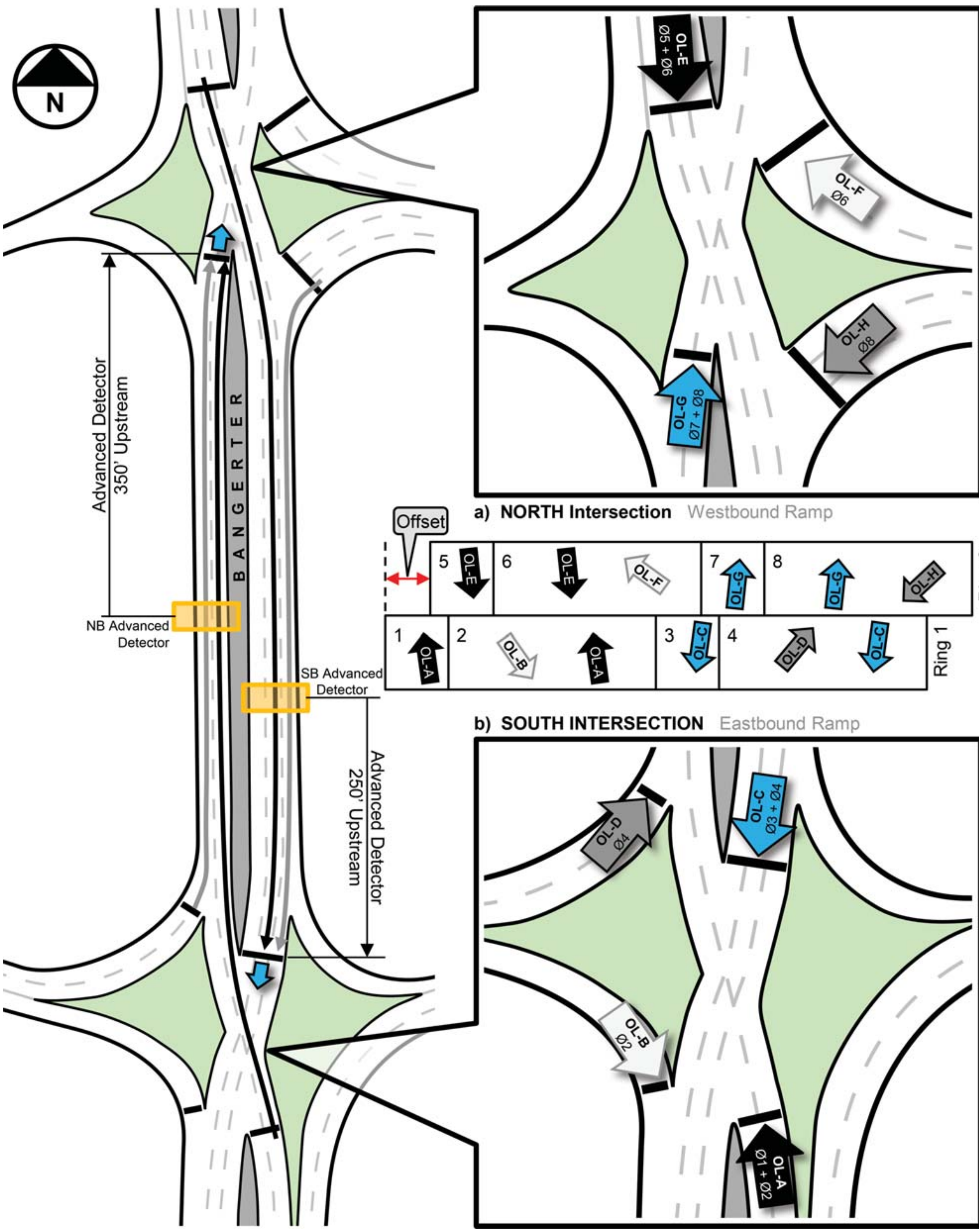


Figure 2.1 SR 201 and Bangerter Highway, Salt Lake City, Utah.

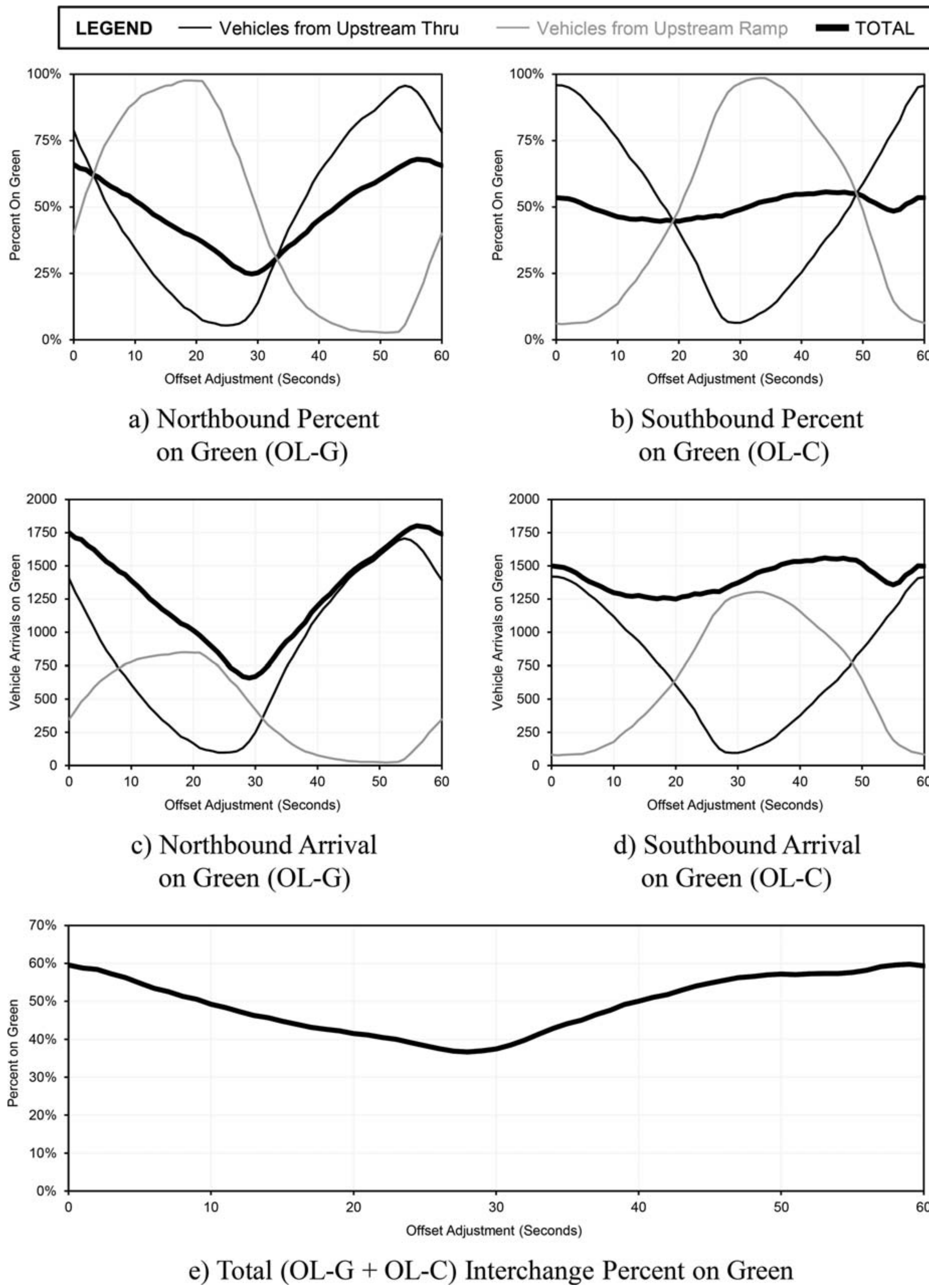


Figure 2.2 Offset optimization within the DDI.

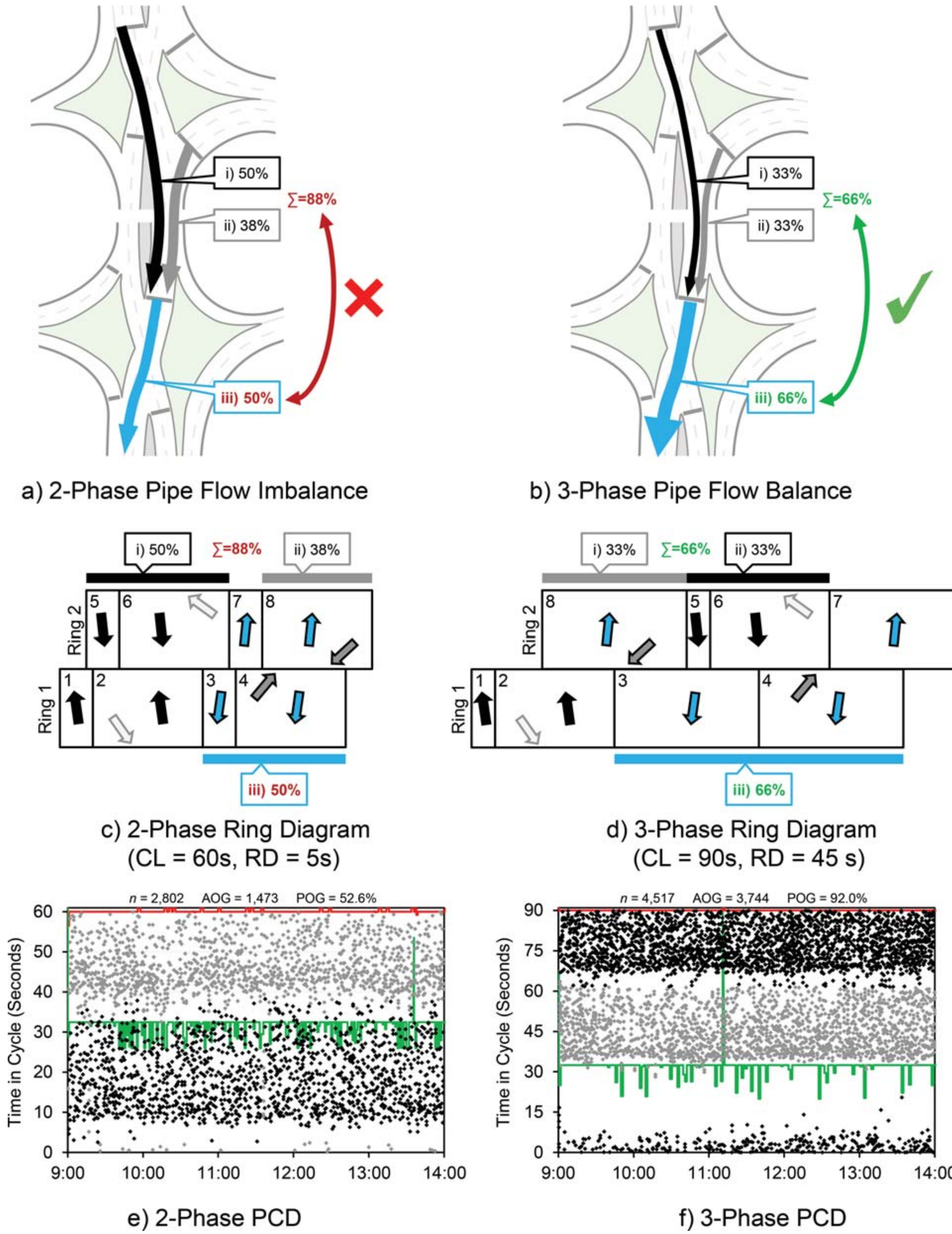


Figure 2.3 "2-phase" versus "3-phase" DDI operation.

good two-way progression in signal coordination in general, but the DDI provides a relatively clean cut example of the origins and destinations of traffic.

One reason for this intersection is due to an imbalance of inflows and outflows between the two intersections of the interchange. The two-phase scenario leads to there being a near-constant inflow of traffic from the ramp and arterial through movements into one of the crossed-over paths of the DDI. However, at the downstream intersection, the signal is green only 50% of the time. By extending the "clearance" phases to add in a "holdback" phase, and increasing the cycle length from 60 to 90 seconds, it is possible to change this dynamic.

Figure 2.3 illustrates the difference between the existing "2-phase" and the new "3-phase" configurations. As Figure 2.3a shows, the initial situation for the southbound movement was a total of 88% of the cycle belonging to upstream green intervals that fed traffic into the downstream movement. Figure 2.3b shows that the longer cycle length changes this to 66% of the cycle for upstream green, and 66% of the cycle for downstream green. Figure 2.3c shows the existing "2-phase" ring diagram, as shown previously, while Figure 2.3d shows the "3-phase" ring diagram. Note that phases 3 and 7 have been increased to provide an interval of time where the ramp left turn movements are held back. This better aligns their departures with the downstream green.

The difference in operations is illustrated by the Purdue Coordination Diagrams (PCDs) in Figure 2.3e and Figure 2.3f. These diagrams show the relationship between vehicle arrivals and the phase status at time of arrival. Each "dot" represents one vehicle arrival, with the vertical position showing the time in cycle, and the horizontal position showing time of day. The red and green lines superimposed on this plot show the status of green. Dots above the green line represent arrivals in green, while dots below the green line represent arrivals on red. Under "2-phase" operation, there are two platoons that occupy the entire cycle, making it impossible to capture both under one green interval (Figure 2.3e). However, with "3-phase" operation, both of these platoons can now be scheduled to arrive on green (Figure 2.3f). This increased the percent on green from 53% to 92%.

While specific conditions at the DDI would determine the need for considering a 2-phase versus 3-phase operating scheme, the results demonstrate the potential for 3-phase operation in to better accommodating flows from multiple input sources.

The complete paper is included in Appendix A.

2.2 Signal Timing at SR 1 and I-69, Fort Wayne, Indiana

The next study investigated operation at the first DDI to be opened in Indiana, which is at the interchange of SR 1 and I-69 at Exit 316. This is the first field study of DDI offset optimization with neighboring intersections. The focus of this study was on the optimization of the DDI as an integrated part of an arterial corridor. Figure 2.4 shows a map of the 5-intersection study corridor, which incorporated the two nearest intersections on SR 1 to the east of the interchange, as well as the first intersection to the west of the interchange, which is operated by the City of Fort Wayne.

To optimize corridor offsets, the Link Pivot algorithm (Day & Bullock, 2011) was applied. The full paper details a method for converting the individual intersection

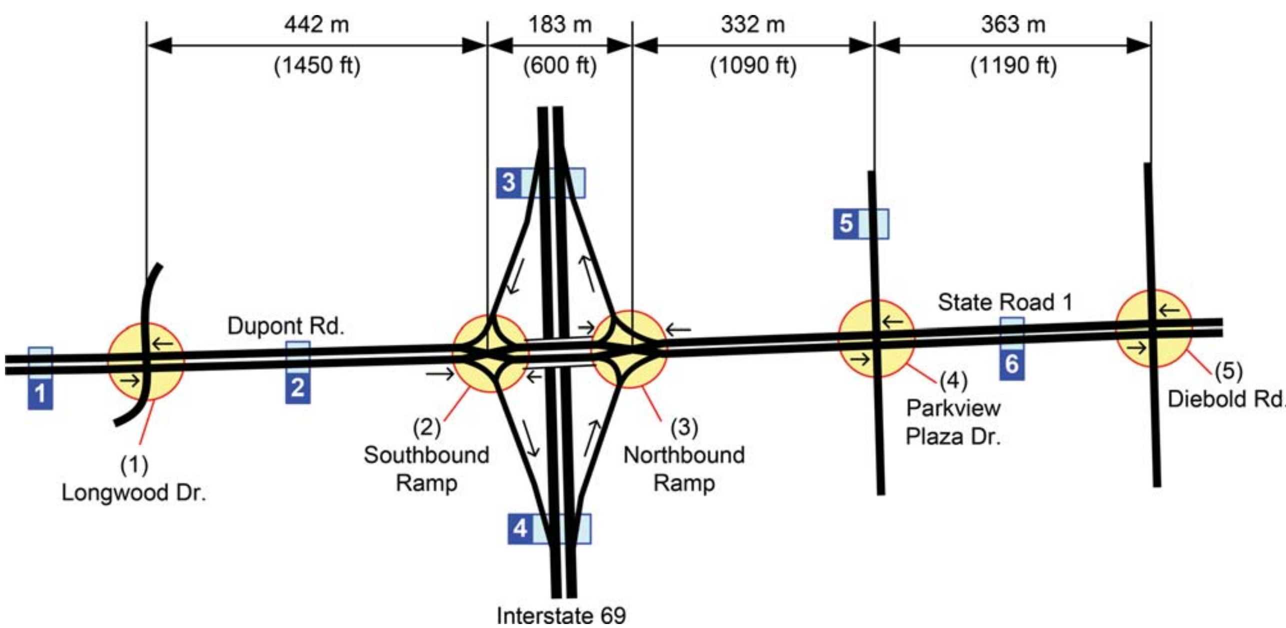


Figure 2.4 SR 1 and Interstate 69 Exit 316 interchange, Fort Wayne, Indiana, and neighboring intersections. The blue numbered boxes show the location of Bluetooth monitoring equipment.

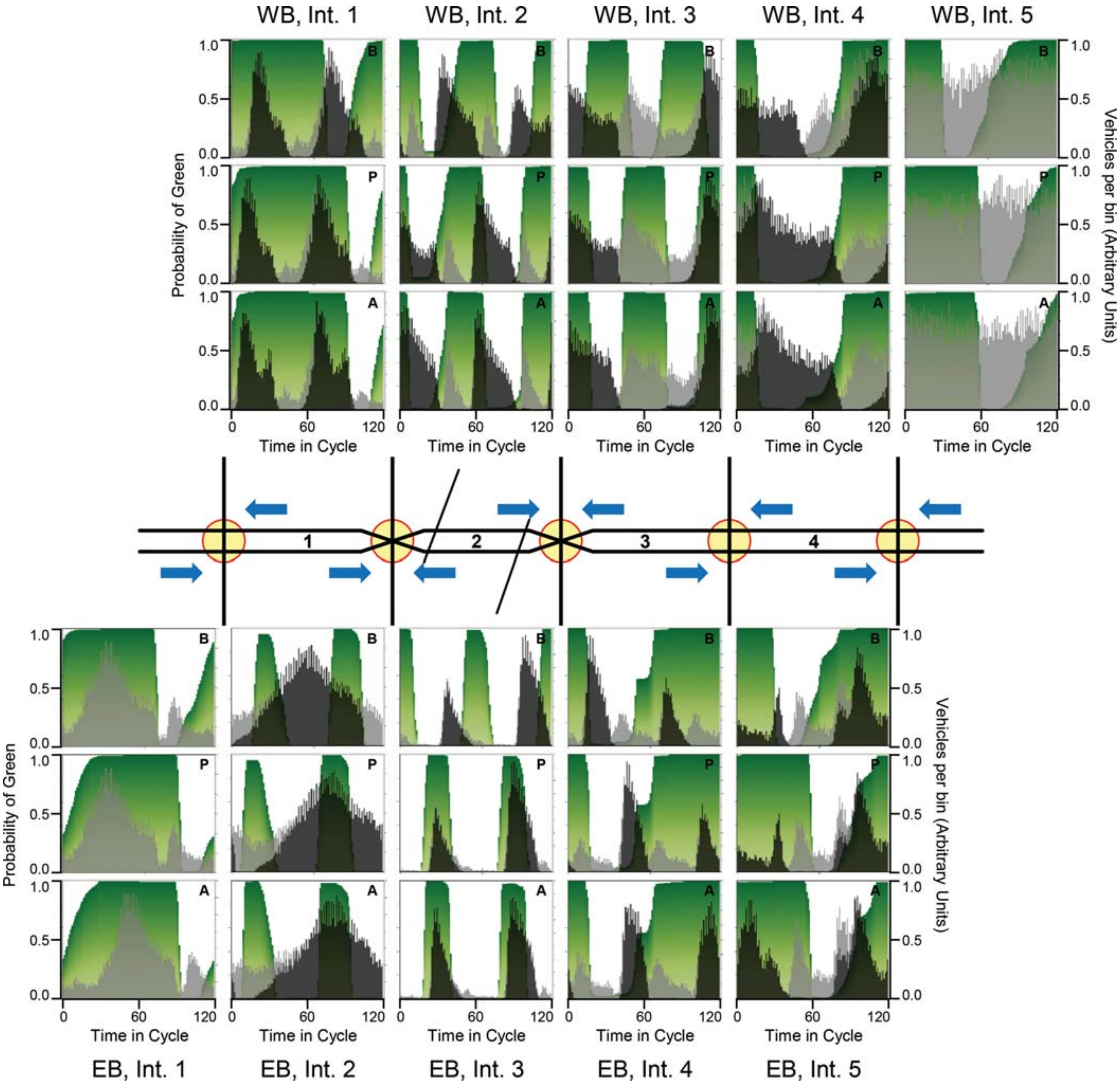


Figure 2.5 Prediction of conditions after offset and ring displacement adjustments for single-controller operation. Results are shown for the midday timing plan.

offsets into the necessary offset and ring displacement parameters needed for single-controller diamond. The process is illustrated in Figure 2.5, which displays flow profiles for the ten signalized approaches before optimization ("B"), predicted after optimization ("P"), and actual after implementation of the optimized settings ("A"). In each of these plots, the gray lines show the distribution of vehicle arrivals, while the green region shows the probability that the signal is green at that time. The dark gray lines show vehicles originating from an upstream through movement, while the light gray lines show vehicles originating from other movements.

Several things can be observed from these plots:

- Note that there are two blocks of green at the Int. 2 and Int. 3 approaches. This is because the DDI operates at half of the cycle length as the rest of the corridor.
- Similarly, the intersections that receive traffic from the DDI (WB, Int. 1 and EB, Int. 4) have several platoons per cycle that originate from the half-cycling that occurs at the DDI crossover intersections.
- The movements interior to the DDI (WB, Int. 2 and EB, Int. 3) show very different characteristics from Bangerter. In the westbound direction, the upstream-through vehicles (dark gray) dominate, while there is a smaller

platoon of non-upstream-through vehicles (light gray—equivalent to "ramp" traffic in the previous study). For the eastbound direction, only one platoon can be seen.

- The other approaches generally have one primary platoon and one green period.

Comparing the before, predicted, and after distributions reveals the outcome of the optimization process. Pairs of approaches are stacked in columns in Figure 2.5 to highlight the tradeoff between the two directions in deciding the optimal offset adjustment affecting each link. The goal of optimization is to find one adjustment that maximizes offsets for *both* directions. In the example shown in Figure 2.5, there were some key tradeoffs. For example, within the DDI (WB, Int. 2 and EB, Int. 3), the prior condition tended to favor westbound progression. Note that WB, Int. 2 "B" has most of its traffic aligned with green while EB, Int. 3 "B" is misaligned. Optimization reversed this situation to some degree, favoring EB, Int. 3.

The changes in the percent on green are shown in Figure 2.6. These are broken down into changes for the westbound and eastbound movements at each of the five intersections, by time of day. The upward-pointing green bars show increases while the downward-pointing red bars show decreases. Overall, the chart exhibits considerably more green than red, meaning that there was a net improvement. This is unsurprising given that the goal was to maximize this value. In general, decreases are associated with a directional tradeoff.

The outcome was independently assessed by measuring travel times using Bluetooth vehicle re-identification (Day, Wasson, Brennan, & Bullock, 2012). Sensors were deployed throughout the system as shown in Figure 2.4. This enabled travel times to be measured for a variety of origin-destination paths, rather than the two arterial routes that are normally considered when evaluating arterial coordination. Routes to and from the freeway were also included. Additionally, the analysis considered not only the overall travel times on these routes, but the reliability of the travel time as well. These were applied to a methodology to compute the user benefit.

Table 2.1 shows the annualized changes in user costs from the optimization process. These costs are shown for a variety of routes through the system and for different times of day. The AM peak period saw an increase in user

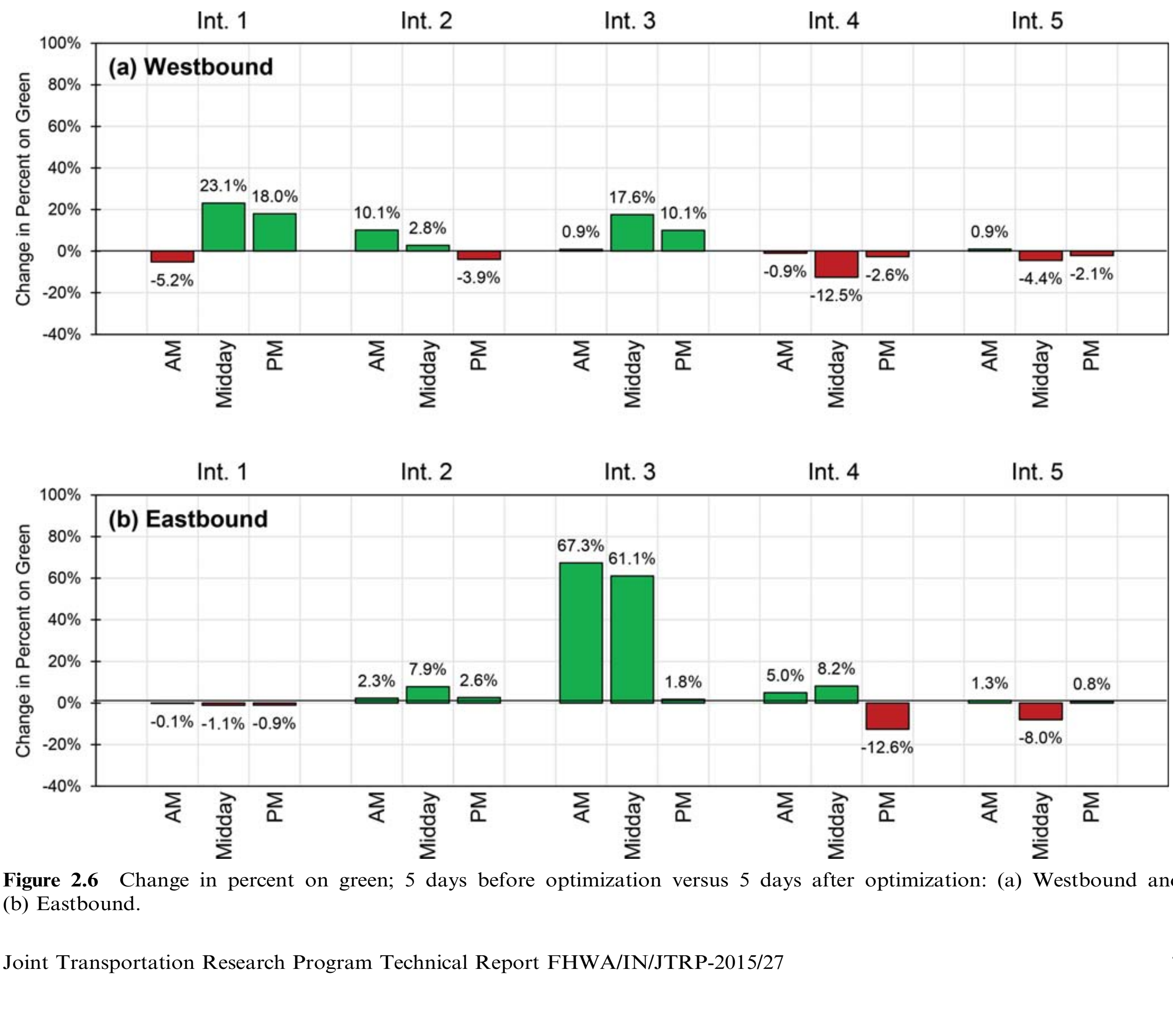


Figure 2.6 Change in percent on green; 5 days before optimization versus 5 days after optimization: (a) Westbound and (b) Eastbound.

TABLE 2.1
Reductions in user costs (positive is decrease; bold is improvement). Values in thousands of US dollars.

	AM			Midday			PM			
Path	**Before**	**After**	**Change**	**Before**	**After**	**Change**	**Before**	**After**	**Change**	**Total Benefit**
Along SR1/ Dupont Rd.										
1 to 6	229	214	**15**	1062	851	**211**	587	640	-54	**173**
6 to 1	92	210	-118	1093	1091	**3**	552	426	**126**	**11**
1 to 5	108	152	-45	517	408	**109**	132	168	-36	**28**
5 to 1	63	88	-25	636	550	**87**	310	273	**37**	**99**
Total			-172			**410**			**74**	**312**
To I-69										
1 to 3	184	177	**7**	741	641	**99**	484	373	**111**	**217**
1 to 4	358	310	**48**	1232	1357	-125	675	771	-97	-174
6 to 3	171	209	-38	631	560	**71**	362	278	**84**	**116**
6 to 4	353	329	**24**	1309	1240	**70**	717	635	**82**	**175**
5 to 3	78	132	-55	402	356	**46**	275	134	**141**	**132**
5 to 4	84	168	-84	662	731	-69	550	494	**56**	-98
Total			-98			**91**			**378**	**370**
From I-69										
3 to 1	137	165	-28	689	547	**143**	232	282	-50	**65**
3 to 6	138	146	-8	383	493	-111	265	233	**32**	-87
3 to 5	79	142	-62	352	326	**27**	199	73	**126**	**90**
4 to 1	91	196	-104	778	842	-65	465	360	**106**	-63
4 to 6	182	178	**4**	754	968	-215	559	637	-78	-289
4 to 5	205	287	-82	655	587	**67**	368	188	**180**	**166**
Total			-280			-153			**315**	-118
Grand Total			-550			**347**			**767**	**564**

costs, due to increases in travel time and variability, which occurred in spite of substantial increase in percent on green. The reason for the decrease is possibly attributable to a slight increase in volume during the study period. However, the other two times of day saw substantial improvements in the measured performance, as travel times decreased and became more reliable. The net result was an annualized user benefit of $564,000 for the three times of day considered. The results suggest that the method holds promise, while there remain opportunities for further improvement.

The complete paper is included in Appendix B.

3. DDI SIGNAL PHASING AND TIMING GUIDELINES

This section presents a detailed discussion of issues related to signal timing of DDIs. At the time when this project was initiated, there was very little literature on this topic, and this is still largely the case at the time of this report, although a few new studies have appeared in the past year. The following discussion discusses some of the critical issues in DDI signal timing in detail and provides some tentative recommendations.

3.1 Literature Review

A few alternative schemes for phase assignment and sequencing at a DDI have been presented to date.

The single controller diamond scheme presented in the previous section was first documented by the Missouri Department of Transportation (MoDOT, 2010). This scheme, using clearance phases as shown in Figure 3.4, was implemented in Utah and Indiana for the field studies discussed in this report.

- An earlier timing scheme was presented by Bared, Edara, and Jagannathan (2005). This paper focused mostly on the geometric design of the DDI rather than the signal timing. The fixed-time phasing scheme does not follow typical phase numbering conventions and does not decouple the two crossover intersections.
- Hu (2013) and Tian, Xu, de Camp, Kyte, and Wang (2015) explored several different phasing schemes that are ultimately based on an eight-phase background timing scheme. Rather than operating the interchange as a typical single controller diamond, with two independent intersections using one ring per intersection, the eight-phase template is used to create intervals that coordinate movement through the interchange. This provides some creative ways of synchronizing the movements, although the timing may be less flexible than single-controller diamond control without barriers.
- Yang, Chang, and Rahwanji (2014) presents a method for maximizing bandwidth on an arterial route including a DDI and two neighboring intersections. The main focus of the paper is the bandwidth-maximization problem, and the method offers what is essentially a fixed-time plan for two-phase operation. For the DDI, the authors consider two alternatives with the two crossover intersections of the DDI running under “one

controller" (two phases in one ring operating the two intersections simultaneously) and under "two controllers" (with the two intersections decoupled). The signal timing plans presented suggest that the "two controller" method was ultimately implemented.

Among these reports, a variety of phase assignment and sequencing schemes are used, and there is no current "standard" for implementation. The closest thing to a standard is the MoDOT (2010) document, which has been adopted in Utah and Indiana. The MoDOT (2010) report also is the only prior report to touch on the need for clearance times of the individual movements at the DDI. That is, it is not sufficient to control the ramp movements with the same signal exact output as the crossover through movements, because the ramp movements require a longer clearance time. Only the MoDOT (2010) report acknowledges this requirement.

It is desirable to prepare a set of common guidelines for coming up with a *template* DDI phasing design. This template can then be adapted to each site as appropriate. This report proposes such a design. Some potential requirements of the template design include the following.

- The overall phasing scheme follow basic single-controller diamond principles, as can be expressed by the rule: "one intersection, one ring". That is, all of the phases within any one ring should apply only to one of the intersections. This allows the two intersections to be completely decoupled with each other, for flexible, barrier-free timing. The parent phases for any overlap should all belong to the same ring.
- The different clearance times of the crossover intersection through movements, and the ramp exit movements, should be accommodated by default in the template design.
  - Assuming a saturation flow rate of 1800 veh/h/lane and a 60-second cycle length, 2 seconds of additional green time provided to a crossover through movement by accommodating different clearance times would add up to an additional 60 veh/h/lane. If there are four crossover movements with two lanes each, this would serve an additional 480 veh/h across the entire interchange.
- Phase numbering should be symmetrical.
  - In eight phase-control of conventional intersections, phases 2 and 6 usually control arterial through movements, while phases 4 and 8 control side street through movements. At a DDI, however, phases 2, 4, 6, and 8 *all* control arterial through movements.
  - We recommend that phases 2 and 6 should be used for entry into the DDI while phases 4 and 8 should be used for exit from the DDI.

Typical coordinated phase assignments could emphasize either entry into or exit from the DDI. Coordinated phases tend to absorb any green time that is given up by early termination of non-coordinated phases. Looking to Figure 3.3 for spatial reference, setting phases 2 and 6 as coordinated would prioritize entry into the DDI. Setting phases 4 and 8 as coordinated would prioritize exit from the DDI.

3.2 Movements and Clearance Times

Figure 3.1 shows a plan view of a hypothetical DDI, with twelve vehicle movements and eight vehicle-vehicle conflict points shown near the two crossover intersections. For now, the movements are labeled with generic identifiers "a", "b", etc., because the details of their assignment to phases and/or overlaps depends on the options available in the signal controller to be used. It is likely that some movements will not be signalized, particularly the on-ramp movements.

The conflict points can be organized as follows:

- Conflicts 1,2,3 belong to the west crossover intersection, while conflicts 4,5,6 belong to the east crossover intersection.

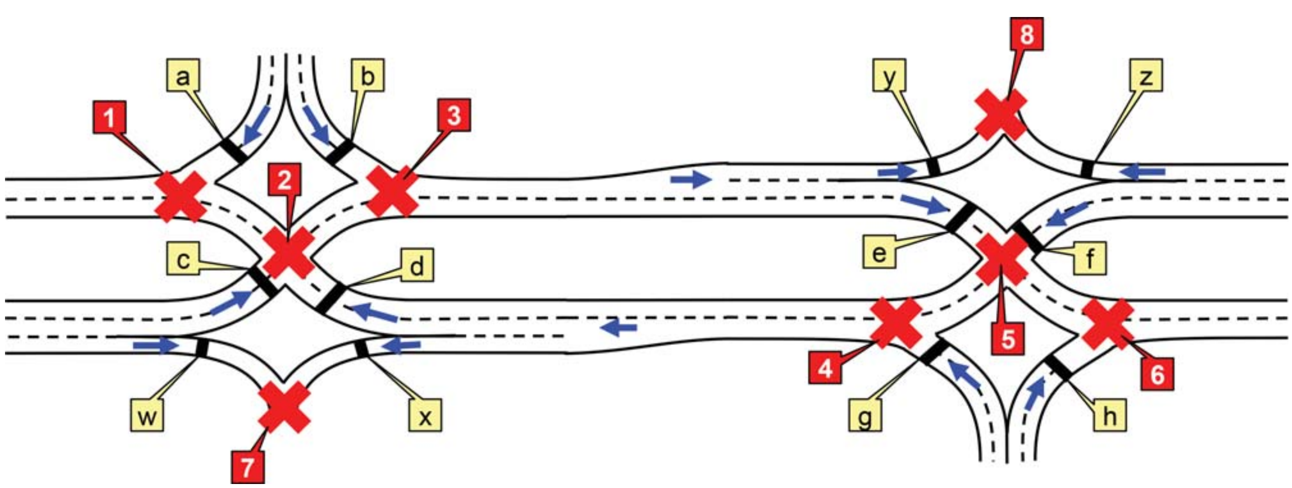


Figure 3.1 Diverging diamond interchange. Callouts indicate the locations of vehicle-vehicle conflict points (1, 2, 3, etc.). Letters indicate vehicular movements (a, b, c, etc.).

- Conflicts 7 and 8 occur where the two on-ramp movements meet. These would likely be controlled by a yield or merge rather than signal control.

The key characteristic of DDIs is that left turn phases are eliminated by crossing over *all* traffic at each intersection. Consequently, each intersection can theoretically be operated by a simple "two-phase" signal. The conflicting movements can be organized into two groups and separated by time, as shown in Table 3.1.

Importantly, the two intersections can be operated independently. For example, there is no reason why Phase "2" must have to be the same duration as Phase "6" in Table 3.1. There is no need for a "barrier" to be inserted into the multi-ring scheme. Doing so couples the timing of the two intersections together tightly. Most of the proposed single-controller diamond schemes in the literature still include barriers, which means that the two intersections cannot time fully independently. With that said, it is still desirable to coordinate the two intersections to provide some progression of traffic. However, this can be accomplished flexibly, as it is with actuated coordinated systems for conventional intersections.

In addition, the two on-ramp intersections (if signalized) could also be operated independently from the rest of the intersection, particularly if the crossing point is far from the crossover. If pedestrians are present, the vehicle-pedestrian conflict may be the more critical one for the on-ramp movements (w, x, y, z).

A review of current DDI literature also reveals a need to better articulate the clearance time requirements. This issue is best explained by an illustration. Figure 3.2 shows the clearance distances for the eastbound movement at the west crossover intersection (movement c).

- When movement c terminates, a certain amount of red clearance time is needed to allow vehicles to exit the space that conflicts with movement d.
- When movement c terminates, an *additional* amount of red clearance time is needed to allow vehicles to exit the space that conflicts with movement b.

What this means is that movement d can begin green a few seconds earlier than movement b. While the extra green for movement "d" is only a few seconds, this can accumulate to a substantial amount over time. If the difference is two seconds, with a 60-second cycle this would represent *two minutes* of additional green for

TABLE 3.1
Grouping of movements into phases at the DDI and assignment of basic phase numbers.

Intersection	Conflict Point	Phase "2"	Phase "4"
West Crossover	1	a. Southbound Right	d. Westbound
	2	c. Eastbound	d. Westbound
	3	c. Eastbound	b. Southbound Left
Southbound On-Ramp	7	w. Eastbound Right	x. Westbound Left
		Phase "6"	**Phase "8"**
East Crossover	4	e. Eastbound	g. Northbound Left
	5	e. Eastbound	f. Westbound
	6	h. Northbound Right	f. Westbound
Northbound On-Ramp	8	y. Eastbound Left	z. Westbound Right

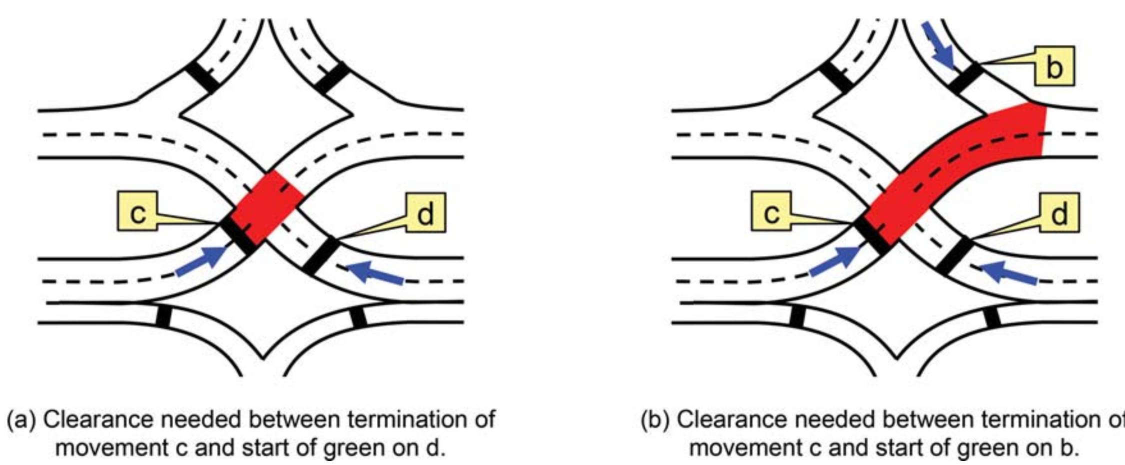


Figure 3.2 Clearance distances for a DDI crossover through movement.

movement “d”. Assuming a saturation flow rate of 1800 veh/h/lane, this equates to 60 additional vehicles per lane in that hour. Without accommodating the earlier start of green for the crossover through movements, that capacity would be lost.

There are various ways to implement the clearance times, varying by the features available in the specific model of signal controller available for the site. This discussion presents two ways that can be used with the controllers currently on Indiana’s approved materials list. Note that the choice of method affects the assignment of phases and overlaps to movements at the DDI. These two options comprise the proposed template DDI design for interchanges without pedestrians:

Delayed Overlaps (Figure 3.3)

- Ramp movements are assigned to overlaps, and the start of green for the overlap is delayed by the additional clearance time. The arterial through movements are assigned to numbered phases. At the time of writing, the Peek ATC has a delayed overlap feature that facilitates this option. However, the Peek ATC does not currently feature ring displacement,

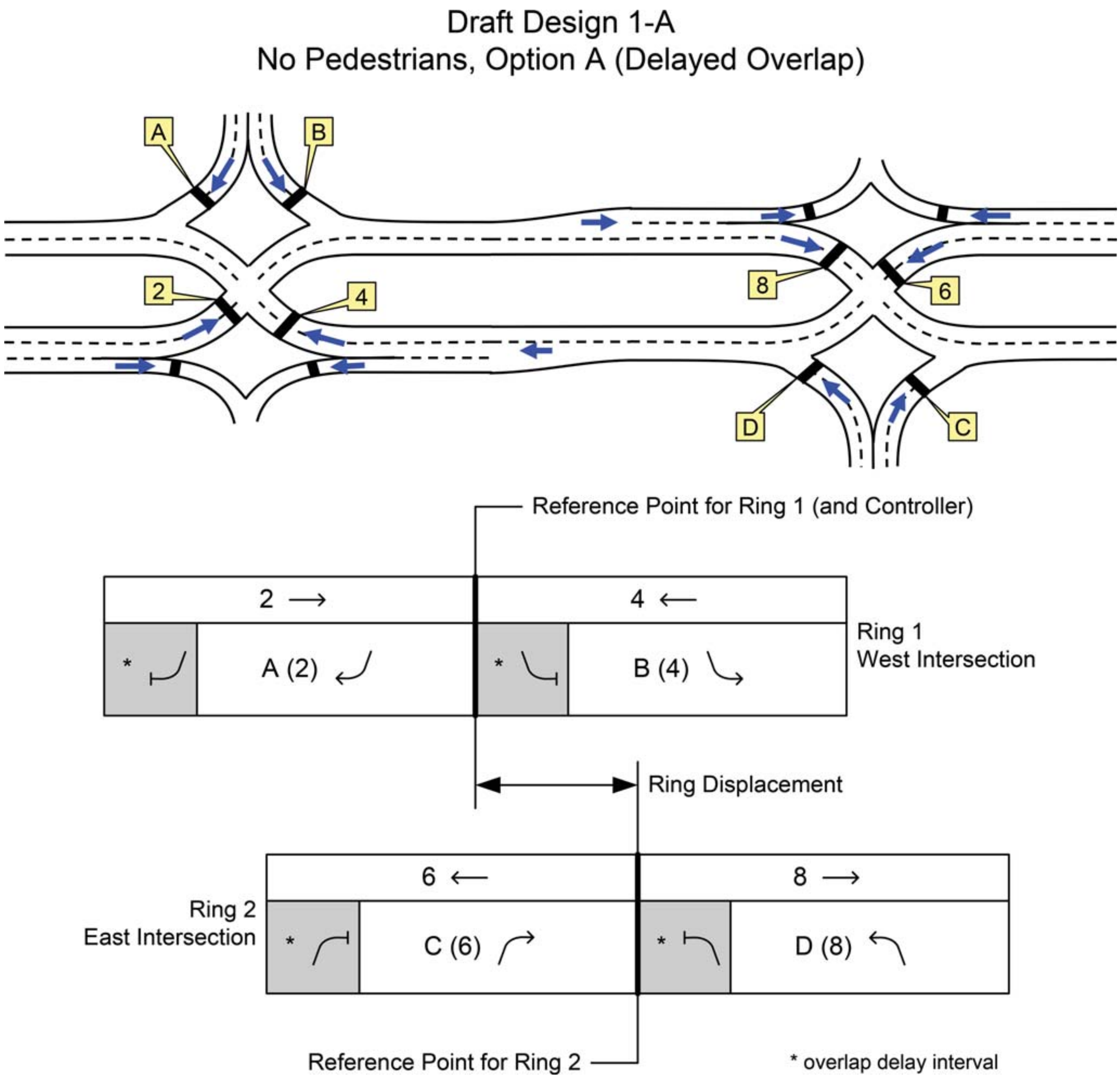


Figure 3.3 DDI template scheme without pedestrians; option A: delayed overlaps.

which makes it better suited to a two-controller deployment.

Clearance Phases (Figure 3.4)

- Arterial through movements are assigned to overlaps and the ramp movements are assigned to numbered phases. Odd-numbered phases are used as "clearance phases" in order to delay the start of green on the ramps. Special programming of the available sequences and backup prevention are required to ensure that the odd-numbered phases are never skipped or served out of sequence. At the time of writing, the Econolite ASC/3 and Siemens M50 controllers would be programmed in this manner.

Both types of programming accomplish the same field timing, but note the reversal of phases and overlaps between the two schemes.

3.3 Implementation in Fort Wayne

The Fort Wayne site deployment itself provides an example of a deployment using the clearance phase scheme of Figure 3.4. The site plan and phase/overlap numbering used in the field are shown in Figure 3.5, while Figure 3.6 shows views of the intersection approaches along the eastbound and westbound directions along the arterial. There are no pedestrian movements at this location, and there are no indications for the on-ramp turns.

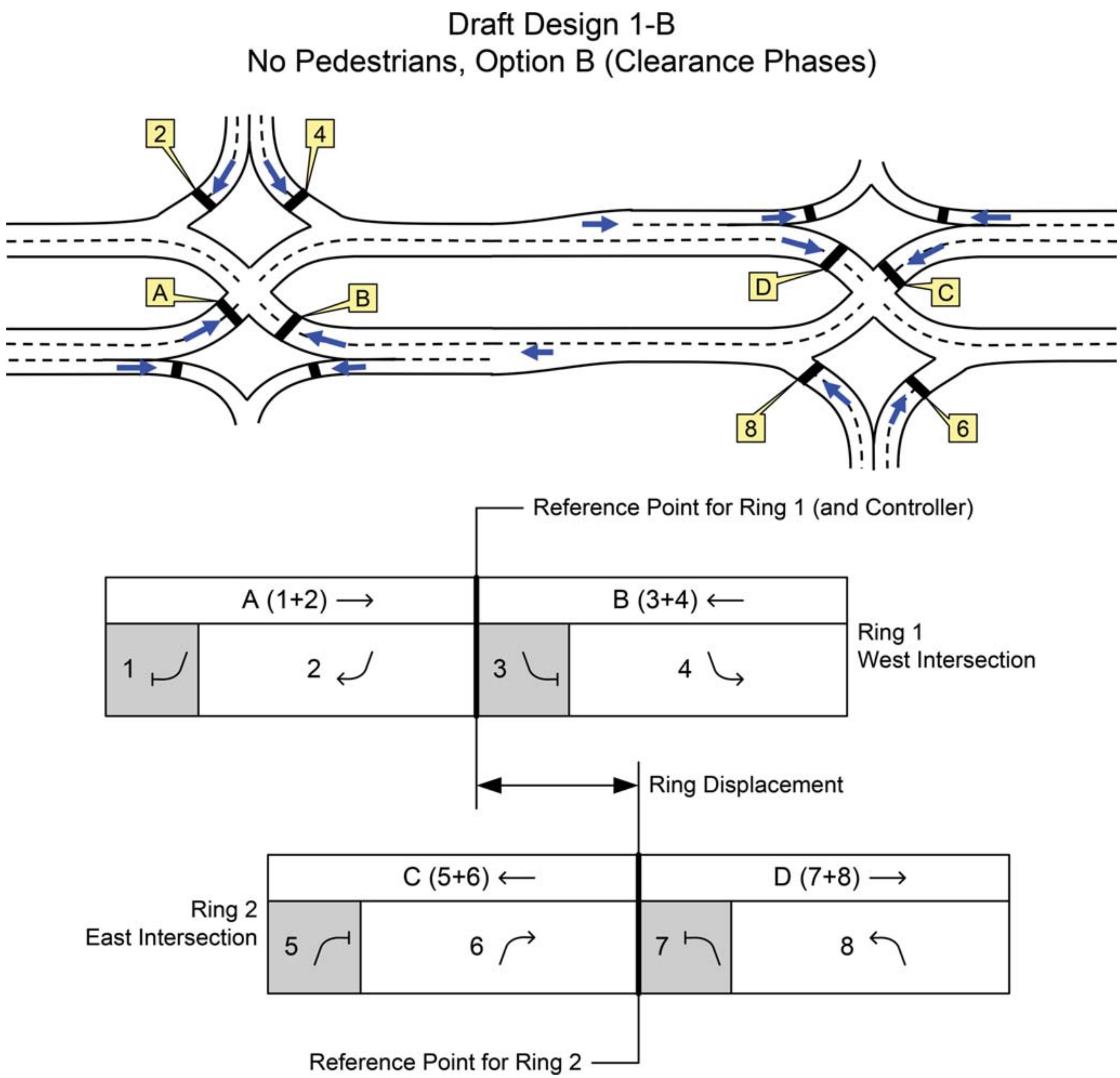


Figure 3.4 DDI template scheme without pedestrians; option B: clearance phases.

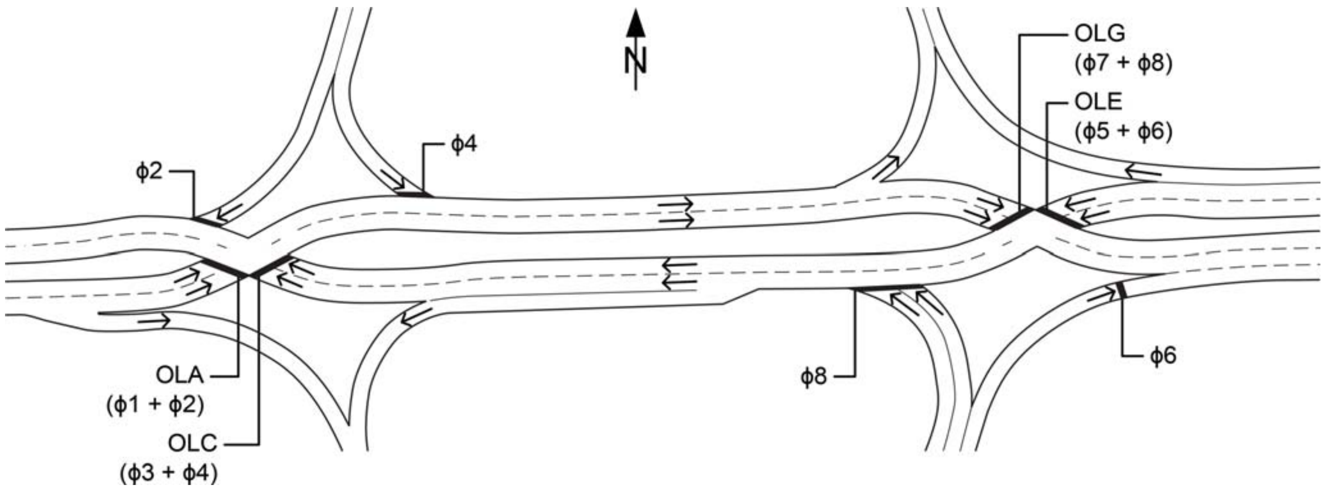


Figure 3.5 SR 1 and Interstate 69 Exit 316 interchange, Fort Wayne, Indiana.

3.4 Accommodation of Pedestrians

The existence of pedestrians at a DDI introduces some complexity into the required signal designs. There are two potential configurations for pedestrian travel across the interchange. Figure 3.7 illustrates these.

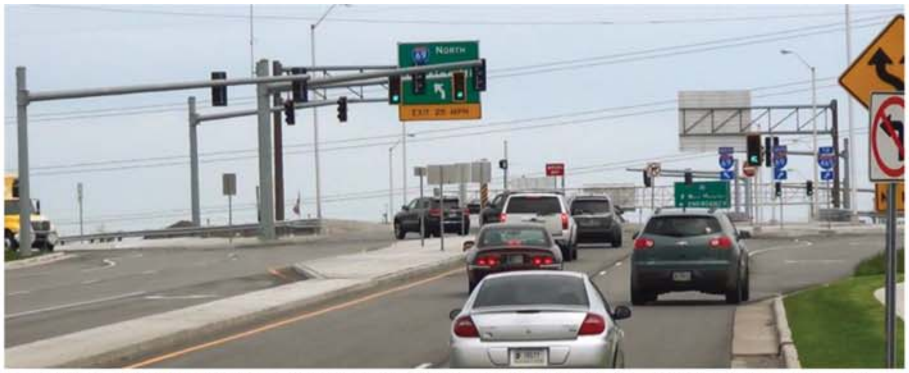
- The inside crossing option (Figure 3.7a) brings the pedestrians at each crossing to the median of the roadway between the two crossover intersections. Pedestrians would traverse each crossover street in alternating pedestrian phases. The pedestrians also must walk across one ramp movement as well.
- The outside crossing option (Figure 3.7b) keeps the pedestrians along the sides of the two streets. No pedestrians enter the crossover intersections, but all eight ramp movements interact with a pedestrian movement.

Note that each option uses 8 pedestrian outputs. Each letter or number in Figure 3.7a and Figure 3.7b would represent a separate signal output channel, each of which requires its own load switch. Counting these up, the inside crossing option requires 18 load switches (presuming that movements x and y do not require signalization), while the outside crossing requires 20 load switches. This would be impossible to accomplish with a single-controller configuration in many traffic cabinets, which do not have this many load switches. The NEMA TS/2 cabinet supports a maximum of 16 load switches.

Another complicating factor is that in order to achieve pedestrian phase timing, additional rings may be needed to hold a dummy phase to provide the pedestrian outputs where the ramps are crossed. Many controller models will support 4 rings, but a total of 6 rings would be needed to provide fully independent control of all the pedestrian movements. Therefore, to implement pedestrian crossing at a DDI will require some additional strategic planning beyond what is normally required for adding pedestrian phases to an intersection.

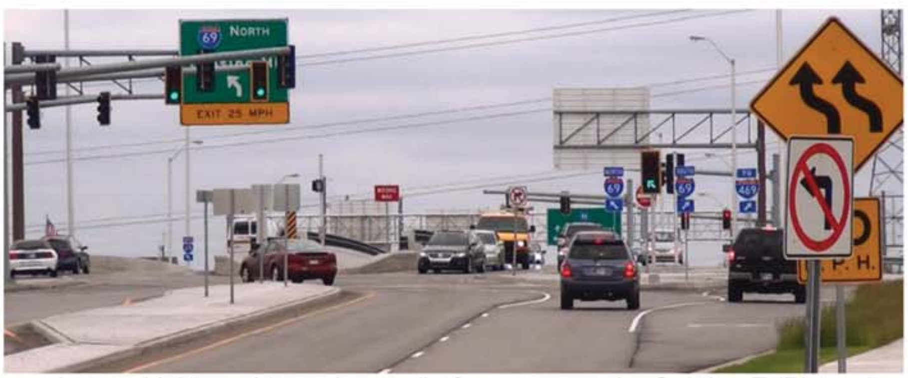
Options for implementing pedestrian phases include the following:

- *Use two controllers and two cabinets.* Rather than attempting single controller operation of the entire interchange, control each intersection from a separate cabinet. This would reduce the number of load switches and rings needed per cabinet/controller to a feasible number. The disadvantage to this approach would be the need for the second cabinet, and the requirement of connecting the two cabinets together for coordination.
- *Use a more advanced controller / cabinet.* The ATC cabinet standard allows up to 32 outputs and 120 detectors, which could easily handle either single-controller DDI configuration. Also, some controller models can support more than 4 rings. However, because this equipment is less frequently used, additional training of technicians and engineers will likely be needed, and expense of setup may be greater than with more familiar assets.
- *Consolidate outputs onto the same channel.*
  - Pedestrian outputs could be combined into a single output for movements that run with the same concurrent pedestrian phase. For example, pedestrian movements 1 and 2 both run concurrently with vehicle movement d, so these could run using the same pedestrian walk and ped clearance outputs. This could potentially reduce the number of pedestrian load switches to 4 for the entire interchange, getting the total load switch count below 16. The disadvantage of this method is that the longest pedestrian clearance time would have to be used for the combined outputs.
  - Vehicle outputs for some on-ramp movements could be controlled by the same output channel as the adjacent through movements. The movement pairs in Figure 3.7 are (c,w); (d,x); (y,e); and (f,z).
- *Do not signalize the onramp crossings.* Signal control of the turning movements onto the onramps could be replaced with yield control or other type of pedestrian priority such as a pedestrian beacon. This might be feasible at some locations if the turns can be channelized



(a) Eastbound toward I-65 southbound ramp (before crossover)—Overlap A (Phase 1 + Phase 2)

(b) Eastbound toward I-65 northbound ramp (after crossover)—Overlap G (Phase 7 + Phase 8)



(c) Westbound toward I-65 northbound ramp (before crossover)—Overlap E (Phase 5 + Phase 6)


(d) Westbound toward I-65 southbound ramp (after crossover)—Overlap C (Phase 3 + Phase 4)

Figure 3.6 Views from the arterial approaches on Fort Wayne DDI. (Photo credit: Steve Lavrenz, Purdue University.)

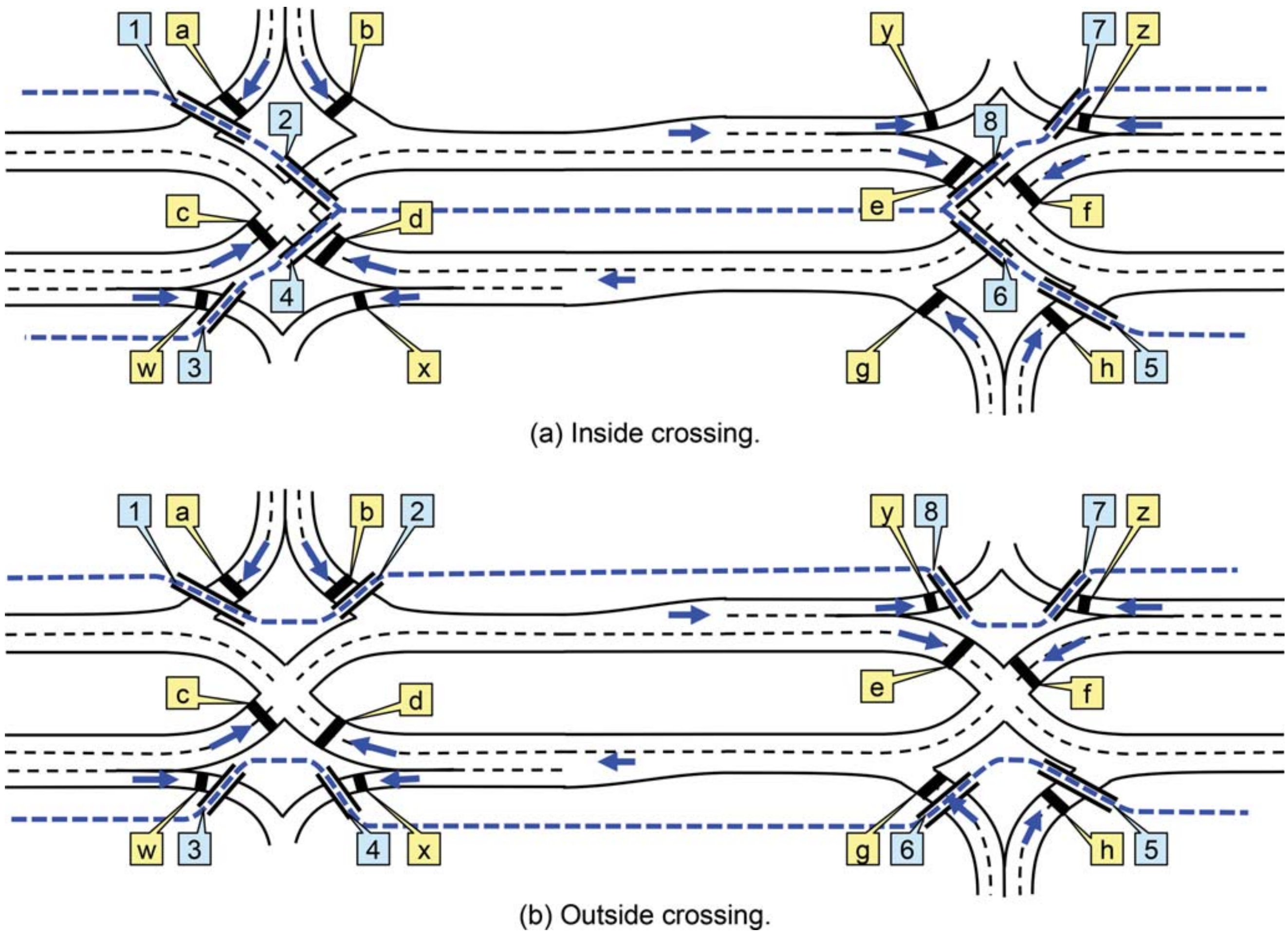


Figure 3.7 Options for serving pedestrians in a DDI.

and designed to discourage drivers from disregarding pedestrians, similar to pedestrian treatments at roundabouts. The disadvantage would be less protection of the pedestrian movement than provided by a red signal for the conflicting vehicle traffic. In general, this solution would not be recommended unless the site conditions present an opportunity to safely implement it.

The next series of figures (Figure 3.8 to Figure 3.15) show some draft designs for pedestrian phase implementation under various configurations. These are explained in Table 3.2, with some summary remarks on how these have been implemented.

- With an inside (median) pedestrian treatment:
  - The two crosswalks traversing the crossover intersection through lanes can be operated concurrently with one of the two crossover through movements.
  - The crosswalks traversing the on-ramp right turn can be controlled independently by a third and fourth ring (phases 11 and 13).
  - The crosswalks traversing the off-ramp right turns can be controlled semi-independently by a fifth and sixth ring (phases 12 and 14).
  - If six rings are not available, these crosswalks can share an output with one of the "crossover" crosswalks. Alternately, a two-controller / two-cabinet configuration may be used.
- With an outside (shoulder) pedestrian treatment:
  - All of the pedestrian crossings could potentially be assigned to a higher number phase and ring combination, and operated somewhat independently from the intersection.
  - In the draft designs, the crosswalks traversing the off-ramp left turns are operated concurrently with one of the crossover through movements that is effectively parallel to that traffic (phases 2 and 6).
  - The crosswalks traversing the on-ramp right turns can be controlled independently by a third and fourth ring (phases 11 and 13).
  - The crosswalks traversing the off-ramp right turns are operated semi-independently by a fifth and sixth ring (phases 12 and 14).
  - The crosswalks traversing the on-ramp left turns can be controlled independently by a seventh and eighth ring (phases 15 and 16).

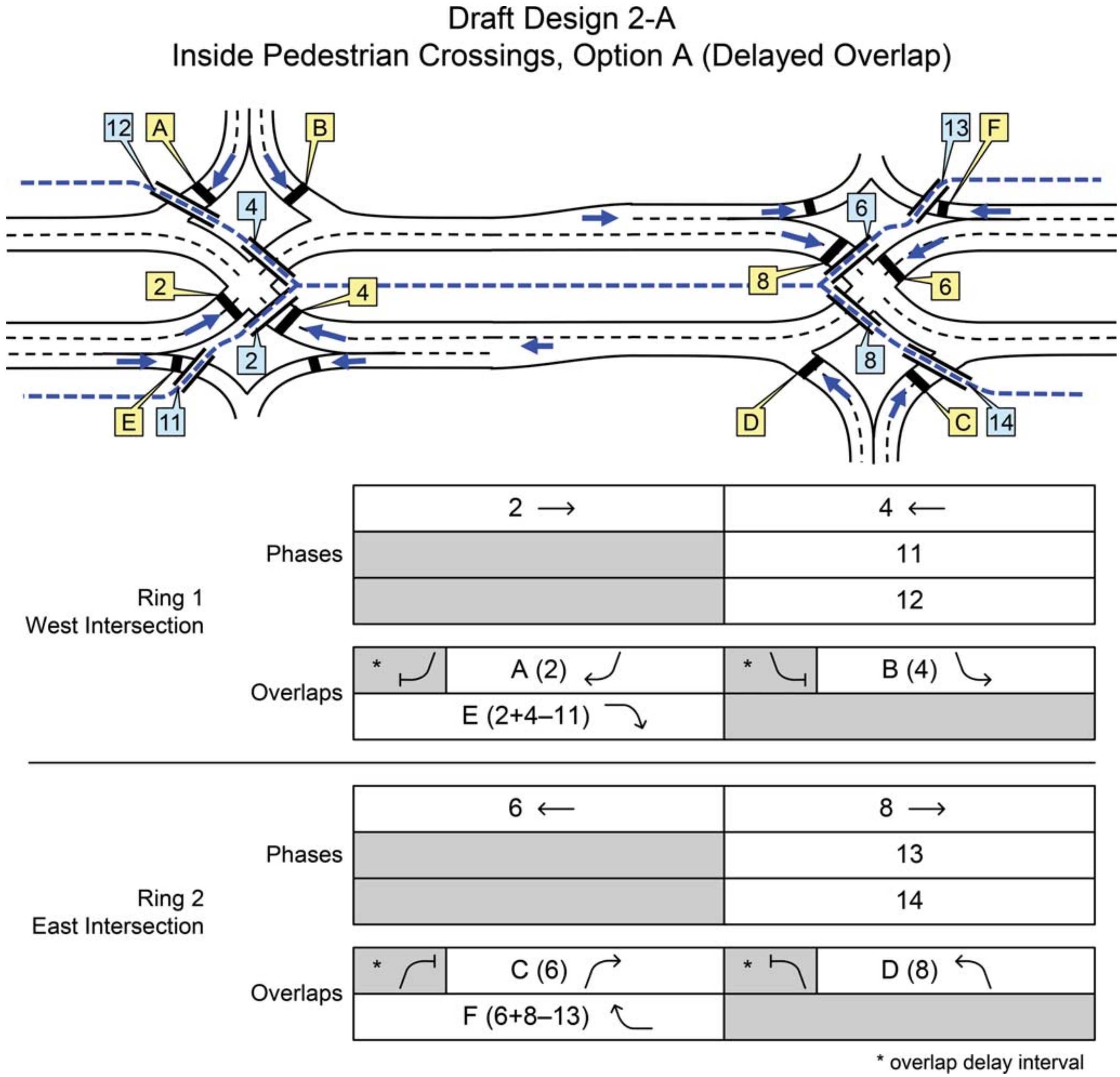


Figure 3.8 DDI template scheme with inside pedestrian crossing; option A: delayed overlaps.

- If eight rings are not available, several of these movements can be combined to yield a four-ring design. Alternately, a two-controller / two-cabinet configuration may be used.
- Designs 4-A and 4-B will not separate the two on-ramp traffic flows, whereas these are separated by designs 5-A and 5-B.

Some care must be taken when designing for outside (shoulder) pedestrian treatments because of the possibility of the two opposing on-ramp turns having a green indication at the same time, in some of these designs (e.g., overlaps E and G in Figure 3.12). Depending on the interchange geometry, this treatment may or may not be appropriate. It is possible to separate those movements by making the controlling phases incompatible.

Related to the above, the clearance time issue relevant to the off-ramp turns may also apply to the on-ramp turns. This is handled in designs 5-A and 5-B by using the same output for the off-ramps and the on-ramps. For example, in design 5-A (Figure 3.14), at the west intersection, the eastbound crossover through movement is operated by phase 2, while the on-ramp right turn and the off-ramp left turn are both operated by overlap B. The amount of overlap delay needed to accommodate the clearance needed for those movements to begin green will be the greater of the two associated conflict areas. The same duration of time would be

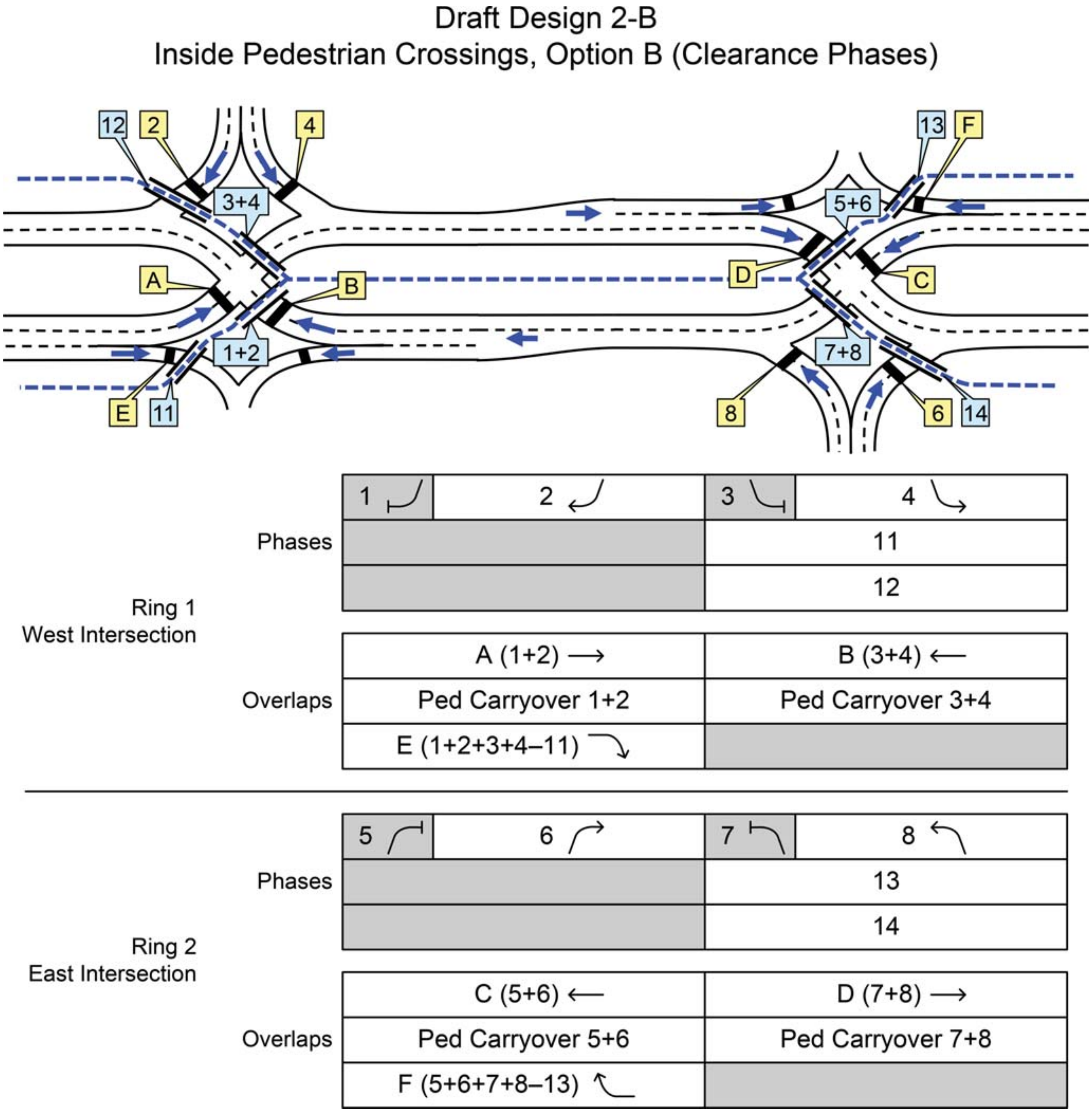


Figure 3.9 DDI template scheme with inside pedestrian crossing; option B: clearance phases.

needed for the duration of the clearance phase interval (in this particular case, phase 3) for the corresponding clearance phase based design (Figure 3.15).

These draft designs are intended as a starting point for a field implementation of pedestrian timing at a DDI. As with all new signal timing configurations, these should be extensively tested on the bench before attempting to proceed with a field deployment. In this case it is particularly important to ensure that no conflicting greens are produced by the design.

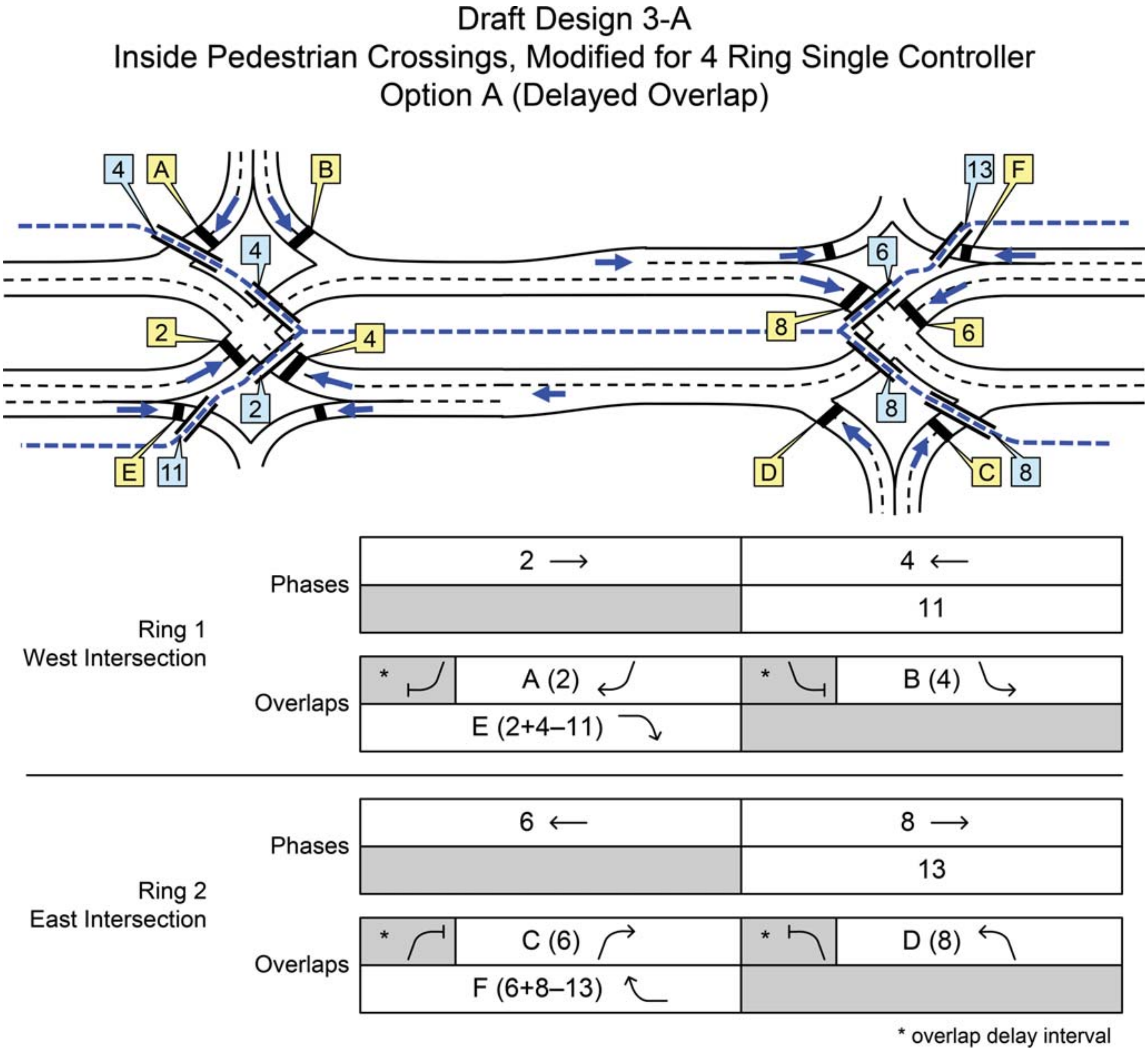


Figure 3.10 DDI template scheme with inside pedestrian crossing, modified for 4-ring single controller; option A: delayed overlaps.

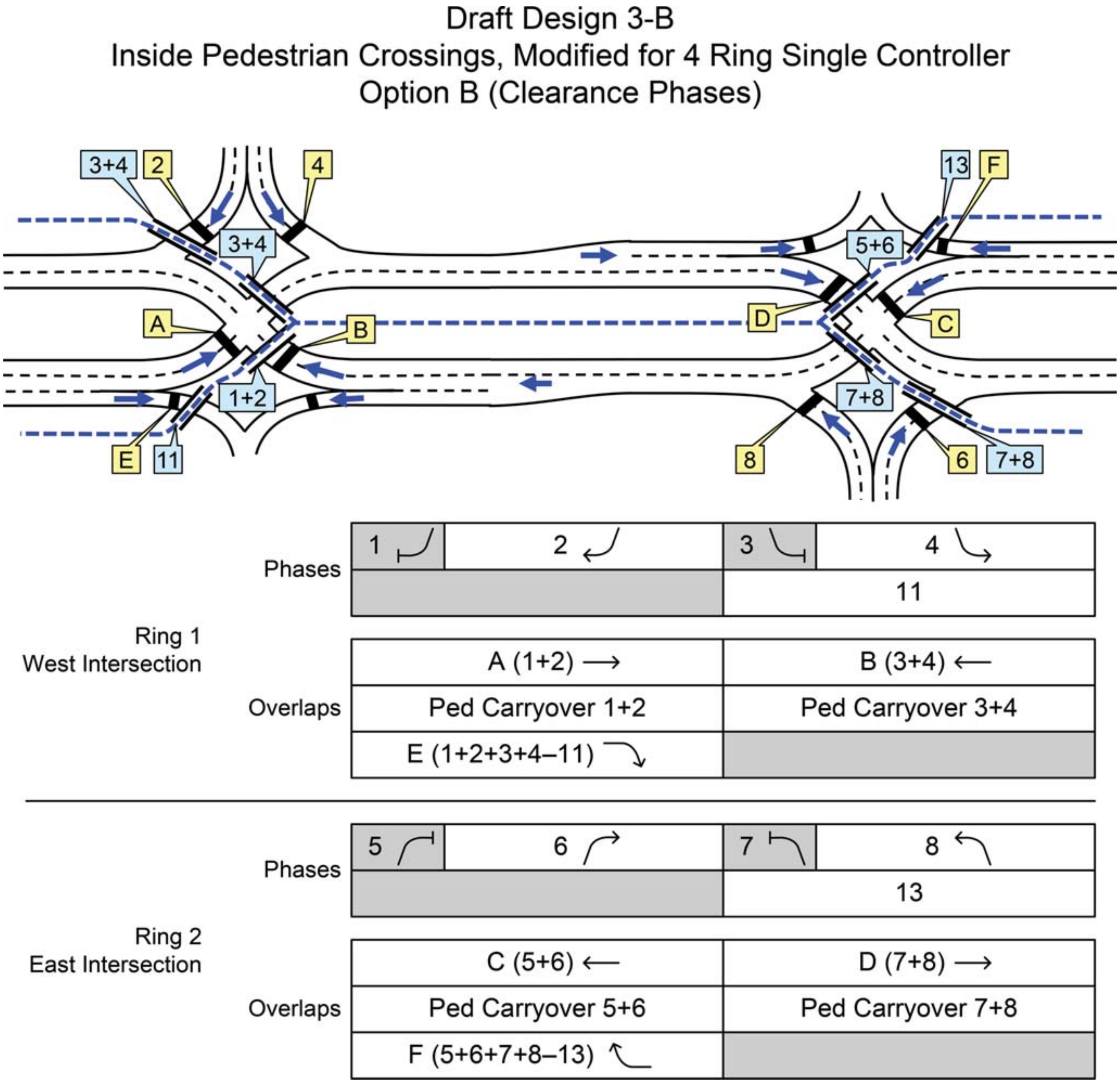
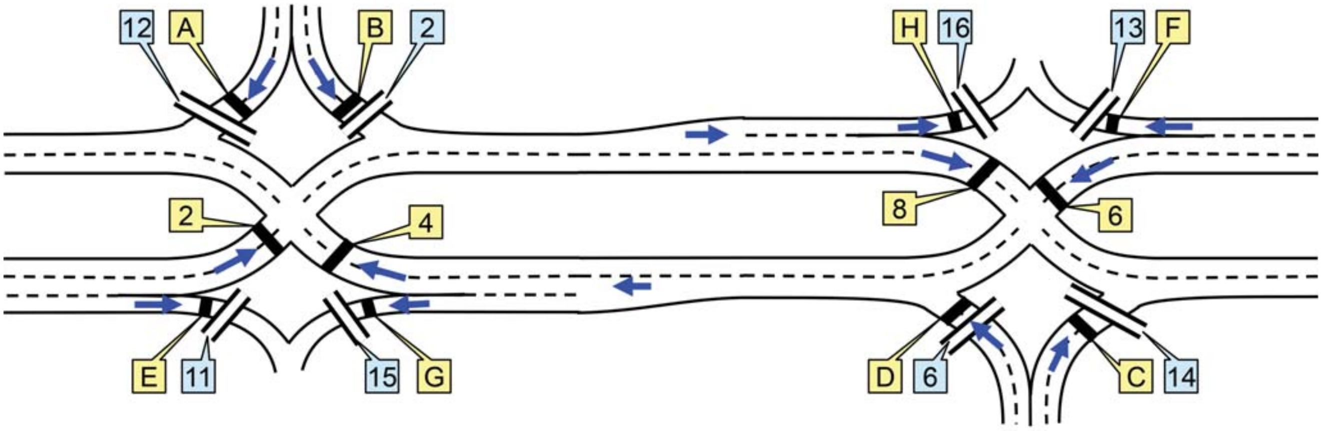


Figure 3.11 DDI template scheme with inside pedestrian crossing, modified for 4-ring single controller; option B: clearance phases.

Draft Design 4-A
Outside Pedestrian Crossings, On-Ramp Turns do not Conflict
Option A (Delayed Overlap)



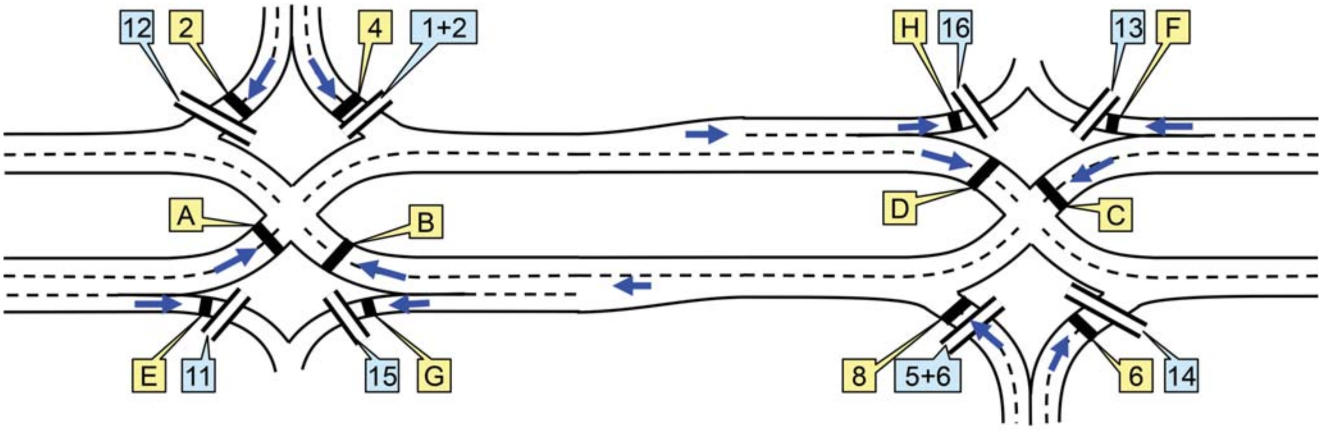
Ring 1 West Intersection – Phases	2 ⟶	4 ⟵
		11
		12
	15	
Overlaps	* A (2)	* B (4)
	E (2+4–11)	
		G (2+4–15)

Ring 2 East Intersection – Phases	6 ⟵	8 ⟶
		13
		14
	16	
Overlaps	* C (6)	* D (8)
	F (6+8–13)	
		H (6+8–16)

* overlap delay interval

Figure 3.12 DDI template scheme with outside pedestrian crossing and non-conflicting on-ramp turning movements; option A: delayed overlaps.

Draft Design 4-B
Outside Pedestrian Crossings, On-Ramp Turns do not Conflict
Option B (Clearance Phases)



Ring 1 West Intersection				
Phases	1	2	3	4
			11	
			12	
	15			
Overlaps	A (1+2) ⟶		B (3+4) ⟵	
	Ped Carryover 1+2			
	E (1+2+3+4–11)			
			G (1+2+3+4–15)	

Ring 2 East Intersection				
Phases	5	6	7	8
			13	
			14	
	16			
Overlaps	C (5+6) ⟵		D (7+8) ⟶	
	Ped Carryover 5+6			
	F (5+6+7+8–13)			
			H (5+6+7+8–16)	

Figure 3.13 DDI template scheme with outside pedestrian crossing and non-conflicting on-ramp turning movements; option B: clearance phases.

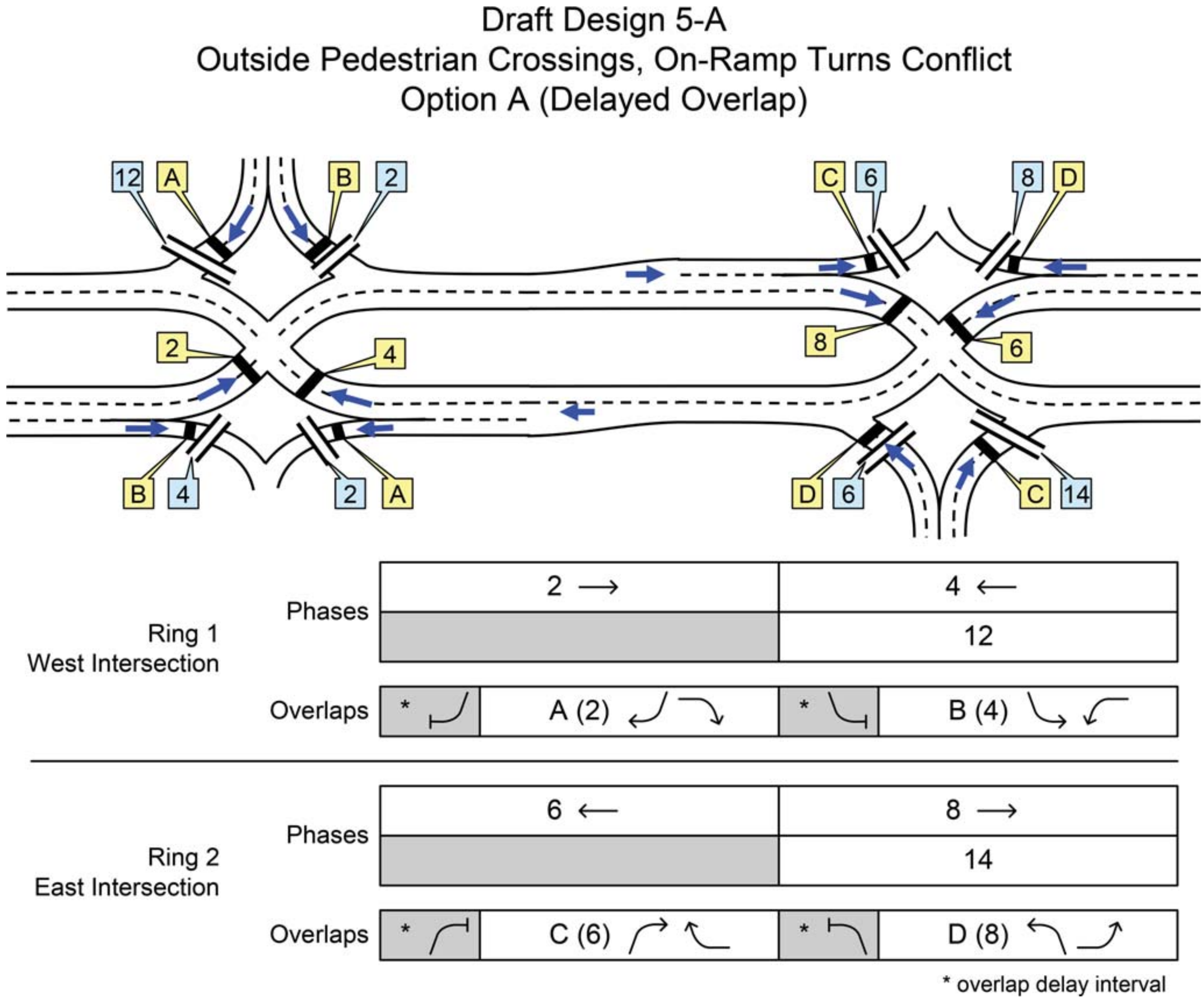


Figure 3.14 Simplified DDI template scheme with outside pedestrian crossing and conflicting on-ramp turning movements; option A: delayed overlaps.

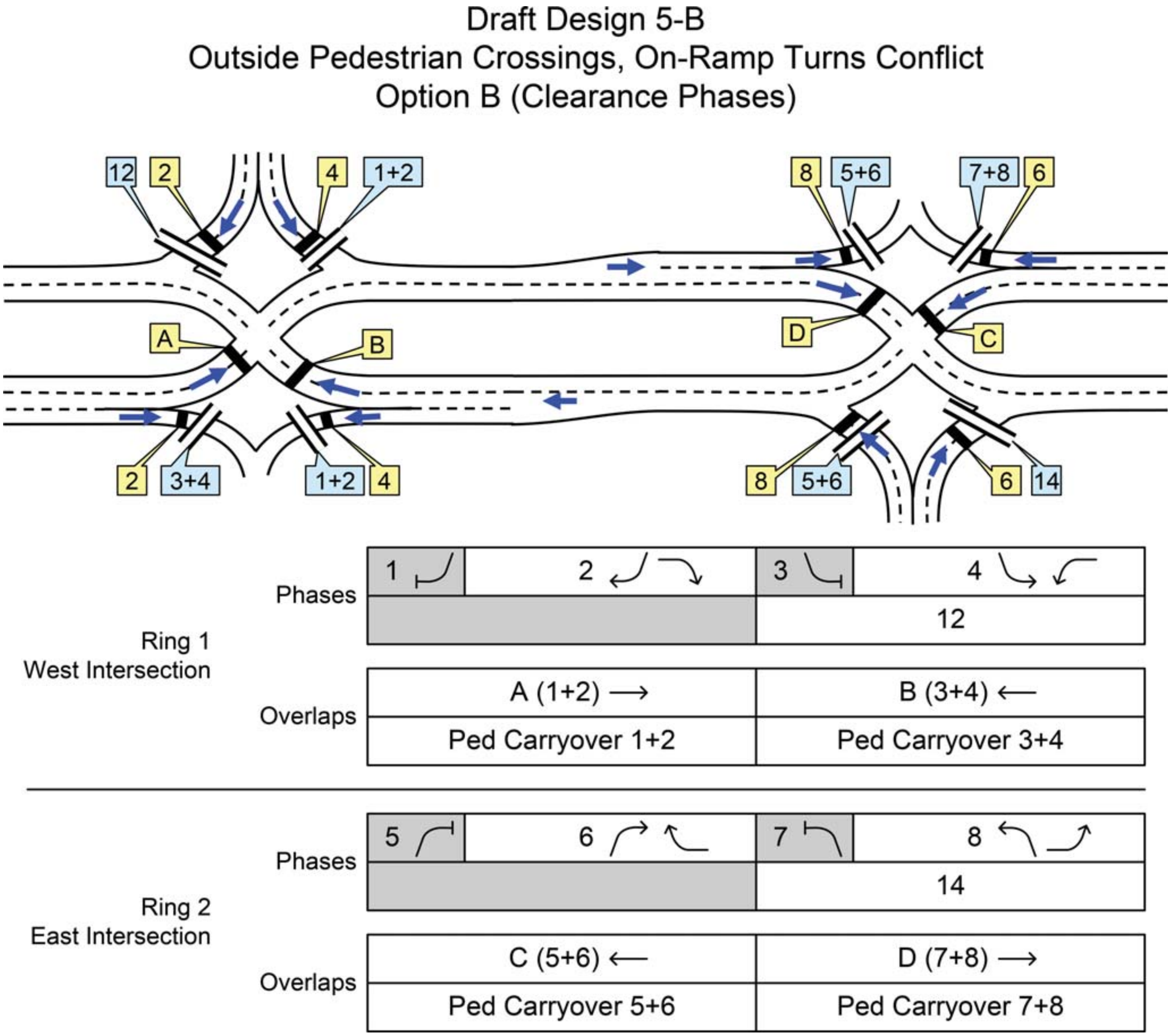


Figure 3.15 Simplified DDI template scheme with outside pedestrian crossing and conflicting on-ramp turning movements; option B: clearance phases.

3.5 Modeling of DDIs in Optimization Software

The creation of an optimization model to optimize signal timing for a corridor is a necessary step in the design of a timing plan for a corridor. The DDI presents a challenge for system modeling because of the crossing over of the arterial segments. Many modeling software programs consider the alternative directions on a roadway to be coupled together as a single object, making it difficult if not impossible to construct a DDI with accurate geometry. Figure 3.16a, for example, shows an example DDI model that comes packaged with the Synchro 8 software. The main interchange movements are numbered. While this creates the overall visual appearance of the DDI with crossovers, it is rather complicated, requiring 14 nodes and the painstaking drawing out of several curved links.

An alternative approach, used by Eric Miller and Amanda Stevens (INDOT system engineers) when preparing the initial timing plan for SR 1 in Fort Wayne, does not attempt to model the crossover geometry exactly, but instead models the crossover intersection left turns as conventional intersection right turns, which have the same operational characteristics. Figure 3.16b shows a screen capture from the SR 1 and I-69 model, with numbered turns corresponding to the equivalents in Figure 3.16a.

- Turn 2, ramp southbound left at the west intersection in Figure 3.16a, is modeled as a northbound right turn in Figure 3.16b.
- Turn 4, westbound left at the west intersection in Figure 3.16a, is modeled as a westbound right turn in Figure 3.16b.
- Turn 5, ramp northbound left at the east intersection in Figure 3.16a, is modeled as a southbound right turn in Figure 3.16b.
- Turn 8, eastbound left at the east intersection in Figure 3.16a, is modeled as an eastbound right turn in Figure 3.16c.
- The crossover movements (11, 9, 7 going east; 13, 10, 3 going west) are modeled as through movements without actually crossing over.

There are no left turn phases in Figure 3.16b, yet the system is modeled with only two nodes, and the entry and exit of the same traffic has a similar effect on traffic. While these changes might not capture the lane use dynamics with the same precision as a more geometrically precise model, they do approximate the operational consequences. That is, while turn 2 might actually originate from the north in reality, it can be modeled as coming from the south, and does not conflict with movement 3 in either case. Similarly, turn 4 does not conflict with movement 11 in either case. While the traffic is not modeled as crossing over in the software, the phases are configured so that they cannot run simultaneously, which forces the software to consider them as conflicting (similar to split-phased intersections), and it will not allow them to overlap each other when optimizing splits.

3.6 DDI Cycle Length Selection

Many if not most signalized arterial-freeway interchanges do not exist in isolation, but are attached to neighboring signalized arterials. Therefore, when designing the timing plan for the interchange, it is required to reconcile the interchange timing with that of the arterial in order to achieve coordination along the entire route.

For DDIs, the “two-phase” nature of the crossover intersections means that it is likely possible to operate the interchange using half the cycle length of the remainder of the arterial. This, in fact, is what was done for the DDI in Fort Wayne. The relatively long arterial cycle lengths of 120–140 seconds were reduced to 60–70 at the interchange. At other locations, the “three-phase” plan explored at the Utah DDI could potentially be used. However, this would typically require a longer cycle length more similar to that used for the remainder of the arterial, in order to accommodate the “holdback” phases.

In order to better illustrate the differences between full-cycle, half-cycle, and three-phase cycle length modes, we constructed a VISSIM model of a DDI with two neighboring intersections (Figure 3.17). The two crossover intersections (Int. 2 and Int. 3) were operated using a single controller. An Econolite ASC/3 virtual controller was used for this purpose. The network was seeded with traffic using an origin-destination matrix, and a base timing plan was developed using Synchro (using the full-cycle at the DDI). The cycle lengths from Synchro and splits for Int. 1 and Int. 4 were used in the simulation, with some minor tweaks. Half-cycle timing plans were developed for the DDI by simply halving the splits. Three-phase timing plans were developed such that the duration of the holdback phase would divide the cycle into three equal parts as closely as possible. For each simulation series, an initial run was used to measure vehicle arrivals, and these were used to optimize offsets using the Link Pivot algorithm (Day & Bullock, 2011). This protocol was followed for each of the scenarios and cycle length strategies tested.

Figure 3.18 presents simulated time space diagrams including vehicle trajectories that illustrate the differences between the three cycle length strategies: half-cycle (Figure 3.18a), full-cycle (Figure 3.18b), and three-phase (Figure 3.18c). These are presented for the westbound direction of travel in the VISSIM model for a traffic scenario with balanced arterial and freeway routing.

- The half-cycle strategy (Figure 3.18a) clearly shows that the durations of red at the two crossover intersections are about half of their duration at the two neighboring intersections (the conventional intersections always use full-cycle). Half-cycling tends to cause long entering platoons to be broken up, and it also produces two exiting platoons that have to be accommodated at the last intersection. The trajectories show that there are some cycles where progression is smoother than others. Within the interchange, two platoons arise that have to

TABLE 3.2
Explanation of draft phase designs for DDIs.

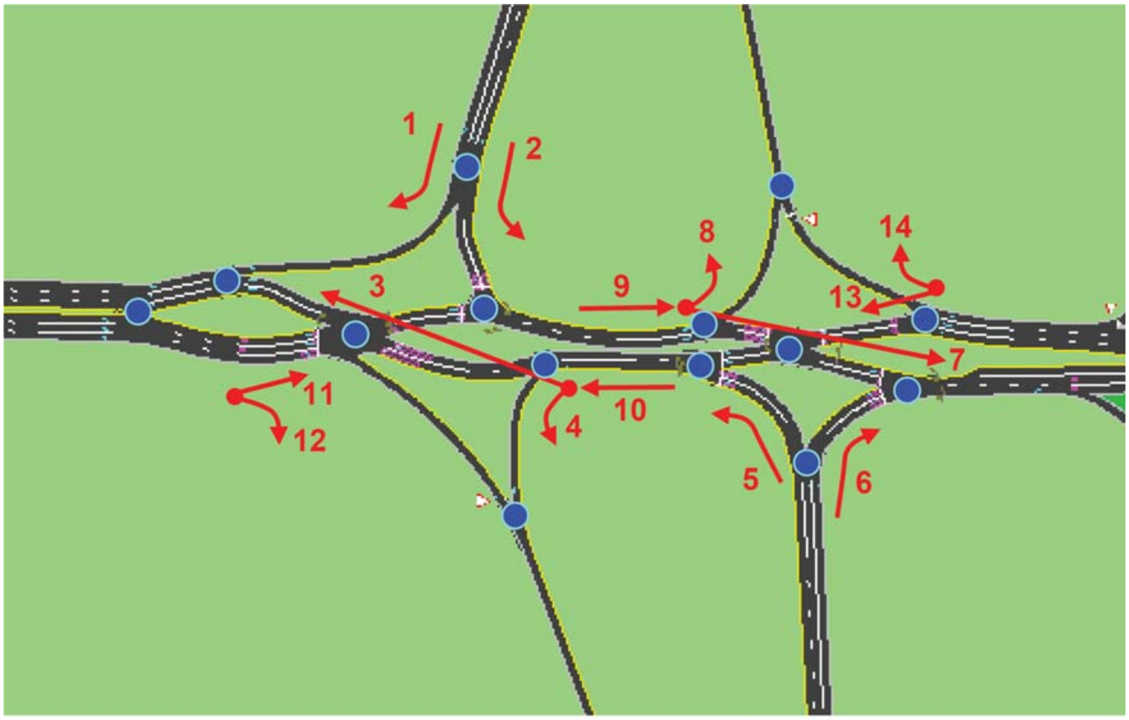
Pedestrian Treatment	Scheme	Explanation of Scheme	Option	Drawing No.
No Pedestrians	—	Standard plan for DDI phasing without pedestrians, assuming that on-ramp turns are not signal controlled. This scheme is used at the two DDIs in the study in Utah and Indiana.	A. Delayed Overlap B. Clearance Phases	1-A (Figure 3.3) 1-B (Figure 3.4)
Inside (Median)	Flexible	Pedestrian crosswalks traversing the on-ramp right turn and the off-ramp right turn are controlled independently by rings 3, 4, 5, 6.	A. Delayed Overlap B. Clearance Phases	2-A (Figure 3.8) 2-B (Figure 3.9)
	Modified for 4-Ring	The pedestrian crossing traversing the off-ramp right turn is combined with the pedestrian crossing traversing the crossover intersection.	A. Delayed Overlap B. Clearance Phases	3-A (Figure 3.10) 3-B (Figure 3.11)
Outside (Shoulder)	On-Ramps Do Not Conflict	All pedestrian crosswalks, except for the off-ramp left turn, are independently controlled by rings 3, 4, 5, 6, 7, 8. The two on-ramp turns are not considered to be conflicting.	A. Delayed Overlap B. Clearance Phases	4-A (Figure 3.12) 4-B (Figure 3.13)
	On-Ramps Conflict	Several crosswalk and vehicular movements have been combined to accommodate the timing with four rings. The two on-ramp turns will now alternate between the two directions and run concurrently with their through movements.	A. Delayed Overlap B. Clearance Phases	5-A (Figure 3.14) 5-B (Figure 3.15)

be dealt with, as shown by callouts. Platoon "i", the upstream through vehicles, and platoon "ii", the vehicles entering from the ramp. In this scheme, the ramp vehicles typically stop and form queues which are then discharged in a relatively short amount of time. The through vehicles are relatively unimpeded.

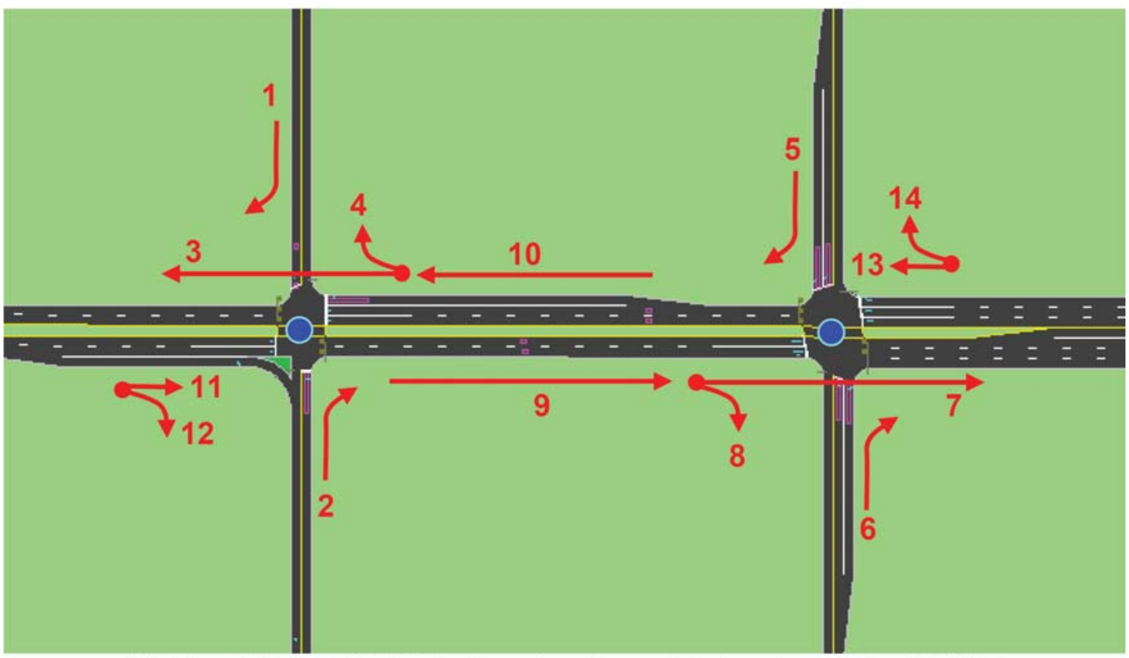
- The full-cycle strategy (Figure 3.18b) exhibits what appears to be somewhat overall progression along the arterial, with longer green times at the two crossover intersections in the westbound direction. Platoons departing from the first intersection are able to clear the two intersections in many cases (e.g., platoon "i"). However, notice that the ramp vehicles ("ii") entering within the cycle must form queues before they can exit the interchange. The amount of time spent in the queue is considerably longer than with half-cycles.
- The three-phase strategy (Figure 3.18c) operates under fairly similar conditions as full-cycle. In this particular example, the results of the offset optimization worked out to be slightly different so the overall progression was not as ideal for westbound travel as seen previously (note that platoon "i" experiences some stopping as it enters the DDI). This would have occurred because the arrival times were slightly different because of the use of holdback phases in both directions. What is more interesting to note is that now the ramp vehicles (platoon "ii") are *not* stopped within the DDI, because they have been effectively lined up better with the green. Those greens are also able to accommodate both the ramp vehicles and a substantial number of the through vehicles as well.

Vehicle trajectories are extremely difficult to obtain from field data, but high resolution signal data enables a "snapshot" of the entire picture to be captured by means of a PCD, as discussed in the previous chapter (see Figure 2.3). Figure 3.19 shows three PCDs for the westbound movement at Int. 2 (exiting from the DDI) for half-cycle (Figure 3.19a), full-cycle (Figure 3.19b), and three-phase (Figure 3.19c) operation. Vehicle arrivals are colored based on their originating upstream movement (ramp or through vehicle). Each group of arriving platoons is labeled by callouts "i" and "ii." The PCDs enable visualization of the full two-hour simulation rather than a 15-minute section.

As seen in the vehicle trajectories, the full-cycle strategy is only able to capture one platoon or the other in green (Figure 3.19b), while the three-phase strategy does a somewhat better job (Figure 3.19c). The half-cycle strategy (Figure 3.19a) in this case appears to fall somewhere in between. While the duration of green in half-cycle could only capture one of the two platoons, the optimal offset in this case enables it to capture most of the upstream through vehicles and some of the ramp vehicles.



(a) An example DDI packaged with Synchro 8.



(b) The SR 1/I-69 DDI in Synchro 8 model developed by INDOT.

Figure 3.16 Modeling of the DDI in optimization software.

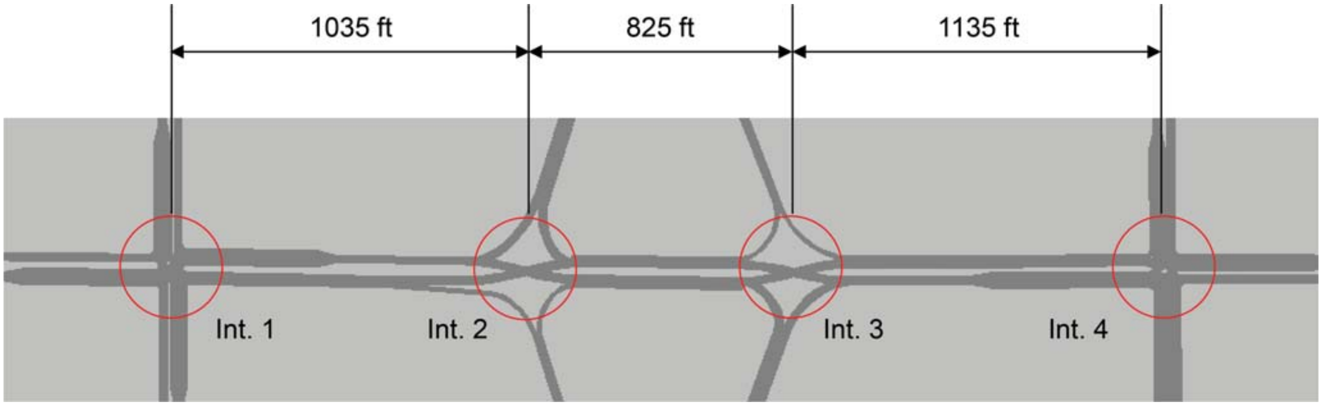


Figure 3.17 VISSIM model for comparing DDI cycle lengths.

To measure the overall impact of cycle length selection, a series of tests were performed under six traffic scenarios covering a variety of situations. Each scenario's origin-destination volumes are shown with the equivalent turning movement counts in Table 3.3. Each scenario was run for a two-hour simulation period under optimized offsets for ten different random seeds. The second hour of the simulation runs were used for the analysis of the system performance. In addition to the three cycle length strategies of half-cycle, full-cycle, and three-phase, a "semi-three-phase" strategy was tested for scenario 5, in which volumes were asymmetrical through the system. In this scenario, the holdback phase in the three-phase strategy was applied only for the westbound direction.

The results are presented in the next few figures (Figure 3.20 to Figure 3.22) in terms of progression quality, DDI movement average delays, and user costs related to travel times on various routes through the system.

Progression quality is evaluated using the total number of arrivals on green (AOG). Good progression is typified by a higher arrival on green. Figure 3.20 shows the results for all of the scenarios and cycle length strategies tested. Table 3.4 also breaks down the results by movement type. These are defined as follows:

- *DDI-exit*. This refers to approaches exiting the interchange (Int. 2, EB; Int. 3, WB).
- *DDI-entry*. This refers to approaches entering the interchange (Int. 2, WB; Int. 3, EB).
- *Coord.* This refers to the approaches with non-random arrivals at the two conventional interchanges (Int. 1, WB; Int. 4, EB).

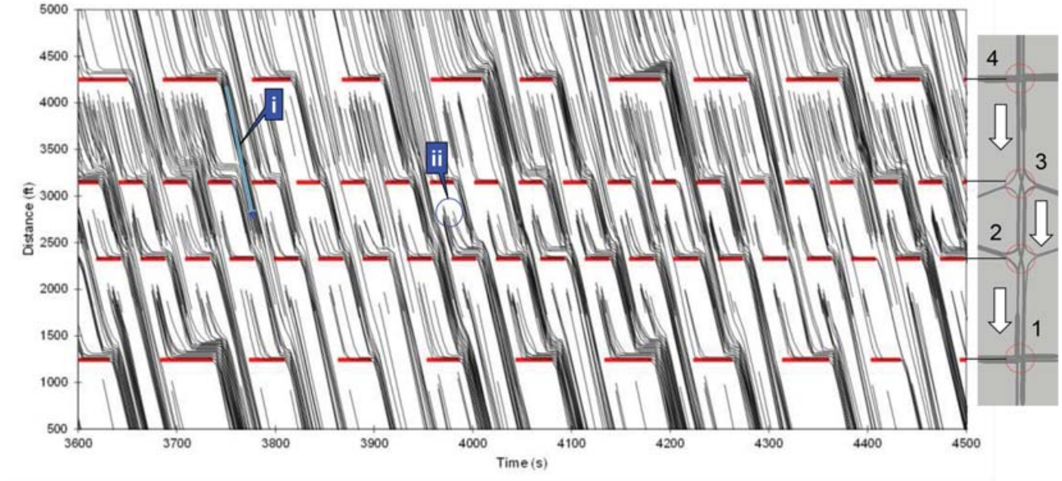
The results are mixed in that there is not one particular strategy that results in the highest AOG for all six scenarios. Full-cycle has the highest AOG under scenarios 1 and 2, while three-phase operation has the highest AOG for scenarios 3, 4, and 6. Half-cycling resulted in the highest AOG under scenario 5. Three-phase operation yielded the highest AOG in half of the scenarios, and in general tends to produce the best results for the DDI-exit movements. This agrees with the observations that we made in the vehicle trajectories and PCDs presented previously, as well as the results of field testing. This strategy does a better job of keeping the roadway between the two crossover intersections clear. Half-cycling has a lower AOG for most scenarios, especially for Scenarios 2 and 6, yet resulted in the highest AOG under Scenario 5.

Average delays for signalized movements within the DDI are presented in Table 3.4. Eight movements are considered in total—the two turns off of the ramps (turns on red were not allowed), and the through movements in both directions at the crossover intersections. The on-ramp turns were not signalized, and there were negligible differences between the various cycle length strategies, so these are excluded from Table 3.4. For each scenario and each movement, the cycle length strategy with the lowest average delay is shown.

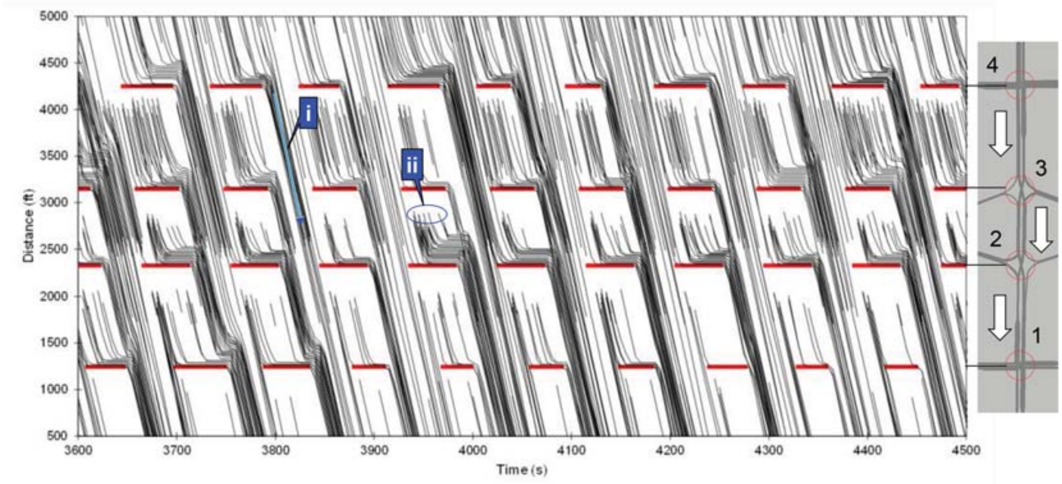
As a glance across Table 3.4 reveals, the half-cycling strategy produced the lowest average delay for 41 out of 48 movement-scenario pairs. The exceptions are the two movements exiting the DDI, for which lower average delay is produced for several scenarios. This agrees with the results presented earlier, again showing the benefit of using three-phase. Some of the scenarios have exceptionally low average delay for the exiting movements. However, three-phase produces higher delays for the other movements in every scenario. This reflects that three-phase achieves the goal of keeping the roadway between the crossover intersections clear, but that it tends to do so by queueing the vehicles at other locations before moving them through the interchange.

The last aspect of the performance used to compare operations is origin-destination travel times. A total of 22 routes through the system were selected for analysis. Figure 3.21 shows these in two map views.

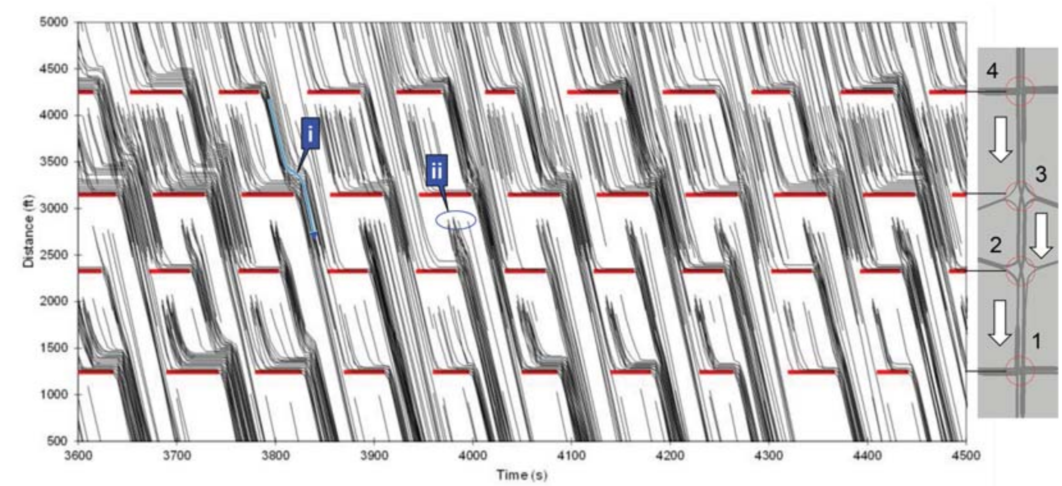
- All of the routes to and from the arterial endpoints and the freeways are considered, as shown in Figure 3.21a. This is similar to the field travel time data collection carried out in the Fort Wayne study.



(a) Half cycle.

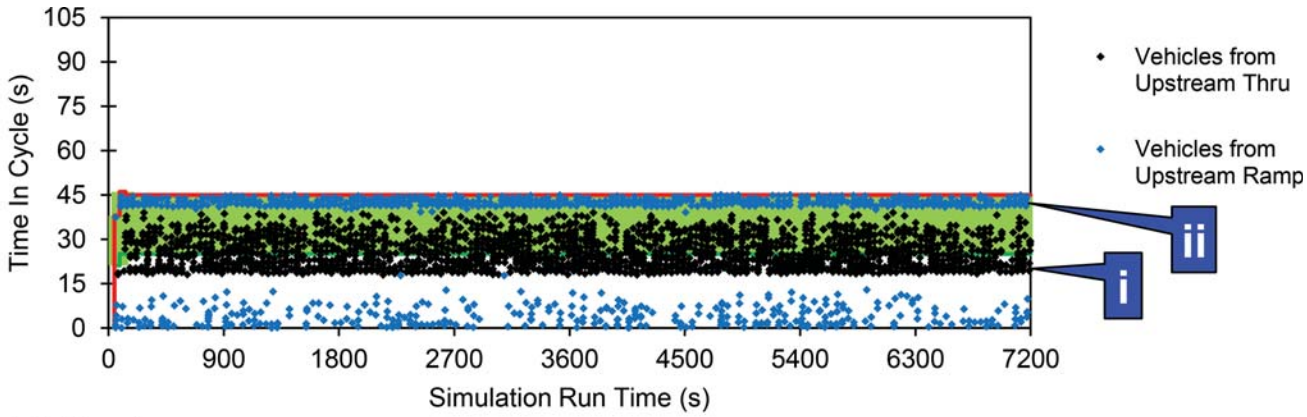


(b) Full cycle (two phase).

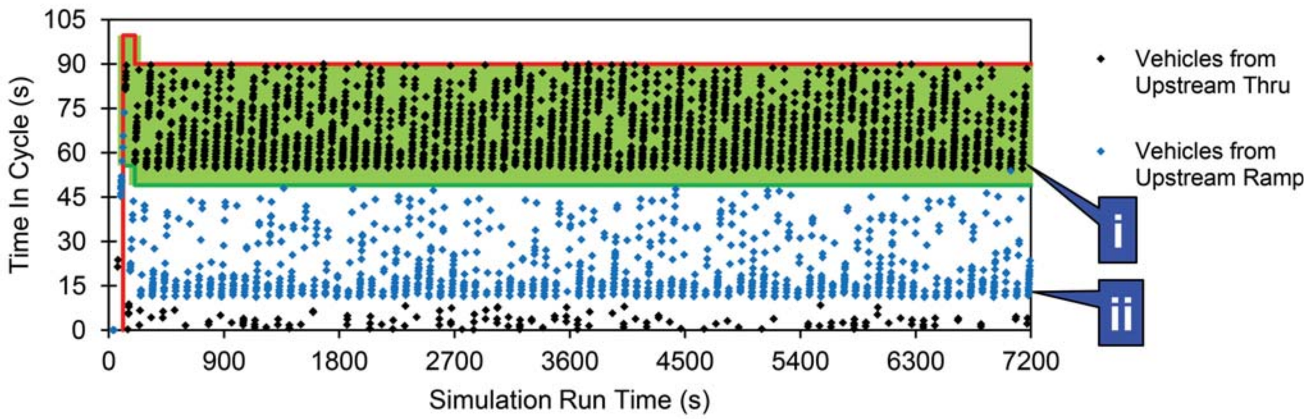


(c) Three phase.

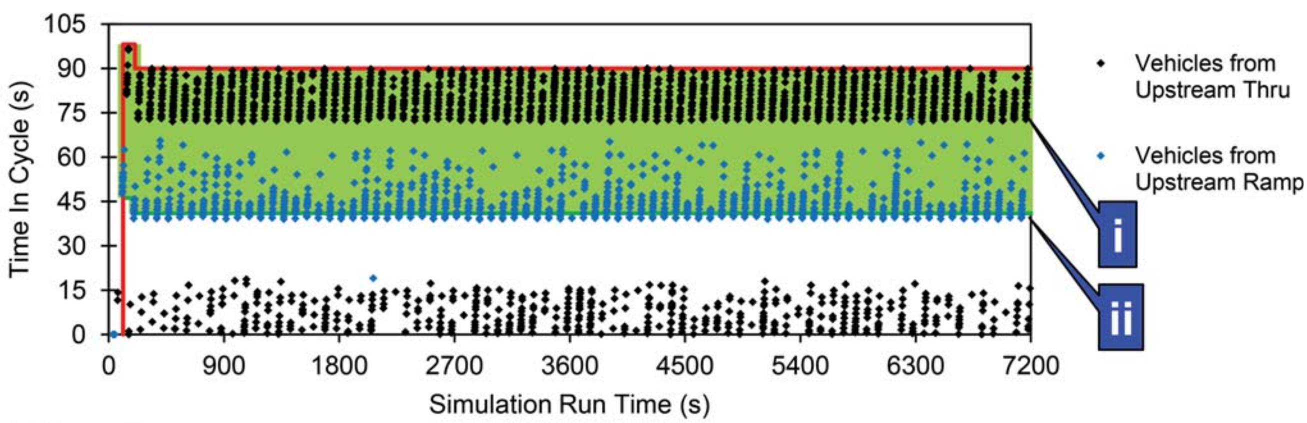
Figure 3.18 Westbound vehicle trajectories for different DDI cycle length strategies.



(a) Half cycle.



(b) Full cycle (two phase).



(c) Three phase.

Figure 3.19 PCDs for different DDI cycle length strategies (Westbound at Int. 2).

TABLE 3.3
Turning movement counts by scenario.*

Intersection	Movement	Scenario 1 Balanced	Scenario 2 Heavier Arterial	Scenario 3 Lighter Arterial	Scenario 4 Heavier Ramp	5 Heavier Eastbound	6 Saturated
1		75	90	60	75	90	105
	EB Thru	**850**	**1020**	**680**	**850**	**1020**	**1190**
	EB Left	75	90	60	75	90	105
	WB Left	525	350	605	795	305	830
	WB Thru	**800**	**890**	**680**	**870**	**410**	**1230**
	WB Right	175	140	185	235	155	270
	NB Left	50	40	50	50	50	80
	NB Thru	75	60	75	75	75	120
	NB Right	375	300	375	375	375	600
	SB Right	50	40	50	50	50	80
	SB Thru	75	60	75	75	75	120
	SB Left	375	300	375	375	375	600
2	EB Right	550	420	580	650	600	830
	EB Thru	**1050**	**1200**	**850**	**950**	**1170**	**1560**
	WB Left	550	420	580	650	495	830
	WB Thru	**1000**	**1080**	**870**	**1100**	**570**	**1530**
	SB Right	500	300	600	800	300	800
	SB Left	500	300	600	800	700	800
3	**EB Thru**	**1000**	**1080**	**870**	**1100**	**1270**	**1530**
	EB Left	550	420	580	650	600	830
	WB Thru	**1050**	**1200**	**850**	**950**	**765**	**1560**
	WB Right	550	420	580	650	495	830
	NB Left	500	300	600	800	300	800
	NB Thru	500	300	600	800	700	800
4	EB Right	175	140	185	235	185	270
	EB Thru	**1150**	**1100**	**1100**	**1430**	**1600**	**1790**
	EB Left	175	140	185	235	185	270
	WB Left	75	90	60	75	45	105
	WB Thru	**850**	**1020**	**680**	**850**	**510**	**1190**
	WB Right	75	90	60	75	45	105
	NB Left	375	300	375	375	375	600
	NB Thru	75	60	75	75	75	120
	NB Right	50	40	50	50	50	80
	SB Right	375	300	375	375	375	600
	SB Thru	75	60	75	75	75	120
	SB Left	50	40	50	50	50	80

***Boldface** rows indicate the arterial through movements.

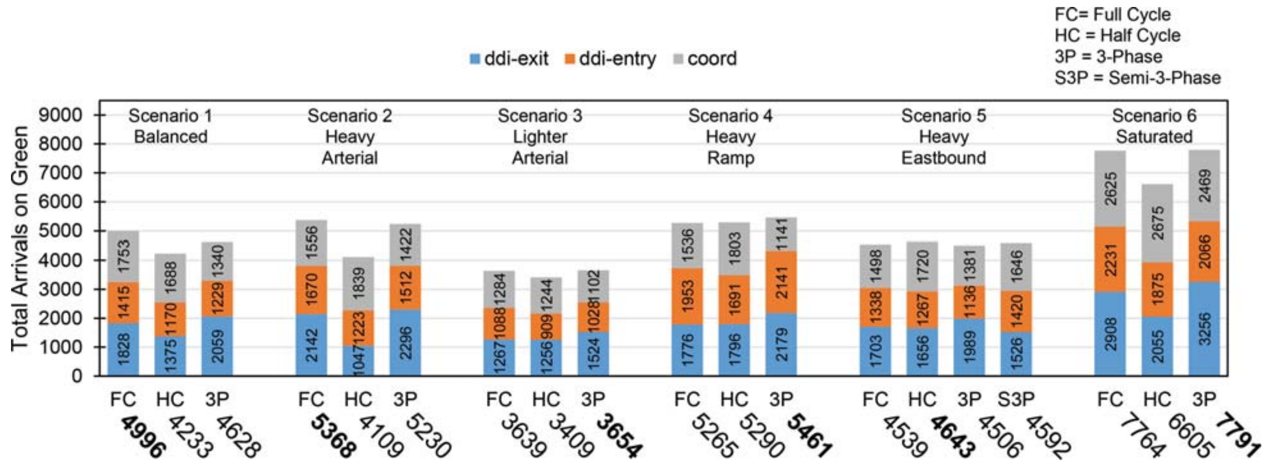


Figure 3.20 Arrivals on green by scenario and cycle length strategy, segmented by movement. The total number of arrivals on green are shown at the bottom. The strategy within each scenario having the greatest number is highlighted in bold.

- Several additional routes from the side streets are also considered, as shown in Figure 3.21b. This includes all of the routes ending at the freeway, as well as routes crossing the interchange and going toward the arterial endpoint at the far end of the system from the originating intersection.

The average and standard deviation of the travel times were tabulated and used to determine an annualized user cost, following a very similar method as was used in the Fort Wayne field study. The user cost values and methodology were adopted from the TTI *Urban Mobility Report* (Schrank, Eisele, & Lomax, 2012), with some additional terms included to reflect the value of the reliability of travel time, following a method developed in an NCHRP study (Small, Noland, Chiu, & Lewis, 2009). The formula for cost, c, is developed as follows (Equation 3.1), afterLi et al. (2015):

$$c=\frac{364}{60}\cdot(T_{avg}v_{pc}o_{pc}u_{pc}+k_{pc}T_{std}v_{pc}o_{pc}u_{pc}+T_{avg}v_{hv}u_{hv}+k_{hv}T_{std}v_{hv}u_{hv}) \tag{3.1}$$

Here,

T_{avg} is average travel time (min), T_{std} is the standard deviation of travel time (min);

v_{pc} and v_{hv} are the total volumes of passenger cars and heavy vehicles;

o_{pc} is the occupancy rate of passenger cars (persons/vehicle);

u_{pc} and u_{hv} are the unit values of time for passenger vehicles and heavy vehicles;

k_{pc} and k_{hv} are the unit values of reliability for passenger vehicles and heavy vehicles; and

60 is a conversion from minutes to hours and 364 annualizes the results.

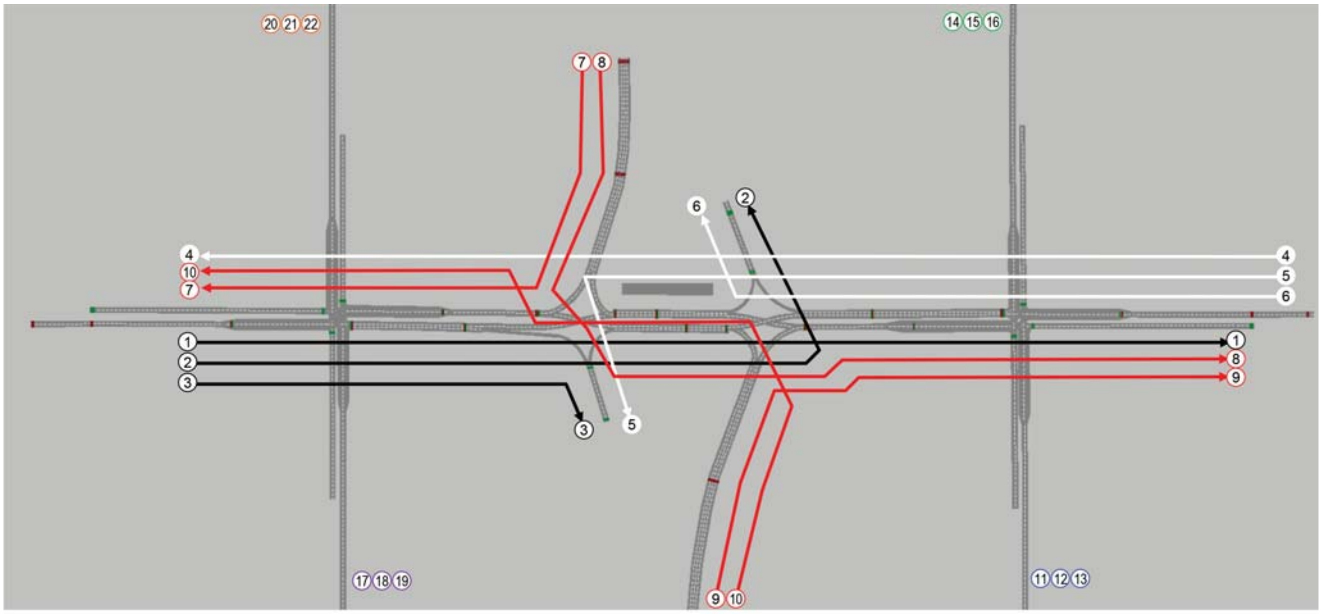
This equation yields c in dollars per year. The k factors represent the value of travel time reliability as a multiple of the overall value of the travel time. For example, $k = 1.0$ means that one unit change in the standard deviation of travel time is equal to one unit change in the average of travel time. For this study, $k_{pc} = k_{hv} = 1.0$ was used. This study used o_{pc} = 1.25 persons/vehicle, u_{pc} = \$17.67 per hour, and u_{hv} = \$94.04 per hour.

The annualized user costs for each scenario-strategy pair are shown in Figure 3.22. The total user cost for all of the movements considered is shown by the value underneath each column. The strategy yielding the minimum user cost is highlighted in bold. The bars segment the user costs according to movement type. Five movement types are identified:

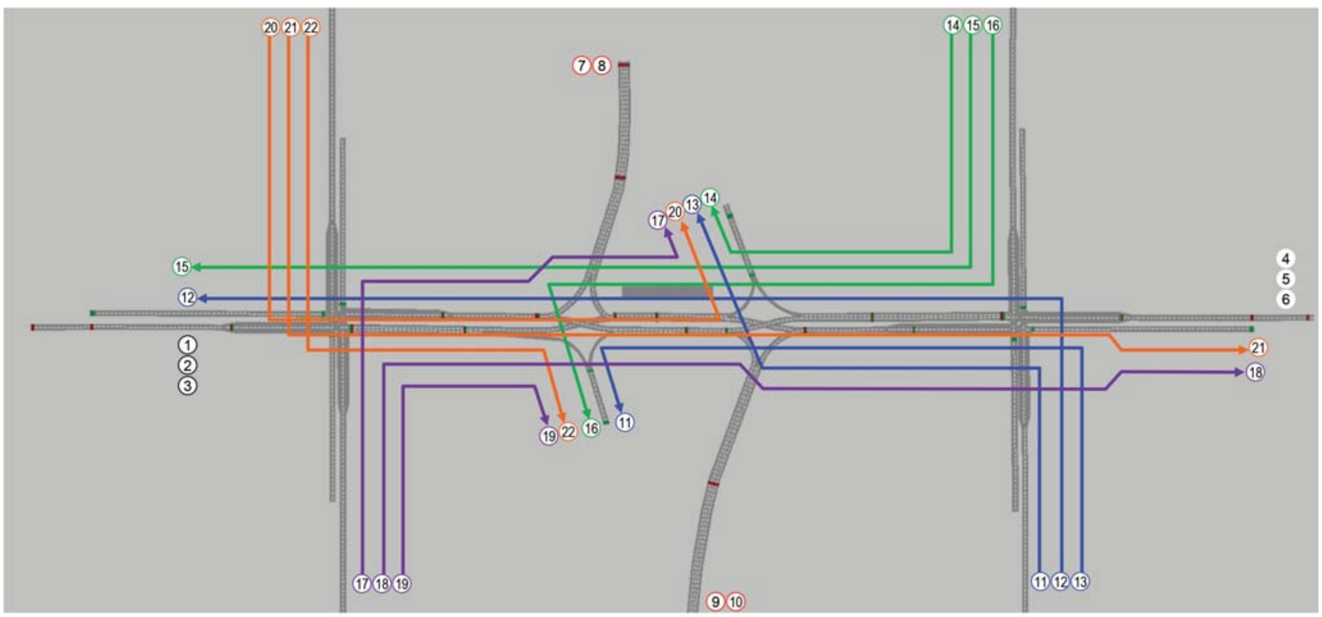
- *Arterial thru.* This represents the two arterial routes (westbound and eastbound) from one arterial endpoint to the other arterial endpoint.
- *Arterial to freeway*. This represents travel from the two arterial endpoints to the northbound or southbound freeway on-ramps.
- *From freeway*. This represents travel from the freeway off-ramps to either arterial endpoint.
- *Side street (SS) to arterial*. This represents travel from a side-street approach to either arterial endpoint.
- *Side street (SS) to freeway*. This represents travel from a side-street approach to the northbound or southbound freeway on-ramps.

The total user cost results are unanimous: half-cycling produced the lowest user cost in all six scenarios. For some scenarios, this cost was considerably lower than the other options. Full-cycle and three-phase operation had similar costs under some scenarios, but three-phase had the higher value. For scenario 5, the semi-three-phase strategy had a lower user cost than either full-cycle or complete three-phase.

To conclude, the results from the annualized user cost analysis and the average delay by DDI movement clearly indicate that the half-cycling strategy yields the optimal result for interchange movements and routes going through the interchange. On the other hand, the



(a) Arterial and ramp O-D paths.



(b) Side street O-D paths.

Figure 3.21 O-D paths used for user cost estimation.

AOG results show that a three-phase or full-cycle strategy can sometimes yield somewhat better progression, especially for the DDI exiting movements. From these outcomes, we would recommend that, when preparing a plan for DDI signal timing on a corridor with neighboring intersections, the favored strategy and the first one that should be attempted would be to use a half-cycle. At locations where keeping the roadway between the crossover intersections is desirable, then a three-phase strategy should be attempted. This reflects the current signal timing strategy in use at the Fort Wayne interchange.

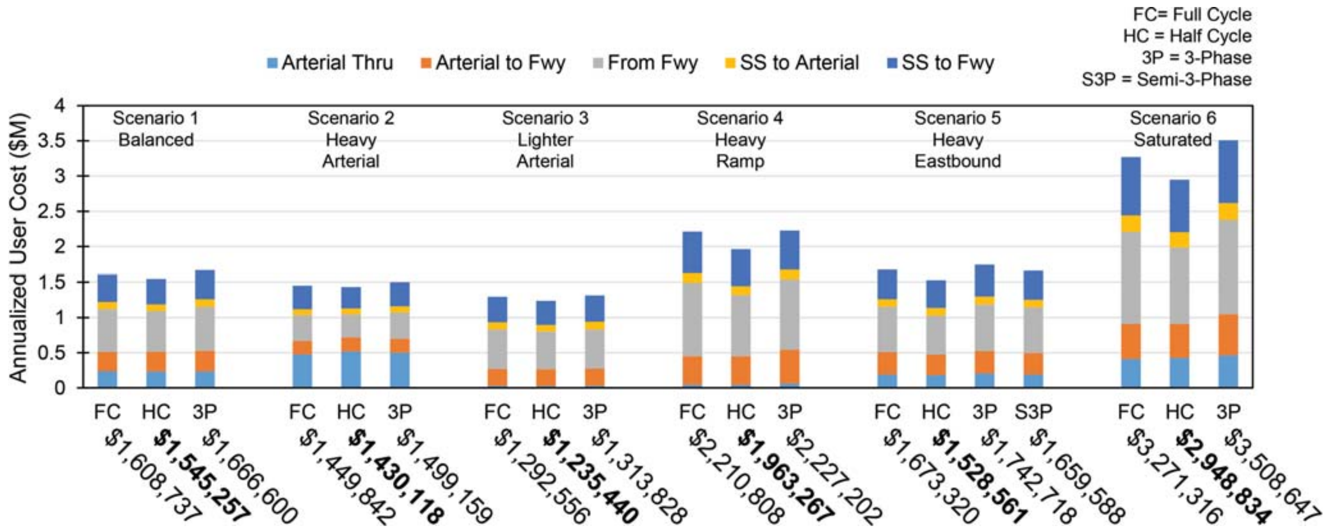


Figure 3.22. Annualized user costs for all of the O-D travel times considered for each scenario under each cycle length strategy. The strategy with the lowest total user cost is highlighted in bold. The bars show the breakdown of user cost by O-D path type.

TABLE 3.4
Average delay (s/veh) by movement for signalized DDI movements.*

		West Intersection (Int. 2)				East Intersection (Int. 3)			
Scenario	**Cycle Length Strategy**	**SB Left Turn (Offramp)**	**SB Right Turn (Offramp)**	**EB Thru (Entering)**	**WB Thru (Exiting)**	**NB Left Turn (Offramp)**	**NB Right Turn (Offramp)**	**EB Thru (Exiting)**	**WB Thru (Entering)**
1. Balanced ($C = 90$)	Full-cycle	19.7	16.7	14.8	20.3	19.7	16.8	21.2	15.5
	Half-cycle	**12.6**	**11.9**	**11.1**	16.0	**12.7**	**11.7**	16.5	**11.4**
	Three-phase	26.9	22.3	21.0	**8.4**	27.0	22.2	**9.4**	21.6
2. Heavier Arterial ($C = 100$)	Full-cycle	20.1	17.5	15.8	16.1	19.8	17.1	15.4	15.7
	Half-cycle	**13.4**	**11.5**	**10.6**	**10.5**	**12.9**	**11.4**	10.6	**14.6**
	Three-phase	30.7	22.9	21.8	11.6	30.4	22.9	**5.4**	21.8
3. Lighter Arterial ($C = 80$)	Full-cycle	17.6	15.6	15.4	17.2	17.6	15.6	16.5	15.8
	Half-cycle	**12.3**	**12.2**	**10.9**	15.4	**11.9**	**12.1**	14.2	**11.9**
	Three-phase	25.9	20.2	20.7	**8.3**	25.6	20.2	**3.5**	22.6
4. Heavier Ramp ($C = 110$)	Full-cycle	23.4	22.6	22.2	31.3	23.1	22.4	23.3	23.4
	Half-cycle	**14.4**	**15.3**	**13.1**	**13.0**	**14.6**	**15.1**	12.9	**14.9**
	Three-phase	32.4	27.7	34.4	22.5	33.3	27.9	**3.5**	32.3
5. Heavier Eastbound ($C = 120$)	Full-cycle	29.5	17.0	17.7	31.8	16.7	29.1	14.4	27.7
	Half-cycle	**18.5**	**10.8**	**10.6**	15.2	**10.5**	**18.3**	**11.4**	**14.2**
	Three-phase	37.3	26.8	29.8	**13.6**	33.6	29.3	13.0	29.5
	Semi-Three-phase	35.9	12.2	13.2	25.0	31.8	30.2	13.6	28.3
6. Saturation ($C = 130$)	Full-cycle	26.8	28.4	29.1	32.6	26.7	26.4	29.7	30.9
	Half-cycle	**16.4**	**20.8**	**19.8**	**16.9**	**16.3**	**19.1**	**13.1**	**20.3**
	Three-phase	42.0	36.4	48.1	17.7	43.3	35.9	19.1	41.2

*The strategy with the lowest average delay for the movement within each scenario is denoted in **boldface**.

4. CONCLUSIONS

This report summarized the findings from two field studies at DDIs in Salt Lake City, Utah, and Fort Wayne, Indiana.

- The Salt Lake City study investigated operations at SR 201 and Bangerter Highway. The study looked at offset optimization within the DDI, as well as alternative phase sequencing. The study demonstrated the option of prioritizing alternative movements, validated the prediction model based on high resolution data, and showed the range of possible timing options. Alternative "two-phase" and "three-phase" schemes were examined. It was found that the "three-phase" scheme permitted the development of a signal timing plan that could accommodate two platoons at a downstream intersection, whereas the "two-phase" forced a choice between either of those two platoons. Implementation of the "three-phase" operation increased the percent on green from 53% to 92%. Full details are provided in the reprint included in Appendix A.
- The Fort Wayne study is the first field study to examine offset optimization in a corridor incorporating a DDI. The study examined a five-intersection system around the interchange of SR 1 and I-69 in Fort Wayne, Indiana. An existing offset optimization methodology was applied to the DDI, incorporating a method for extracting the ring displacement parameter from the suggested offset adjustments. Evaluation of the timing was done using a network of Bluetooth vehicle sensors that considered not only the arterial through movements, but also origin-destination paths leading to and coming from the freeway. An estimation of user costs related to the observed travel times and their reliability showed an annualized benefit of $564,000. Full details are provided in the reprint included in Appendix B.

The report included a discussion of practical issues related to DDI signal timing. The clearance phase requirements, and how to implement these in different controller types, were discussed in detail. Guidelines for signal phasing and several draft template timing plan designs were prepared for a variety of circumstances, including both inside and outside pedestrian crossings. Finally, software modeling for optimizing timing plans was discussed.

Three strategies for cycle length selection were identified and compared against each other using a VISSIM simulation of a DDI with two neighboring intersections under six different traffic scenarios. The study outcomes agreed with the field comparison of two- and three-phase operation in Utah, in that three-phase operation improved coordination within the interchange. However, the study went further and examined overall corridor operations. When comparing overall interchange and corridor operations, a half-cycling strategy yields the lowest user cost and the lowest average delay for most movements (although three-phase does reduce delays on the movements exiting the DDI). From this outcome, it is recommended to use a half-cycling strategy where possible. This is the current strategy used at the Fort Wayne interchange.

Future research on DDI operations should consider criteria for selecting two-phase, three-phase, or other alternative timing schemes, and compare DDI operation with other interchange types under similar volume conditions to assess the differences in performance, in order to develop recommendations for interchange selection and to understand what conditions a DDI will provide the best return on investment compared to alternative treatments.

REFERENCES

Bared, J. G., Edara, P. K., & Jagannathan, R. (2005). Design and operational performance of double crossover intersection and diverging diamond interchange. *Transportation Research Record*, 1912, 31–38. http://dx.doi.org/10.3141/1912-04

Day, C. M., & Bullock, D. M. (2011). Computational efficiency of alternative algorithms for arterial offset optimization. *Transportation Research Record*, *2259*, 37–47. http://dx.doi.org/10.3141/2259-04

Day, C. M., Wasson, J. S., Brennan, T. M., & Bullock, D. M. (2012). *Application of travel time information for traffic management* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2012/06). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284314666

Day, C. M., Lavrenz, S. M., Stevens, A. L., Miller, R. E., & Bullock, D. M. (2016). Extending link pivot offset optimization to arterials with single controller diverging diamond interchange. In *TRB 95th annual meeting compendium of papers,* Paper No. 16-0111. Washington, DC: Transportation Research Board.

Hainen, A. M., Stevens, A. L., Day, C. M., Li, H., Mackey, J., Luker, M., Taylor, M., Bullock, D. M. (2015). Performance measures for optimizing diverging diamond interchanges and outcome assessment with drone video. *Transportation Research Record*, *2487*, 31–43. http://dx.doi.org/10.3141/2487-03

Hu, P. (2013). *Advanced signal control strategies and analysis methodologies for diverging diamond interchanges* (Doctoral dissertation). Reno, NV: University of Nevada, Reno.

Li, H., Lavrenz, S. M., Day, C. M., Stevenz, A., Sturdevant, J. R., & Bullock, D.M. (2015). Use of both travel time and travel time reliability measures to quantify benefits of signal timing maintenance and optimization. *Transportation Research Record*, *2487*, 55–68. http://dx.doi.org/10.3141/2487-05

MoDOT. (2010). *Missouri's experience with a diverging diamond interchange: Lessons learned* (Report No. OR10-021). Jefferson City, MO: Missouri Department of Transportation.

Schrank, D., Eisele, B., & Lomax, T. (2012). *TTI's 2012 urban mobility report*. College Station, TX: Texas A&M Transportation Institute.

Small, K. A., Noland, R., Chiu, X., & Lewis, D. (1999). *Valuation of travel time savings and predictability in congested conditions for highway user-cost estimation* (NCHRP Report 431). Washington, DC: Transportation Research Board.

Tian, Z., Xu, H., de Camp, G., Kyte, M., & Wang, Y. (2015). Readily implementable signal phasing schemes for diverging diamond interchanges. *TRB 94th annual meeting compendium of papers,* Paper No. 15-0723. Washington, DC: Transportation Research Board.

Yang, X., Chang, G.-L., & Rahwanji, S. (2014). Development of a signal optimization model for diverging diamond interchange. *Journal of Transportation Engineering*, *140*(5), 04014010. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000657

APPENDIX A: REPRINT OF "HIGH-RESOLUTION CONTROLLER DATA PERFORMANCE MEASURES FOR OPTIMIZING DIVERGING DIAMOND INTERCHANGES AND OUTCOME ASSESSMENT WITH DRONE VIDEO"

A reprint of the following article, available for download at http://dx.doi.org/10.5703/1288284316012, is included for the project panel reviewers.

Hainen, A. M., Stevens, A. L., Day, C. M., Li, H., Mackey, J., Luker, M., Taylor, M., Bullock, D. M. (2015). Performance measures for optimizing diverging diamond interchanges and outcome assessment with drone video. *Transportation Research Record*, *2487*, 31–43. http://dx.doi.org/10.3141/2487-03

APPENDIX B: REPRINT OF "EXTENDING LINK PIVOT OFFSET OPTIMIZATION TO ARTERIALS WITH SINGLE CONTROLLER DIVERGING DIAMOND INTERCHANGE"

A reprint of the following article, available for download at http://dx.doi.org/10.5703/1288284316012, is included for the project panel reviewers.

Day, C. M., Lavrenz, S. M., Stevens, A. L., Miller, R. E., & Bullock, D. M. (2016). Extending link pivot offset optimization to arterials with single controller diverging diamond interchange. In *TRB 95th annual meeting compendium of papers,* Paper No. 16-0111. Washington, DC: Transportation Research Board.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

About This Report

An open access version of this publication is available online. This can be most easily located using the Digital Object Identifier (doi) listed below. Pre-2011 publications that include color illustrations are available online in color but are printed only in grayscale.

The recommended citation for this publication is:

Day, C. M., Stevens, A., Sturdevant, J. R., & Bullock, D. M. (2015). *Evaluation of alternative intersections and interchanges: Volume II—Diverging diamond interchange signal timing* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2015/27). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316012