Readily Implementable Signal Phasing Schemes for Diverging Diamond Interchanges

Zong Tian*, Ph.D., P.E.
Hao Xu, Ph.D
Center for Advanced Transportation Education and Research
University of Nevada, Reno
Reno, NV 89557
Email: zongt@unr.edu

Gerry de Camp, P.E.
Free-Lance Signal Operations Consultant
Email: gerry.de.camp@gdecamp.com

Michael Kyte
Department of Civil and Environmental Engineering
University of Idaho
Moscow, ID 83843
Email: mdkyte@gmail.com

Yinhai Wang, Ph.D., P.E.
Pacific Northwest Transportation Consortium (PacTrans)
University of Washington, Seattle, WA 98195-2700
Email: yinhai@uw.edu

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Abstract

Diverging Diamond Interchanges (DDI) are emerging as an efficient alternative to conventional diamond interchanges with proven safety and operational efficiency. The number of DDIs is expected to increase significantly in the U.S. over the next decade. While geometric design of DDIs is getting mature based on experiences from existing sites, traffic operations, particularly the various signal phasing schemes, are not yet well defined and recognized. This paper provides five feasible signal phasing schemes which can be easily implemented using standard NEMA 8-phase signal controllers. Discussions are provided regarding the advantages and disadvantages of each phasing scheme. These phasing schemes should be implemented according to the specific traffic pattern and geometric layout of DDI sites in order to achieve the best operational performance. Other relevant issues included in the paper are pedestrian handling, yellow change and red clearance intervals at DDIs.

Keywords: Diverging diamond interchange, signal control, operations, signal phasing
Introduction

The first diverging diamond interchange (DDI) in the U.S. was put into operation in Springfield, Missouri in 2009, six years after Gilbert Chlewicki (1) first introduced this innovative design concept. Due to the great success of its operations, the number of DDIs has grown significantly in the past few years with over 20 now in operation and more than 50 under planning and design. DDI has proven to be a cost effective interchange type, providing both efficient and safe traffic operations.

Considering DDI still a relatively new concept, there is an urgent need to gather the knowledge and lessons learned from existing research and practices in order to better guide future design and operations. A review of the current state of the practice has shown that most DDIs implemented so far are not operating using the most efficient signal phasing schemes, neither in free mode nor coordination mode. There is also a lack of understanding of how a phasing scheme can be designed and implemented to fit certain traffic and geometric conditions. The purpose of this paper is to provide a comprehensive documentation of the various signal phasing schemes that can be easily implemented into standard signal controllers following the NEMA phase/ring/barrier convention. Other relevant signal control aspects covered in this paper include pedestrian phasing and special consideration of signal change intervals. In order for readers to easily understand the phasing principles, links to YouTube are provided for viewing the animations of the presented phasing schemes. It is the desire of the authors that the paper serves as a practitioners’ guide on implementing safe and efficient signal phasing schemes for DDIs under different traffic and geometric conditions.

Phasing Scheme Categorization

At a DDI, the off-ramp control type influences the phasing options. The left-turn and right-turn movements at a DDI’s off-ramp can be signalized or unsignalized (e.g., yield or stop control). When controlled by traffic signals, they can be on the same phase or separate phases. Off-ramp right turns rarely become critical movements because of the possible use of overlaps or through channelized design (2). Therefore, the DDI phasing schemes described next only include the signalized off-ramp left turn phases.

Based on our best knowledge, we categorize DDI phasing schemes into five types as summarized in Figure 1. Each is described below, ranging from the simplest to the most sophisticated schemes. Controller overlap phases are used in three of the schemes. Using overlaps is common at signalized interchanges where a movement can be controlled by more than one phase. All phasing schemes are based on the operation of a single controller, which is a common and effective practice at DDIs. For convenience, we follow a convention, whenever possible, that designates phases 1,2,5,6 for the north-south off-ramps and phases 3,4,7,8 for the east-west arterial approaches. We also try to comply with the default NEMA 8-phase, dual ring,
and 2-barrier structure. We use the term “stage” to differentiate it from the NEMA phase. A “stage” indicates a duration during which multiple signal phases can occur simultaneously. For a better visualization of how each phasing scheme works without taking too much space, we provide the stage diagrams for three of the phasing schemes. In the stage diagrams, the phase(s)/movement(s) in each stage are shown for both signals to better illustrate progression between the two signals. Links to the YouTube videos for most of the phasing schemes are also provided for easier visualization of the operations.

*Phasing Scheme 1-A (P1-A): 2-stage split with off-ramp overlap*

This phasing scheme is found to be the most commonly used scheme at existing DDI sites. This scheme was first documented in a report by the FHWA (3). The Missouri DOT (4) included a slightly modified barrier structure which ensures no stopping between the signals for the arterial movements. The advantages of this phasing scheme include: (a) no stops between the signals for the arterial traffic; (b) only two critical phases, thus with less lost time, higher capacity, and shorter cycle length; and (c) easy to implement and efficient when off-ramp traffic is light. The major disadvantage of this phasing scheme is that off-ramp traffic generally stops between the signals and internal queue spillback can occur if the spacing is short and off-ramp left-turn volume is high. Figure 2 illustrates the stage diagram to depict the traffic progression between the two signals.

*Phasing Scheme 1-B (P1-B): 2 or 3-stage split with off-ramp overlap*

This is a variation of P1-A with each side having two phases (φ3, φ4) and (φ7, φ8). Therefore, the arterial phases in the same direction (e.g., φ4 and φ8 for the EB direction) do not have to end together, potentially reducing individual movement delay. The trade-off is possible stops for the arterial traffic. The off-ramp phases still overlap with the arterial phases. The two overlaps (D, E) for the off-ramps are needed if separate phases are given to the off-ramps (e.g., φ2 and φ6 in this case). This phasing scheme shares the same fundamental issues with P1-A, where internal queue spillback could result if spacing is short and off-ramp left-turn volume is high. Following this same operation, there could be other forms of phase numbering and overlap usage.

*Phasing Scheme 2 (P-2): 2-stage concurrent with off-ramp overlap*

This phasing scheme allows the two signals to turn green at the same time for both directions. Therefore, the two arterial directions move concurrently. When the phase splits are shorter than the travel time between the two signals, arterial movements do not stop, resembling in some way a simultaneous two-way progression. Under low volume conditions, the two sides can operate barrier free to minimize local intersection delays. The major disadvantage of this scheme is that the arterial traffic most likely stops between the signals when spacing is short and volume is high. A potential internal queue spillback can result in higher lost time for the off-ramp phases. A YouTube animation of this scheme can be found at: http://www.youtube.com/watch?v=d-xCRbhOIIQ.
Figure 1. Classification of DDI phasing schemes
Figure 2. Stage and progression diagram using phasing scheme P1-A

**Phasing Scheme 3 (P-3): 3-stage split without off-ramp overlap**

This is essentially a split phasing operation, and is currently being used at the I-580/Moana Lane DDI site in Reno, Nevada. Two overlaps (A,B) are used for the internal approaches. The major advantage of this scheme is excellent progression for all movements. The internal links are mostly free of vehicle queues, a highly desirable objective for DDIs where signal spacing is short. However, due to the nature of split phasing with three critical phases, this results in higher lost time and lower capacity. Longer queues on the external approaches can also be problematic to interfere with the adjacent signals and freeway. A YouTube video demo can be found at: http://youtu.be/P8JONSc8xjY.

**Phasing Scheme 4 (P-4): 6-stage split with arterial-ramp overlap**

This is a phasing scheme invented by the authors, which resembles the TTI-4 phasing scheme at conventional diamond interchanges (5,6). Four overlaps (A, B, C, D) are used. The stage diagram of this phasing scheme is illustrated in Figure 3. Phases are numbered so that the default NEMA phasing structure remains unchanged. The only caution is to set both $\phi_1$ and $\phi_7$ equal to the internal travel time (T.T.) and to be operating under max recall. All vehicle stops are essentially eliminated between the two signals. Because of the use of overlaps to allow off-ramp phases and arterial phases to move at the same time, some efficiency is gained compared to phasing scheme 3. Although it is a 6-stage scheme, there are only three phases that incur lost times.
This is a slightly modified phasing scheme from what was invented by researchers at the University of Nevada, Reno and was presented at the 93rd TRB Annual Meeting (7). It was fully tested using hardware-in-the-loop simulation. Details of this phasing scheme are illustrated in Figure 4, including the progression diagram and the NEMA phase/ring/barrier structure.

Phasing Scheme 5 (P-5): 4-stage split with arterial-ramp overlap

This scheme also has three phases that incur lost times due to the use of overlaps. For example, there is no lost time between φ1 and φ3 for overlap C. This phasing scheme also adopts a strategy similar to operating conventional diamond interchanges where the arterial and off-ramp phases are allowed to move simultaneously while still maintaining no stops between the signals. In this example, the southbound left-turn and the westbound arterial have an overlap stage for the duration of the travel time (T.T.) by using two dummy phases: φ1 and φ5. This is an additional efficiency gained by the southbound off-ramp traffic. The length of φ1 and φ5 can also be

Figure 3. 6-Stage split with arterial-ramp overlap
increased to exceed the travel time by trading off some internal stops with an increased capacity. This treatment proves to be very efficient when the interchange operates near capacity (8). The slight delay in the middle is generally not a concern as vehicles are cleared out rather quickly.

Stage 1: SBL and WB move simultaneously for a duration of T.T.

Stage 2: SBL arrives at the right side signal without stopping exactly after EB stops. The NBL progresses

Stage 3: The later arrivals from NBL do not stop at the off-ramp, but stop inside DDI.

Stage 4: WB starts and progresses through without stopping.

A YouTube video can be found for this phasing at http://youtu.be/Aq9W7aQEuTs

As for the northbound off-ramp, it allows overlap with φ4, thus significantly increasing the phase time and capacity. Because the first part of φ2 runs concurrently with φ6, those vehicles stopped at the off-ramp signal in a queue can mostly progress through the left signal. Vehicles arriving after the queue discharge will go through the off-ramp signal without stopping; and then stop at the left signal. This operation does not increase the total number of stops for the northbound off-ramp. A potential internal queue spillback is unlikely unless the off-ramp traffic volume is very high. For example, for a 300-ft and 2-lane internal storage spacing, it can store approximately (300 ft/25 ft per car) * 2 lanes = 24 cars. For an off-ramp left-turn volume of 1,000 vph, it would require about 24/(1000/3600) = 86 seconds to fill the storage space, which is unlikely with a typical cycle length and phase split setting. The sequence for φ3 and φ4 can be switched to achieve the desired operational objectives for the two off-ramps.
Pedestrian Crossings and Handling

Pedestrian crossings and timing are directly related to the type of pedestrian path designs. There are generally two types of designs related to pedestrian path: external and internal (4). The external design places all the crosswalks and pedestrian path outside of the interchange, while the internal design takes the pedestrians to the inside median (see Figure 5). From a signal control point of view, the internal design has many advantages compared to the external design. One of the most significant benefits is to eliminate signalized crosswalks crossing the left-turn movements onto the freeway, which are supposed to be free flow movements.

The four signalized crosswalks can be easily accommodated by the non-conflicting vehicle phases. For example, the four crosswalks can be controlled by the following corresponding vehicle phases with the DDI P5 scheme: X1 by φ6; X2 by φ4; X3 by φ2; and X4 by φ3. The use of overlap to control pedestrian crosswalks could potentially improve pedestrian services by reducing delay times (9). For the case shown, X1 can be controlled by an overlap phase of φ6 and φ3 while X3 can be controlled by an overlap phase of φ2 and φ4.

Yellow and Red Clearance Intervals

The calculation of yellow change interval is no different from typical signalized intersections where the ITE recommended guidelines could be applied. However, due to the special geometric layout, the calculation of red clearance interval deserves some attention. In particular, the clearance distances as well as the red clearance intervals for the arterial phases are longer than that at normal intersections. For example (refer to the DDI layout in Figure 6 from a Utah site), the red clearance of φ2 (NBT facing to the left) needs to ensure that the vehicle passes the conflicting point before starting φ4 (EBL). On the other hand, the red clearance interval for φ4
may be shorter than the ITE recommendation due to the longer move-up distance for \( \phi_2 \). Utah DOT (10) has exercised a unique phasing and detector setup where downstream detectors are placed between the crossover and the off-ramps (see detectors calling \( \phi_3 \) and \( \phi_1 \) in Figure 6). Instead of using a long red clearance interval for \( \phi_2 \), the downstream detector (calling \( \phi_3 \)), once triggered will delay the start of \( \phi_4 \), similar to a dynamic red clearance extension. This innovative design deserves further evaluation as part of this research.

Figure 6. Utah DOT detector design to reduce all-red clearance (courtesy of Matt Luker at Utah DOT)

Summary

Various signal phasing schemes are documented in this paper for operating DDIs. The advantages, disadvantages, and their applicable conditions are also discussed. This paper fills some of the knowledge gaps in the signal control aspect of DDI operations. While no detailed analyses were conducted to provide quantitative assessments on the various phasing schemes, the descriptions are intuitive enough for easily visualizing how each phasing scheme works and whether it is suitable for certain traffic flow and geometric conditions. It is the desire of the authors that this paper serves as a valuable guide for practicing signal engineers to identify and implement safe and efficient signal phasing schemes at DDIs.
References


