University of Nevada, Reno

An Innovative Signal Phasing Scheme for Diverging Diamond Interchanges

A thesis submitted in partial fulfillment of the requirements for the degree of

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by Jeffrey Bickett

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ABSTRACT

This thesis presents the development of an innovative signal phasing scheme for Diverging Diamond Interchanges (DDIs) through a case study of the diverging diamond interchange at Moana Lane & Interstate-580 freeway (Moana Ln & I-580 DDI) in Reno, Nevada.

An innovative phasing scheme was derived and compared against four DDI phasing schemes that had been identified through field deployment or prior publications, and subsequently evaluated in this research effort categorized by two, three, and four critical movements. The strengths and weaknesses of using phase overlaps and dummy phases were outlined to achieve operational objectives regarding if internal stops and queueing were allowed and if signal control lost time can be minimized.

The effectiveness of the developed signal phasing schemes was evaluated based on a case study where Moana Ln & I-580 DDI was used as an example. A set of 30-minute vehicle volume counts were collected during the both AM and PM peak hours and interpolated into full-hour traffic counts which were used for the analysis. As the PM peak counts were substantially greater than the AM peak counts, the analysis only evaluated the PM operations. The PM peak operations were primarily studied using a VISSIM model that was built and calibrated according to real-world geometry and traffic operations.

Given a fully actuated PM timing plan implemented as the base scenario, comparative phasing schemes were tested under various conditions. Modified Webster's equations were employed to produce phase splits for the phasing schemes with trailing overlaps. Split derivation was found to share characteristics with typical diamond interchanges, though the phasing varied. The phasing schemes with their optimized splits were then modeled in VISSIM simulation. A comparative evaluation was performed based on the simulated measures of effectiveness (MOEs), such as delay time, stop delay time, and average number of stops. Simulation results indicated that the proposed phasing scheme with internal stops could allow for reductions in traffic delay as compared to other schemes.

The field condition of Moana Ln & I-580 DDI do not meet all requirements for implementing the optimal proposed phasing schemes, such as the absence of detection in interior lanes that eliminate internal stops or rewiring of the controller. Thus, the recommendation of the proposed phasing scheme only applies to certain conditions, such as new or renovated interchanges, which have been presented in the thesis. The findings presented in the thesis would facilitate transportation agencies making an informed decision on the development of traffic signal timing for a DDI for use in the field or for design alternative analysis.

ACKNOWLEDGMENTS

Thanks to Dr. Zong Tian of University of Nevada, Reno, without whose teachings and dedication I would not have had the opportunity nor the skills with which to both analyze the existing transportation networks but also develop potential improvements.

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Thanks to Andrew Jayankura for his work in teaching myself and the other graduate students the art of signal timing and the passion with which it can be performed.

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1. INTRODUCTION

1.1 Background

Diverging Diamond Interchanges (DDI) are an emerging interchange type that is increasingly adopted in the United States since 2009, when the first DDI was constructed in Springfield, Missouri [1], which is presented in Figure 1. As an alternative to conventional diamond interchanges and other interchange types, a DDI is characterized by two directional crossovers located on either side and continuous left turns onto and off freeway facilities [2].

Figure 1. A Diverging Diamond Interchange in Springfield, MO

DDIs have currently become one of the widely recognized interchange retrofits because of the significant vehicle traffic safety and operational improvements compared to conventional interchange designs. DDIs facilitate vehicle turning onto and off freeway entrance and exit ramps with reduced conflict points and delay time at signals, which are considered the major benefits that DDIs can provide, leading to safer and more efficient operations between freeway and local arterial traffic flows. Such benefits imply reductions in angle and rear-end crashes as well as crash severity [3]. As reported in several studies, applications of DDI could reduce delay up to 60% and the number of stops up to 50% [4, 5]. In addition, the construction of a DDI can potentially achieve savings in budgetary investment and project time with a similar footprint compared to conventional interchange types. A two-lane DDI can serve a similar level of traffic demand as a three-lane conventional diamond interchange, thereby reducing right-of-way acquisition needs or conversely, allowing for additional capacity within the same footprint. Conventional diamond interchanges require drivers to pass through two signalized intersections for access onto the freeway, whereas one signal is passed through in a DDI.

In recent years, there are increasing number of DDIs deployed in the US, as shown in Figure 2 [6] outlining which states have operating DDIs open to the public, those under construction, those at the planning or engineering design phase, or research interests. In some states, various modifications and refinements have been applied to the standard DDI configuration, and traffic signal control at a DDI is a vital component that can dramatically influence the safety and operational performance [7], which indicates a need for relevant studies signal timing schemes and optimization.

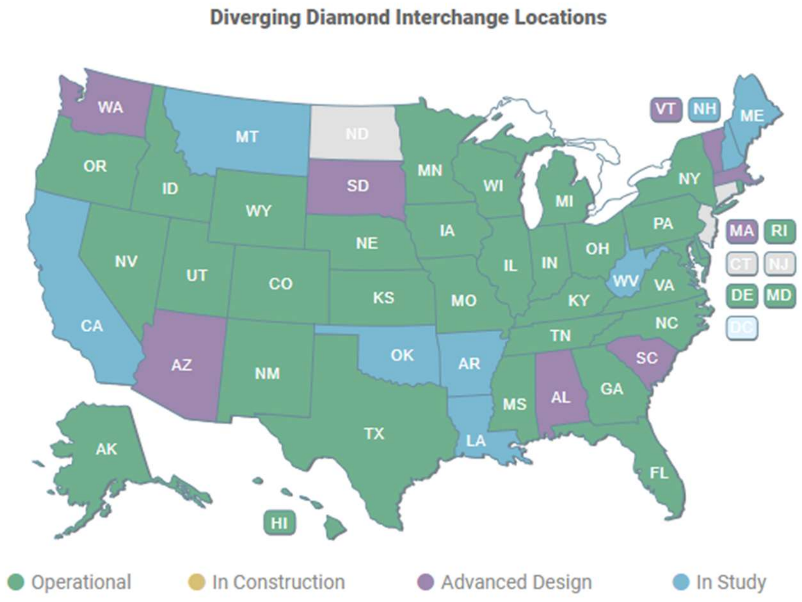


Figure 2. Current Deployment of DDI in States As of 2023 [6]

1.2 Problem Statement and Research Motivation

The development of this research was due to both an intellectual and practical challenge. The DDI at Moana has been and is still experiencing problems will high delays and excessive queuing, in addition to running free adjacent to a busy coordinated corridor and a secondary free signal. RTC Washoe as part of the local signal timing effort reached out to UNR CATER to evaluate solutions.

Dr. Tian, during one of his classes was showing the class how DDIs operated and a debate emerged one how lost time was calculated for their unique configurations. From there it was shown that standard signal timing practices would not adhere to DDIs without addition investigation and in doing so the issues at the Moana DDI changes from a recommendation for updated signal timing to an effort to derive a state of practice for DDI timing and evaluation.

Given that DDIs are an emerging type of interchange, the traffic signal control for DDIs is still under development and varies by maintaining agency. Due to minimal state or federal guidance determination and optimization of the signal phasing scheme is essential. Despite the same number of signal-controlled points that a DDI has as compared to a typical diamond interchange, the traffic signal operations can be of unique characteristics due to different geometric and traffic operational conditions.

Signal phasing schemes are a fundamental and critical element of traffic signal operations. Although signal phasing schemes are rather standard at typical urban intersections and interchanges, the development of signal phasing schemes for DDIs can be challenging. There are three reasons as follows:

1) **Traffic movements and conflicts**: A essential goal of traffic signal control is to organize all traffic movements at roadway intersections in the context of safe and efficient operations. The determination of signal phasing scheme involves identifying concurrent phase pairs that should not have any conflicts between each other. DDIs have lanes with multiple assignments in various directions, differing to conventional diamond interchanges and other interchange designs. Consequently, the considerations for conflicts between each two traffic movements at DDIs are

not conventional, with an alternative approach needed when determining the phasing.

2) **Traffic control facilities**: At an interchange, one or two traffic controllers may be used. When two controllers are used, the traffic signals on the two sides of the interchange will be controlled separately. The two-controller configuration can be concise and intuitive when only looking at each single signal, but coordination between the two signals is required for efficient operations in the presence of congestion. Although the coordinated operations can be achieved through certain designs of signal timing, it requires reliable communication and system clock. If not correctly managed, two controllers may cause deficiencies caused by internal queuing. One traffic signal controller is sufficient to run two traffic signals as modern traffic signal controllers supply enough control phase slots to accommodate various combinations of traffic movements. Using a single controller often means a simpler setup, which can lead to faster deployment and easier troubleshooting, and the one-controller configuration allows for lower initial purchase costs and potentially reduced maintenance costs for above ground utilities. On the other hand, coordinated operations between the two interchange signals can largely rely on the design of signal phasing scheme, which can increase the complexity in signal timing development and maintenance. At DDIs, the one-controller configuration is often employed, and sophisticated DDI signal phasing schemes may be required to achieve signal coordination that can address queuing issues in the interchange middle area and minimize traffic delay caused by phase changes.

3) **Traffic controller features**: Given that a single controller is used at a DDI, traffic controller features usually furnish limited flexibility to develop signal coordination between two interchange signals. For example, in the case of the National Electrical Manufacturers Association (NEMA) standard, although the current traffic signal controllers can have up to 16 phase slots and 4 control rings, the "ring-and-barrier" structure must be fulfilled, which restricts the release time and sequence of traffic movements. To conduct nuanced adjustments, the ad-hoc use of dummy phase and phase overlap is commonly needed.

In practice, DDIs usually run with inefficient signal phasing schemes that merely satisfy the conflict diagnosis [8]. To clear queues within a DDI and produce traffic progression, very long clearance times are used, resulting in capacity loss and increased delay. Knowledge gaps can also be found in literature that a substantial number of evaluations about DDIs were based on very limited signal phasing considerations, mostly according to the default phasing selections provided by simulation packages [9, 10, 11]. A study is needed to develop implementable signal phasing schemes that can satisfy the special requirements at DDIs to achieve various operational goals such as minimizing stops and queues within the DDI.

1.3 Research Objectives

This thesis presents a research effort that aims to study traffic signal control at DDIs focusing on phasing scheme development. Three research objectives are listed as follows:

1) Produce a review of traffic signal control at DDIs.

2) Develop an innovative signal phasing scheme for DDIs that can achieve operational goals such as clearing the queues in the storage between the two ramp terminals. The signal phasing scheme should accommodate the NEMA standard and therefore be readily implementable.
3) Perform a case study based on the DDI at Moana Lane & Interstate-580 freeway (Moana Ln & I-580 DDI) in Reno, Nevada. Through simulation, the effectiveness of the proposed phasing scheme is explored.

2. LITERATURE REVIEW

The current literature in relation to DDIs focus on four major aspects: planning, safety, multimodal, and operations [12], in which traffic signal control at DDIs can mainly influence the operational performance. Considerations in safety and multimodal perspectives are mostly deemed basic requirements for traffic signal control, for instance, traffic signal timing should provide sufficient clearance times for multimodal users at a DDI to eliminate conflicts. When determining signal phasing schemes, such requirements should be fully met in most cases. Such requirements are documented in the Signal Timing Manual [13].

In this review, studies regarding traffic signal timing at DDIs have been mainly surveyed. The traffic operations at a DDI are first introduced, where whether the right turns are controlled by signals can influence the development of traffic signal timing. The considerations for signal phasing scheme development are reviewed next, including clearance time, travel time between ramp terminals on the two sides, and queues in the middle storage. In addition, three categories of DDI phasing schemes are explored, and the techniques used for performance analysis are summarized.

The sections that follow are written based on the conventions and terminology documented in two NCHRP reports, the Diverging Diamond Interchange Informational Guide [12] and Signal Timing Manual [13].

2.1 Traffic Operations at A DDI

The primary difference in traffic operations between a DDI and a conventional diamond interchange is the directional crossovers on either side of the interchange, which eliminate the need for left-turning vehicles to cross the movements of approaching through-vehicles.

As a result, DDIs simplify signal movements by converting all signalized left-turn phasing into free-flow movements after the first entrance signal. As traffic proceeds to the opposite side of the road within the DDI, vehicles that want to make a left turn can move onto the entrance ramp without any conflicts with other major traffic movements, the only exception being the opposing direction right turn onto the freeway, which typically includes an add lane or is yield controlled. The through traffic can continue to proceed to pass through the second signal, which crosses vehicles back to the right side of the roadway. Figure 3 presents the turning movements and potential control type at a DDI. The exit ramp geometric and right turn treatments can impact the traffic operations at DDIs [14, 15].

It should be noted that the concept of “free” turning movements only applies in the discussion considering vehicular traffic only. The right turning movements onto and off of the freeway have conflicts with pedestrians, and such conflicts cannot be eliminated. In practice, pedestrian phases need to associate with vehicular phases, which implies pedestrians commonly need to use multiple stages to finish crossing. This may impact the comfort level for pedestrians and cyclists; however, to facilitate pedestrian flows is extremely difficult with all possible phasing schemes. Given that pedestrian volumes are generally low at freeway interchanges, pedestrian timing considerations are not included in this study.

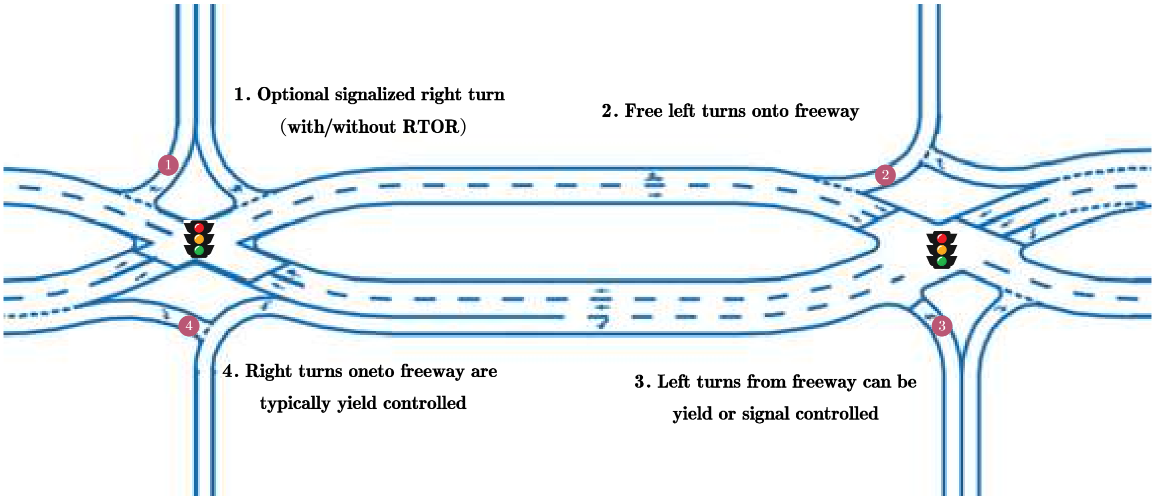


Figure 3. Turning Movements at a DDI

In the most simplified case, the traffic signal on either side of the DDI can be controlled by only two phases to separate two conflicting movements in two directions. However, only either of the arterial through and turning onto freeway traffic flows can be prioritized. And to minimize the number of vehicles queued in the middle storage, long clearance times should be employed. The overall capacity at the DDI may deteriorate due to the use of long clearance times.

Als a result, more complex phase schemes are developed to address the abovementioned issues to improve travel efficiency and capacity. These phasing schemes are designed with considerations such as clearance time, travel time between ramp terminals, and queuing on the middle approaches of the DDI.

2.2 Considerations for Phasing Scheme Development

There are three important factors that influence the determination of signal phasing schemes at a DDI:

1) Clearance time that is based on the distance for through movement to clear the conflicting off-ramp movement;
2) Travel time between ramp terminals that is based on the distance between the crossovers, which is usually used for calculating offsets in time between two phases to create traffic progression;
3) Queues occurring within the middle storage of the DDI. Note that such queues are in relation to clearance time and travel time. If clearance time is not provided sufficiently, the queuing issue will occur, and the travel time used for progression development will be different with existing queues.

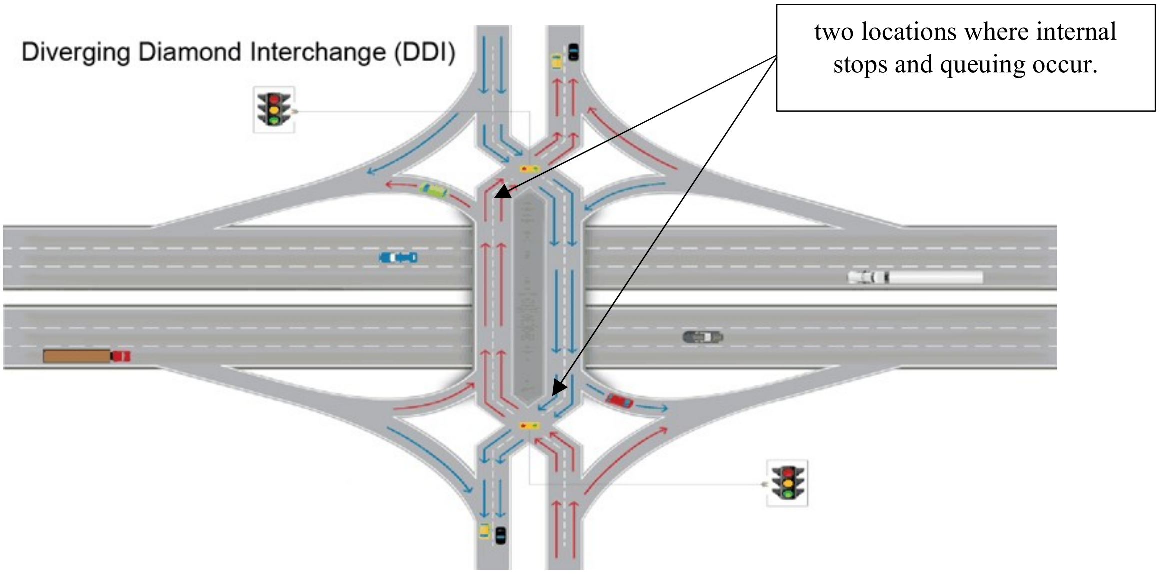
Clearance times can fundamentally influence the choice of signal phasing schemes as well as cycle length of signal timing. Unlike a conventional intersection, a through movement at a DDI has two distinct clearance times that need to be considered. The first is the time required to clear the opposing through movement at the crossover. This time is typically short because of the width of the crossover. The second is the time required to clear the conflict point with the downstream left-turn or right-turn movement from the freeway exit ramp. This time can be significantly longer than the time required to clear the opposing through movement depending on the geometry of the DDI. Without a complex phasing scheme, clearance times should usually be reckoned lost times in cycle length calculation. The elongated lost times would impose a long cycle length at the DDI to maintain enough capacity at the expense of traffic delay [16].

Travel times are the times to travel between the crossovers that can be used to minimize vehicle stops on the middle approaches of the DDI. If the signal greens turn on sequentially within the interval of travel time along the traffic movements, no stops will be made by vehicle between the two signals of the DDI.

Depending on the phasing scheme, clearance time and travel time might be used to determine the length of "fixed time" dummy phases. The use of a fixed amount of time for a movement to travel the distance between the crossovers can reduce vehicle stops and queuing and keep the space between the crossovers clear.

In the Informational Guide [12], typical DDI internal clearance between the ramps is recommended to be 550 feet whereas the average internal space is 300 feet for a conventional diamond interchange. As many DDIs are converted from previous diamond interchanges, there exist cases that the internal distance between the two crossovers may be insufficient, for example, the internal lane distance is only 300 feet at the Moana & I-580 DDI in Reno, Nevada, which considerably restricts the vehicle storage inside the DDI. Therefore, many agencies including the City of Reno have deemed that internal stops and queuing, as exhibited in Figure 4, shall not be permitted, and such internal stops and queuing need to be eliminated by implementing some certain phasing schemes. Queuing can also influence the overall delay at the DDI as found in two studies [17, 18].

Long clearance time and queuing can be factors contributing to an increase in red-light violations. Based on a driver behavioral study [19], an increased frequency of red-light violations was observed. In practice, drivers can be confused and practice red-light running if they see no conflicting traffic during the clearance time, especially for those who are stopped on the middle approaches.



two locations where internal stops and queuing occur.

Figure 4. Internal Vehicle Stops and Queuing at a DDI

2.3 Signal Phasing Schemes

In the Information Guide [12], three types of signal phasing schemes are identified according to different critical movement scenarios:

1) Two-critical-movement schemes emphasize progression for either the arterial movements or the off-ramp movements and is most applicable for DDIs with one dominant movement.
2) Three-critical-movement schemes emphasize progression for the arterial movements and the exit ramp left-turn movements and is most applicable for DDIs

with one or multiple dominant movements. The three-critical-movement scheme is often the most flexible and most efficient DDI phasing option.

3) Four-critical-movement schemes emphasize progression for both the arterial movements and the exit ramp movements and is most applicable to DDIs with low to moderate volumes, either dominant through or left-turn movements and short to internal spacing within DDIs.

The Information Guide and relevant studies [20, 21] addressed the use of actuation and barriers to improve coordination and methods for reducing lost time to provide practitioners with basic guidance on the selection of proper phasing schemes in various scenarios.

Several phasing schemes were developed in the previous studies [22, 23]. These innovative signal phasing schemes derive from the ideas originated by signal timing practitioners and have been programmed into signal controllers with a readily appliable formation, i.e., a set of controller parameters such as NEMA sequence code, phase number, and the use of phase overlap and dummy phase.

The determination of signal phasing scheme also involves consideration from a network perspective, e.g., using the phase scheme at DDI that allows for coordination between the DDI and neighboring intersections. Existing studies have explored the coordinated operations between a DDI and intersections, finding the use of sophisticated phasing schemes that balance the progression opportunities for both freeway and arterial traffic flows can achieve improved coordination with adjacent intersections [24, 25, 26, 27].

Signal phasing schemes are also a key factor in signal timing optimization for DDIs. Studies related to timing optimization at DDIs usually focused on signal timing parameters, such as offset, phase sequence, cycle length, and phase splits, based on certain signal phasing schemes [28, 29, 30]. However, signal phasing schemes can be dynamic among time-of-day plans to accommodate traffic flow fluctuations.

2.4 Evaluation of Signal Phasing Schemes

To validate the selection of signal phasing schemes is important for traffic signal timing implementation and maintenance at DDIs. Prior to the implementation, traffic simulation tools are commonly used to obtain measures of effectiveness (MOEs) such as number of stops, travel delay, speed, and queue length. Studies focusing on operational performance evaluation of DDIs adopted commercial simulation software, e.g., PTV VISSIM, to perform before and after comparisons [31, 32] or comparisons with other interchange designs [33, 34, 35].

In the development of simulation models, it is critical to choose suitable simulation parameter settings and conduct effective calibration [36]. The simulation tool should feature a NEMA-compliant controller emulator to support the test of signal phasing schemes.

After the traffic signal control is implemented in the field, real-world data that reflect traffic operations can be collected. Manual data collection is the option in most cases; however, data collection and processing are commonly costly, time-consuming, and labor intensive. Connected vehicle data and high-resolution controller event data are two emerging data sources that lead to surrogate measures for assessing the operational performance of DDIs [37, 38].

2.5 Research Needs

Based on the findings of this review, the following research needs have been identified:

1) Traffic signal control at DDIs can be complex and diverse according to various geometric and turning movement treatments and timing considerations regarding clearance times, travel times, and queuing. In literature, the comments on two-critical-movement, three-critical-movement, and four-critical-movement signal phasing schemes were presented with approximations of where each DDI phasing scheme would be the most appropriate considering the strengths and weaknesses according to specific conditions; however, these comments only outline several general phasing designs and considerations. As four-critical-movement phasing schemes allow for flexible uses of dummy phases and overlaps, innovative designs of this phasing scheme type can be worth exploring to achieve operational improvements.
2) Current studies regarding signal timing development and optimization are mostly based on theoretical and generalized analyses, while controller features may be significantly different. To develop readily implementable signal phasing schemes, the constraints of controller functionality, such as overlaps and detection, should be well considered.

3) To evaluate an innovative signal phasing schemes a quite challenging as many geometric and non-geometric factors can influence the effectiveness. It is unlikely to develop a signal phasing scheme to accommodate all potential scenarios. As a result, case studies are very valuable, which can be used as references for field practices. The simulation model used for the study needs to well reflect the field conditions in the case study.

3. ANALYSIS OF DDI PHASING SCHEMES

The development of signal phasing schemes at DDIs varies greatly from that at typical four-leg intersections. A DDI can run with numerous phasing schemes without pre-determined break point between major movement in which one configuration would supersede another, unlike conventional intersections or interchanges that signal phasing schemes are dependent on critical movements with the inclusion of protected left turns.

In literature, a series of warrants and analytical methodologies have been established to facilitate the selection of phasing schemes at conventional intersections and interchanges according to various geometric and traffic conditions; however, such techniques cannot be directly introduced into the signal timing practices for DDIs.

Developing a DDI signal phasing scheme also requires special considerations, including:

1) Selecting signal phasing schemes at DDIs is associated with detection layouts. As for a DDI where no detectors installed at the internal stop lines, signal phasing must accommodate this constraint, not allowing vehicles to stop in the middle of the DDI.
2) Through the addition of phase overlaps, practitioners should allow for "advanced release", which represents that signals at the upstream signal are meant to turn green early to let vehicles start to move prior to the end of conflicting phases. Due to the unique geometry of DDIs, this "advanced release" would not lead to conflicts physically but improve interchange capacity by thoroughly using the effective green in the context of safe operations.

In the Information Guide [12], three typical designs of DDI phasing schemes were presented. However, using overlaps, practitioners need to produce modifications to these typical DDI phasing schemes. It is very important to revisit such DDI phasing schemes in a specific case. The sections that follow are based on the DDI at Moana Lane & Interstate-580 freeway in Reno, Nevada.

3.1 Two Critical Movement Schemes

Phasing schemes with two critical movements have been widely used at DDIs. These schemes don't have overlaps or other timing tricks, designating right-of-way according to each of two directions that the arterial through and left traffic and opposing off-ramp left traffic may progress simultaneously. Additionally, another option is that arterial through and left movements in two directions are progressed at the same time, followed by two off-ramp left movements. Both options are illustrated in Figure 5 below. These two types of two-critical-movement schemes are not essentially divergent but the resulting number of stops and delay may be different according to freeway off-ramp and arterial volumes.

As internal stops cannot be avoided with two-critical-movement schemes without the use of trailing overlaps, these simplistic approaches for phasing DDIs are intended for use where long internal storage lengths are present. In some practices, short cycle times have been used to reduce interior queues; however, this strategy is appliable only if interchange volume is low as split lengths cannot exceed the interior travel time without spilling back into the intersections.

Because Moana & I-580 DDI shows a very limited interior storage and heavy operating volumes, none of two-critical-movement schemes are applicable.

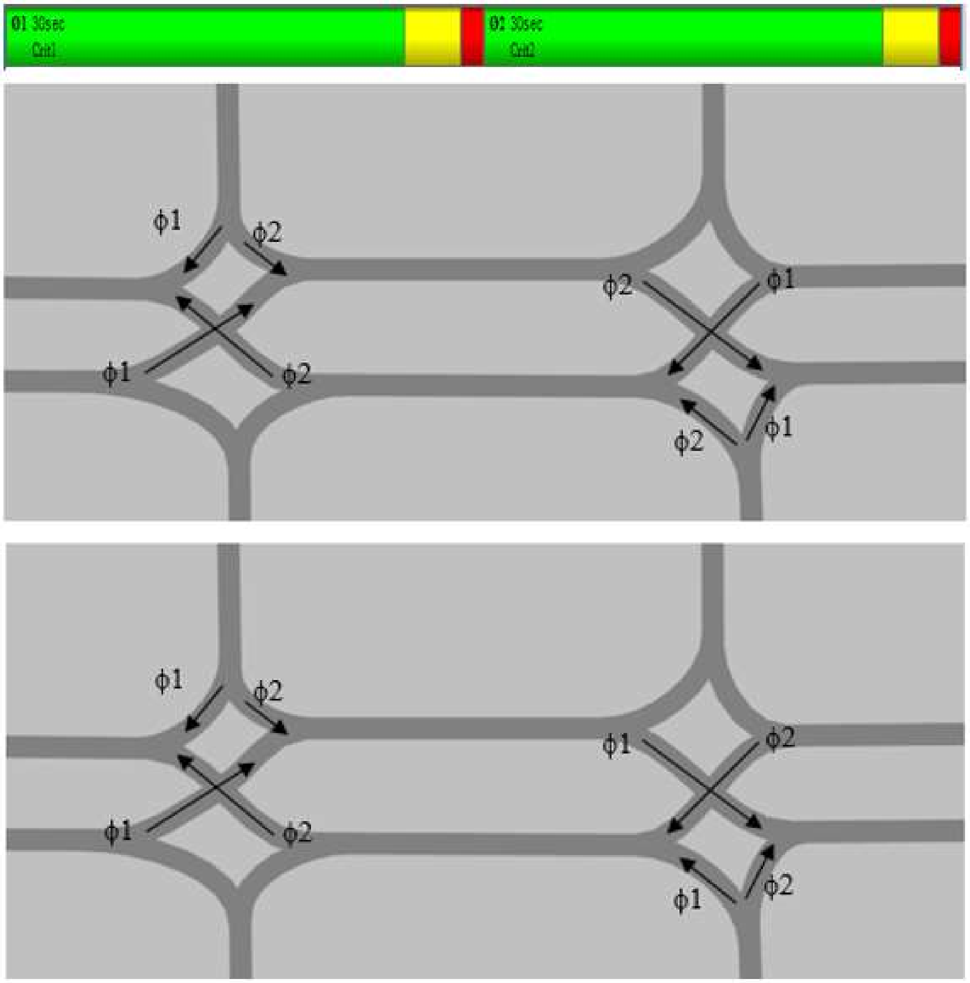


Figure 5: Basic Two Critical Movement Phasing Scheme Phase Assignment

3.2 Three Critical Movement Schemes

Phasing schemes operating with three critical movements are derived from the base configuration exhibited in Figure 6. Typical three-critical-movement schemes at DDIs assign phases to both arterial through and left movements, operating with split-phasing, and run dual progression for the off-ramp left turns.

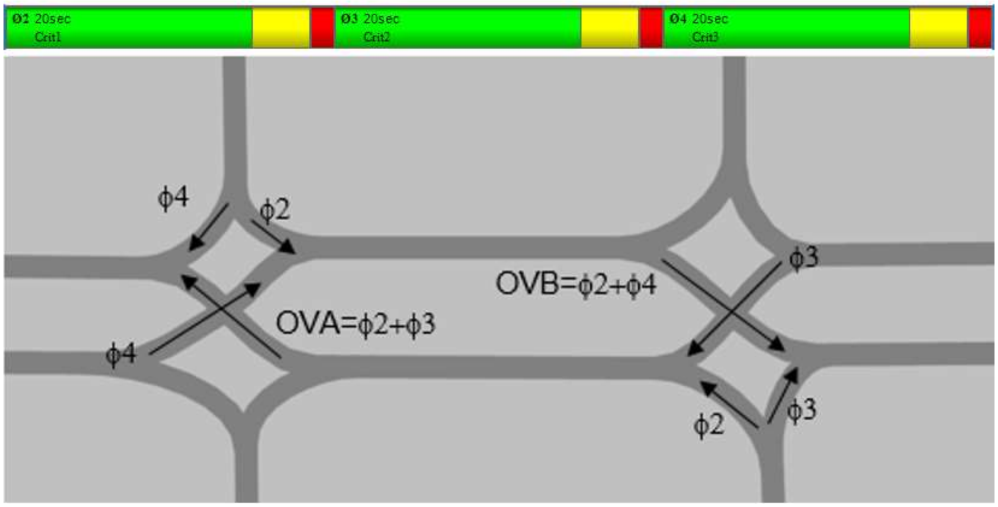


Figure 6: Basic Three Critical Movement Phasing Scheme Phase Assignment

(OVA=ϕ2+ϕ3 Overlap A includes phase 2 and phase 3)

Under default conditions, both off-ramp lefts should run concurrently but dual entry is also permitted between arterial movements and an off-ramp left turn from the opposite side of the DDI. While this configuration is permitted, engineering judgement should be used to determine the most appropriate dual-entry phases, such as an off-ramp with sufficiently low volumes in comparison to the opposite off-ramp.

Three-critical-movement schemes are currently the default configuration to operate at heavy volume conditions. This is due primarily to three-critical-movement schemes operating without significant queue build-up that may occur as compared to two-critical-movement schemes.

Three-critical-movement configuration offers the most diversity in the number of schemes that can be derived when combined with overlaps, both trailing and nested.

For a basic design of three-critical-movement schemes as shown in Figure 3, with phase 3 following phase 2, any vehicles that have left the phase 2 approach will be forced to make internal stops at the DDI. If the vehicles are discharged from the phase 2 approach at phase 2's force-off point, some of those vehicles will find themselves within the Type-II Dilemma Zone, regardless of advanced detector location. This will cause confusion for the drivers with indecision as whether to stop or go and may lead to an increase in rear-end collisions. The dilemma zone is more prevalent when the volume progressing through the interior is high, as the left turns free movements prevents the possibility of spill back, but the through movement may spill back into the left-turn movements travel path.

One means of negating this effect, without the use of additional phases, is using trailing overlap phases. This is the current practice being used at Moana & I-580 DDI, as shown in Figure 7. The trailing overlap will hold the green for a certain amount of time after the phase force-off point, typically the travel time through the interior. This additional time will be added to the second green that vehicles encounter during passing through, which effectively eliminates stops in the middle of a DDI. However, practitioners should use caution that signal controllers will allocate time from the proceeding phase to this trailing overlap, leading to possible issues with splits also adding to unsafe driving conditions. Additionally, trailing overlaps can be regarded as red-clearance by the external movements, increasing lost time; thus, signal control efficiency declines.

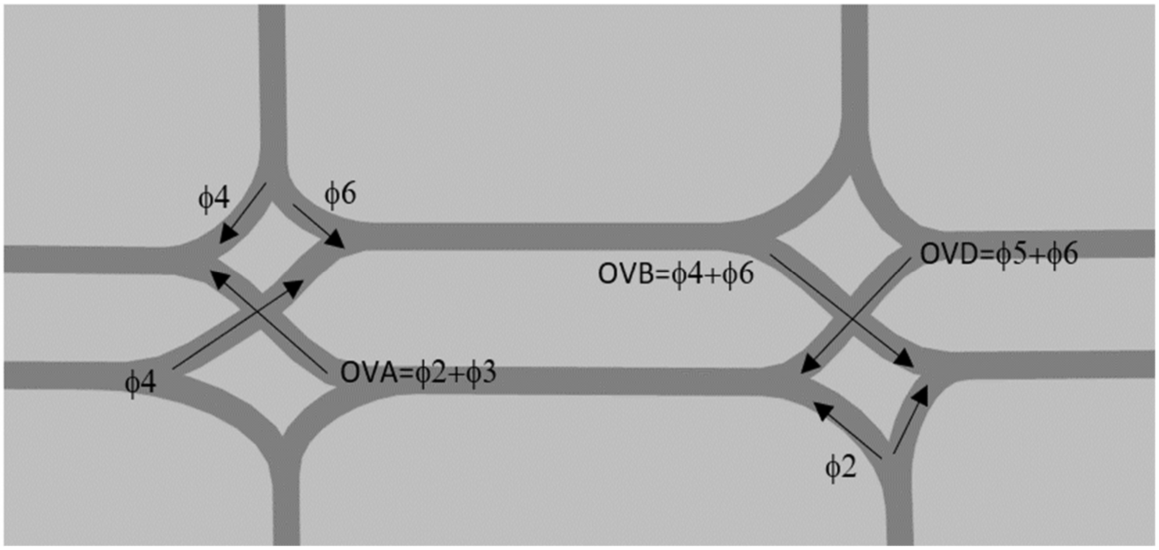
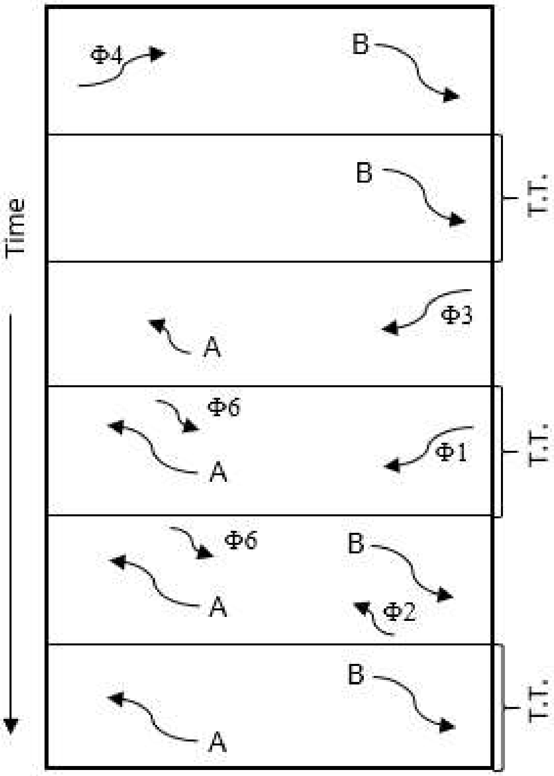


Figure 7: Moana DDI Current Phase Assignment Phase Assignment

The current phasing scheme at the Moana & I-580 DDI is operating with three critical movements with dual progression of the off-ramp left turns. Trailing overlaps are used, eliminating internal stops at the expense of a large lost time. Minor modifications can be made to permit “advanced release” for the off-ramp left movements to reduce the splits and cycle time, which is similar to the TTI-3 Phase scheme [39] at conventional diamond interchanges.

An update to the Current Scheme would be to allow for the advanced release of one of the ramp movements, shown in Figure 8, allowing for dual progression of one arterial and one ramp.



Stage 1: EB starts and progresses through the right side without stopping.

Stage 2: Trailing Overlap clears interior.

Stage 3: NBL arives at the left side signal exactly after EB stops, so NBL does not stop. SBL starts and progresses through right side without stopping.

Stage 4: WBT continues as SBL releases, T.T.

Stage 5: Dual progression of the off-ramps.

Stage 6: Trailing Overlaps clears interior, T.T.

(a) Stage and progession diagram

A=Φ3+Φ6
B=Φ2+Φ4
EB=Φ1+Φ3
Φ1 is internal travel time

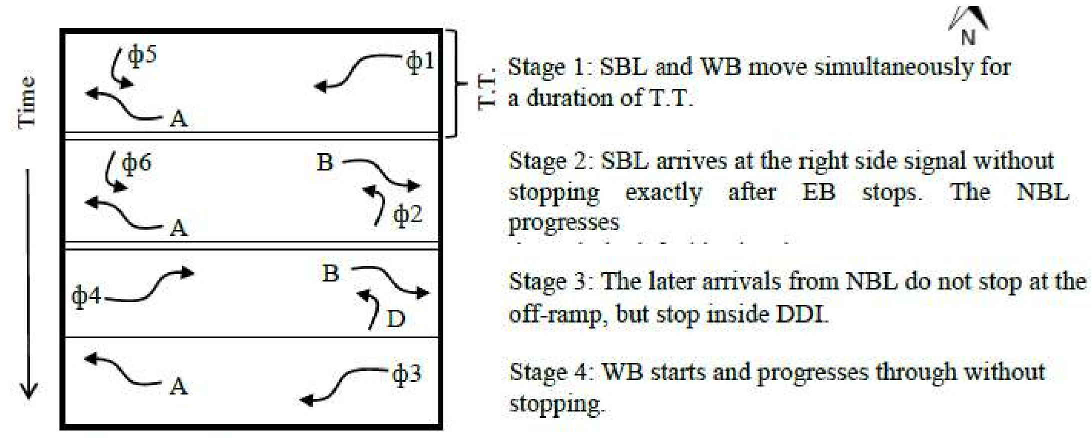
φ1	φ2	φ4	φ3
φ6		φ8	

(b) Phase/ring/barrier diagram

Figure 8: Current Scheme with Altered Scheme

(T.T. = Travel Time)

The three-critical-movement schemes can be further adjusted to increase interchange capacity if internal stops are acceptable. An alternative phasing scheme presented in Figure 9 causes internal stops. This phasing stores vehicles from one of the off-ramp approaches, the northbound left turn. Additionally, the eastbound through approach in this example is not given a trailing overlap to clear the through movement. Because the trailing overlaps are abandoned, the lost time is reduced, and interchange operating efficiency is improved. In addition, the through approach with internal stops is still allowed the free left-turn onto the freeway. The lack of internal clearance only becomes an issue when the through volume percentage is higher than the left-turn onto the on-ramp. As only the volume from the off-ramp is allowed to queue, it can be inferred that a most of the vehicles will be using the through movement and will thus not conflict with left turning vehicles, as is the primary concern with internal stops.



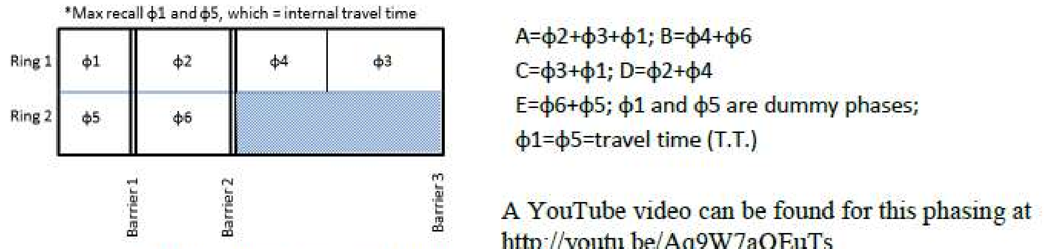
Stage 1: SBL and WB move simultaneously for a duration of T.T.

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) Stage and progression diagram



A=ϕ2+ϕ3+ϕ1; B=ϕ4+ϕ6
C=ϕ3+ϕ1; D=ϕ2+ϕ4
E=ϕ6+ϕ5; ϕ1 and ϕ5 are dummy phases;
ϕ1=ϕ5=travel time (T.T.)

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

(b) Phase/ring/barrier diagram

Figure 9: UNR Scheme [22]

An additional benefit to avoiding internal stops is that detection on the interior lanes would be no longer required. This can reduce the construction and maintenance costs of a DDI, and practitioners should allow for a predetermined phasing choice that influences the DDI planning and design.

3.3 Four Critical Movement Schemes

Basic four-critical-movement schemes operate in such a manner that only one movement is progressed at any given time, as shown in Figure 12. This phasing also facilitates the coordination between adjacent intersections. One drawback to this approach is that the schemes would lead to the longest cycle length under the same volume conditions as compared to two and three critical movement schemes.

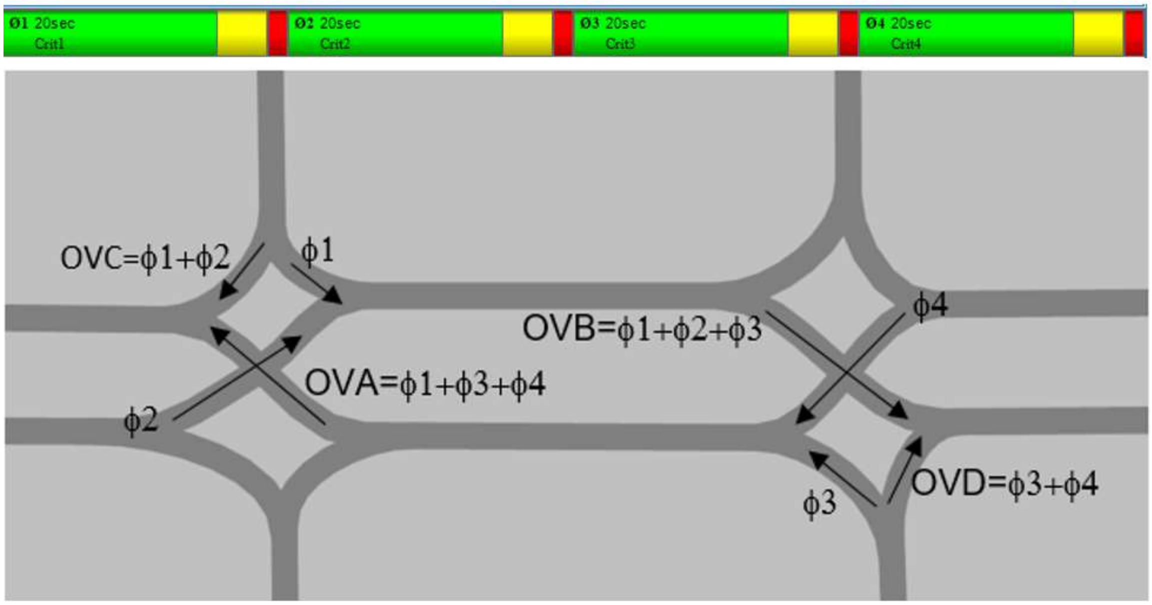
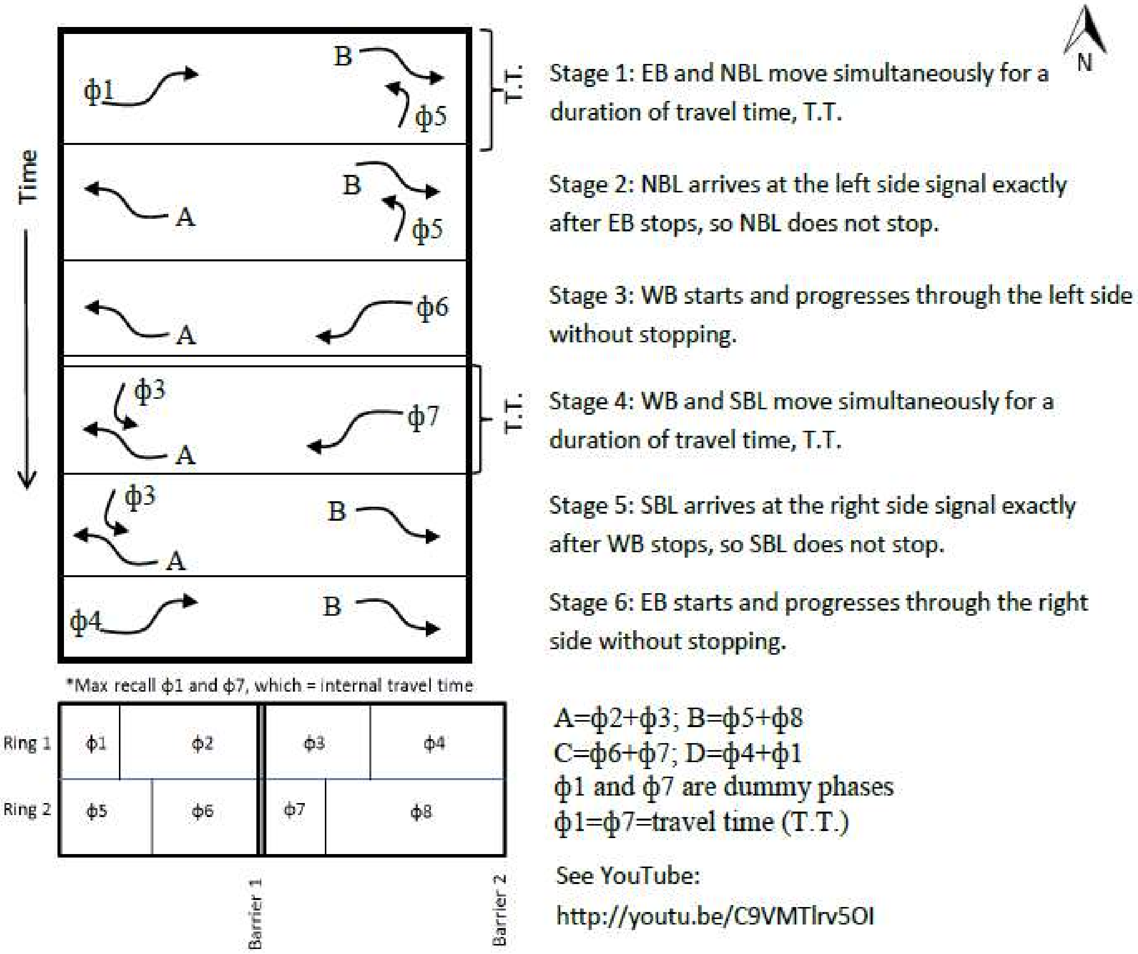


Figure 10: Basic Four Critical Movement Scheme

While four-critical-movement phasing schemes offer a variety of solutions for optimized bandwidth along a signalized corridor, care should be taken when choosing the phase order as internal stops can be avoided according to specific phasing designs. The Gerry de Camp phasing, outlined in Figure 13, utilizes both optimal phase sequence order as well as advanced releases to minimize the negative effects associated with four-critical-movement phasing.



Stage 1: EB and NBL move simultaneously for a duration of travel time, T.T.

Stage 2: NBL arrives at the left side signal exactly after EB stops, so NBL does not stop.

Stage 3: WB starts and progresses through the left side without stopping.

Stage 4: WB and SBL move simultaneously for a duration of travel time, T.T.

Stage 5: SBL arrives at the right side signal exactly after WB stops, so SBL does not stop.

Stage 6: EB starts and progresses through the right side without stopping.

*Max recall ϕ1 and ϕ7, which = internal travel time

A=ϕ2+ϕ3; B=ϕ5+ϕ8
C=ϕ6+ϕ7; D=ϕ4+ϕ1
ϕ1 and ϕ7 are dummy phases
ϕ1=ϕ7=travel time (T.T.)

See YouTube:
http://youtu.be/C9VMTlrv5OI

Figure 11: Gerry de Camp Phasing Scheme

(T.T. = Travel Time)

The Gerry de Camp phasing scheme was developed in conjunction between the research team at UNR and Gerry de Camp. The scheme contains four critical phases and several overlaps. Most four-critical-movement schemes do have the potential for internal stops, though the Gerry de Camp phasing eliminates internal stops by a unique sequence order.

In the Gerry de Camp phasing scheme, the critical phases are 3, 4, 5, and 6 with the remaining phases being either pretimed overlaps or dummy phases. The overlaps progress vehicles from a non-conflicting movement, the southbound left in this example, such that the vehicles arrive approximately when the westbound through-left terminates, allowing the platoon to progress through the interior with no stops and minimal slowdown. These overlaps, phase 7 in this example, are pretimed based on the assumed speed and distance between origin and destination. Phase 7 is an overlap with phase 6, the westbound through-left, and runs concurrently with the southbound left. As a result, the westbound through-left, when utilizing the current method for allocation of cycle length to splits, will receive more time than would otherwise be appropriated, regardless of the movements volume, without the use of an overlap-based sole on the distance between the origins.

An additional benefit to the Gerry de Camp phasing is allowance for a two-phase overlap serving the off-ramp right-turn movements. This feature can be utilized when the right-turn movement volumes exceed those of the internal movement volumes.

An alternative scheme to the current Moana & I-580 DDI phasing is presented in Figures 12 and 13, developed by UNR CATER, called Proposed Phasing Scheme. Note that is scheme is not necessarily the final recommendation, only proposed as a potential solution. This phasing operates with four-critical-movement. This scheme was derived from the Gerry de Camp phasing scheme, allowing the southbound off-ramp left turn, shown in

Figure 12 below, to be served during the part of the northbound off-ramp split in addition to receiving a dedicated phase. This allows for the reduction of the dedicated phase for southbound off-ramp split by the amount of time served during the northbound left.

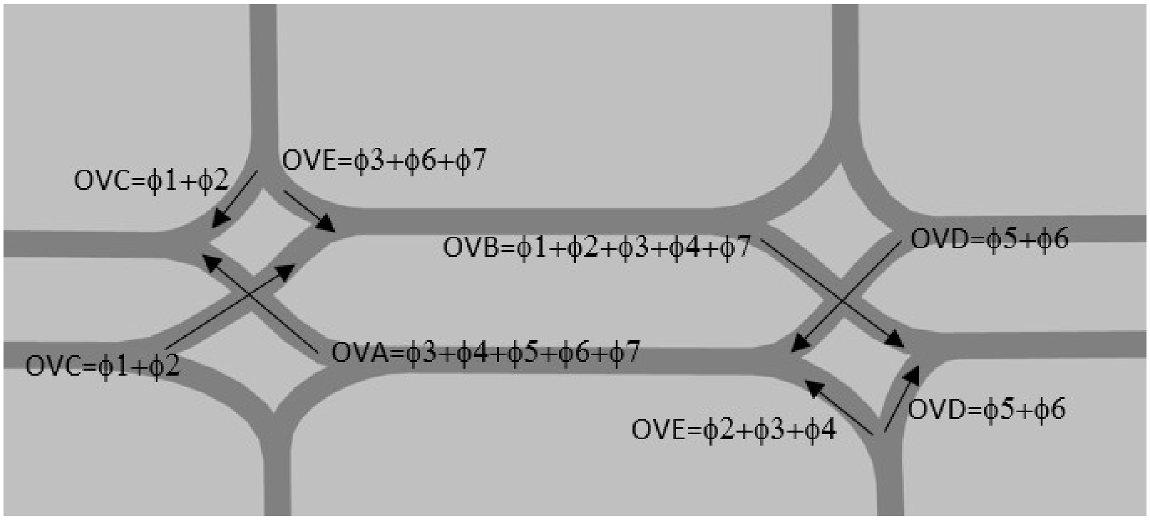
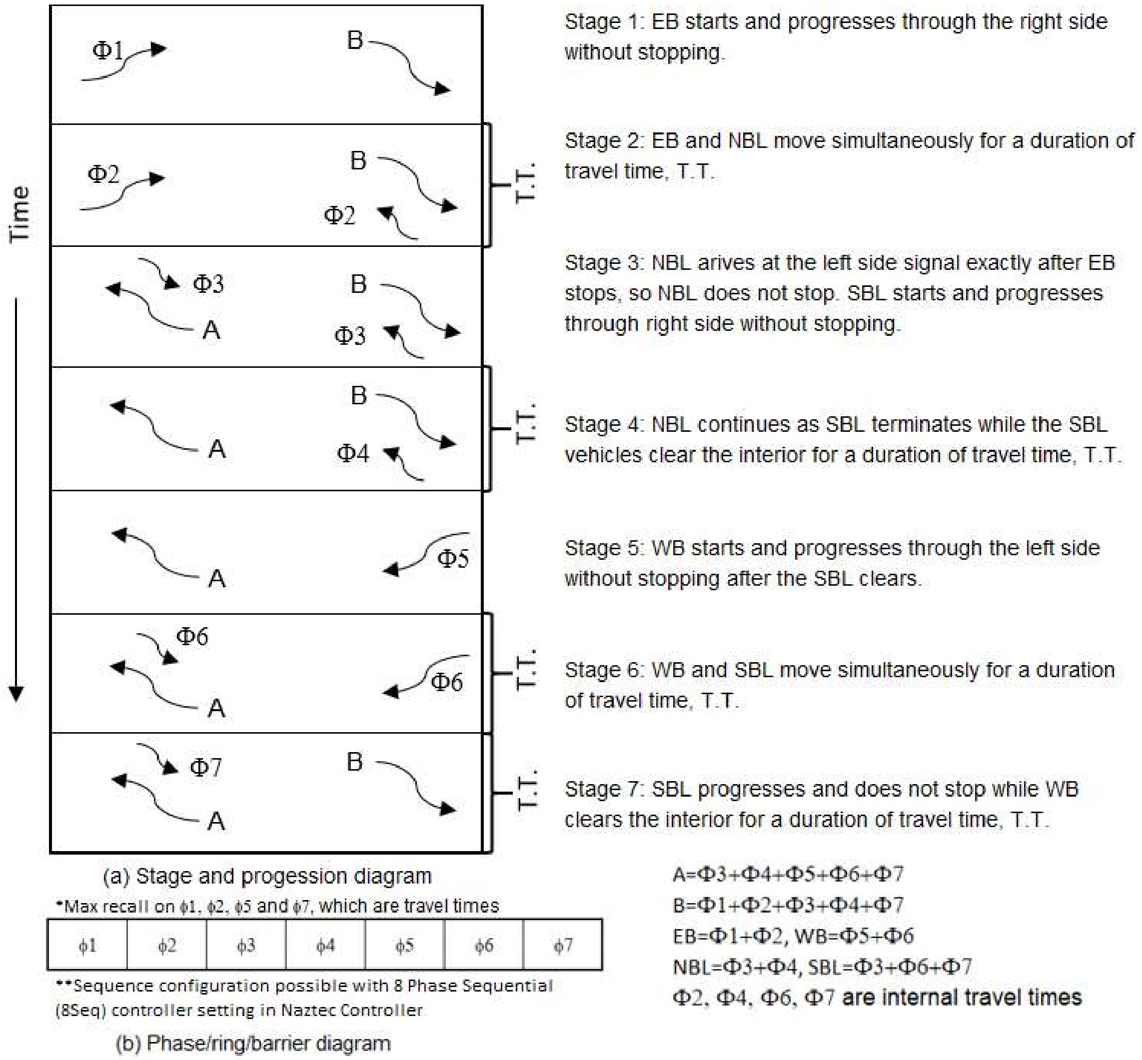


Figure 12 : Proposed Phasing Scheme Phase Assignment



Stage 1: EB starts and progresses through the right side without stopping.

Stage 2: EB and NBL move simultaneously for a duration of travel time, T.T.

Stage 3: NBL arives at the left side signal exactly after EB stops, so NBL does not stop. SBL starts and progresses through right side without stopping.

Stage 4: NBL continues as SBL terminates while the SBL vehicles clear the interior for a duration of travel time, T.T.

Stage 5: WB starts and progresses through the left side without stopping after the SBL clears.

Stage 6: WB and SBL move simultaneously for a duration of travel time, T.T.

Stage 7: SBL progresses and does not stop while WB clears the interior for a duration of travel time, T.T.

(a) Stage and progession diagram

*Max recall on ϕ1, ϕ2, ϕ5 and ϕ7, which are travel times

**Sequence configuration possible with 8 Phase Sequential (8Seq) controller setting in Naztec Controller

(b) Phase/ring/barrier diagram

A=Φ3+Φ4+Φ5+Φ6+Φ7
B=Φ1+Φ2+Φ3+Φ4+Φ7
EB=Φ1+Φ2, WB=Φ5+Φ6
NBL=Φ3+Φ4, SBL=Φ3+Φ6+Φ7
Φ2, Φ4, Φ6, Φ7 are internal travel times

Figure 13: Proposed Phasing Scheme

Due to the reservice of the southbound right in the above example the phasing is complex and recommended to run a single ring. The phasing can also be achieved through a typical dual ring but would require 11 unique phases.

The inherent benefit and limitation to this phasing scheme is tied to the amount of volume present on both off-ramps left-turn movement. If the northbound left-turn traffic volume is low, such that the split is less than approximately two times the internal travel time, the time for the southbound left-turn movement could be reduced below an appropriate amount to serve the demand leading no usable overlap timing, result in identical phasing to the of the Gerry de Camp scheme or potential unused green. As such, this phasing scheme is applicable for DDIs with a high percentage of the volume on both off-ramps left turns.

4. CASE STUDY OF AN INNOVATIVE DDI PHASING SCHEME

The diverging diamond interchange at Moana Lane and I-580 in Reno, Nevada, shown in Figure 14, was opened to traffic on November 21, 2012, having been converted from a diamond interchange due to the heavy demand for left-turns from eastbound Moana onto US-395 North, what today is I-580 North.

Figure 14: Moana & I-580 DDI

The Moana DDI is of the busiest interchanges in the Reno/Sparks area, with the northbound on-ramp alone serving an Annual Average Daily Traffic (AADT) of 19,200. AADT data provided by the Nevada Department of Transportation (NDOT) TRINA system are listed in Tables 1 gives a perspective of the flow in the area, with a plurality of volume coming to and from North of I-580 and West of the interchange. Turning movement counts were collected on Wednesday April 24th, 2019, using video recordings. 30 minutes periods were recorded during the AM and PM peaks and extrapolated into a full peak hour. The turn movement counts were converted to entry volume, shown in Figure 2 below.

Table 1: Annual Average Daily Traffic of Moana DDI Approaches as of 2018

Moana DDI	
Approach	***AADT***
Moana Lane, West Approach	15,800
Moana Lane, East Approach	3,600
I-580, Southbound Exit Ramp	17,600
I-580, Southbound Entrance Ramp	5,650
I-580, Northbound Exit Ramp	5,550
I-580, Northbound Entrance Ramp	19,200

Table 2: Peak Hour Traffic Volumes Counts at Moana DDI

Traffic Counts (vehicles per hour)		
Approach	***AM (7AM-8AM)***	***PM (5PM-6PM)***
Eastbound	706	1,490
Southbound	542	470
Northbound	472	392
Westbound	230	338

The Moana DDI is currently running “free” all day, with one controller for both signals, utilizing split phasing with dual progression of the freeway offramps. In addition to the delays caused by the current phasing scheme, both the offramp lefts and westbound through movements are followed by a trailing overlap, required keep the interior of the DDI clear of vehicles. This leads to a natural Free-Timing average cycle length of 150 to 160 seconds during the PM peak according to Reno’s Advanced Traffic Management System (ATMS). Due to the nearby intersections of Kietzke and Moana running a 130 second cycle during the 5:00 PM peak hour and the intersection of Moana and Neil running Free-Timing with a shorter natural cycle length, this leads to heavy queue build up on both arterial approaches, with spillback to their upstream intersection during the PM peaks.

Due to the unique geometry of DDIs, phasing schemes vary greatly from those developed from standard intersections, especially in the case of one controller DDIs. As some conflicting movements are separated by the internal spacing, overlaps may be used to progress subsequent movements through the interior of the DDI while the current phase is still active, a counterpoint to the trailing overlaps used to clear the interior before a subsequent phase is activated.

As there exist no readily accessible software products available for the evaluation of DDIs, such as Synchro or Sidra, a simulation software, VISSIM, was used to evaluate and compare the various phasing schemes applicable to the Moana DDI.

4.1 Example of Signal Timing Calculation with Nested Overlaps

A nested overlap, herein defined as an overlap that progresses two critical phases simultaneously, is a common occurrence in the phasing schemes applicable at DDIs. Figures 15 and 16 below indicate the evaluated volume condition and phasing scheme with Phases 4, 5, and 6 as the critical phases, with Phase 5 assigned to both off-ramps left movements. The roadway characteristics for each approach, such as saturation flow rate, are assumed to be identical.

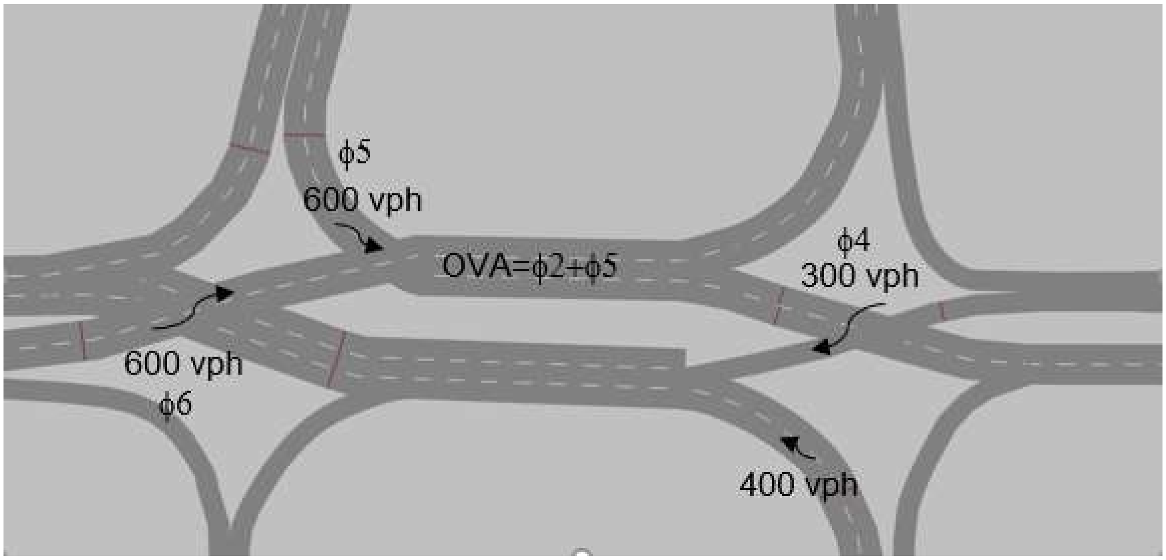


Figure 15: Evaluated Volume Scenario

<table>
<tr><td>ϕ1 Dummy</td><td>ϕ2</td><td>ϕ5</td><td>ϕ6</td></tr>
<tr><td colspan="2">ϕ4</td><td colspan="2">ϕ8 Dummy</td></tr>
</table>

Figure 16: Example Phasing Scheme for Webster's and Altered Webster's Method

While typical split derivation can be performed by the Webster's Method [40]. Equation 1 presents the calculation for green splits; however, adaption is needed in this case as overlaps are used. Hence, Equation 2 and 3 have been developed, as an alteration that can be used for DDIs.

$$g_i = \frac{y_i(C-L)}{Y} \tag{1}$$

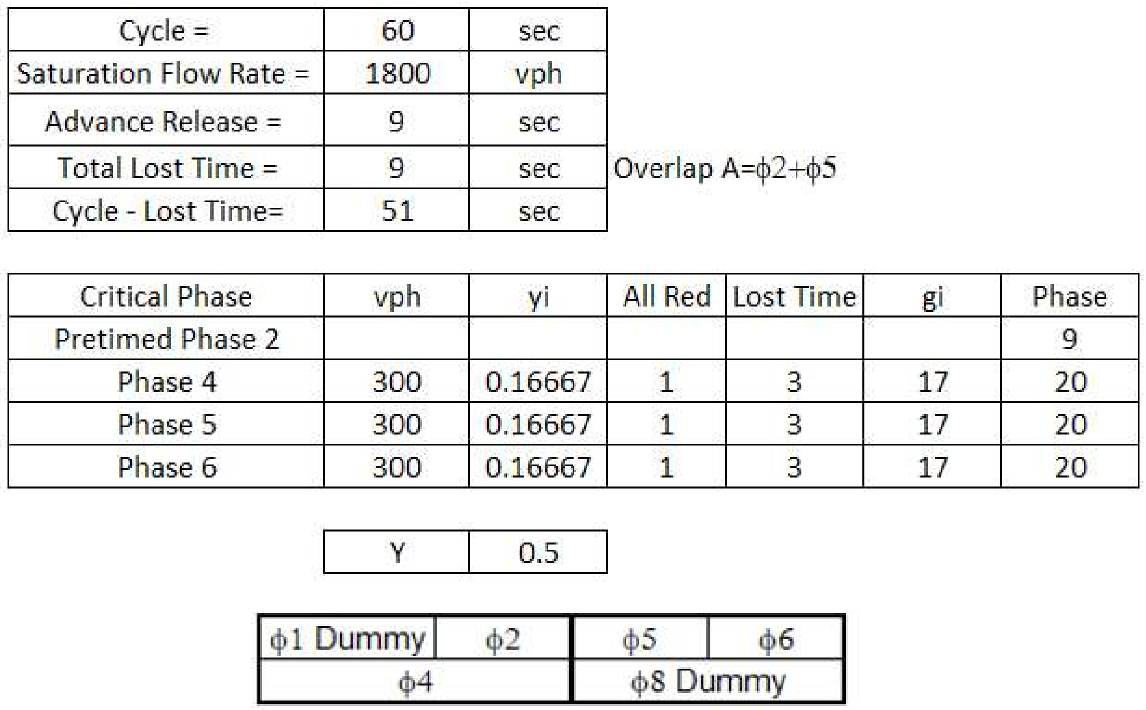
$$g_i = \frac{y_i(C-L+\sum \mathrm{A}R_i)}{Y} \tag{2}$$

$$g_i = \frac{y_i(C-L+\sum \mathrm{A}R_i)}{Y} - \mathrm{A}R_i \tag{3}$$

where g_i =Phase *i* effective green, in seconds, y_i = Phase *i* saturation flow rate; C = cycle length, in seconds; L_i = Phase *i* lost time = 2 + all red_i; L = total lost time = the sum of the lost time of each phase; AR_i (advance release) = “fixed time” overlap to progress a non-conflicting Phase *i*

Directly applying the Webster’s Method, the derived splits can be seen in Table 3. with Overlap A containing both phase 2 and phase 5, has a combined time of 29 seconds despite having identical volumes to the other movements. Note that the vph in Table 3 and 4 represent vehicles per hour per lane.

Table 3: Webster's Method Split Allocation Example



Cycle =	60	sec
Saturation Flow Rate =	1800	vph
Advance Release =	9	sec
Total Lost Time =	9	sec
Cycle - Lost Time=	51	sec

Overlap A=ϕ2+ϕ5

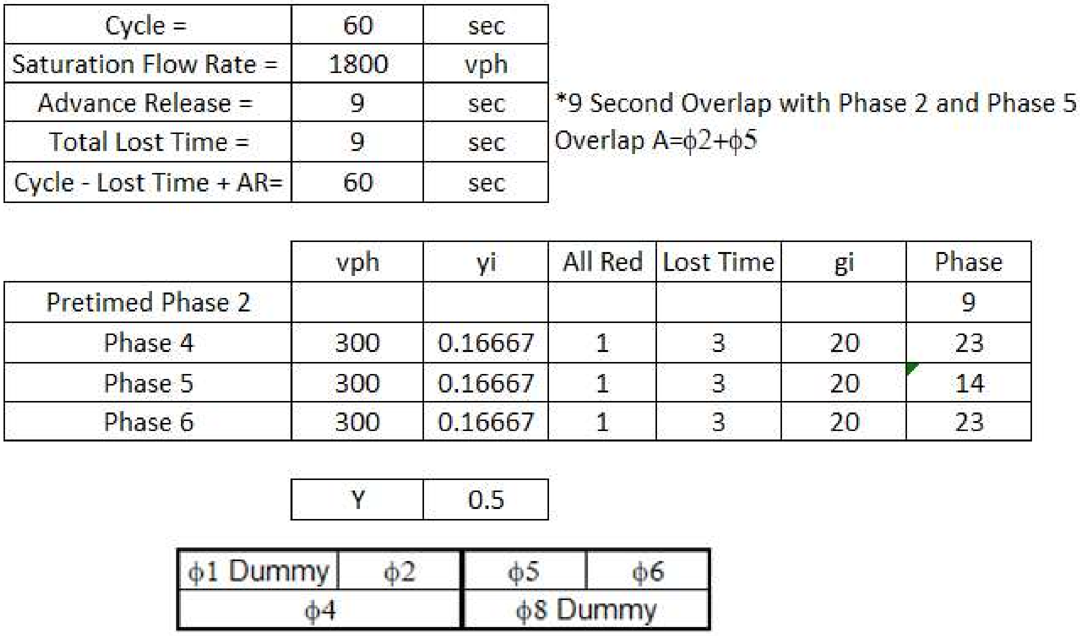
Critical Phase	vph	yi	All Red	Lost Time	gi	Phase
Pretimed Phase 2						9
Phase 4	300	0.16667	1	3	17	20
Phase 5	300	0.16667	1	3	17	20
Phase 6	300	0.16667	1	3	17	20

Y	0.5

ϕ1 Dummy	ϕ2	ϕ5	ϕ6
ϕ4		ϕ8 Dummy	

As overlaps such as these occur in some of the custom phasing for DDIs, Webster's Method required alteration as a mean of incorporating these Advance Release overlaps to correctly proportion the splits with inclusion of the overlap. Equation 2 is a modification to the classic Webster's Method. By including the overlap between two critical phases back into the total effective green time, the signalized intersection is able to operate as though the cycle length is longer than actually programed when comparing the volume to capacity ratio. For critical phases which utilize advanced release, which is typically the travel time through the interior section of an interchange, Equation 3 is used in which the advanced release time is then subtracted from the g_i to not be double counted. An example how the splits can be allocated with the addition of the overlap can be seen in Table 4 below.

Table 4: Altered Webster's Method Split Allocation Example



Cycle =	60	sec
Saturation Flow Rate =	1800	vph
Advance Release =	9	sec
Total Lost Time =	9	sec
Cycle - Lost Time + AR=	60	sec

*9 Second Overlap with Phase 2 and Phase 5
Overlap A=$\phi2+\phi5$

	vph	yi	All Red	Lost Time	gi	Phase
Pretimed Phase 2						9
Phase 4	300	0.16667	1	3	20	23
Phase 5	300	0.16667	1	3	20	14
Phase 6	300	0.16667	1	3	20	23

Y	0.5

ϕ1 Dummy	ϕ2	ϕ5	ϕ6
ϕ4		ϕ8 Dummy	

The Webster's Method also provides minimum and optimal cycle lengths; however, the selection of cycle length at a DDI can be affected by many other considerations. In practice, a DDI will typically be part of a signalized corridor. As such, the optimal cycle length for the corridor will generally already have been determined based on another intersection within the corridor as DDIs are not subject to the higher pedestrian crossing times seen at typical four leg intersections. The minimum cycle length should be checked against the cycle length for the corridor to ensure that the minimum cycle length is at or below the corridor cycle length. If the minimum cycle is less than half of the corridor cycle length, an option to run a half cycle at the DDI becomes available. Use of other fractional cycle lengths shall be left to engineering judgements. Considering the advanced release can progress a secondary critical phase, during which a primary phase is undergoing conventional All-Red time, no lost time is actually present during the overlap. This further reduces the applicability of Webster's cycle length equations.

4.2 VISSIM Simulation Development and Calibration

A microsimulation model was developed using Vissim. The existing geometry was modeled with approximate stops bar locations with approach speeds assumed to be 35 mph to coincide with the posted speed limit.

The existing phasing parameters were extracted from the City of Reno's ATMS server and programed into the model, apart from the All-Red Timing. Calibration was performed to match the models queue lengths to those observed in the field. To that end, the volumes on the westbound approach were adjusted to replicate the oversaturated conditions observed.

List of Assumptions:

1) An interior progression speed of 30 mph on the interior to reflect the reduced sight distance and curves.
2) Advanced detectors exact locations are unknown so were assumed to be 100-feet from the stop bar and 6-feet long.
3) The City of Reno uses a standard All-Red time of 1.5 seconds, and it is assumed these values will be updated to 1.5 seconds during the retiming.
4) Volumes for the off-ramp right-turns were not counted or modeled as those approaches will be serviced by overlaps or free right-turns in the case of the Moana DDI, and thus do no play a defining role in phasing scheme evaluation.

5) Percentage of through and left turns on interior from the arterials was assumed to be 20% and 80% respectively.
6) Lane distribution.
7) 130 second cycle optimal to be added into coordination with Moana intersections.

Calibration of the base model was performed matching volume and field observed queuing. Once calibrated, each phasing scheme was evaluated by the average of 5 runs, with 30 minutes of seed time to saturate the region and 60 minutes to evaluation the peak hour. Figure 17 presents a screenshot of the simulation operations.

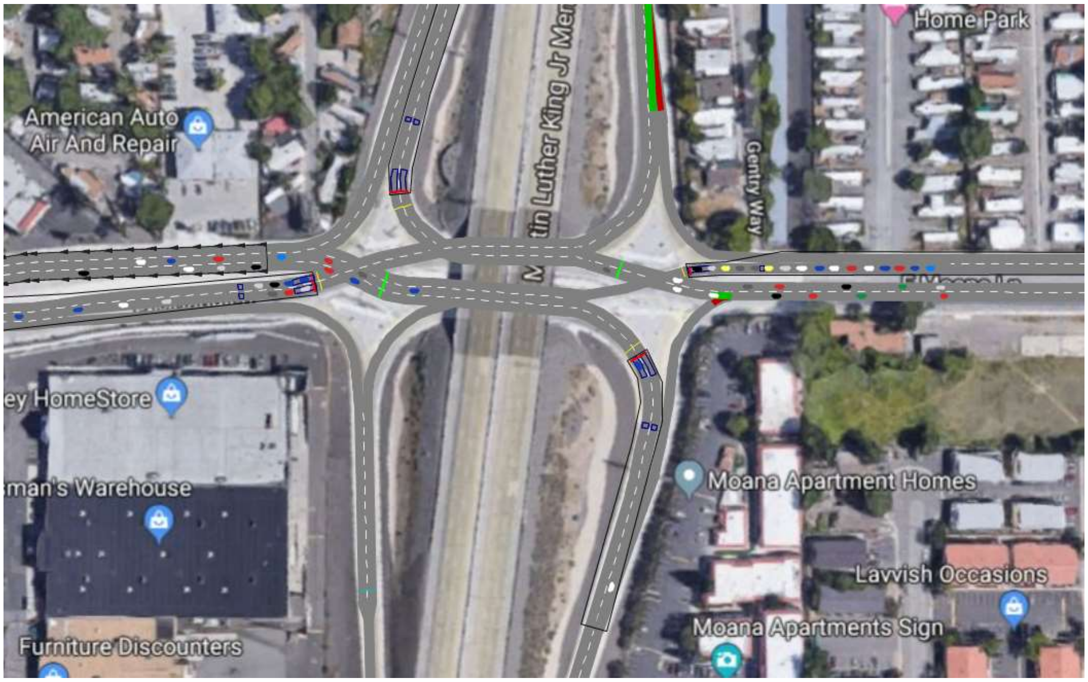
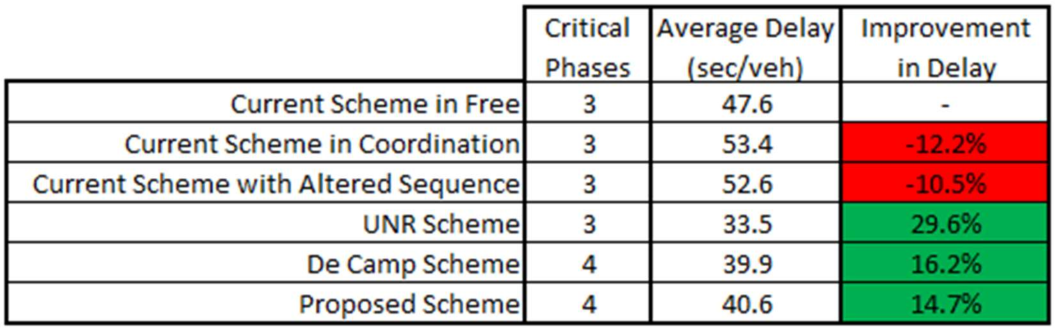


Figure 17: VISSIM Simulation for Moana & I-580 DDI

4.3 VISSIM Simulation Development and Calibration

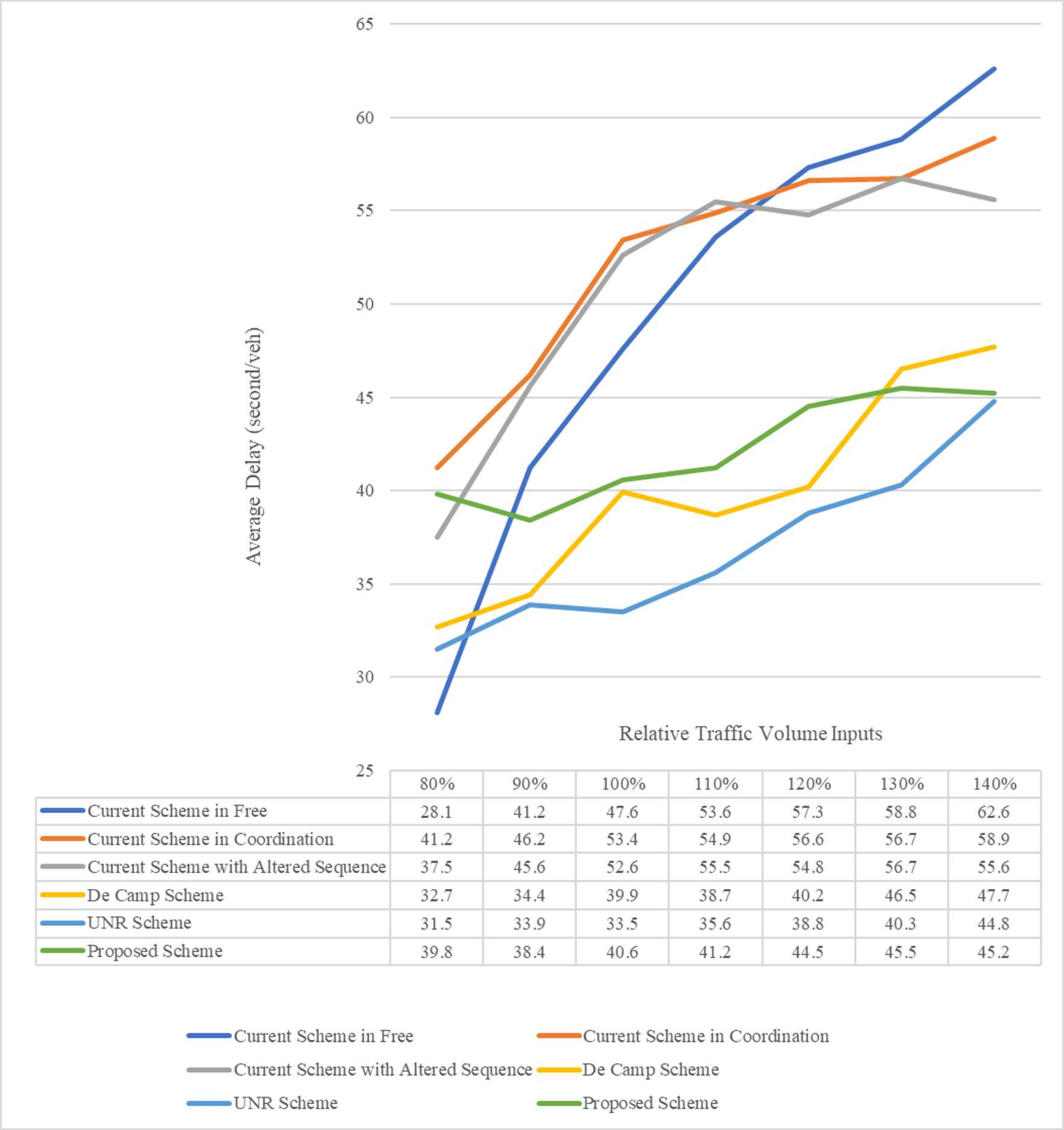
For each of the phasing schemes outlined in this report, splits were derived based on an altered Webster's Method equations and input to VISSIM for evaluation. The average delay for each phasing schemes is noted below in Figure 18.



	Critical Phases	Average Delay (sec/veh)	Improvement in Delay
Current Scheme in Free	3	47.6	-
Current Scheme in Coordination	3	53.4	-12.2%
Current Scheme with Altered Sequence	3	52.6	-10.5%
UNR Scheme	3	33.5	29.6%
De Camp Scheme	4	39.9	16.2%
Proposed Scheme	4	40.6	14.7%

Figure 18 Average Delay Comparison of Existing PM Peak Volumes by Signal Phasing Schemes

A sensitivity analysis was performed in terms of the volume of traffic inputs for the five signal phasing schemes. The existing volumes were altered from 80% of the calibrated volume, increasing by 10% per iteration, up to 140%. As the increased traffic volume inputs may cause oversaturated conditions, thereby leading to dramatically increased average delay times, the effectiveness of the comparison could be weakened. Hence, the cycle lengths used for simulation were adjusted along with the traffic volume settings being changed, and the maximum green settings in "free" scenarios were modified accordingly.



	80%	90%	100%	110%	120%	130%	140%
Current Scheme in Free	28.1	41.2	47.6	53.6	57.3	58.8	62.6
Current Scheme in Coordination	41.2	46.2	53.4	54.9	56.6	56.7	58.9
Current Scheme with Altered Sequence	37.5	45.6	52.6	55.5	54.8	56.7	55.6
De Camp Scheme	32.7	34.4	39.9	38.7	40.2	46.5	47.7
UNR Scheme	31.5	33.9	33.5	35.6	38.8	40.3	44.8
Proposed Scheme	39.8	38.4	40.6	41.2	44.5	45.5	45.2

Figure 19 : Sensativity Analysis for Average Delay Comparison by Signal Phasing Schemes

As shown in Figure 19, the proposed phasing scheme, once ramp volume reaches a certain threshold, will result in the lowest delay among the schemes that allow for internal stops, while the UNR scheme indicated the overall lowest delay because permitting internal stops can reduce the cycle length by 10 seconds. However, the delay difference between the proposed and UNR schemes is within one second.

Note that while delays do not reach Level of Service (LOS) F, defined in the HCM as 80 seconds or greater, all Current Scheme iterations experience some split failure or a volume to capacity ratio of greater than one, which also is a triggering criterion for LOS F. Despite the clear result when compared by only lowest average delay, a final recommendation for phasing sequence still need to involve additional considerations for the case study:

1) Current Scheme in Free is the base condition for comparison. The existing condition does not require any medication to the system and all issues with queueing and delays persist with diminishing operations with typical volumes increase.

2) Current Scheme in Coordination is the easiest to implement update, adjusting splits and adding in a defined cycle of 130 seconds to match the adjacent corridor. Due to the current phasing scheme with excessive loss time, the minimum cycle exceeds 130 seconds leading to diminished operations, split failure, and more queuing than the Current Scheme in Free.

3) Current Scheme with Altered Sequence is another option that is easily implementable with little to no hardware updates. The scheme however suffers from the same drawbacks as the Current Scheme in Coordination in that the minimum cycle length is higher than the corridor cycle length due to the long lost

time, resulting in high delays and split failure. While this scheme allows for the advanced release on one of the ramp movements, if the ramp volumes are similar the opposing side ramp would still dual progress with the advanced release ramp for the full split, results in no benefits.

4) The UNR Scheme is the first of phasing schemes with a reduction in delay compared with Current Scheme in Free. This scheme eliminates the trailing overlap found in the three previous schemes thereby reducing the lost time low enough that the interchange could run a half cycle of 65 seconds if desired and found to be beneficial to corridor throughput. The only drawback to this scheme is the internal stops which drivers may not be expecting. While previously discussed that internal stops are not a spillback issue for offramp movements, underpass DDIs have limited visibility for the internal signal. Limited sight distance can be a safety concern and is one of the reasons why internal stops may be avoided from a maintaining agency perspective.

5) Gerry De Camp Scheme is a versatile scheme, showing a reduction in delays as compared to the Current Scheme in Free while also maintaining the no internal stops. This scheme through use of two advanced releases this scheme can also run half cycle. In addition to half cycling, this scheme was found to function well under lower volume conditions as well, making it an ideal choice for low volume or free operations. Functions similarly to TTI-4 phasing from conventional diamond

interchanges. Due to having four critical phases it can be speculated that it would be the first, between itself, UNR, and the Proposed Scheme to reach capacity.

6) Proposed Scheme also shows delays improvements while maintaining no internal stops. Due to three uses of advanced released and a trailing overlap all running for a pre-timed duration equivalent to the travel time, this scheme does not allow for half cycling compared to the other two improved schemes. Conversely, due to the option for partial dual progression of the offramp left turns, the capacity of this scheme should be higher than the Gerry De Camp Scheme making it optimal under heavily saturated ramp conditions. Conflict monitoring and overlap assignment may cause confusion for implementation due to the unique ring/barrier structure.

5. CONCLUSIONS

This study sought to detail the operations and optimization process for signal timing at DDIs. To achieve this result, existing signal timing operation and design for DDIs, including best practices were reviewed. Phasing schemes, divided in two, three, and four critical phase categories were evaluated for their applicability to the case study at the existing DDI at I-580 and Moana Lane. The strengths and deficiencies of the categories were outlined with the most applicable identified for further evaluation at the study location.

Modified Webster equations were derived for the unique configurations possible with DDIs, finding similarities with diamond interchange TTI-3 and TTI-4 phase signal scheme. The modified equations derived splits for use in microsimulation.

A Vissim model was calibrated to existing conditions at the time of data collection and evaluated using the existing, readily deployable, and innovating phasing schemes. A comparison on delay for the various schemes identifies the advantages and disadvantages of each.

5.1 Research Findings

The findings are summarized as follow:

- Current research is subjective and vastly generalized. Critical research finding is that detailed equations are required and have been derived.
- During medium and high-volume conditions, both three and four critical phase schemes can achieve optimal delays, with the UNR, Gerry de Camp, and Proposed

sequences shown to have the most favorable delay given the Moana DDI geometry and roadway characteristic assumptions.

- Internal length of DDIs play a large role determining storage length, travel time, and can also limit the use of a single controller with spacing exceeds 600 feet between signals.
- The Proposed Scheme shows increasing efficiency as volumes increase, having the highest theoretical capacity under saturated conditions for scheme that do not allow internal stops.
- The Proposed Scheme experiences higher delays during under saturated conditions due to the number of pretimed travel time overlaps.
- The Proposed Scheme phasing can be altered to run identically to the Gerry de Camp Scheme by omitting Phase 3 and 4, allowing for the adaptability of the latter during off-peak or low volume conditions, but with the option for increased capacity during peak hours or due to future growth.
- Finding the optimal phasing schemes for new and renovated DDIs should consider microsimulation, or basic delay equations using the modified Webster equations in the event microsimulation is not feasible.
- Assumed cost savings for single controller setups do not include utility and wiring costs or maintenance.
- Pedestrian impacts were not considered in this or prior research.

5.2 Future Study

This study identified two additional research avenues:

- Internal stops and the issues associated with them could be reduced by detections on the interior of the DDI on the though lanes, allowing for gapping out of the trailing phases. This should also consider the potential effects of detection failure and lane change restrictions.
- The safety and delay impacts for multimodal transportation. With crossings from refuge islands to the center median and back across, pedestrians and bicyclists are required to utilize two or more, in the event of signalized right turns, pedestrian phases to cross the major movements. Due to the use of overlaps, detailed understanding of pedestrian phase activation and termination are required. The phasing scheme effect on delay as well as safety should be considered if multimodal transportation is an agency priority.

REFERENCES

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[1]. Chilukuri, V., S. Siromaskul, M. Trueblood, and T. Ryan. Diverging Diamond Interchange: Performance Evaluation (I-44 and Route 13). Report OR-11012. Missouri Department of Transportation, Jefferson City, 2011.

[2]. Schroeder, B., et al. Diverging diamond interchange: informational guide. No. FHWA-SA-14-067. United States. Federal Highway Administration. Office of Safety, 2014.

[3]. Nye, T. S., C. M. Cunningham, and E. Byrom. National-Level Safety Evaluation of Diverging Diamond Interchanges. Transportation Research Record: Journal of the Transportation Research Board, 2019. 2673: 696–708.

[4]. Siromaskul, S., and S. B. Speth. A Comparative Analysis of Diverging Diamond Interchange Operations. Presented at 2008 Annual Meeting and Exhibit of the Institute of Transportation Engineers, Washington, D.C., 2008.

[5]. Hunter, M., Guin, A., Anderson, J., & Park, S. J. Operating performance of diverging diamond interchanges. Transportation research record, 2673(11), 801-812. 2019

[6]. Diverging diamond interchange locations. Diverging Diamond Interchange. (n.d.). https://divergingdiamond.com/#

[7]. Missouri's Experience with a Diverging Diamond Interchange: Lessons Learned. Report OR 10-021. Missouri Department of Transportation, Jefferson City, 2010.

[8]. DDI Guideline: A UDOT Guide to Diverging Diamond Interchanges. Utah Department of Transportation, Salt Lake City, 2014.

[9]. Yang, X., Chang, G.L. and Rahwanji, S. Development of a signal optimization model for diverging diamond interchange. Journal of Transportation Engineering, 140(5), p.04014010. 2014.

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[10]. Chlewicki, G. New interchange and intersection designs: The synchronized split-phasing intersection and the diverging diamond interchange. 2nd Urban Street Symposium, Anaheim, California. 2003.

[11]. Bared, J.G., Edara, P.K. and Jagannathan, R. Design and operational performance of double crossover intersection and diverging diamond interchange. Transportation Research Record, 1912(1), pp.31-38. 2005.

[12]. Cunningham, C., Chase, T., Deng, Y., Carnes, C., Pyo, K., Jenior, P., Schroeder, B., Ray, B., Urbanik II, T., Knudsen, J. and Rodegerdts, L. Diverging Diamond Interchange Informational Guide (No. NCHRP Project 03-113). 2021.

[13]. Urbanik, T., A. Tanaka, B. Lozner, E. Lindstrom, K. Lee, S. Quayle, S. Beaird, S. Tsoi, P. Ryus, D. Gettman, S. Sunkari, K. Balke, and D. Bullock. NCHRP Report 812: Signal Timing Manual, 2nd ed. Transportation Research Board, Washington, D.C., 2015.

[14]. 14 Warchol, S., Schroeder, B.J. and Cunningham, C., 2016. Impact of exit ramp geometric treatments at diverging diamond interchanges on queue spillback. Transportation Research Record, 2556(1), pp.75-85.

[15]. 15 Warchol Obrien, S.E., 2015. Impact of Right Turn Treatments at Diverging Diamond Interchanges and Adjacent Intersections.

[16]. 16 Yeom, C. and Cunningham, C., 2017. Comparison of analytical and field-estimated lost times at DDIs. Journal of Transportation Engineering, Part A: Systems, 143(10), p.05017009.

[17]. 17 Xu, H., Liu, H. and Tian, Z., 2010. Control delay at signalized diamond interchanges considering internal queue spillback. Transportation Research Record, 2173(1), pp.123-132.

[18]. 18 Pang, B., Liu, H. and Xu, H., 2016. Calculating Approach Capacity of Diverging Diamond Interchanges with Consideration of Internal Queue Effects. Transportation Research Record, 2553(1), pp.63-71.

---

[19]. Meuleners, L.B. and Roberts, P. Diverging diamond interchanges: A driving simulator study. Transportation research part F: traffic psychology and behaviour, 71, pp.250-258. 2020.

[20]. Warchol, S., Chase, T. and Cunningham, C. Use of Microsimulation to Evaluate Signal-Phasing Schemes at Diverging Diamond Interchanges. Transportation Research Record, 2620(1), pp.10-19. 2017.

[21]. Cunningham, C., Schroeder, B.J., Phillips, S., Urbanik, T., Warchol, S. and Tanaka, A. Signal Timing for Diverging Diamond Interchanges: Fundamentals, Concepts, and Recommended Applications. Transportation Research Record, 2557(1), pp.1-10. 2016.

[22]. Tian, Z., H. Xu, G. de Camp, M. Kyte, and Y. Wang. Readily Implementable Signal Phasing Schemes for Diverging Diamond Interchanges. Presented at 94th Annual Meeting of the Transportation Research Board, Washington, D.C., 2015.

[23]. Hu. P. Advanced Signal Control Strategies and Analysis Methodologies for Diverging Diamond Interchanges. Doctoral Dissertation, University of Nevada, Reno. 2013.

[24]. Day, C.M. and Bullock, D.M. Cycle-length strategies for a diverging diamond interchange in a coordinated arterial. Journal of Transportation Engineering, 142(12), p.04016067. 2016.

[25]. Coogan, S. and Thitsa, M. Coordinated Anti-Congestion Control Algorithms for Diverging Diamond Interchanges (No. FHWA-GA-21-1913). Georgia. Department of Transportation. Office of Performance-Based Management & Research. 2021.

[26]. Cunningham, C.M., Warchol, S. and Schroeder, B.J. Exploring corridor operations in the vicinity of a diverging diamond interchange (DDI) (No. FHWA/NC/2014-13). North Carolina. Dept. of Transportation. 2016.

[27]. Day, C.M., Lavrenz, S.M., Stevens, A.L., Miller, R.E. and Bullock, D.M., Extending link pivot offset optimization to arterials with single controller diverging diamond interchange. Transportation Research Record. 2016.

---

[28]. Do, D., Chen, Y.Y. and Chang, G.L. Concurrent optimization of cycle length, green splits, and offsets for the diverging diamond interchange. Transportation research record, 2676(12), pp.653-665. 2022.

[29]. Cheng, Y., Chang, G.L. and Rahwanji, S. Concurrent optimization of signal progression and crossover spacing for diverging diamond interchanges. Journal of Transportation Engineering, Part A: Systems, 144(3), p.04018001. 2018.

[30]. Kim, S., Warchol, S., Schroeder, B.J. and Cunningham, C. Innovative method for remotely fine-tuning offsets along a diverging diamond interchange corridor. Transportation Research Record, 2557(1), pp.33-43. 2016.

[31]. Khan, T. and Anderson, M. Evaluating the application of diverging diamond interchange in Athens, Alabama. International Journal for Traffic and Transport Engineering, 6(1), pp.38-50. 2016.

[32]. Maji, A., Mishra, S. and Jha, M.K. Diverging diamond interchange analysis: planning tool. Journal of transportation engineering, 139(12), pp.1201-1210. 2013.

[33]. Autey, J., Sayed, T. and El Esawey, M. Operational performance comparison of four unconventional intersection designs using micro-simulation. Journal of Advanced Transportation, 47(5), pp.536-552. 2013.

[34]. Alzoubaidi, M., Molan, A.M. and Ksaibati, K. Comparing the efficiency of the super diverging diamond interchange to other innovative interchanges'. Simulation Modelling Practice and Theory, 106, p.102174. 2021.

[35]. Wang, H., Cheng, J. and Wang, L. Theoretical and Simulation-Based Analysis of Diverging Diamond Interchanges in China. In CICTP 2015 (pp. 2454-2466). 2015.

[36]. Schroeder, B.J., Salamati, K. and Hummer, J. Calibration and field validation of four double-crossover diamond interchanges in VISSIM microsimulation. Transportation Research Record, 2404(1), pp.49-58. 2014.

---

[37]. Hainen, A.M., Stevens, A.L., Day, C.M., Li, H., Mackey, J., Luker, M., Taylor, M., Sturdevant, J.R. and Bullock, D.M. High-Resolution Controller Data Performance Measures for Optimizing Diverging Diamond Interchanges and Outcome Assessment with Drone Video. Transportation Research Record. 2015.

[38]. Saldivar-Carranza, E.D., Li, H. and Bullock, D.M. Diverging diamond interchange performance measures using connected vehicle data. Journal of Transportation Technologies, 11(4), pp.628-643. 2021.

[39]. Tian, Z.Z., Balke, K., Engelbrecht, R. and Rilett, L. Integrated control strategies for surface street and freeway systems. Transportation Research Record, 1811(1), pp.92-99. 2002.

[40]. Webster, F.V., Traffic signal settings (No. 39). 1958.