TEMPORARY TRAFFIC CONTROL FOR MOBILE AND INNOVATIVE GEOMETRIC DESIGN WORK ZONES

A Thesis

presented to

the Faculty of the Graduate School

at the University of Missouri-Columbia

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

TIMOTHY COPE

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MAY 2015

The undersigned, appointed by the dean of the Graduate School,

have examined the thesis entitled

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Master of Science

And hereby certify that, in their opinion, it is worthy of acceptance.

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Dedication

I would like to thank my parents, Brian and Mary Beth Cope, for supporting me through my post graduate studies, my brother, Matt, for encouraging me along the way, and my girlfriend, Nicole, for being very supportive during the process of completing my thesis. I would also like to thank my friends and peers for being there for me through the completion of my master’s degree.

Acknowledgments

The author is thankful for the assistance provided by Andrew Hanks, Tom Blair, John Russell, Julie Stotlemeyer, and others from MoDOT. The author would also like to thank all who completed the survey, sent example project plans, and participated in phone interviews. The author would like to wish to acknowledge the contributions of Amirhossein Khezerzadeh who aided in conducting a survey as well as with data analysis and Zach Osman, Pedro Ruiz Fabian, Jon Bachelor, and Dylan Hackman who aided with data collection and processing.

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Temporary Traffic Control for Mobile and Innovative Geometric Design Work Zones
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ABSTRACT

Work zone safety and operations are of growing concern through recent years. With increasing traffic demand on the transportation system and advancing technology raising new situations, such as texting while driving and the proliferation of portable devices, new approaches and solutions need to be formed relating to transportation safety. This thesis addresses two issues pertaining to work zone safety. This first issue related to the increase of distracted driving through mobile work zones leading to an increase in collisions with work zone vehicles. Mobile work zones are continuous slow moving operations utilized for various maintenance applications such as pavement striping, sweeping, and pothole repair. This type of work zone is unique because no portion of the work zone is static and the use of and advance signage must remain mobile. The speed differential between the work zone vehicles and normal traffic flow, and the rise in distracted driving can lead to potential collisions. A possible solution to this problem involves the use of an audible warning system. This thesis evaluates two types of mobile work zone alarm systems: an Alarm Device and a Directional Audio System (DAS). Three modes of operation were tested: continuous, manual, and actuated. The evaluation consisted of sound level testing, analysis of merging distances and speeds, and observations of driving behavior. The mobile work zone alarm study found that the Alarm Device and DAS operate within national noise standards. All of the tested configurations increased vehicle merging distance except for the Alarm Actuated setup. The DAS Continuous setup reduced vehicle speeds and the standard deviation of merging distance. Some instances of undesirable driving behavior were observed for some configurations; however, it is unclear whether these behaviors were due to the use of the audible warning system. Analysis of the alarm activations showed that horizontal and vertical curves had a significant effect on false alarm and false negative rates. This research found that the use of an audible warning system has potential to be an effective tool in improving safety through mobile work zones. Further tests to the system, such as modifying the alarm sounds, could improve the warning system's effectiveness.

The second issue relates to the rising trend of utilizing innovative geometric designs to address increasing traffic and increase traffic safety. Currently there are no guidelines within the Manual on Uniform Traffic Control Devices (MUTCD) on construction phasing and maintenance of traffic (MOT) through retrofit construction projects involving innovative geometric designs. The research presented in this thesis addressed this gap in existing knowledge by investigating the state of the practice of construction phasing and MOT for several types of innovative geometric designs including the roundabout, single point urban interchange (SPUI), diverging diamond interchange (DDI), restricted-crossing left turn (RCUT), median U-turn (MUT), and displaced left turn (DLT).Goals through the innovative geometric design portion of this thesis include providing guides for transportation practitioners in developing construction phasing and MOT plans for innovative geometric designs. This involves providing MOT Phasing Diagrams to assist in traffic control measures such as barriers, delineators, and striping. Guidelines were developed for MOT through a review of literature, survey and interview of industry experts, and review of plans from innovative geometric design projects. These guidelines are provided as a tool to assist in improving work zone safety through construction of projects with innovative geometric designs. A literature review, survey of industry experts, interviews of industry experts, and analysis of project plans provided knowledge of existing practices for these types of designs. This process allowed for the development of MOT Phasing Diagrams and suggestive guidelines for each of these intersection types.

Chapter 1 Problem Description and Introduction

Work zone safety and operations are of growing concern through recent years. With increasing traffic demand on the transportation system and advancing technology bringing new concerns, such as distractions created by the use of cell phones and texting while driving, new approaches and solutions need to be formed relating to transportation safety. This thesis focuses on two issues pertaining to work zone safety in the transportation field. The first issue addresses the increase of distracted driving through mobile work zones leading to a rise in mobile work zone incidents. The second work zone safety and operations issue pertains to the use of innovative geometric designs as a response to increased system demand and a lack of funding. Currently, there is a lack of guidance to transportation practitioners with regards to the construction phasing and MOT for projects with innovative geometric design intersections and interchanges. This lack of guidance pertains to both initial construction and maintenance of these designs leaving each practitioner to develop methods for these types of projects which may lead to an inconsistency in work zone setups. This thesis aims to improve work zone safety and operations through addressing these two transportation issues.

1.1. Mobile Work Zone

Mobile work zones are continuous slow moving operations utilized for various maintenance applications such as pavement striping, sweeping, and pothole repair. The Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) contains typical applications for the setup of mobile work zones as shown in Figure 1.1.1. These work zones consist of arrow boards, shadow vehicles, signs, and flashing lights to aid in warning approaching drivers of the slow moving operation. A Truck-Mounted Attenuator (TMA) attached to a work zone vehicle is utilized to mitigate collision force in the instance of an impact from a highway vehicle.

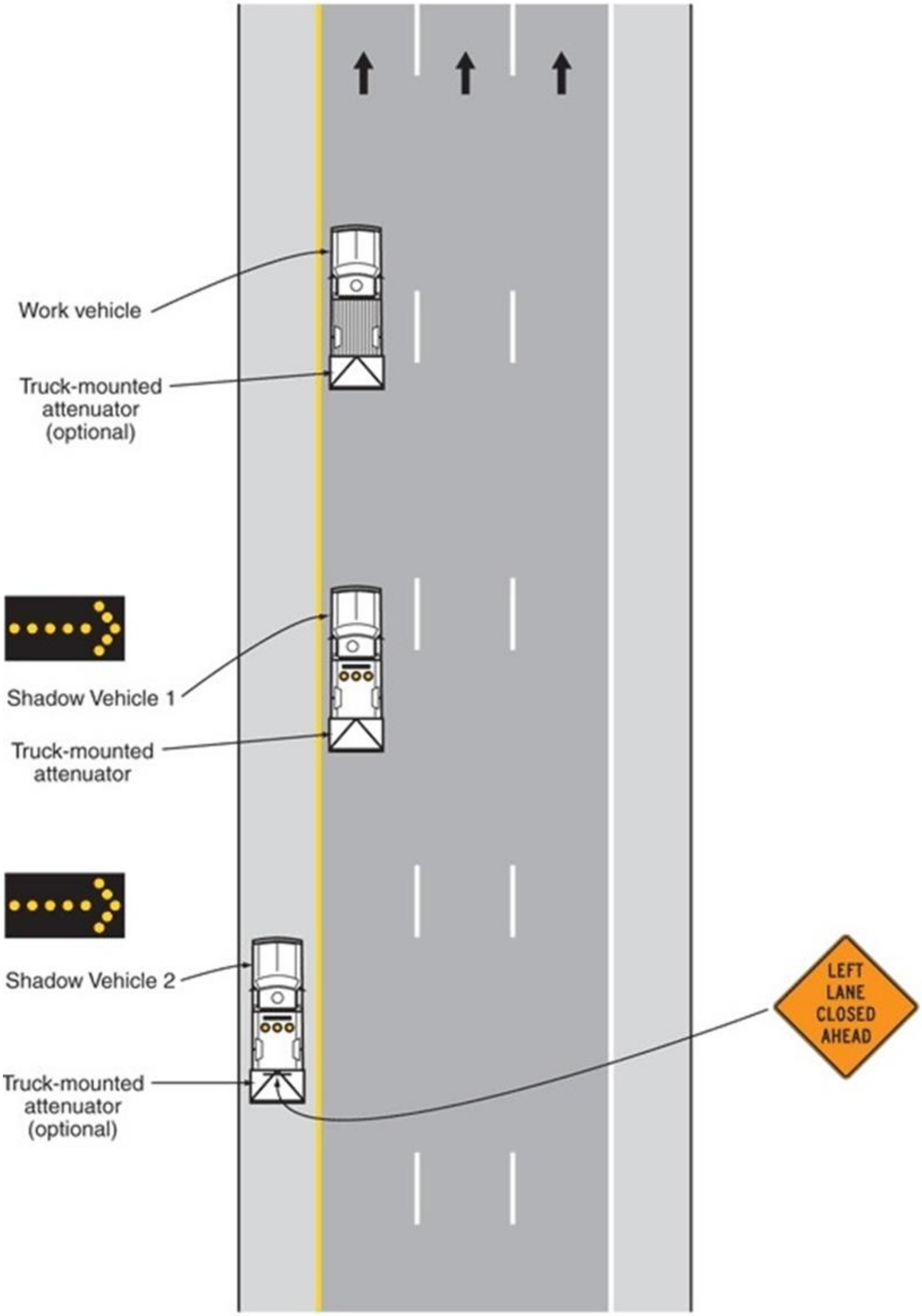


Figure 1.1.1 MUTCD typical application sheet for mobile work zone layout (FHWA, 2009)

Despite precautions, collisions with the TMA occur. This trend has experienced an increase in recent years through the rise of distracted driving via texting and cell phone use. Figure 1.1.2 shows the Missouri Department of Transportation (MoDOT) recorded TMA hits by year. From January through June of 2012, 22 third-party TMA incidents occurred in which a traveler collided with a TMA while 13 third-party TMA collisions occurred from January to June in 2013. Despite this downward trend between 2012 and 2013, there remain a significant number of TMA hits which include through mobile work zones. Figure 1.1.3 shows the aftermath of two separate instances in which a traveler collided into a mobile work zone TMA.

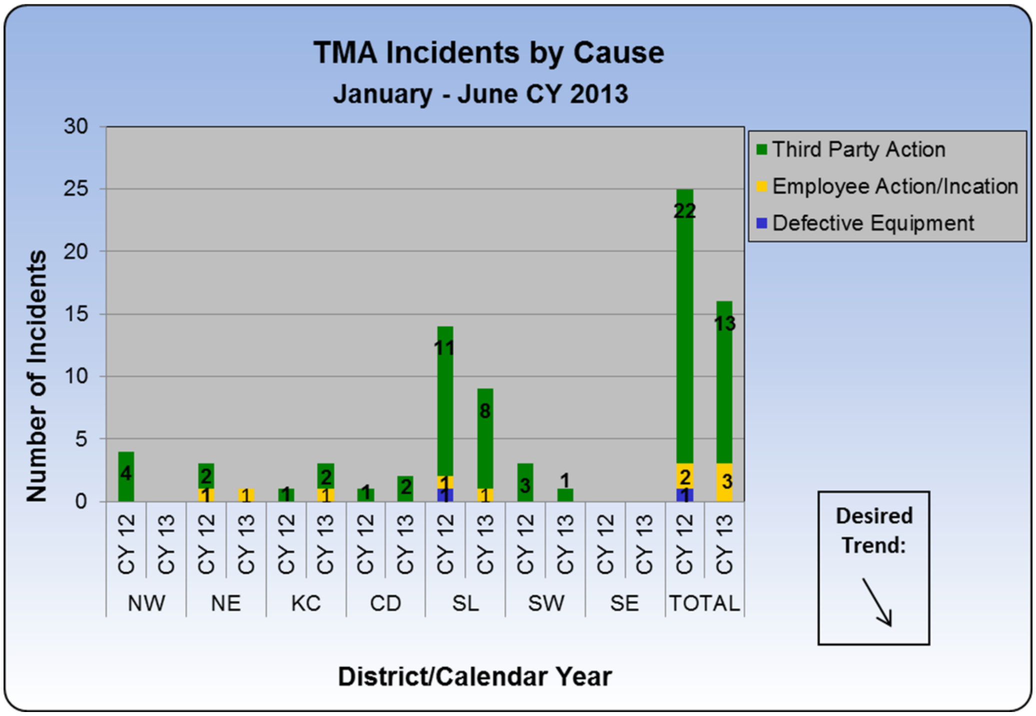


Figure 1.1.2 MoDOT Traffic and Highway Safety Division Tracker (MoDOT, 2013)

Figure 1.1.3 Aftermath of two separate mobile work zone TMA collisions

One tool that could help to reduce the number of collisions between highway vehicles and TMAs is a mobile work zone alarm system which sounds an audible warning to approaching drivers. Audible warning systems have not previously been tested for use within mobile work zones and previous research is limited. This thesis explores the use of audible warning systems through mobile work zones and resulting effects on driver behavior.

Goals for the mobile work zone portion of the thesis include evaluating two mobile work zone alarm systems and the resulting driver behavior. The first alarm system is the Alarm Device which has seen some use with MoDOT's St. Louis District for the mobile work zone application. A mobile work zone TMA truck with the rear-facing Alarm Device can be seen in Figure 1.1.4. This device utilizes air horns to emit the audible warning to approaching drivers behind the TMA truck.

Figure 1.1.4 TMA truck with Alarm Device

The second alarm type tested was the Directional Alarm System (DAS). This system emits high intensity directional sound waves. The DAS sound is customizable in terms of sound type, level, and frequency but remained constant through the extent of this research. Phanomchoeng et al. (2008) suggested that a DAS could be beneficial in a work zone application. However, there is no known use of the DAS in a mobile work zone. The DAS is particularly useful to convey messages or sounds over long distances. Several versions of the DAS exist which include models which utilize reduced sound levels for general public use. These smaller units are more affordable. The DAS used in this test can be seen in Figure 1.1.5.

Figure 1.1.5 TMA truck with DAS unit

Multiple trigger mechanisms were tested for each alarm type in addition to continuous operation. This was done in order to determine possible differences in driver behavior between actuated and non-actuated systems. For the Alarm Device tests, a manual trigger mechanism and an actuated trigger mechanism were tested. The manual trigger mechanism involves a two-stage alert system in which warning lights followed by alarm sound is activated by the driver of the TMA truck when appropriate, based on approaching vehicle speed and distance behind the TMA truck. The actuated system automatically triggers the alarm sound based on approaching speed and distance behind the TMA truck. Both continuous and actuated operating modes were tested for the DAS. The continuous setup involves an uninterrupted sounding of the alarm throughout the extent of alarm use.

The objective of this study is to evaluate each alarm setup for potential use as a mobile work zone alarm. This evaluation includes sound level testing, spectral analysis to evaluate alarm sound distinctiveness, analysis of resulting driver behavior through each setup, and analysis on false alarm and false negative rates through the manual and actuated systems. Proper implementation of a mobile work zone alarm could improve safety and operations through mobile work zones and protect both workers and travelers.

1.2. Innovative Geometric Design

The second work zone safety operations issue pertains to the growing use of innovative geometric designs. Innovative geometric designs are considered to be a solution to many state Departments of Transportation's problems caused by meeting growing traffic demand that increase safety risks and congestion with limited funding. These designs implement unconventional traffic movements through intersections and interchanges. Implementing these designs require works zones and often require MOT throughout construction through work zones. Innovative geometric designs examined in this thesis include the roundabout, single point urban interchange (SPUI), diverging diamond interchange (DDI), restricted crossing U-turn (RCUT) intersection, median U-turn (MUT) intersection, and displaced left-turn (DLT) intersection.

Each intersection type provides various safety and operational benefits. The roundabout eliminates right-angle crossings and causes traffic to move continuously in a one-way circular motion (Figure 1.2.1). In eliminating right-angle crossings, the potential for serious crashes is substantially reduced.

Figure 1.2.1 Roundabout intersection in Branson, MO, Business 65 and Branson Landing Blvd. (Google, 2014)

The SPUI utilizes a single signalized intersection which leads to a more simplistic signal phasing sequence and an increased capacity when compared to a conventional diamond intersection (Figure 1.2.2). SPUIs are typically used in urban areas with high traffic volumes.

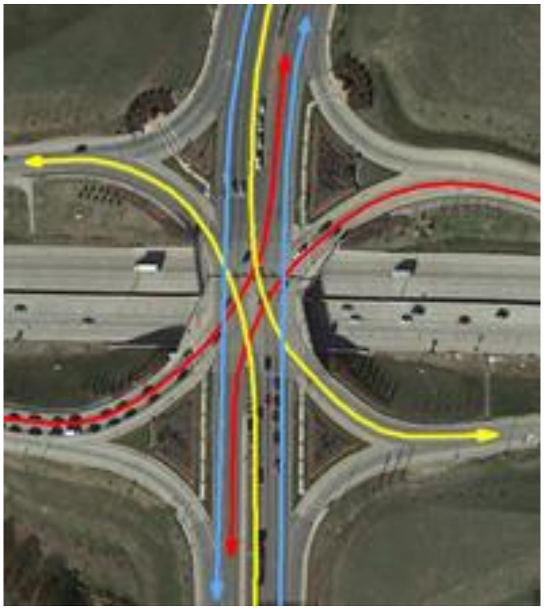


Figure 1.2.2 Single Point Urban Interchange (SPUI) in St. Louis, MO, I-64 and S. Kingshighway Blvd. (Google, 2014)

The DDI shifts cross-street traffic to the left side of the roadway and is also known as the double crossover diamond interchange (Figure 1.2.3). This design utilizes unrestricted left-turn movements for on-ramps leading to increased capacity and safety.

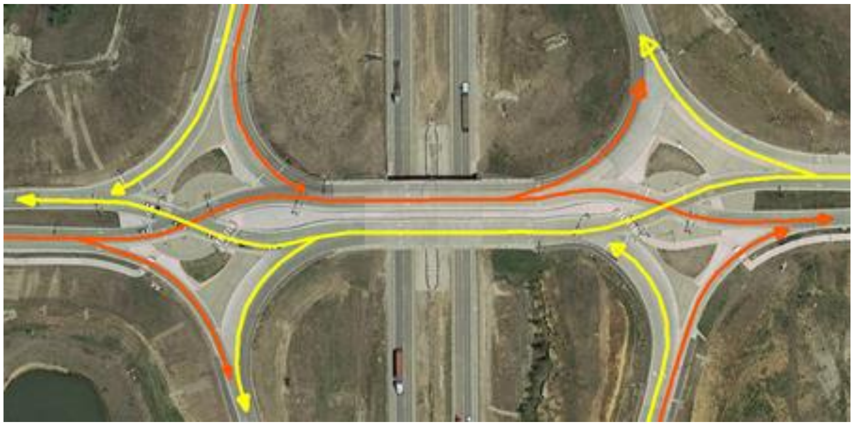


Figure 1.2.3 Diverging Diamond Interchange (DDI) in Grandview, MO, Rt. 150 and Botts Rd. (Google, 2014)

The RCUT involves eliminating cross-street left and through movements through the use of median U-turns but allows for major street cross and through movements (Figure 1.2.4). The RCUT improves traffic safety and operations by eliminating minor movements with conflicts of high severity potential. The RCUT is also known as a superstreet intersection or J-turn intersection.

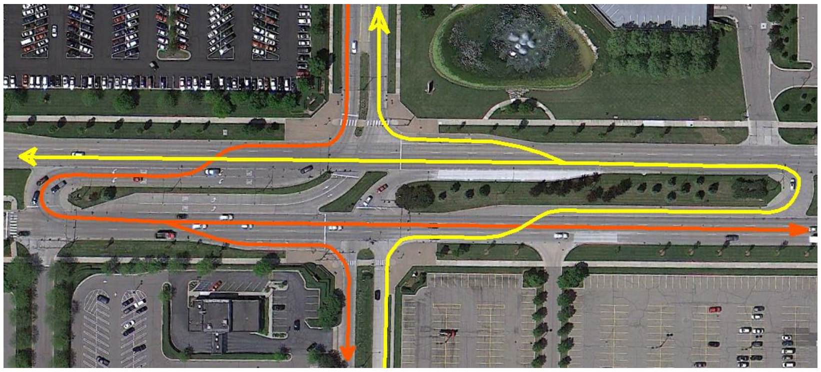


Figure 1.2.4 Restricted Crossing U-Turn (RCUT) intersection in Troy, MI, W. Big Beaver Rd. and Lakeview Dr. (Google, 2014)

The MUT eliminates left turn movements within an intersection and provides median U-turns after the street crossing (Figure 1.2.5). This configuration is utilized in both rural and urban settings.

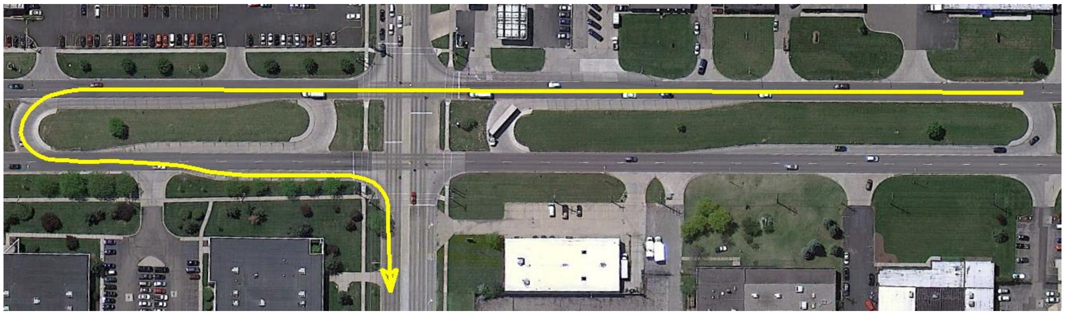


Figure 1.2.5 Median U-Turn (MUT) intersection in Clawson, MI, W. 13 Mile Rd. and Stephenson Hwy. (Google, 2014)

The DLT moves left-turn traffic of an intersection to the opposite side of opposing lanes in advance of the intersection (Figure 1.2.6). This eliminates the left-turn phase at the intersection signal.

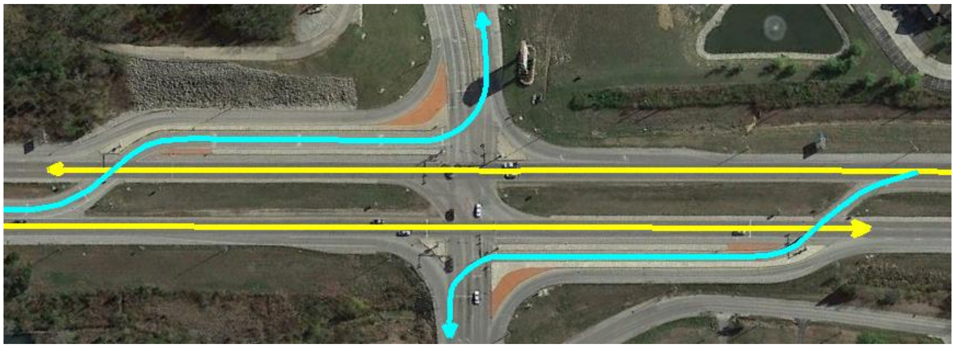


Figure 1.2.6 Displaced Left Turn (DLT) intersection in Fenton, MO, Rt. 30 and Summit Rd. (Google, 2014)

Several challenges are faced when implementing these intersections. This thesis focuses on the challenge of initial construction phasing and maintenance of traffic (MOT) through retrofit construction of these intersections. The MUTCD provides guidelines and typical applications for the MOT through construction projects; however, no specific guidelines are currently in place to aid transportation practitioners in organizing this process for projects with innovative geometric designs. Some construction phasing suggestions exist and will be further discussed in the literature review.

Goals for the innovative geometric design portion of this thesis include providing guidance for transportation practitioners in developing MOT plans for both initial construction and maintenance for projects with innovative geometric designs. This involves providing guidance in developing an overall MOT strategy and MOT Phasing Diagrams for deploying traffic control measures such as barriers, delineators, and striping. Guidelines were developed for MOT through a review of literature, survey and interview of industry experts, and review of plans from innovative geometric design projects. These guidelines are to aid in improving work zone safety through construction projects of innovative geometric designs.

Chapter 2 Literature Review

This chapter includes a review of literature pertaining to mobile work zone alarms as well as construction phasing and MOT for innovative geometric designs.

2.1 Mobile Work Zone

This section gives an overview of Mobile Work Zone Alarm sound level standards and work zone alarm applications through a review of existing literature. Since there is no existing literature on mobile work zone alarm sounds, the literature on emergency vehicle warning signals was reviewed.

2.1.1 Sound Level Standards

The Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety (NIOSH) were established from the Occupational Safety and Health Act of 1970 (Niquette, 2014). Each of these agencies has a variety of responsibilities which include establishing national standards for allowable sound level exposure to workers. OSHA standards are enforceable by law while NIOSH standards serve as guidelines and are not legally enforceable. NIOSH sound level standards are established by Equation 2.1.1.1 in which duration (T) is determined as a function of exposure level (L).

$$T(\text{min}) = \frac{480}{2 * \frac{(L-85)}{3}} \qquad \text{Equation 2.1.1.1}$$

Duration is a measure of daily exposure limit rather than per exposure. This measure must remain below 100 and is computed through Equation 2.1.1.2.

$$D = \left[\frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{C_n}{T_n}\right] * 100 \qquad \text{Equation 2.1.1.2}$$

Where:

C_n = exposure time at a specific noise level, and

T_n = point at which exposure time for a given sound level becomes harmful.

NIOSH standard sound levels to duration in hours can be seen in Table 2.1.1.1. These standards are more stringent than OSHA guidelines but are not enforceable by law and serve more as recommendations.

Table 2.1.1.1: NIOSH Sound Level Standards (NIOSH, 1998)

Duration (Hours)	Sound Level (dBA)
0.25	100
0.5	97
1	94
2	91
4	88
8	85
16	82

OSHA (1983) allows for a base sound level intensity of 85 dBA and halves the allowable duration of exposure for every five decibel increase in sound level. Table 2.1.1.2 shows OSHA standards for the same durations as NIOSH standards. Similarly to NISOH standards, duration of exposure is a daily value and follows the same constraints as equation 2.1.1.2.

Table 2.1.1.2: OSHA Sound Level Standards (OSHA, 1983)

Duration (Hours)	Sound Level (dBA)
0.25	115
0.5	110
1	105
2	100
4	95
8	90
16	85

2.1.2 Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations

Maddern et al. (2011) studied auditory warning signals factors such as perceived urgency, localization, and masking of emergency sirens. Perceived urgency is the importance inherently placed on a sound by the driver. Fast repetition of sound was found to be the largest factor leading to a higher level of perceived urgency. Another aspect which can have an effect on perceived urgency is attenuation. An attenuated sound is said to be recognized as more urgent than a non-attenuated sound.

Maddern et al. (2011) states that localization relates to how quickly a traveler is able to determine what direction a sound is coming from. This factor is desirable because it allows travelers to know where the vehicle with the siren is and, in the case of this thesis, have an inattentive driver realize the presence of the slow moving work zone vehicles more quickly. Localization can be improved by widening the range of frequencies emitted. However, frequencies above 3000Hz are not advised because hearing-impaired individuals may not be able to distinguish such frequencies.

According to Maddern et al. (2011), masking is the tendency of a sound to be covered up by background noise. Sounds consisting of low frequencies or that cannot penetrate surfaces are said to have a greater tendency to be masked by background noise causing the sound to be more difficult to hear.

2.1.3 Effectiveness of Audible Warning Devices on Emergency Vehicles

The United States Department of Transportation Office of the Secretary (Potter et al., 1977) found that for an alarm to be distinct it must have a larger decibel level than background noise by at least 10 decibels. This would ensure a level of distinctiveness between the alarm warning and usual noise of the roadway.

2.1.4 Directional Sound for Long Distance Auditory Warnings from a Highway Construction Work Zone

Phanomchoeng et al. (2008) concentrated on the use of audible warning systems for static work zone applications. While the DAS was mentioned, only Loud Speakers and Loud Speaker Arrays were tested in this research. It was found that any configuration involving a single loudspeaker would be inadequate for long distance auditory warnings while an ultrasound based parametric array may have the ability to generate a highly directional sound. However, this sort of setup is difficult for work zone applications due to need of vacuum pump and other special devices. A parametric array with inexpensive components was found to be inadequate for long distance warning applications. The device recommended was an array of multiple ordinary loudspeakers arrayed in a specific pattern that would be suitable for long distance auditory warnings. This setup was said to be portable, inexpensive, and easy to maintain while having good performance for long distance auditory warnings. The DAS was discussed but determined to be too expensive compared to the loudspeaker setups and therefore was not tested.

2.1.5 Crash Avoidance Warning Systems

Tan and Lerner (1995) studied auditory warnings that could be used in crash avoidance applications. The experimental study investigated 26 acoustic signals and identified four acoustic signals that were preferred for this application. The study also evaluated verbal warnings but did not find a verbal warning that performed significantly better than the others.

2.1.6 Review of Emergency Vehicle Warning Systems

De Lorenzo and Eilers (1991) reviewed existing literature on emergency vehicle warning systems. This synthesis found that several research studies had concluded that emergency vehicle sirens had significant limitations as a warning device especially since their effectiveness is limited to low distances and speeds.

2.1.7 Effectiveness of Warning Signals in Capturing a Driver's Attention

Ho and Spence (2005) investigated possible benefits of spatial auditory cues to capture a driver's attention through the use of 5 experiments. The use of auditory cues that helped give the driver a spatial reference for the sound were found to be beneficial to obtaining the attention of drivers. The study suggests that verbal warnings were not as effective as non-verbal cues because they require additional processing by the driver of the vehicle.

2.2 Innovative Geometric Design

This section gives an overview of construction phasing and MOT practices currently used throughout state agencies and municipalities implementing innovative geometric design intersections.

2.2.1 Roundabout

Roundabouts are generally categorized into two groups: single lane and multi-lane. This section presents existing literature relating to both single and multi-lane roundabouts. The Virginia DOT Work Area Protection Manual (VDOT, 2011) includes operational guidelines for roundabout construction and maintenance projects. Flagging operations may be needed through work zones within single lane roundabouts due to the necessity to close the lane within the single lane roundabout. For this setup, a flagger is placed at each entrance to the roundabout and one entryway is allowed to travel through the roundabout at a time. Figure 2.2.1.1 shows a typical work zone setup for a single lane roundabout using flagger control.

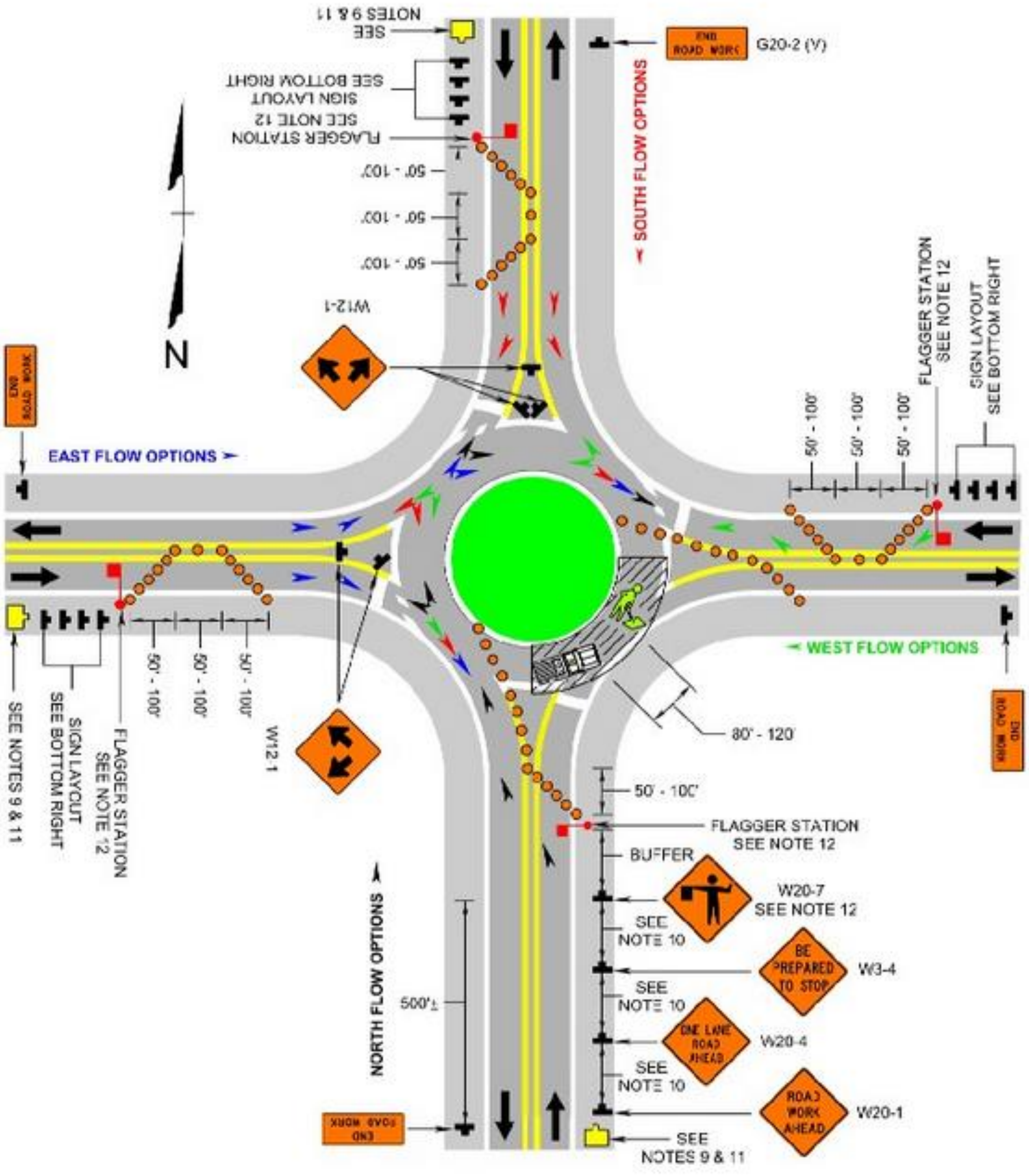


Figure 2.2.1.1 Standardized setup for single lane roundabout with flagger control on a single lane roundabout (VDOT, 2011)

VDOT (2011) states that multi-lane roundabout work zones with a closure of the innermost lane are required to include proper signage and traffic control to ensure easy navigation through the roundabout during construction. Figure 2.2.1.2 shows a standard work zone organization of this scenario. In this setup, approaching roadways are reduced to one lane of travel in which roundabout operation is similar to a single lane roundabout.

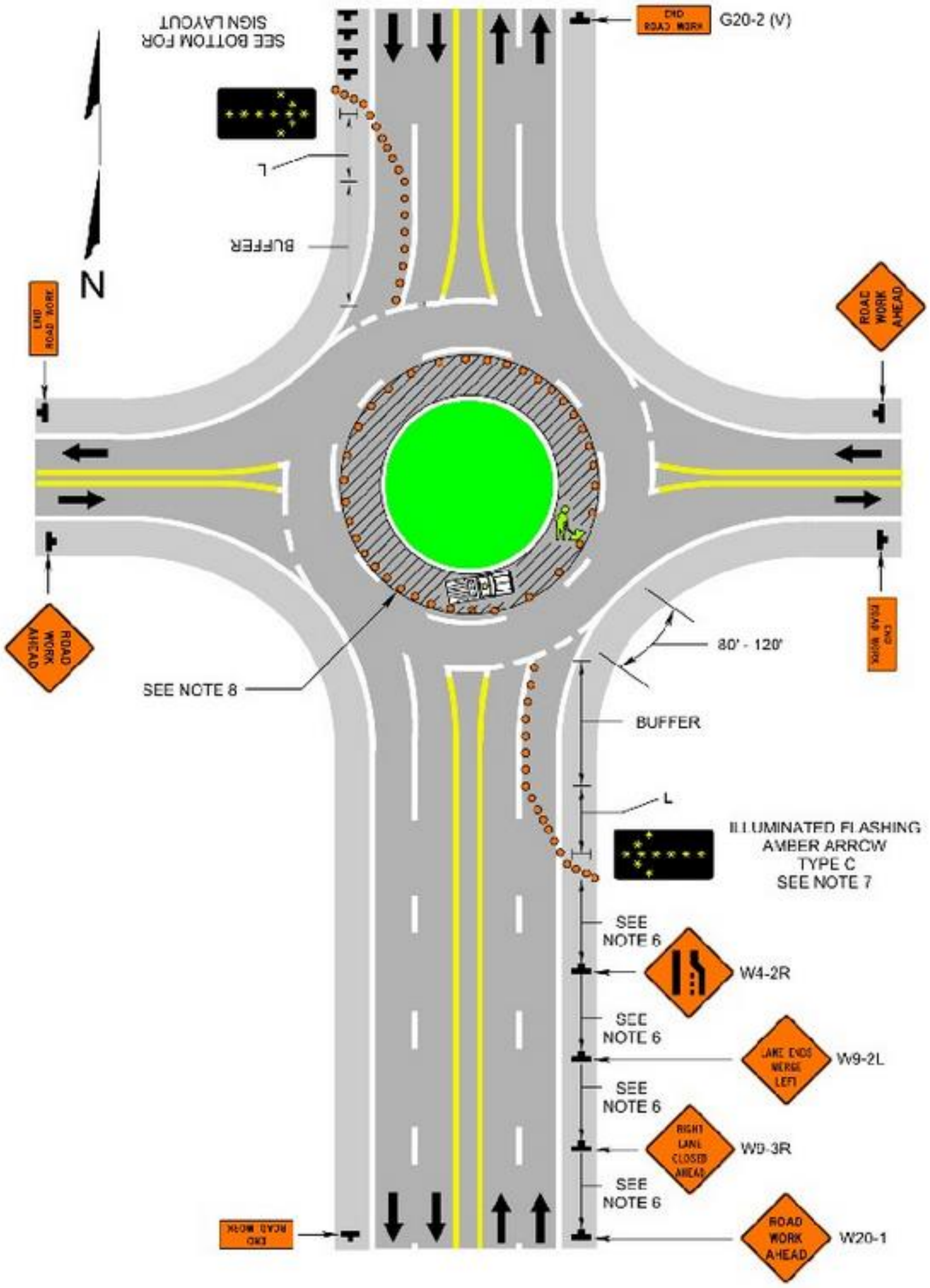


Figure 2.2.1.2 Standardized setup for inner lane closure through multi-lane roundabout

(VDOT, 2011)

Multi-lane roundabout work zones which result in the closure of the outer lane through quadrant closures call for careful work zone setup and traffic control to ensure travelers can easily traverse through the roundabout during construction as stated by VDOT (2011). Figure 2.2.1.3 shows a standardized setup of this scenario. This work zone setup requires a flagman operation in which flaggers are stationed at each leg of the roundabout throughout construction providing access through the roundabout on a turn basis.

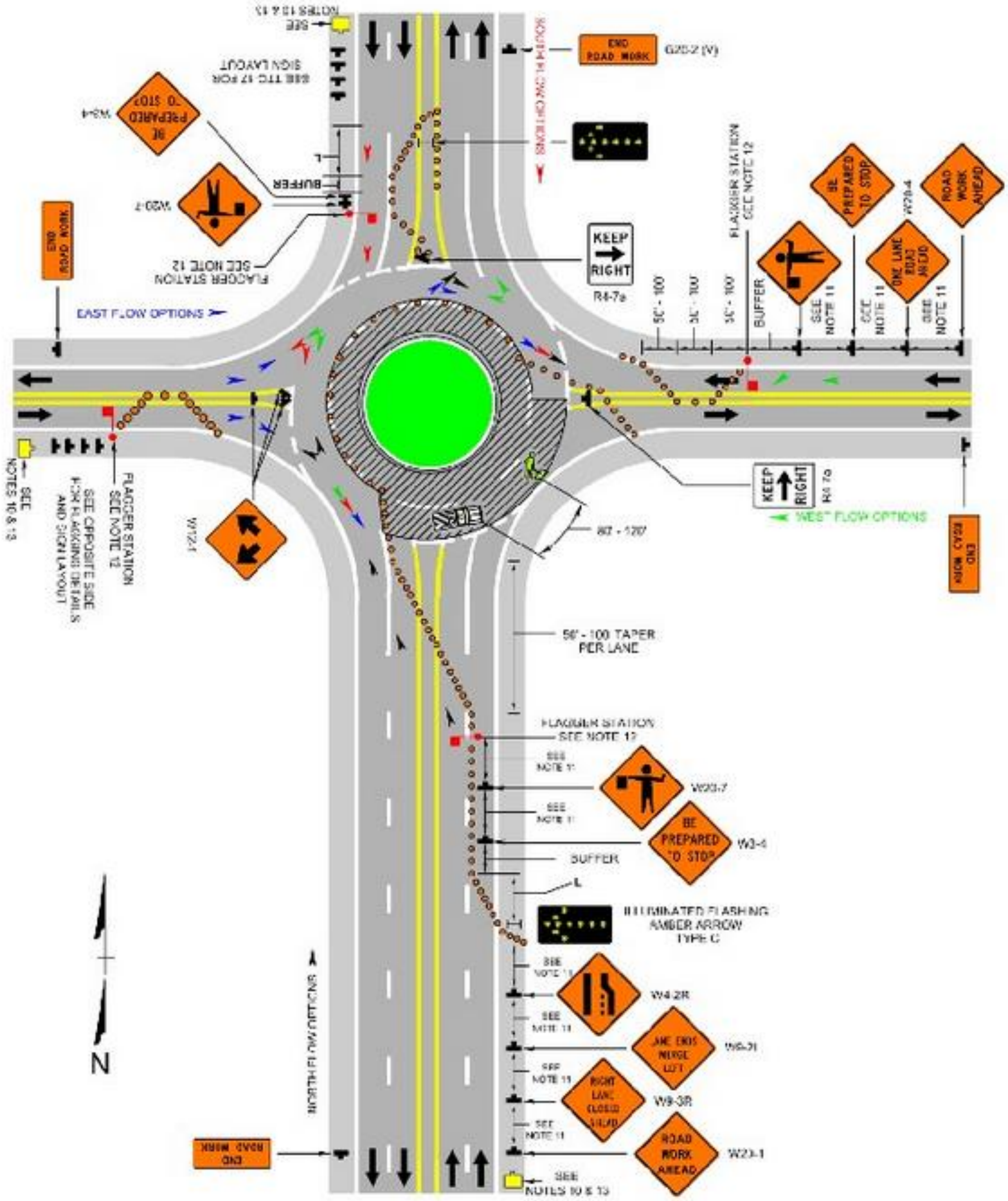


Figure 2.2.1.3 Standardized setup for outer lane closure of multi-lane roundabout (VDOT, 2011)

FHWA (2013) states various considerations when leaving uncompleted work in a roundabout overnight. These considerations include construction of splitter islands, clearly marking uncompleted portions, adding temporary overhead lighting, and the use of flagging operations at the roundabout.

The Wisconsin Department of Transportation roundabout guide (WisDOT, 2013) provides guidelines on roundabout MOT considerations. According to this guide, detouring traffic away from roundabout construction is ideal in order to increase safety and reduce congestion throughout roundabout construction. If detours are not available, then careful consideration must be placed on the construction staging of the roundabout. Typical roundabout construction staging is organized in 6 phases. In Phase I, proposed signing is installed and covered. Phase II involves removing pavement markings that do not conform to intended travel paths. Phase III encompasses construction of outside widening, if needed, while Phase IV involves reconstructing the approaches to the intersection, if applicable. Phase V involves construction of splitter islands and the delineation of the central island. Once these are complete, the installed signage should be uncovered and the intersection operated as a roundabout. In Phase VI, the construction on the central island is completed. If roundabout construction is not completed by nighttime, it is necessary to construct splitter islands before the central island in order to ensure travels will follow the path of the roundabout. Any section of the roundabout left uncompleted during nighttime hours must be clearly marked, and temporary lighting may need to be deployed to ensure traveler safety.

2.2.2 Single Point Urban Interchange

No existing studies were found pertaining to SPUI initial construction phasing or maintenance project traffic control. Information related to initial construction and maintenance project MOT was obtained through the survey and interview of industry experts.

2.2.3 Diverging Diamond Interchange

The FHWA Diverging Diamond Informational Guide (Schroeder et al., 2014) provides a thorough guide to aid transportation professionals in examining DDIs. This informational guidebook contains many aspects of the design process which includes but is not limited to: policy and planning, safety, operational characteristics, construction and maintenance, etc. The scope of this research focuses only on the construction and maintenance aspects of the DDI.

Schroeder et al. (2014) asks a series of questions to consider in determining construction phasing. These questions include whether or not a complete closure is possible, and if existing pavement is to be used through the DDI. The answers to these questions aid in determining whether or not construction phasing is necessary and the manner in which it should be orchestrated. One issue which leads to the need for more specific construction phasing is that the DDI requires a greater footprint at the crossovers than a standard diamond interchange design. Figure 2.2.3.1 displays a generalized change in footprint from transitioning into a DDI from a conventional interchange (Hughes et al., 2014).

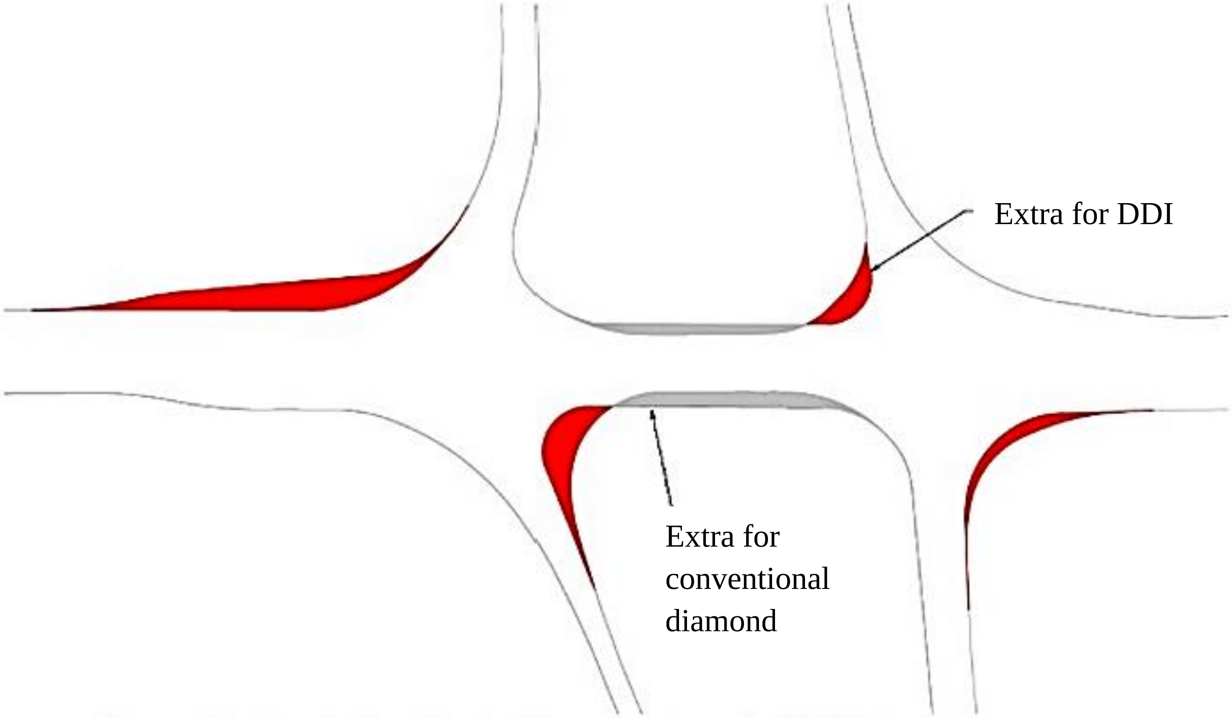
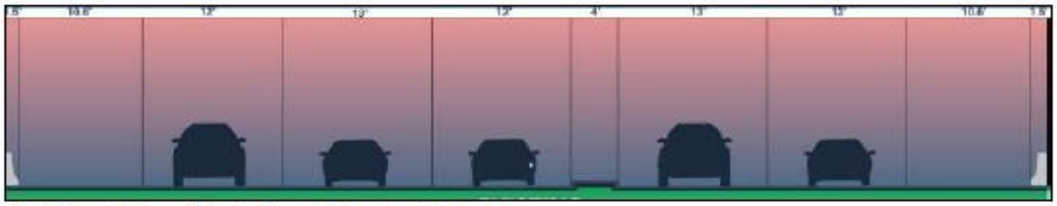


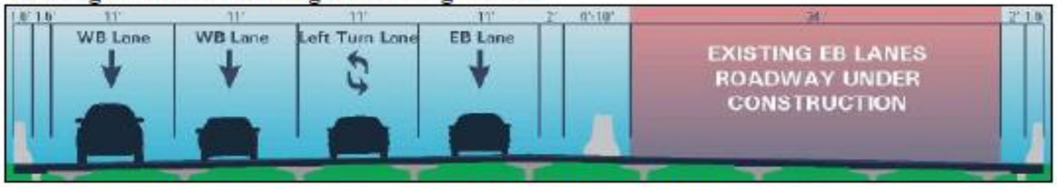
Figure 2.2.3.1 Footprint comparison between a DDI and conventional diamond interchange (Hughes et al., 2014)

This increased footprint leads to a need for construction on one or both sides of the roadway as well as through the turning movements in the process of a retrofitting. However, Hughes et al. (2014) does not contain information relating to construction phasing. Schroeder et al. (2014) provides an example of traffic phasing across a DDI bridge in which no additional cross-section right-of-way is required (Figure 2.2.3.2). In this example, Stage I involves shifting all traffic onto the north side of the roadway in which two westbound lanes, a left turn lane, and the eastbound lane share the allowable roadway. This allows for open construction on all of the eastbound lanes at once. In Stage II, eastbound traffic is shifted back to the southern side of the roadway while leaving an area in the center for pedestrian trail construction. Stage III involves shifting westbound lanes onto the newly constructed pavement on the southern portion of the cross-section which allows for the existing westbound lanes to be under construction. In Stage

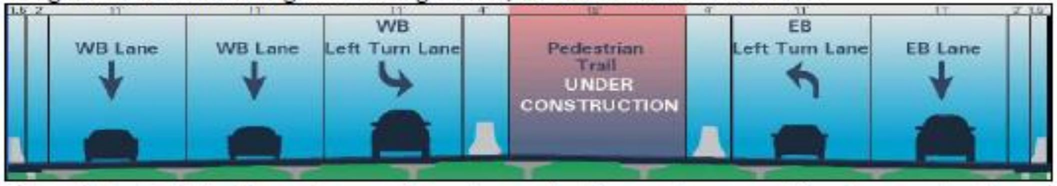
IV, traffic is shifted onto the final DDI configuration while leaving protection barriers at the pedestrian walkway. In Stage V, the DDI construction phasing is complete and the intersection is fully opened. Schroeder et al. (2014) does not contain information relating to the construction phasing of the DDI cross-overs.



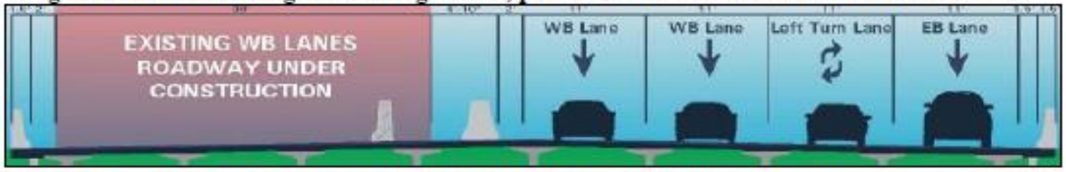
Existing diamond interchange lane configuration



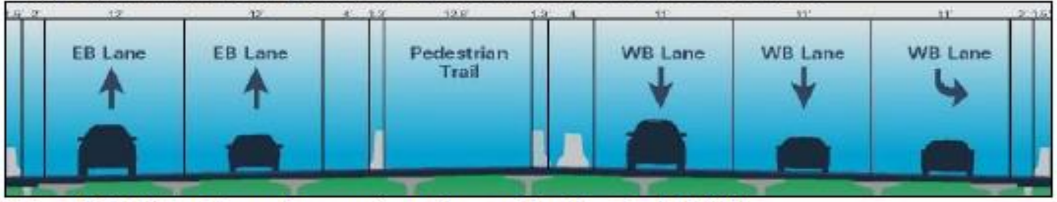
Stage 1. Partial interchange lane configuration, EB lanes under construction



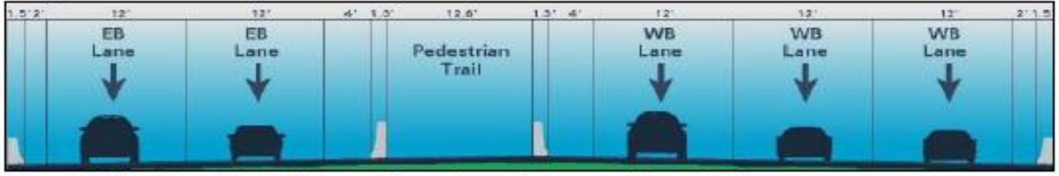
Stage 2. Partial interchange lane configuration, pedestrian center crosswalk under construction



Stage 3. Partial interchange lane configuration, WB lanes under construction



Stage 4. Full interchange lane configuration, median barrier in ROW



Stage 5. Final interchange lane configuration prior to opening of DDI

Figure 2.2.3.2 Staging of DDI construction from an existing interchange (Schroeder et al., 2014)

Schroeder et al. (2014) includes another method of DDI construction which involves utilizing separate bridges for each direction of travel for the final DDI configuration. This method allows for the possibility for traffic to remain uninterrupted through the existing lanes until the new bridge and portions of the crossovers are complete. Once traffic is shifted, the remaining portions of the final configuration can be constructed (Figure 2.2.3.3). Through this construction strategy, the existing roadway is unaffected until only the intersection connections are ready to be made which allows for more uninterrupted traffic movement.

Figure 2.2.3.3 Construction staging using pre-cast construction methods

(Schroeder et al., 2014)

Schroeder et al. (2014) as well as other sources include little information on the specifics of MOT through maintenance projects. Schroeder states that DDI maintenance considerations are similar to that of standard interchange forms such as a single temporary lane closure.

2.2.4 Restricted Crossing U-Turn Intersection

The Alternative Intersections/Interchanges: Informational Report (Hughes et al., 2010) states that construction phasing and MOT generally only becomes an issue in RCUT implementation whenever widening a two-lane road into a divided highway or retrofitting an existing intersection. Figure 2.2.4.1 shows an example construction phasing scheme for an instance in which RCUT construction involves widening a two-lane roadway. Phase I involves construction of lanes to carry one direction of traffic on the new roadway alignment. Phase II involves shifting the existing traffic onto the newly constructed lanes and beginning the construction of the opposite lanes as well as U-turns within the medians. In Phase III, the center of the main intersection is closed in order to allow the construction of through movements. Throughout Phase III, traffic utilizes median U-turn movements. Phase IV involves shifting traffic onto the permanent RCUT configuration.

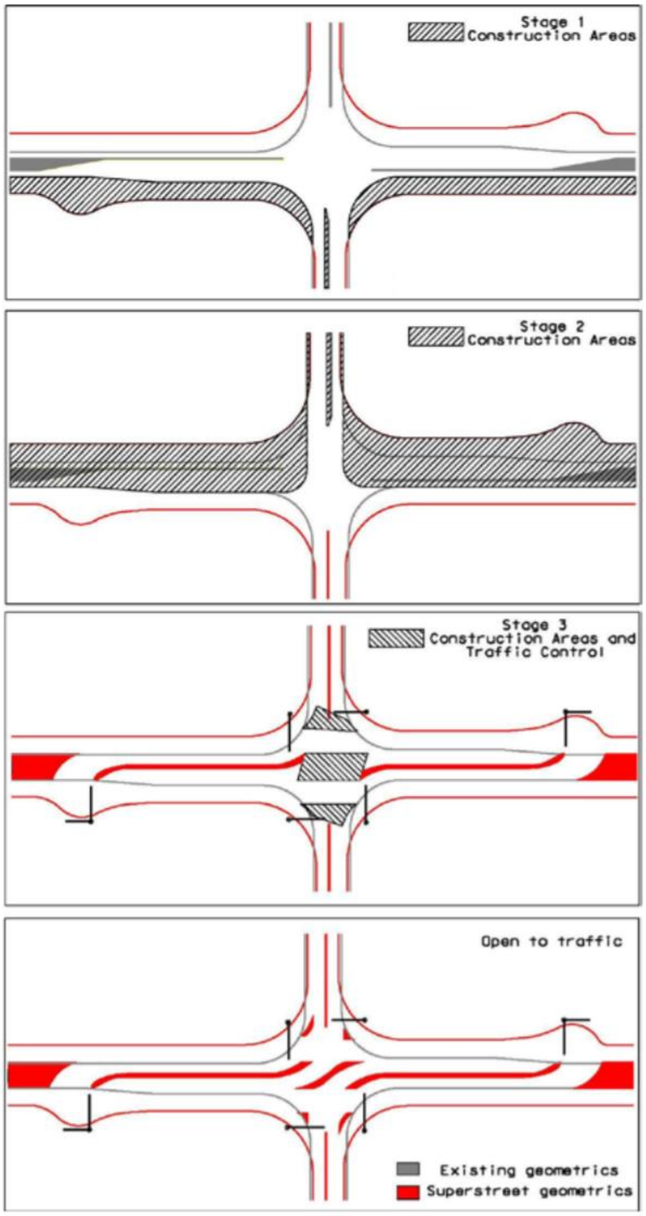


Figure 2.2.4.1 Construction phasing for converting a two-lane roadway intersection into a multi-lane RCUT intersection (Hughes et al., 2010)

Hughes et al. (2010) provides an example for of construction phasing through the retrofit of an existing multi-lane intersection to a RCUT intersection. In Phase I, U-turn crossovers and areas of left-turn crossovers that do not overlap minor roadway are constructed. Phase II involves completing construction of median U-turns and areas outside of the roadway intersection. In

Phase III, all minor street through traffic and main street left-turn traffic is shifted to the median U-turns and the main intersection center is closed. This allows for complete construction of main intersection center. Phase IV encompasses shifting all traffic to permanent RCUT configuration. Figure 2.2.4.2 shows this phasing scheme.

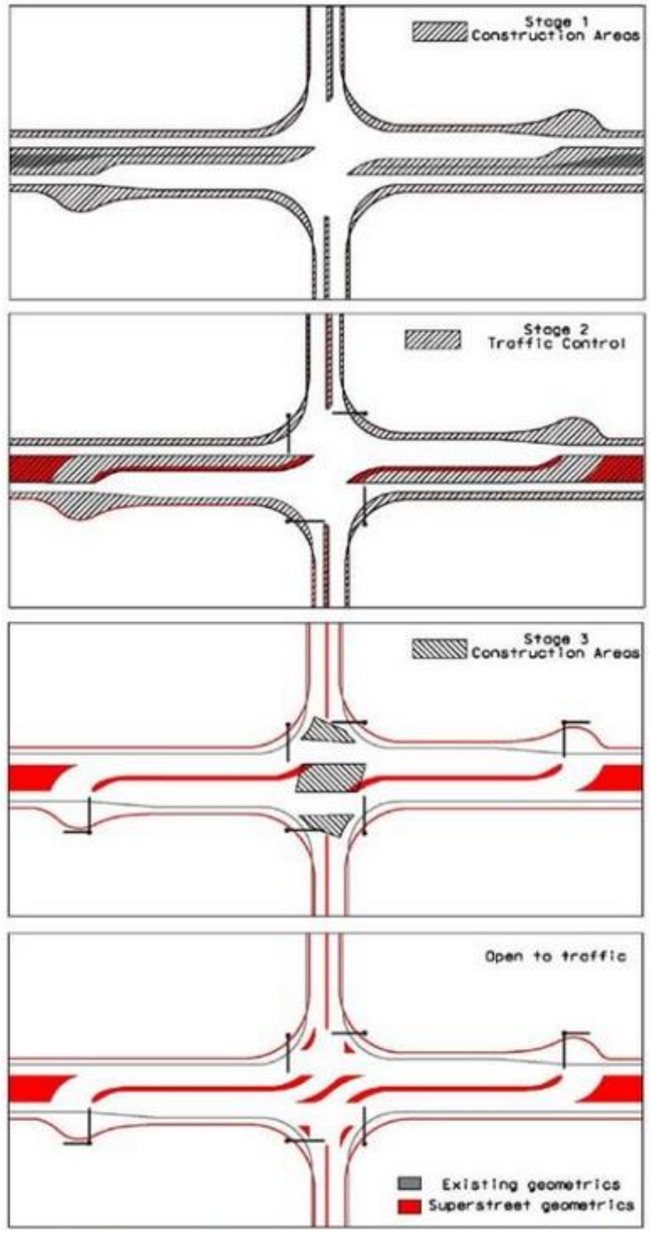


Figure 2.2.4.2 Construction phasing for retrofitting an existing intersection with a RCUT intersection (Hughes et al., 2010)

2.2.5 Median U-Turn Intersection

According to Hughes et al. (2010), MOT only becomes an issue in MUT implementation whenever widening a two-lane road into a divided highway or retrofitting an existing intersection. MUT intersections are similar to a traditional intersection except for the median U-turns. An example construction phasing setup involving a roadway widening to form a multiple-lane divided highway, as provided by Hughes et al. (2010), contains three phases. Phase I involves the construction of new lanes to become one direction of travel. In Phase II, traffic is shifted onto newly constructed roadway segments, allowing construction to begin on the opposite direction and on median U-turns. Phase III involves completing the construction of median U-turns and the roadway. Once complete, all traffic is shifted to the final MUT intersection configuration.

Hughes et al. (2010) provides an example construction phasing scheme for an instance which involves an existing single-lane or multi-lane intersection retrofit into a MUT intersection through three construction phases. Phase I of this example encompasses constructing median U-turns under normal traffic flow. In Phase II, all left-turn traffic is shifted onto median U-turns. Phase II involves completing the conversion from the traditional intersection configuration into the permanent MUT traffic layout. Once all construction is complete, traffic is shifted to the final MUT configuration in phase III.

2.2.6 Displaced Left Turn Intersection

The FHWA Displaced Left Turn Informational Guide by Steyn et al. (2014) provides guidelines for both construction phasing and MOT through DLT intersections. Considerations and objectives through implementing a DLT intersection are similar to conventional intersections. Similarly to other innovative geometric designs, DLTs can be implemented through retrofitting an existing intersection and often vary in construction and MOT strategies.

Steyn et al. (2014) describes three overall construction strategies for DLT intersections. These strategies include: complete closure, closure of one cross road at a time, and providing full access of all traffic movements throughout construction. Each construction strategy has implications for construction phasing and MOT. Consideration of each construction strategy is suggested to be determined on a case-by-case basis through public meetings and outreach in order to best serve the surrounding area as well as through the context of the surrounding environment. In cases in which it is determined that either partial or full access should be kept open throughout construction, construction staging must be organized. The use of new pavement for temporary movements through construction is discouraged in order to avoid from exposing travelers to new driving scenarios and setups multiple times through the extent of the project.

Steyn et al. (2014) includes a general three phase construction approach for the DLT intersection for retrofitting an existing conventional intersection. Figure 2.2.6.1 shows Phase I of this approach involving construction of outer portions of the DLT intersection. This construction involves constructing right-turn bypass lanes as well as installing a temporary traffic signal at the intersection for the purpose of Phase II operations. Traffic is maintained under existing signal operations at the main intersection throughout Phase I.

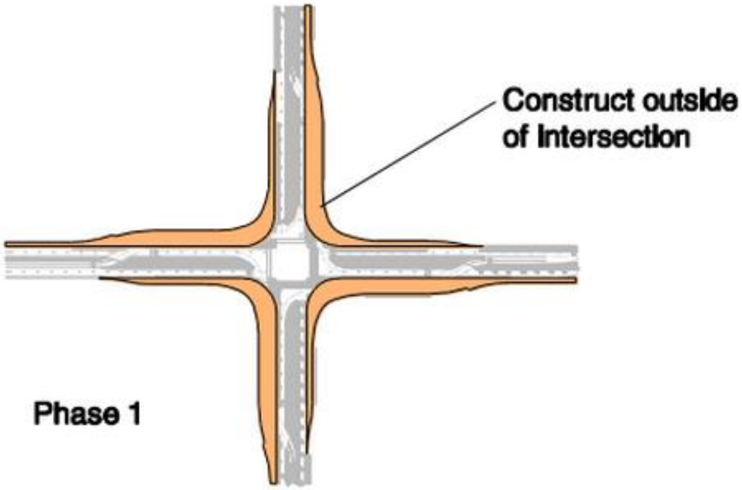


Figure 2.2.6.1 Phase I of DLT retrofit construction (Steyn et al., 2014)

Phase II, as stated in Steyn et al. (2014), involves construction of major pedestrian islands, new traffic signals at the main intersection, and major street left-turn lanes at the crossover intersections and traffic signals. Right turns should also be diverted onto the newly constructed right-turn bypass lanes while maintaining the other movements. Figure 2.2.6.2 shows affected areas in Phase II.

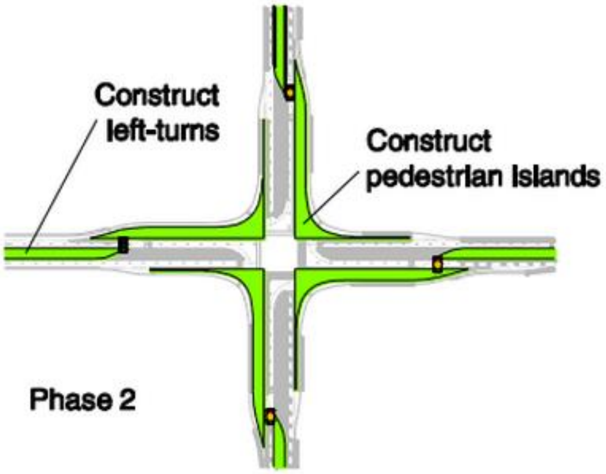


Figure 2.2.6.2 Phase II of DLT retrofit construction (Steyn et al. 2014)

Steyn et al. (2014) sets Phase III to involve construction of medians along the minor streets and finalization of the street lighting installation, permanent signing, and pavement markings. Traffic is then to be directed to its final travel pattern. Figure 2.2.6.3 shows the affected areas in Phase III.

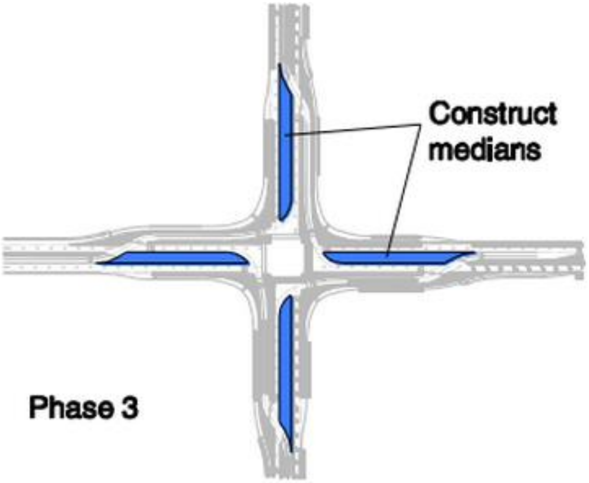


Figure 2.2.6.3 Phase III of DLT retrofit construction (Steyn et al., 2014)

Pertaining to MOT, Steyn et al. (2014) suggests the use of more detailed work zone traffic control. The DLT Informational Guide suggests the use of guide signs prior to implementing the final DLT traffic layout to aid travelers through the new movements. Portable changeable message signs are suggested to aid in notifying travelers of the new intersection configuration.

According to Steyn et al. (2014), maintenance projects are similar to that of conventional intersections with the exception of additional raised median barriers. Maintenance pertaining to the raised median barriers typically requires the temporary closure of one adjacent lane.

Chapter 3 Methodology

This chapter describes the methods used for both addressing inattentive driving through mobile work zones and construction phasing practices with MOT through innovative geometric designs.

3.1 Mobile Work Zone

The methodology for evaluating the effectiveness of mobile work zone alarm systems is described in this section. This includes measuring alarm sound levels for each device, observing driver behavior, estimating merge distances, and computing false alarm and false negative occurrences for the actuated and manual trigger mechanisms. The data used for these tests include sound levels while stationary and while traveling on an area interstate, video data from the TMA during deployment, and video data from inside a test vehicle which traveled through each of the mobile work zone setups.

3.1.1 Data Collection

Data was collected in the Kansas City area on I-435 from mile marker 40 to mile marker 51 on November 19th and 20th 2013. Figure 3.1.1.1 shows the section of I-435 utilized for the mobile work zone tests. The roadway segment consists of 5.5 miles of 6-lane interstate and 7 miles of 4-lane interstate resulting in a total test area of 12.5 miles. The roadway consists of asphalt pavement and has an AADT of 21,534 vpd (2012) with 14% trucks.

Figure 3.1.1.1 Aerial imagery of the I-435 test area in northern Kansas City, Missouri (Google, 2014)

Five mobile work zone alarm setups were tested, including Alarm Manual setup, Alarm Actuated setup, DAS Continuous setup, DAS actuated setup, and a control setup in which no alarm was utilized. Each alarm setup was tested along the segment of I-435. These tests allow for the safety and effectiveness of each setup to be analyzed and compared.

3.1.2 Parking Lot Testing

Parking lot tests were devised to test the sound characteristics of each warning system. The test parking lot surface consisted of asphalt pavement. These tests represent the sound characteristics of each alarm without background noise.

3.1.3 Sound Testing

Sound level testing on each alarm device determined the level of exposure for both the approaching travelers and TMA crews. As mentioned in the literature review, OSHA and NIOSH provide national sound level standards with respect to duration of exposure and sound level. NIOSH standards are more stringent than OSHA standards, however, only OSHA standards are enforceable by law. Figure 3.1.3.1 shows both OSHA and NIOSH standards with respect to duration of exposure.

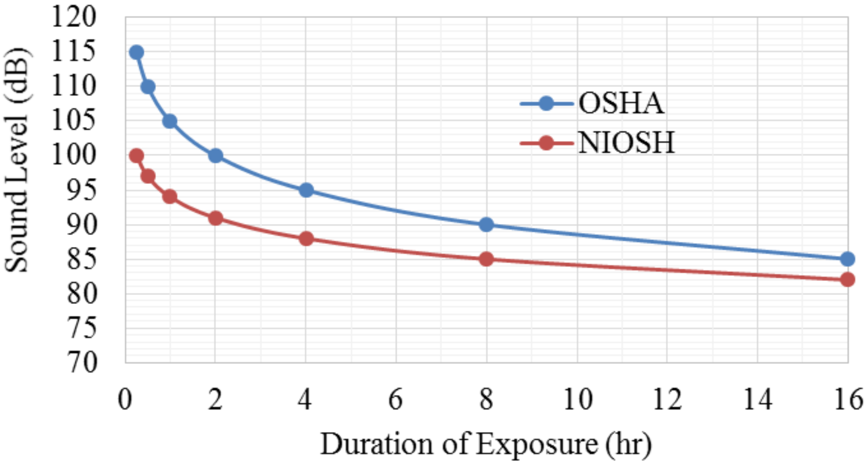


Figure 3.1.3.1 OSHA and NIOSH sound level standards with respect to duration of exposure

Each alarm system required testing to determine sound level safety in terms of OSHA and NIOSH compliance. These tests involved measuring sound levels at various distances from within a parked vehicle with the windows up and engine off, while walking outside of the vehicle, and while within the TMA truck utilizing the alarm system. The sound levels at varying distances were measured in a controlled parking lot consisting of asphalt pavement. Decibel levels from within the parked vehicle were recorded from 10ft, 50ft, and increments of 50ft until 600ft had been reached for the Alarm Device and DAS. Decibel levels taken while walking were recorded at the same distance increments as the in vehicle readings until 600ft had been reached for both alarm warning systems. To ensure accuracy, ten consecutive readings were recorded to mitigate any fluctuations in sound level readings. The average of the ten sound readings was then calculated for each location. The recorded sound levels were then compared to OSHA and

NIOSH standards to determine sound level standard compliance. Figure 3.1.3.2 shows the sound meter used for the sound level readings.

Figure 3.1.3.2 Sound level test while walking for DAS

Duration is an important factor when considering acceptable sound level exposure to the TMA truck operator utilizing the alarm system because there is a much longer exposure time than the passing travelers. This causes the allowable limit to be much more stringent. Sound level readings were collected from within the cab of the TMA vehicle for both the Alarm Device and DAS.

In order to determine effects of the roadway noise, sound levels were recorded from within a test vehicle to determine OSHA and NIOSH compliance. For this test, a video camera was used to record both the field of view and sound levels from within the test vehicle while passing through each alarm system mobile work zone. Figure 3.1.3.3 shows an example of recording the sound levels from with the test vehicle.

Figure 3.1.3.3 Field of view from within test vehicle

3.1.4 Evaluation of Driver Behavior

Driver behavior was a main indicator used to determine overall safety implications of each alarm setup. Factors used for investigating driver behavior include merging distances, average vehicle speeds, and undesirable driving behaviors. Undesirable driving behaviors must first be defined. The American Association of State Highway and Transportation Officials Green Book (AASHTO, 2011) was referenced for safe stopping sight distance (SSD). SSD is the distance at which a vehicle may safely come to a halt from a given velocity and reaction time. The SSD is given by;

$$SSD = 1.47Vt + 1.075\frac{V^2}{a} \qquad \text{Equation 3.1.4.1}$$

where:

SSD = stopping sight distance, ft

V = vehicle speed, mph

t = brake reaction time (s)

a = deceleration rate (ft/s^2).

AASHTO recommends 2.5 seconds to be used as a standard value for brake reaction time and 11.2ft/s^2 for deceleration rate. Figure 3.1.4.1 shows SSD with respect to vehicle speed based on the recommended standard values. These recommended values were used through the extent of this research.

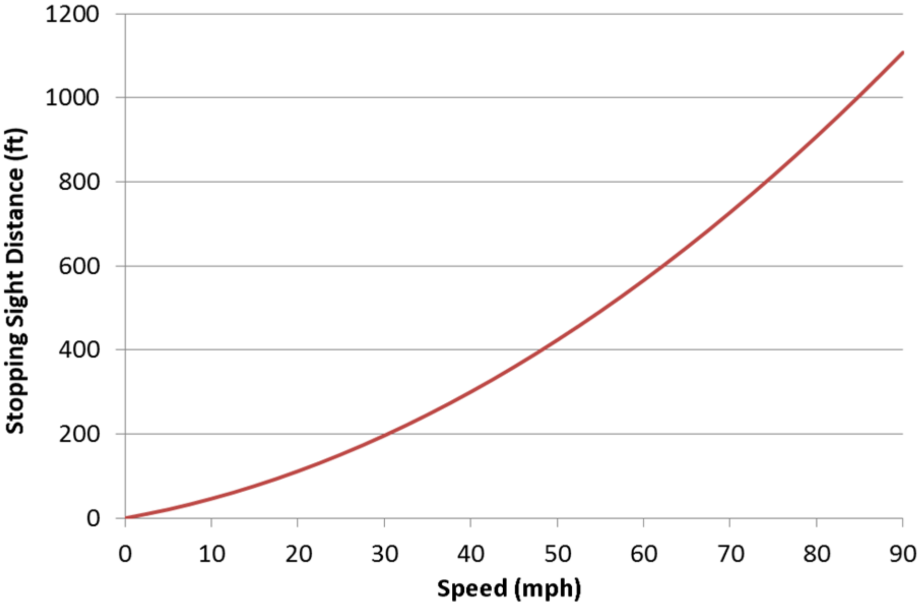


Figure 3.1.4.1 Stopping sight distance with respect to vehicle speed (AASHTO, 2011)

The speed differential between the mobile work zone and the speed limit of the I-435 test area was 60mph. From Figure 3.1.5, at 60mph the proper SSD equates to 600ft. Therefore, any merge observed to be within 600ft behind the TMA was considered to be undesirable.

A camera was attached to the rear of each TMA truck facing the approaching traffic to observe the vehicle merges through each mobile work zone setup. Figure 3.1.4.2 shows an example of the collected video data facing traffic approaching the TMA truck. From the collected video data, vehicle merging distances could be collected using photogrammetry. Photogrammetry is the use of images to measure distances. Photogrammetry was the method of choice over other distance measuring methods for many reasons. First, video data processing allowed the collection of additional data such as a false alarm and false negative analysis while an active infrared method would only gather distance. Manually analyzing the data also allowed for additional notes to be taken pertaining to roadway alignment such as horizontal and vertical curves which aided in understanding results. Photogrammetry is accurate up to approximately 600ft while infrared is capable of reaching up to 2400ft depending on target reflectivity. Taking measurements without looking at roadway alignment could result in misleading data due to issues with horizontal and vertical curves, especially at great distances. Another reason for the use of photogrammetry is due to the ease of post-processing of video data. Post-processing allows for more time to be devoted to ensure accuracy and also allows for further investigation of undesirable diver behaviors.

Figure 3.1.4.2 Example of video data to be processed from Alarm Manual setup

The centerline stripe of the roadway was used as a reference for the photogrammetry process. MoDOT uses a standard 40ft distance from the beginning of one white stripe (skip) to the beginning of the next. As stated previously, merges within 600ft are considered undesirable. Therefore any merge within 15 skips were considered undesirable and were further analyzed. However, in looking at Figure 3.1.6, it is difficult to determine the exact location of skips at a distance greater than 5 skips behind the TMA truck using visual inspection. Therefore a calibration process was used to determine the relationship between actual distance and distance on the image. Separate calibrations were performed for each TMA due to variations in camera mountings. The calibration process was used to form an image to be overlaid onto each video showing distinct lines at skip locations until 15 skips. This process was started by measuring the distance between easily differentiable skips and determining a regression function of distance measured compared to actual distance. This regression was then expanded until 15 skips had been reached. Figure 3.1.4.3 shows the regression function for the TMA with the Alarm Device.

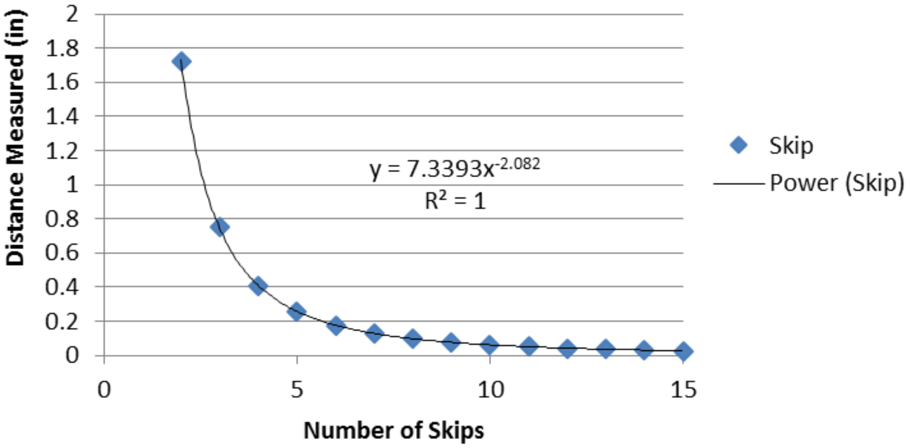


Figure 3.1.4.3 TMA with Alarm Device regression function for measured distance compared to actual distance

For use with the fitted regression curve, a drawing depicting skip locations was constructed to be overlaid onto the video files. The drawing constructed for the TMA with Alarm Device can be seen in Figure 3.1.4.4.

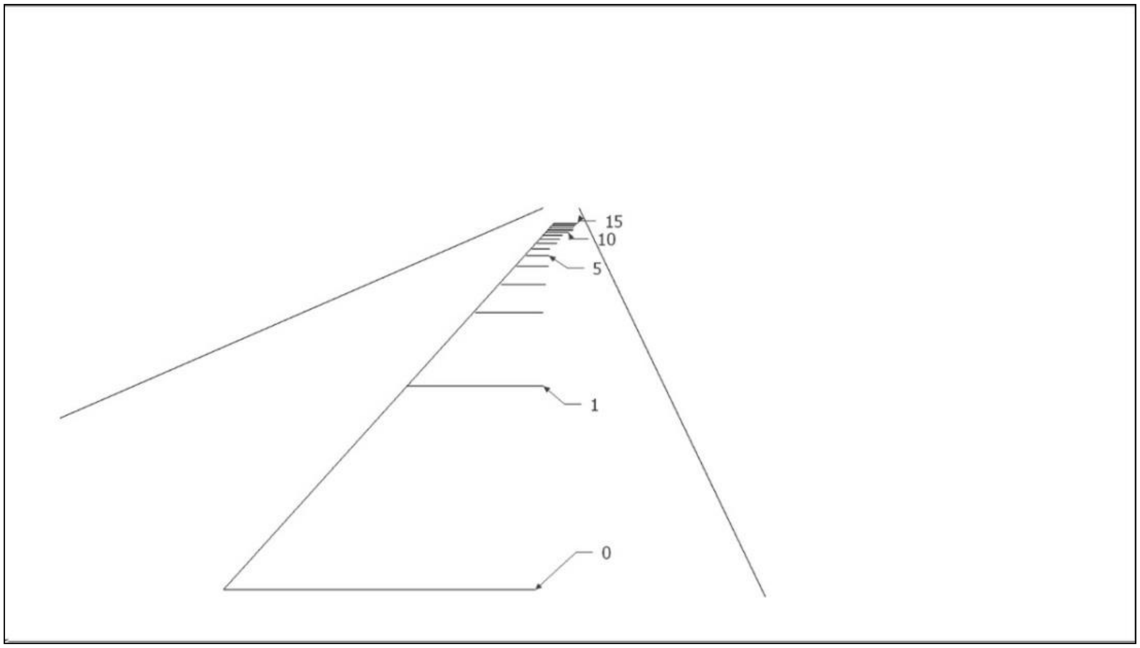


Figure 3.1.4.4 Example drawing to be overlaid onto video files for TMA with Alarm Device

Once the drawing had been overlaid, the centerline skips could be easily identified. This would aid in determining vehicle merging distances. Figure 3.1.4.5 shows an example of the resulting image once the drawing was overlaid onto the video data for the TMA with Alarm Device.

Figure 3.1.4.5 Example of TMA with Alarm Device resulting image to be used in the vehicle merge analysis

Merging speeds were also calculated by measuring the distance and time traveled by the merging vehicles. The time calculation was performed by using the frame rate of the video player which was 30 frames/sec. Therefore, the number of frames required for a vehicle to travel a set distance was utilized to determine vehicle speeds.

ANOVA tests were performed in order to determine statistical significance for the merge distances within 600ft and merging vehicle speeds within 600ft for each warning setup. ANOVA is an analysis of variance between entries and outputs a p-value that is used to determine statistical significance. The statistical confidence is determined by subtracting the p-value from 1.00. This value was used to evaluate the statistical significance of driving behavior results.

3.1.5 Alarm Activations

Along with analyzing driver behavior, an important component of the analysis between alarm setups is the manual and actuated alarm activation accuracy through rates of false alarms and false negatives. For both the manual and actuation trigger mechanisms, the alarm was intended to sound in the event of a vehicle being within the threshold distance behind the TMA truck. A false alarm is the event at which the alarm sounded when no vehicle was within the threshold distance. A false negative is the instance at which the alarm did not sound while a vehicle was within the threshold distance.

For the actuated system, the threshold distance was the SSD as discussed previously. The SSD for each vehicle that merged within 600ft was determined through the vehicle speed. For the manual mode, the threshold distance was based on the instructions that were given to the driver for activating the alarm. Drivers were instructed to first turn on the lights at 26 skips (1,056ft) and then sound the alarm once a vehicle was at a distance of 13 skips (528ft). To account for uncertainties of estimating skips, a threshold distance of 11 skips (440ft) to 15 skips (600ft) was used to evaluate false alarms and false negatives through the manual trigger approach.

3.2. Innovative Geometric Design

This section explains methods used to create construction phasing and MOT Phasing Diagrams for each of the innovative geometric designs. Information obtained through an online survey of industry experts, in-person and telephone interviews of industry experts, and review of sample plans are discussed in this section. Each aspect serves as a source of information along with the literature review to determine best practices as well as factors to consider when developing MOT plans for innovative geometric designs.

3.2.1 Survey

An online survey of industry experts was conducted in order to assess current practices pertaining to temporary traffic control at innovative geometric design intersection work zones. The temporary traffic control practices for innovative geometric designs survey was created using an online survey creation website and distributed to industry experts throughout the United States including representatives from state departments of transportation, cities, counties, private consultants, etc. Contact information of industry experts originated from agencies such as MoDOT and FHWA. The survey was also sent to the listserv of the Transportation Research Board (TRB) Roundabout Committee to allow committee members and colleagues to participate. This survey consisted of 16 questions including multiple-choice and describe answers. The multiple-choice questions involved asking the number of intersections for which the respondent's agency is responsible for through a scale of 0, 1 to 5, 6 to 10, and greater than 10. Respondents were asked about which methods have been utilized and were given choices of complete closure, phased construction with partial closure, construct temporary runaround, temporary traffic signal, and other. Respondents were also asked how frequently specific methods are utilized through a scale of rarely, sometimes, almost always, and always. Questions asking for a description provided further insight to industry expert experiences with each method and intersection type. This online survey was open for 5 weeks from January 5th to February 19th 2015.

The survey concluded by asking if the respondent would be willing to participate in a follow up interview and send project MOT plans for use as examples in constructing MOT Phasing Diagrams. The entire survey as it appeared on the website is included on the following pages.

SWZDI
Smart Work Zone Deployment Initiative

Temporary Traffic Control Practices for Innovative Geometric Designs

This is a short 16-question survey that will take approximately 5 minutes.

Development of maintenance of traffic plans for innovative geometric designs can be challenging, especially when retrofitting existing intersections. This Federal Highway Administration (FHWA) Smart Work Zone Deployment Initiative (SWZDI) project will develop guidelines for the preparation of maintenance of traffic plans for projects with innovative geometric designs in both rural and urban implementations.

Your input based on your experience in implementing these designs will help to develop MOT Phasing Diagrams. If it would be more appropriate for someone else at your organization to take this survey, please send their name and email address to Henry Brown (brownhen@missouri.edu).

Examples of some of the innovative geometric designs are shown below.


Single Point Urban Interchange (SPUI)


Diverging Diamond Interchange (DDI)


Displaced Left Turn (DLT)


Restricted Crossing U-Turn (RCUT - Urban)


Median U-Turn (MUT)


Roundabout


Restricted Crossing U-Turn (RCUT - Rural)

1. What type of agency do you represent?

○ What type of agency do you represent? State DOT

○ City

○ County

○ Consultant

○ Other

2. Approximately how many of the following designs does your agency operate in total?

	0	1-5	6-10	>10
Roundabout	○	○	○	○
SPUI	○	○	○	○
DDI	○	○	○	○
RCUT	○	○	○	○
MUT	○	○	○	○
DLT	○	○	○	○

3. For how many designs listed in question 2 has your agency performed maintenance projects (such as resurfacing, re-striping, etc.)?

	0	1-5	6-10	>10
Roundabout	○	○	○	○
SPUI	○	○	○	○
DDI	○	○	○	○
RCUT	○	○	○	○
MUT	○	○	○	○
DLT	○	○	○	○

Questions 4-7 aim to differentiate methods used during initial construction versus maintenance projects for each intersection type.

4. What is the predominant method used by your agency during initial construction for each intersection type?

	Complete Closure	Phased Construction with Partial Closures	Construct Temporary Runaround	Temporary Traffic Signal	Other	N/A
Roundabout	☐	☐	☐	☐	☐	☐
SPUI	☐	☐	☐	☐	☐	☐
DDI	☐	☐	☐	☐	☐	☐
RCUT	☐	☐	☐	☐	☐	☐
MUT	☐	☐	☐	☐	☐	☐
DLT	☐	☐	☐	☐	☐	☐

If "Other" Please Describe

5. How frequently does your agency use each method listed in question 4 for initial construction?

	Always	Almost Always	Sometimes	Rarely	N/A
Roundabout	☐	☐	☐	☐	☐
SPUI	☐	☐	☐	☐	☐
DDI	☐	☐	☐	☐	☐
RCUT	☐	☐	☐	☐	☐
MUT	☐	☐	☐	☐	☐
DLT	☐	☐	☐	☐	☐

6. What is the predominant <u>method</u> used by your agency during <u>maintenance projects</u> for each intersection type?

	Complete Closure	Phased Construction with Partial Closures	Construct Temporary Runaround	Temporary Traffic Signal	Other	N/A
Roundabout	☐	☐	☐	☐	☐	☐
SPUI	☐	☐	☐	☐	☐	☐
DDI	☐	☐	☐	☐	☐	☐
RCUT	☐	☐	☐	☐	☐	☐
MUT	☐	☐	☐	☐	☐	☐
DLT	☐	☐	☐	☐	☐	☐

If "Other" Please Describe

7. How frequently does your agency use each method mentioned in question 6 for <u>maintenance projects</u>?

	Always	Almost Always	Sometimes	Rarely	N/A
Roundabout	☐	☐	☐	☐	☐
SPUI	☐	☐	☐	☐	☐
DDI	☐	☐	☐	☐	☐
RCUT	☐	☐	☐	☐	☐
MUT	☐	☐	☐	☐	☐
DLT	☐	☐	☐	☐	☐

8. What resources did you use to decide on the maintenance of traffic plans for your facilities? Check all that apply.

- ☐ MUTCD
- ☐ State Design Manual
- ☐ Experience/Knowledge
- ☐ Other (please specify)

9. What factors did you take into consideration when determining the maintenance of traffic plans for your facilities? Check all that apply.

- ☐ Traffic Counts
- ☐ Operating Speed
- ☐ % Trucks
- ☐ Availability of Alternate Routes
- ☐ Other (please specify)
- ☐ Land Use Access
- ☐ Duration of Construction
- ☐ Rural/Urban
- ☐ Ped./Bike/ADA

10. Did you find that certain techniques for maintenance of traffic work particularly well over others?

- ● Yes
- ○ No

Please describe

11. Did you find that certain techniques for maintenance of traffic were less effective than others?

☐ Complete Closure
☐ Phased Construction with Partial Closures
☐ Construct Temporary Runaround
☐ Temporary Traffic Signal
☐ Other

Please describe

12. Do you have any additional recommendations for developing maintenance of traffic plans for projects with innovative geometric designs? If so, please describe them here.

13. Would you be willing to provide additional information about your experiences through a follow-up phone call?
If yes, please leave your name and telephone number below.

Name
Telephone

14. Would you be willing to send project typical application sheets for use as examples for maintenance of traffic?

○ Yes
○ No

If yes, please provide your email address for follow-up

15. Would you like to receive a copy via email of the final project report that will include maintenance of traffic typical application sheets for different alternative geometric designs when it is completed?

○ Yes
○ No

If yes, please provide your email address if you did not already provide it in Question # 14.

16. Do you have any additional comments on maintenance of traffic plans for alternative geometric designs?

Do you have any additional comments on maintenance of traffic plans for alternative geometric designs?

Thank you for participating in this survey. Your input will greatly aid us in determining best temporary traffic control practices pertaining to innovative geometric designs.

Done

3.2.2 Interviews of Industry Experts

Survey respondents were asked for the opportunity to further share experiences through developing MOT via phone interviews. Survey respondents that wanted to take part in the interview process as well additional contacts collected from FHWA and other sources were asked to provide insight on MOT for innovative geometric designs. The content of these phone interviews included discussing lessons learned, factors considered, and recommendations for designing MOT Phasing Diagrams. Responses and recommendations from the interviews of industry experts facilitated the process of designing of MOT Phasing Diagrams for each facility type.

3.2.3 Project Plan Examples

Survey respondents were asked to provide project plans relating to MOT of innovative geometric designs to serve as examples of construction phasing and MOT. The obtained plans were examined for current MOT practices for each facility type. Respondents that provided plans and participated in the interview process were asked additional questions relating to the project plans. These questions involved the performance of specific methods of MOT through each facility type and what factors led to the chosen MOT and construction phasing method.

3.2.4 MOT Phasing Diagrams

MOT Phasing Diagrams were produced for each facility type, utilizing information compiled from the literature review, survey of industry experts, interviews of industry experts, and review of sample plans provided. Interviews of industry experts comprised of more detailed discussions relating to MOT through innovative geometric designs. These interviews provided information on lessons learned, special considerations, and challenges faced through MOT. Interviews of industry experts also provide more knowledge to what factors should be considered and their effects on MOT. Recommendations and aspects applied to the MOT Phasing Diagrams are further discussed in the results section of this thesis. Collection of project plans to serve as examples for MOT through innovative geometric designs were vital in determining current MOT practices through these designs. Project plans received and methods used relating to MOT and construction phasing are further described in the results section of this thesis. Various factors and considerations to be considered through the MOT Phasing Diagrams are further explored through the results section. The MOT Phasing Diagrams show each stage of construction through roundabout, SPUI, DDI, RCUT, MUT, and DLT facility types.

Chapter 4 Results

This chapter presents results obtained through the analysis of mobile work zone alarm systems as well as the construction of MOT Phasing Diagrams with construction phasing for innovative geometric designs.

4.1. Mobile Work Zone Alarm

4.1.1 Sound Level Testing Results

Sound levels were measured at varying distances for each alarm system from 10ft to 600ft in order to determine if compliance with OSHA and NIOSH standards was met. A total of 10 consecutive sound readings were taken from each distance increment. The average, minimum, maximum, and standard deviation at each location for the DAS while inside a vehicle with the windows up and engine off can be seen in Table 4.1.1.1.

Table 4.1.1.1 DAS in Vehicle Sound Level Analysis

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
10	91.9	79.5	115.7	11.3
50	85.7	67.1	110.2	11.6
100	79.4	69.2	100.6	10.1
150	77.1	69.1	88.0	7.0
200	73.9	64.6	88.5	7.9
250	72.4	64.7	83.2	6.2
300	69.7	64.0	78.8	4.8
350	67.3	58.6	79.7	5.4
400	66.1	59.0	70.5	3.4
450	65.8	58.3	72.1	4.0
500	64.8	59.5	76.3	4.8
550	63.1	57.6	71.9	4.1
600	60.6	53.5	65.4	3.6

The same process was completed for the DAS walking sound readings, and the results are shown in Table 4.1.1.2. An additional distance of 3ft was also included as a worst case scenario. This scenario, however, would be highly improbable to occur in a moving work zone.

Table 4.1.1.2 DAS Walking Sound Level Analysis

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
3	116.4	81.5	129.2	14.9
10	99.9	79.5	118.3	10.7
50	97.4	72.5	119.6	16.2
100	96.8	73.5	113.9	12.5
150	93.2	74.7	113.9	11.8
200	89.1	68.4	108.5	13.1
250	87.0	69.3	114.6	12.7
300	85.5	72.1	103.0	9.6
350	83.3	73.1	101.8	8.6
400	82.1	73.4	101.0	7.5
450	81.2	70.7	95.0	6.8
500	79.9	68.4	98.0	7.2
550	78.6	68.5	91.6	6.7
600	77.1	68.4	89.1	5.5

Sound levels for the Alarm Device while in the parked vehicle with the windows up and engine off were also recorded at varying distances from 10ft to 600ft. Average, minimum, maximum, and standard deviation sound levels are shown in Table 4.1.1.3.

Table 4.1.1.3 Alarm Device in Vehicle Sound Level Analysis

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
10	83.6	82.0	85.1	1.0
50	77.1	75.6	78.8	1.1
100	71.9	69.6	74.8	1.5
150	70.7	66.8	73.0	1.9
200	68.3	65.7	70.8	1.7
250	66.1	62.6	68.0	1.6
300	66.1	64.1	68.0	1.5
350	64.1	60.4	69.8	2.9
400	63.3	61.0	65.7	1.5
450	62.6	59.8	66.8	2.1
500	61.3	57.2	63.9	2.2
550	60.8	57.2	67.6	2.8
600	58.8	56.8	61.5	1.6

Lastly, sound levels for the Alarm Device while walking were tested as shown in Table 4.1.1.4. Similarly to the DAS while walking, an additional measurement of 3ft was recorded to simulate the worst case scenario.

Table 4.1.1.4 Alarm Device Walking Sound Level Analysis

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
3	120.9	118.8	123.6	1.4
10	106.3	103.8	108.8	1.5
50	102.0	100.3	103.2	1.0
100	96.5	95.2	98.0	0.8
150	92.8	90.7	95.3	1.4
200	92.7	90.7	95.3	1.4
250	88.2	86.2	91.1	1.4
300	85.0	82.9	86.8	1.1
350	84.4	79.7	89.0	2.7
400	84.2	81.6	86.4	1.4
450	82.1	79.2	85.3	2.0
500	80.2	75.9	84.8	2.6
550	79.2	76.3	82.0	1.6
600	76.6	72.4	79.7	2.4

Figure 4.1.1.1 shows sound level measured at each distance increment for each alarm setup as well as OSHA and NIOSH standards for a 0.25 hours exposure period. In comparing each of the sound levels, differences can be seen between each alarm setup. Any portion found to be greater than OSHA or NIOSH standards is determined to be out of sound level compliance.

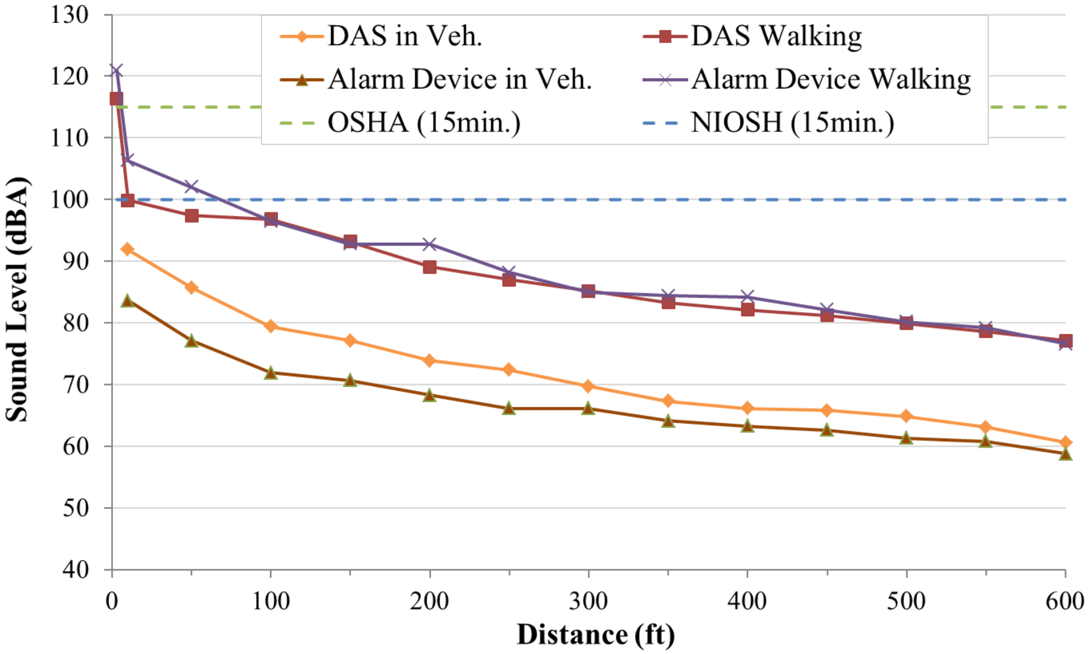


Figure 4.1.1.1 Sound level results from parking lot tests

From Figure 4.1.1.1, it can be determined that sound levels for both the DAS and Alarm Device systems fall below OSHA and NIOSH standards with exception to the Alarm Device at 50ft while walking and both systems at 3ft while walking. However, the resulting points above OSHA and NIOSH guidelines were determined not to be significant because these results were based on a 15 minute exposure period. It can be assumed that one would not remain behind the TMA truck within 50ft for a 15 minute period during alarm activation. In a typical mobile work zone application, the exposure time would typically be less than one second at near normal or normal highway speeds. In comparing the sound levels recorded from within a vehicle, the DAS maintains a higher decibel level reading than the Alarm Device. This result indicates that the sounds produced by the DAS penetrate through objects better than that of the Alarm Device. When comparing sound levels of the DAS while walking and Alarm Device while walking, both have similar decibel readings over varying distances with a similar regression in sound level.

Figure 4.1.1.2 shows the sound results while walking at 10ft behind each alarm system compared to OSHA and NIOSH standards. The DAS measured at 99.9dBA while the Alarm Device measured at 106.3dBA. The DAS exceeds OSHA standards at approximately 2 hours of exposure per day while the Alarm Device exceeds OSHA standards at approximately 0.75 hours of exposure per day.

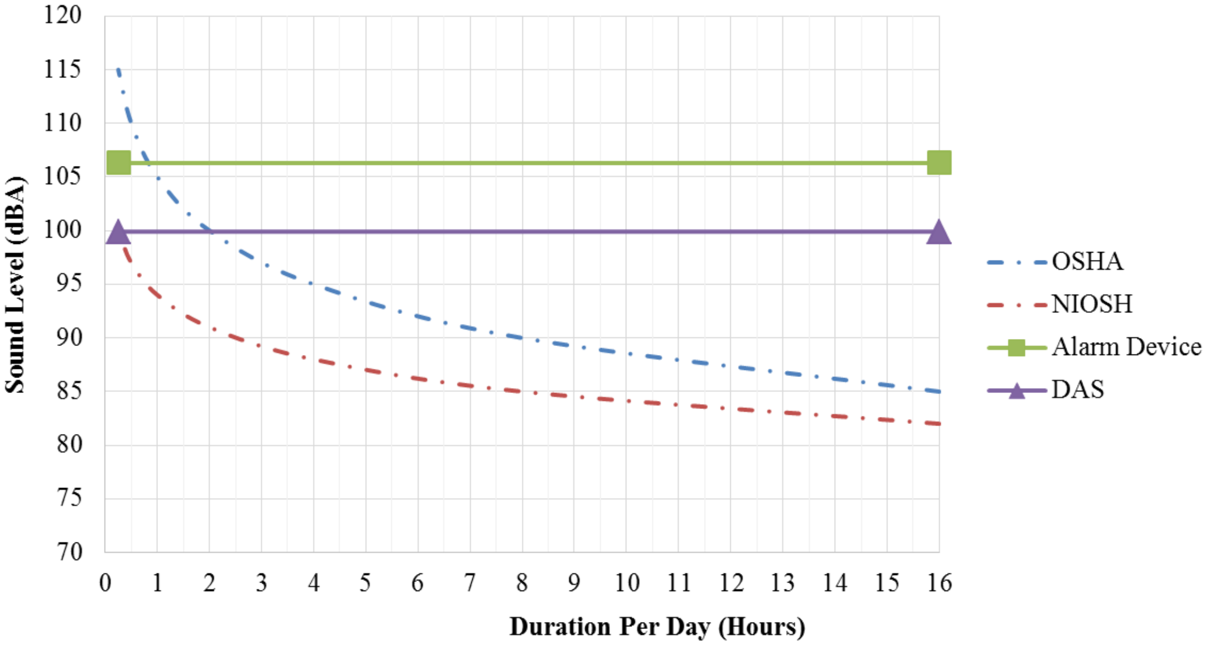


Figure 4.1.1.2 Sound level results for DAS and Alarm Device at 10ft while walking

Figure 4.1.1.3 shows the sound results while walking 3ft behind each alarm system compared to OSHA and NIOSH standards. The DAS measured at 116.4dBA while the Alarm Device measured at 120.9dBA. At this level, both the DAS and Alarm Device exceed OSHA and NIOSH standards at all durations of exposure. Therefore it was determined that additional care should be taken while operating each system in an area which may have pedestrian traffic.

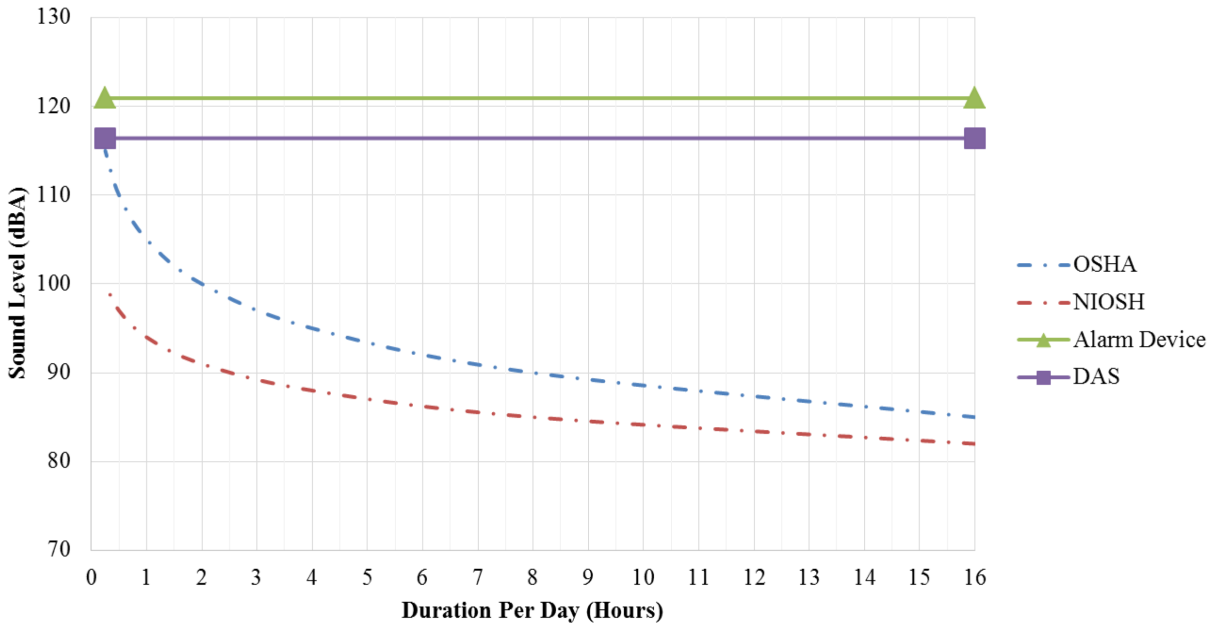


Figure 4.1.1.3 Sound level results for DAS and Alarm Device at 3ft while walking

In-cab exposures are especially important due to the long-term duration of exposure to the TMA operator. Sound level measurements were used to determine whether or not the worker would be exposed to sound levels outside of NIOSH and OSHA compliance for each alarm system. For this test, measurements were taken from within the TMA vehicle cab with the windows up and with the windows down separately. With the windows up, the DAS measured at an 80.5dBA sound level while the Alarm Device was found to measure at 76.7dBA. In comparing the in-cab with the windows up tests to OSHA and NIOSH standards, both were determined to be within OSHA and NIOSH compliance through a 16 hour daily exposure time. With the TMA truck windows down, the DAS measured at a sound level of 80.2dBA while the Alarm Device measured at a sound level of 90.3dBA. In comparing the windows down results with OSHA and NIOSH standards, the DAS with windows down meets both OSHA and NIOSH standards through a 16 hours exposure period. The Alarm Device with windows down exceeds OSHA standards at approximately 8 hours of exposure per day and NIOSH standards at approximately 2.25 hours of exposure time per day. This result indicates that during the use of the Alarm Device, windows of the cab should not be down for more than 8 hours per day of a continuous alarm operation. Figure 4.1.1.4 shows results for each of the in-cab sound reading tests with OSHA and NIOSH standards up to a 16 hour exposure time per day. In looking at sound level change from having the cab windows down and up between the DAS and Alarm Device, it can be seen that the DAS sound level increased by 0.3dBA while the Alarm Device sound level increased by 13.6dBA. This result indicates the sound emitted from the DAS is able to travel through objects such as windshields and windows without having a major effect on decibel level received.

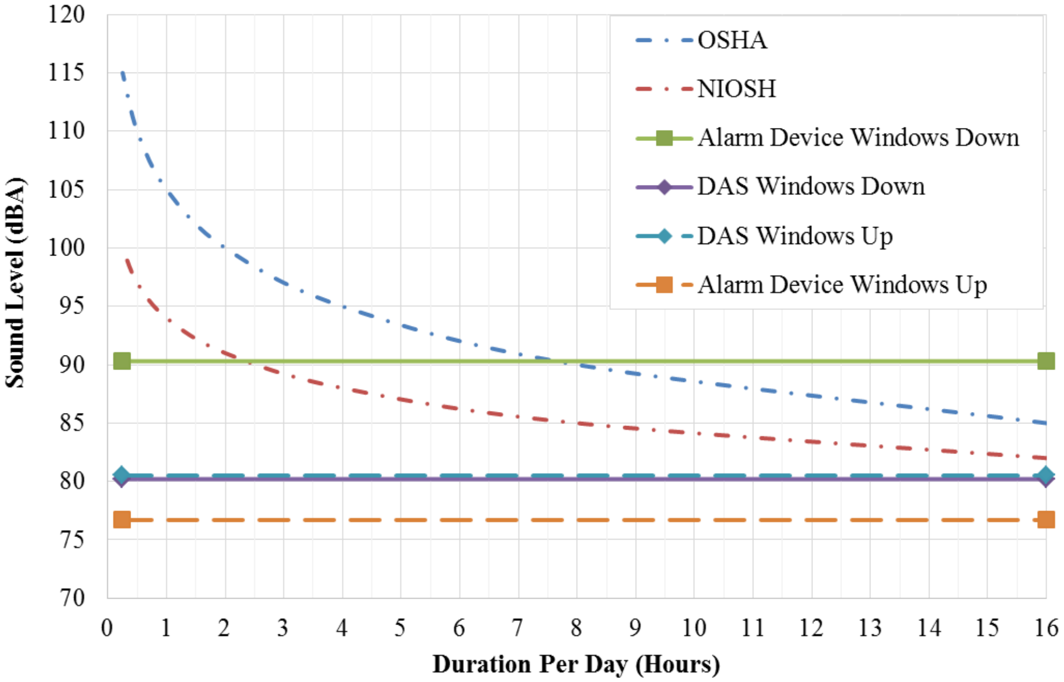


Figure 4.1.1.4 Sound level results for DAS and Alarm Device from within TMA vehicle with windows up and down

Figure 4.1.1.5 shows the results from the highway test vehicle sound analysis in which sound levels were measured from inside of a test vehicle passing each mobile work zone setup. The highway alarm sound level was determined through measuring sound levels from within the test vehicle during alarm activations. Highway base sound level was determined through measuring the sound level within the test vehicle before alarm activations. Highway alarm sound levels and highway base sound levels were averaged and compared for each alarm setup in order to determine if a significant change in sound level resulted through alarm activation. A 45° line represents no change in sound level before and after alarm activation. The results from this plot show that the sound levels inside the vehicle did not increase significantly when the alarm sounded. This result reinforces the importance of looking at the distinctiveness of the sounds in addition to the sound levels. The following section looks at these sound differences in terms of sound distinctiveness.

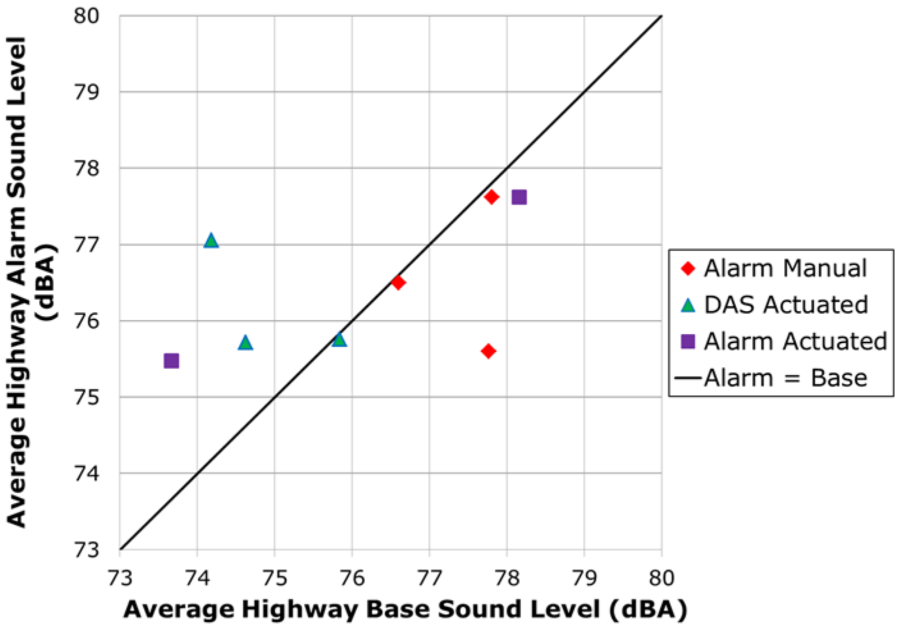


Figure 4.1.1.5 Highway vehicle testing sound level results

4.1.2 Spectral Analysis

Sound distinctiveness is another important factor to consider aside from sound level. Figure 4.1.1.5 shows that the Alarm Device was determined to not significantly increase the sound level. In order to analyze the sound distinctiveness, frequencies of the sounds emitted need to be studied. A spectral analysis is the examination of frequencies through a spectrogram. A spectrogram is the plot of frequency versus time in which amplitudes of frequencies are displayed in a red-green scale where red represents a high intensity. Therefore, higher concentrations of frequencies result in dark orange or red colors through the spectrogram and are indicative of a more intense and distinct sound. A spectral analysis was performed on both the DAS and Alarm Device with and without the background noise on the highway. Through analyzing frequency concentrations for each alarm type, a measure of distinctiveness could be determined for each alarm.

Figure 4.1.2.1 shows the spectrogram for the Alarm Device sound without background noise. The Alarm Device utilized air horns to produce the warning sound and was observed to emit a wide range of frequencies with little concentration.

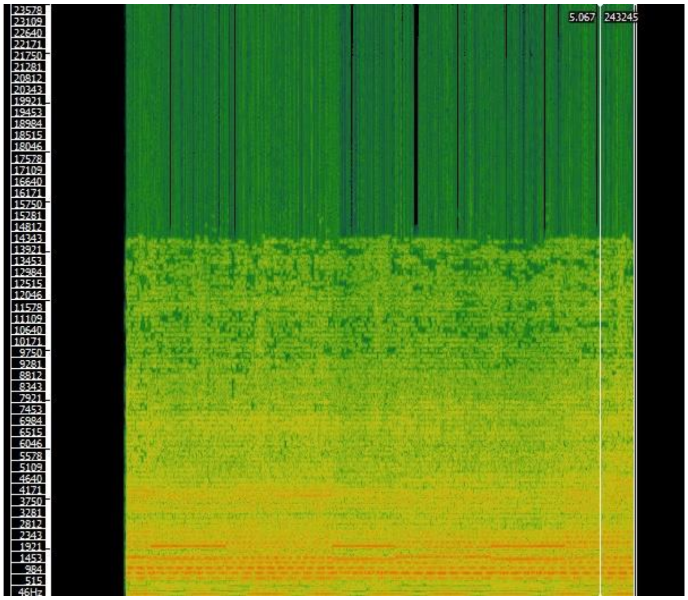


Figure 4.1.2.1 Alarm Device spectrogram without highway background noise

Figure 4.1.2.2 shows the DAS spectrogram without the background noise on the highway. The alarm sound tested from the DAS Actuated setup emits a short pulsing sound followed by a message stating, “Slow vehicles ahead”. The highly concentrated section of the spectrogram represents the pulsing sound while the more dispersed section represents the audible message.

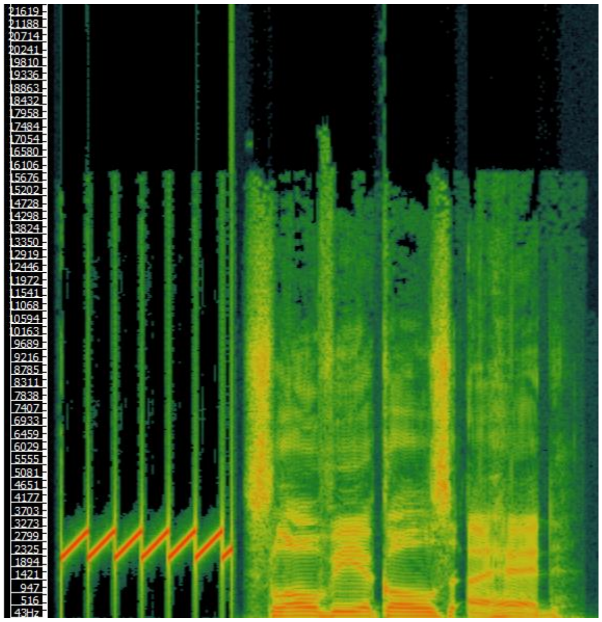


Figure 4.1.2.2 DAS spectrogram without highway background noise

Through initial inspection without the background noise, the DAS appears to be more distinct than the Alarm Device due to the high concentration of frequencies through the initial pulsing sound of the alarm. The addition of the background noise on the highway provides further understanding of each alarm’s distinctiveness while the alarm is being used on the highway.

Figure 4.1.2.3 shows the spectrogram for the Alarm Device with the background noise on the highway. The alarm activation is shown as the horizontal yellow lines within the red box while the background noise consists of a wide range of green lines. From visual inspection the background noise on the highway appears to have a masking effect on the Alarm Device sound. This is due to the range of frequencies utilized by the alarm being wide.

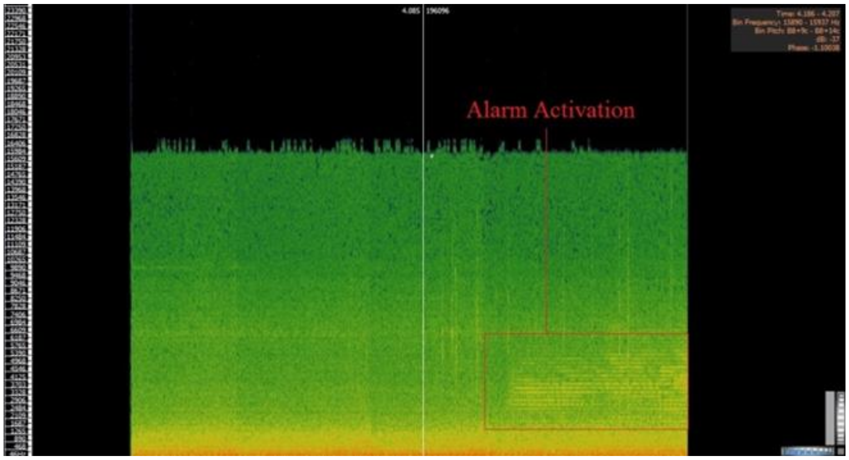


Figure 4.1.2.3 Alarm Device spectrogram with background noise on the highway

Figure 4.1.2.4 shows the spectrogram for the DAS with background noise on the highway. The alarm activation can be seen within the red box as the vertical yellow and red lines while the background noise is represented by the range of green lines. The alarm sound of the DAS does not appear to be masked by the background noise on the highway due to the darker red and yellow colors exhibited through the spectrogram.

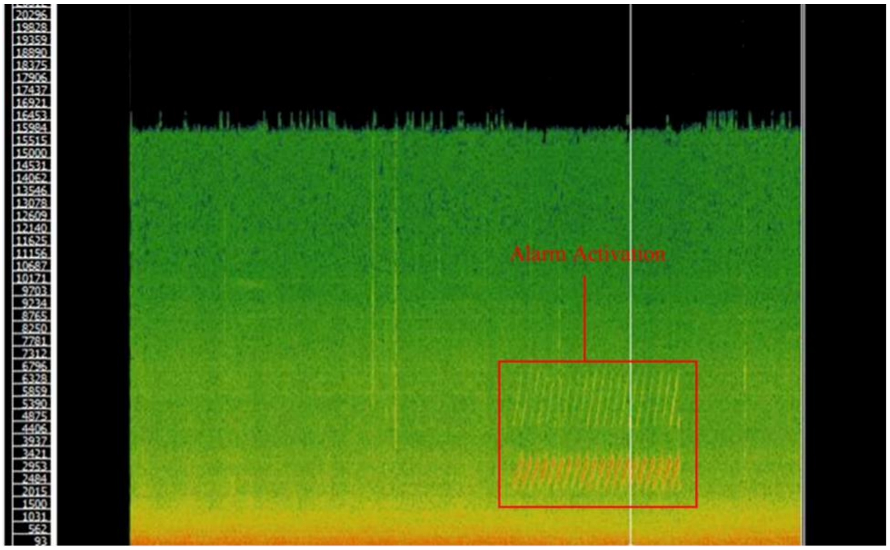


Figure 4.1.2.4 DAS spectrogram with background noise of highway

In comparing the analyses for the Alarm Device and DAS sounds, the DAS produced a much more distinct sound than the Alarm Device even with background noise of a highway.

With this distinctiveness, travelers would much more easily hear the DAS while approaching a mobile work zone than the Alarm Device.

4.1.3 Luminance Testing

It is important to ensure the luminance emitted from each setup was similar in order to avoid bias between tests. Luminance is a measure of light intensity in units of $\frac{cd}{m^2}$ or NITS and was determined for each setup. The recorded luminance levels were determined to be similar and not cause of bias. Figure 4.1.3.1 shows a typical light setup on the TMA trucks.

Figure 4.1.3.1 Typical warning lights setup on TMA truck

4.1.4 Results for Merging Distance and Speeds

Driver behavior is the main indicator of work zone safety used to compare each alarm setup. In total, approximately 13 hours of video data was collected from the alarm setups and control site. The total time of observations excludes segments in which data was not being collected such as changing roadways or during worker breaks in which cameras were recording. The DAS Continuous setup was observed to have the largest number of merges while the Alarm Actuated experienced the fewest number of merges. Totals for time of observations and number of merges through each alarm setup can be seen in Table 4.1.4.1.

Table 4.1.4.1 Total Time of Observations and Total Number of Merges by Setup

Setup	**Total Time of Observations**	**Total Number of Merges**
Control	2:24	884
Alarm Manual	2:02	711
Alarm Actuated	2:53	807
DAS Continuous	2:28	816
DAS Actuated	3:02	894
Totals	**12:49**	**4112**

A 15-minute volume count was collected for each test site and converted to vehicles per hour which gave an estimate for the average volume experienced at each location. The percentage of trucks was also recorded during this volume count. Table 4.1.4.2 shows the average volume and percentage of truck experienced through each setup. The traffic conditions for all five setups were determined to be similar with light traffic and approximately the same percentage of trucks. In general, freeway lane capacities are greater than 2000 vehicle per hour which is much higher than the values in Table 4.1.4.2. This is important to ensure that vehicle interaction effects do not pollute the data because the objective of this research is to determine the effects of mobile alarm systems without interaction effects due to other vehicles.

Table 4.1.4.2 Average Volume and Percentage Trucks for each Setup

Setup	**Avg. Volume (vph)**	**% Trucks**
Control	676	27%
Alarm Manual	577	25%
Alarm Actuated	857	29%
DAS Continuous	488	24%
DAS Actuated	739	24%

Of the total number of merges, more detailed information such as percentage of merges within 600ft, percentage of merges involving commercial vehicles, percentage of merges on horizontal curves, and percentage of merges on 3-lane segments was determined. A majority of the merges were observed to be on tangent 2-lane segments. On average, 15% of the merges occurred on horizontal curves and 8% of the merges occurred on 3-lane roadway segments. The majority of the merges were also observed to involve private vehicles with 19% of the merges involving commercial vehicles. Table 4.1.4.3 shows percentages of merges within 600ft, merges involving commercial vehicles, merges on curve, and merges on 3-lane segments for each setup along with the total number of merges observed.

Table 4.1.4.3 Properties of Total Merges by Alarm Setup

Setup	Total Number of Merges	Percent Merges within 600'	Percent of Merges Involving Commercial Vehicle	Percent of Merges on Curve	Percent of Merges on 3-Lane Segment
Control	884	11%	20%	11%	5%
Alarm Manual	711	15%	18%	26%	14%
Alarm Actuated	807	7%	21%	5%	8%
DAS Continuous	816	21%	20%	17%	7%
DAS Actuated	894	18%	18%	16%	4%

For the vehicle merges within 600ft, values for average merging distance, standard deviation of the merging distance, average vehicle speed, and standard deviation of the vehicle speed are listed in Table 4.1.4.4. An increase in average merging distance represents desirable driver behavior and it was determined that the DAS setups observed the greatest increase in merging distances. The DAS Continuous setup experienced an additional 122ft merging distance in comparison to the Control setup and the DAS Actuated observed an increase of 53ft over the Control. This additional merging distance results in an additional 1.2 and 0.52 seconds of reaction time at 70mph. The DAS Continuous setup also observed the lowest standard deviation of merging distance which signifies that the merging distance variations were less than that of the other setups. In terms of vehicle speed, the DAS Continuous setup resulted in a decrease in average vehicle speed in comparison to the Control while the other setups experienced an increase in speed over the Control. The increase in speed through the DAS Actuated setup could be due to drivers being startled by the activation of the alarm system putting a sense of urgency onto the driver. The greatest increase of speed over the Control was seen through the Alarm

Device setups. This could be due to the sound being more difficult to localize, placing a greater sense of urgency on the driver as it could appear that the sound would be coming from various directions. The DAS setups were determined to have a greater standard deviation than the Alarm setups but were less than the Control setup.

Table 4.1.4.4 Merge Distances and Speeds for Merges within 600ft

Setup	Number of Merges within 600'	Average Merge Distance (ft)*	Std. Dev. Merge Distance (ft)	Average Speed (mph)**	Std. Dev. Speed (mph)
Control	95	392	146	58.4	9.6
Alarm Manual	108	408	183	62.7	7.3
Alarm Actuated	57	357	161	61.7	7.9
DAS Continuous	171	514	126	55.4	9.2
DAS Actuated	157	445	183	58.9	8.4

* and ** individual Anova tests – each statistically significant 99% confidence interval

ANOVA tests were performed to analyze the statistical significance of average merging distances within 600ft and average speeds of vehicles merging within 600ft independently. Both average merging distance and average vehicle speed were determined to be statistically significant to a 99% confidence interval and therefore none of the results were due to randomness.

In looking at the merges within 600’ for each warning type, subdivisions were set at every 200’ in order to determine the percentage of merges from 0-200’, 201-400’, and 401-600’ (Figure 4.1.4.1). Three subdivisions were chosen to divide the data into groups in order to provide a distribution of merging distances within each alarm setup. If too many divisions were chosen the data would be too divided while too few would not accurately describe the results. As shown in Figure 4.1.4.1, each warning setup had the greatest percentages of merges within the

401-600ft distance group. However, the comparison between warning setups show that the DAS Continuous has a greatest ratio of merges within the 401-600' group than any other setup.

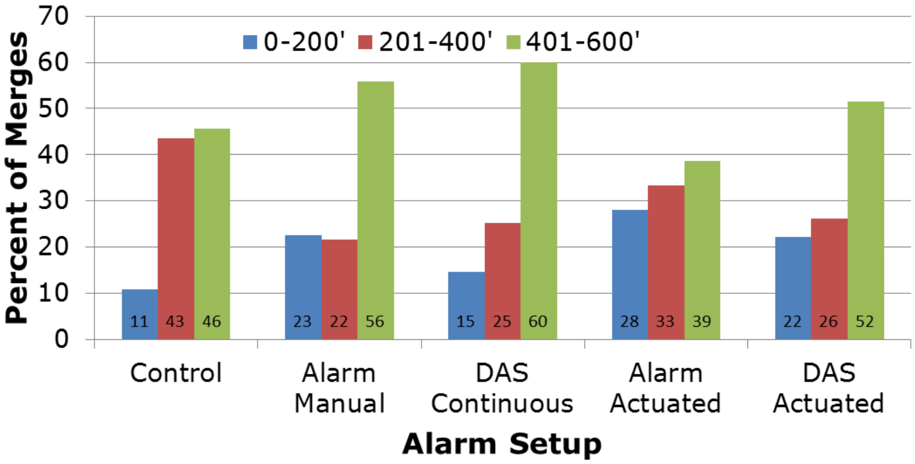


Figure 4.1.4.1 Distribution of merges in 200ft segments by setup

The average merging distance for each alarm setup was observed to increase through all alarm setups except for the Alarm Actuated when compared to the control. The increased merging distance for the Alarm Manual setup could be due to this being the only setup with a two stage alarm system in which the TMA driver first triggered the lights and then triggered the sound alarm when the vehicle got closer. Lights and sound were activated simultaneously for the actuated setups.

4.1.5 Observations of Driver Behavior

Through the data collection process, observations of undesirable behavior were recorded. Undesirable driving behavior was observed through both DAS setups. The DAS Continuous setup observed some cases in which travelers would pass the TMA while driving on the outside shoulder, giving additional room to the TMA truck. Figure 4.1.5.1 shows an example of a driver passing the TMA driving on the outside shoulder. This reaction could be due to the audible "Slow vehicles ahead" message or by the presence of the mobile work zone. Some drivers had a tendency to dramatically slow down and match the speed of the work zone vehicles. However, MoDOT personnel indicated that this driving behavior was not uncommon through mobile work zones without an audible alarm system and therefore may not be due to the DAS Continuous setup itself.

Figure 4.1.5.1 Example of driver passing TMA truck on opposite shoulder

The DAS Actuated setup experienced some instances of sudden maneuvers at the time of alarm activation. These sudden maneuvers included breaking, swerving, and quick merging and could be due to drivers being startled by the alarm activation as a reaction to the unexpected DAS sound. Figure 4.1.5.2 shows an instance in which a silver car applied the brakes quickly when the alarm was actuated by the merging dump truck close behind the silver car. This caused the dump truck to suddenly apply the brakes. Since video on traffic conditions ahead of the silver car was unavailable, it is unclear whether the instance was due to the DAS Actuated alarm or another event ahead of the silver car.

Figure 4.1.5.2 Example of sudden breaking by silver car causing dump truck to quickly apply the brakes at DAS Actuated setup

4.1.6 Evaluation of Alarm Activations

Table 4.1.6.1 shows the total number of false alarms, actuation events, and false alarm rate. False alarm rate was calculated as the number of false alarm divided by the number of activation events that happened within the threshold distance. The Control setup was able to measure number of false alarms due to the actuation system running in the background, and the recorded data was used to determine a false alarm rate. The DAS Continuous setup also had an actuation system running in the background but was not collecting data properly throughout the test.

Table 4.1.6.1 False Alarm Analysis with Horizontal Curves by Setup

Setup	No. False Alarms	No. Activation Events	False Alarm Rate
Control*	19	61	31%
Alarm Manual**	51	97	53%
Alarm Actuated	27	39	69%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	90	145	62%

* had actuation program running in background
** based on 440-600ft acceptable manual actuation threshold
*** actuation system was not properly collecting any data

A large contributor to false alarms was determined to be the presence of horizontal curves in which the actuation system may sound on adjacent vehicles through curves. In order to determine other factors causing false alarms, cases in which a false alarm was caused by a horizontal curve was filtered out. Table 4.1.6.2 shows number of false alarms, number of actuation events, and false alarm rate of the sample without false alarms due to the presence of horizontal curves. Some other factors determined to be causing false alarms include swerving of the TMA truck which caused alarm actuation on vehicles in the adjacent lane driving closely to the center stripe. The high false alarm rate pertaining to the Alarm Manual setup could be due to the TMA drivers being more cautious and sounding the alarm earlier than intended.

Table 4.1.6.2 False Alarm Analysis without Horizontal Curves by Setup

Setup	No. False Alarms	No. Activation Events	False Alarm Rate
Control*	18	60	30%
Alarm Manual**	42	97	43%
Alarm Actuated	17	39	44%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	25	145	17%

* had actuation program running in background
** based on 440-600ft acceptable manual actuation threshold
*** actuation system was not properly collecting any data

An additional analysis of false negatives was performed for both the actuated trigger and manual trigger. False negatives are instances in which the alarm did not sound when it should have. Similar to false alarms, the threshold for the actuated systems was determined by the vehicle speed. For the manual trigger approach, the threshold was 600’. The total number of false negatives, number of merges within the threshold distance, and false negative rates are shown in Table 4.1.6.3.

Table 4.1.6.3 False Negative Analysis with Horizontal Curves by Setup

Setup	No. False Negatives	No. of Merges < Threshold Distance	False Negative Rate
Control*	42	74	57%
Alarm Manual**	6	48	13%
Alarm Actuated	26	48	54%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	25	97	26%

* had actuation system running in background
** based on 440-600ft acceptable manual actuation threshold
*** actuation system was not properly functioning in background

The number of instances in which the alarm should have been triggered was determined through the number of merges that occurred within the stopping sight distance for the actuated setup and within 600ft for the manual setup. The false negative rate was determined as the number of false negatives divided by the total number of merges within the threshold distance. The control site was able to collect false negative rate information due to having the actuation system running in the background and collecting data on theoretical alarm activations.

Horizontal curves were determined to have a major effect on the number of false negatives and therefore, in order to determine other factors involved with false negatives, were filtered out. Table 4.1.6.4 shows the number of false negatives, number of merges within threshold distance, and false negative rate. Other causes of false negatives were determined to be vertical curves in which the curve would cause the actuation sensor to be aiming above or below approaching vehicles and TMA truck swerving within the lane.

Table 4.1.6.4 False Negative Analysis without Horizontal Curves by Setup

Setup	No. False Negatives	No. of Merges < Threshold Distance	False Negative Rate
Control*	28	74	38%
Alarm Manual**	4	48	8%
Alarm Actuated	20	48	42%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	6	97	6%

* had actuation system running in background
** based on 440-600ft acceptable manual actuation threshold
*** actuation system was not properly functioning in background

4.1.7 Warning System Evaluation

For a decision of what system is appropriate to use, many factors and trade-offs exist such as performance, cost, maintenance requirements, etc. Table 4.1.7.1 summarizes some of these trade-offs.

Table 4.1.7.1 Alarm Setup Design Trade-Offs

Factor	DAS Continuous	DAS Actuated	Alarm Manual	Alarm Actuated	Desirable
Merge Distance (ft)	+122	+53	+16	-35	+
Standard Deviation of Merge Distance (ft)	-20	+37	+37	+15	-
Approach Speed (mph)	-3.0	+0.5	+4.3	+3.3	-
False Positive (Including Horizontal Curves)	N/A^{+}	62%	53%	69%	0%
False Negative (Including Horizontal Curves)	N/A^{+}	26%	13%	54%	0%
Observed Driver Behavior	Drive on Shoulder	Sudden Maneuvers	None Observed	None Observed	None Observed
Sound Safety 50' In Veh. (dB)	86	86	77	77	< 115^{++} < 100^{+++}
Sound Distinctiveness	****	****	**	**	****
Cost	$$$$	$$$$$	$	$$	$
Convenience	Automatic	Calibration	Manual	Calibration	Automatic
Energy Consumption	*****	****	*	***	*

$^{+}$ DAS Continuous did not have actuation system properly collecting data in background
$^{++}$ OSHA, 0.25 h
$^{+++}$ NIOSH, 0.25 h

Each alarm setup experienced an increase in average merging distance over the control setup except for the Alarm Actuated setup. The DAS Continuous setup was the only setup to experience a decrease in the standard deviation of merging distance indicating more uniformity in merging behavior. The DAS Continuous setup observed the greatest increase in average merging distance. The DAS Continuous setup was the only setup to experience a decrease in vehicle speed. The Alarm Device setups observed the greatest increase in vehicle speed which could be due to the sound of the Alarm Device sound being more difficult to localize thus placing a greater sense of urgency on the driver traveling through the work zone. The Alarm Manual trigger setup and actuated trigger mechanism experienced false alarms and false negatives, however, the majority of false alarms with regards to the manual setup were likely due to TMA drivers being cautious and sounding the alarm earlier than anticipated. Horizontal and vertical curves had a major effect on false alarm and false negative rates. In terms of observed driving behavior, the DAS Continuous setup observed a tendency for some travelers to pass the TMA work truck on the opposite shoulder, giving extra room while passing the TMA truck. The DAS Actuated setup experienced some sudden maneuvers at the time of alarm activations.

Other factors to be taken into consideration include sound safety, sound distinctiveness, cost, convenience, and energy consumption. Both the DAS and Alarm Device were determined to operate within OSHA and NIOSH guidelines. In terms of sound distinctiveness, the DAS was determined to be much more distinct than the Alarm Device through the spectral analysis. However, the DAS is significantly more costly than the Alarm Device and including the actuation system further increases costs. When considering calibration convenience, the DAS Continuous is the most convenient due to the alarm being continuous and not requiring calibration such as the actuation system. The DAS Continuous consumes the greatest amount of energy while the Alarm Manual setup requires the least amount of energy to operate.

4.2. Innovative Geometric Design

This section presents the results obtained through the survey of industry experts, key findings from the interviews of industry experts, and sample project plans. Findings were applied to develop the MOT Phasing Diagrams sheets through initial construction of each innovative geometric design intersection studied which is presented at the end of this section.

4.2.1 Survey Results

The survey was completed by 47 industry experts across the United States from various state departments of transportation, cities, counties, consultants, and other agencies. Figure 4.2.1.1 shows the distribution of participants throughout the country.

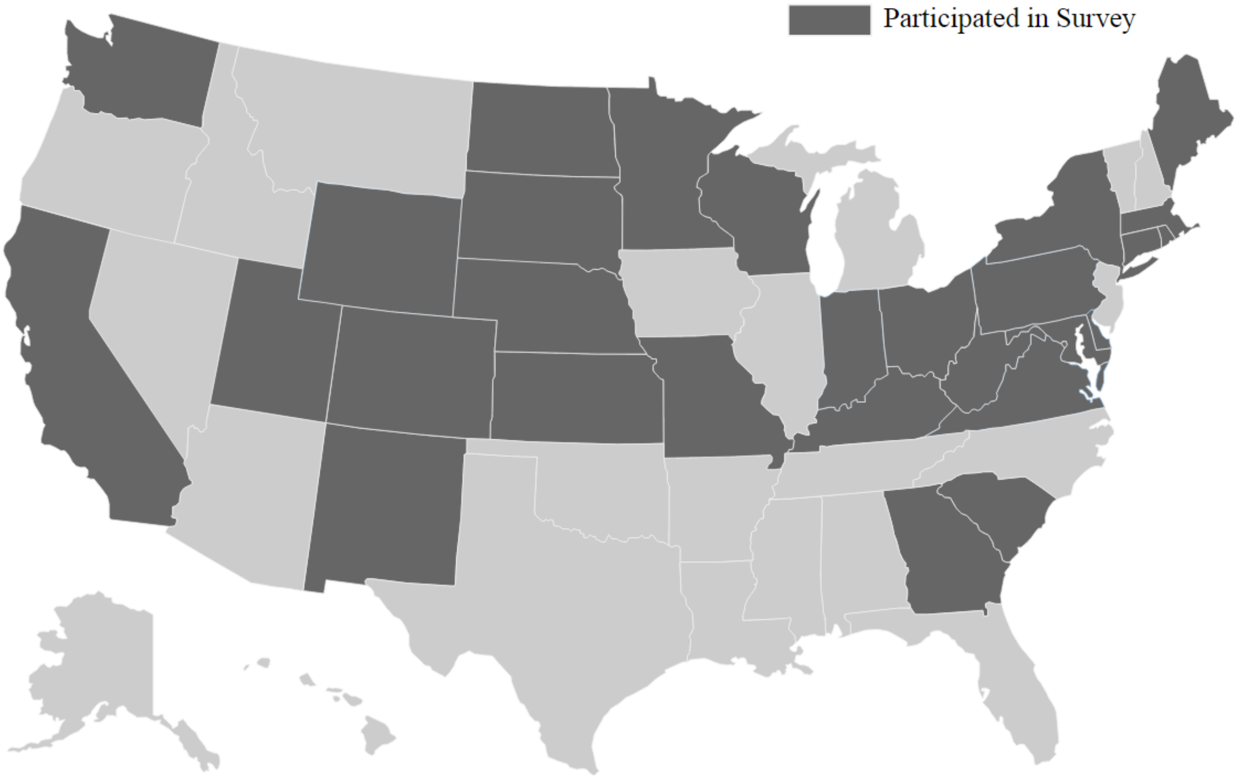


Figure 4.2.1.1 Distribution of survey participants by state

Table 4.2.1.1 shows the distribution between each agency type represented through survey respondents. A majority of the respondents represented various state DOTs at 63%. The smallest percentage of respondents was from within various cities at 4%. Consultants represented 19% of the respondents while various counties were represented by 6% of the respondents.

Table 4.2.1.1 Distribution of Agencies Represented by Survey Participants

		Percentage	Response Count
What type of agency do you represent?	State DOT	64%	30
	City	4%	2
	County	6%	3
	Consultant	19%	9
	Other	6%	3
	Total		47

Each respondent was asked about initial construction and maintenance operations through each of the innovative geometric design intersections. These questions asked for the total number of each intersection type the respondent's agency is responsible for, what type of method is preferred through initial construction and maintenance projects, and how frequently the preferred method type is utilized for both initial construction and maintenance projects. Table 4.2.1.2 shows the results of all survey respondents' answers relating to initial construction.

Table 4.2.1.2 Survey Respondent Answers Regarding Initial Construction

			Number of Intersections					Response Count
			0	1 to 5	6 to 10	Greater than 10		
Approximately how many of the following designs does your agency operate in total?	Roundabout		7	11	10	19		47
	SPUI		20	11	8	3		42
	DDI		30	11	2	1		44
	RCUT		24	15	0	2		41
	MUT		28	9	3	1		41
	DLT		33	6	0	2		41
	answers							47
	skipped							0
		Complete Closure	Phased Construction with Partial Closures	Construct Temporary Runaround	Temporary Traffic Signal	Other	N/A	Response Count
What is the predominant method used by your agency during initial construction for each intersection type?	Roundabout	8	37	1	2	1	4	45
	SPUI	1	21	1	5	0	17	40
	DDI	2	14	0	2	0	23	39
	RCUT	1	15	0	1	0	23	38
	MUT	1	12	0	1	0	25	38
	DLT	2	7	0	1	0	30	39
	answers							46
	skipped							1
		Always	Almost Always	Sometimes	Rarely	N/A		Response Count
How frequently does your agency use each method listed in previous question for initial construction?	Roundabout	8	27	6	1	5		46
	SPUI	5	15	2	1	19		42
	DDI	3	9	2	0	26		40
	RCUT	1	14	0	1	24		40
	MUT	1	12	0	0	27		40
	DLT	2	6	0	0	32		40
	answers							46
	skipped							1

Survey participants were asked what methods are most widely used throughout the initial construction of each intersection. Phased construction with partial closures proved to be the most widely utilized method between every intersection type investigated. Each listed selection of initial construction methods were selected at least once from various agencies and one respondent selected the “other” option. This respondent stated that utilizing temporary truck detours was another method utilized through the initial construction of an innovative geometric design. When asked about the frequency at which the most prevalent initial construction method was used, 72% of responses, when excluding N/A, were observed to be “Almost Always” while only 17% were found to be in the “Always” category when excluding N/A responses. These results reinforce the idea that there is no one-size-fits-all approach to initial construction for innovative geometric designs and that a case-study approach should be used.

Roundabouts were found to be very common among survey respondents. A total of 19 respondent agencies were responsible for more than 10 roundabouts. Complete closures were found to be utilized more frequently for roundabouts than other facility types. This could be due to limited right-of-way and effected area of existing pavement through roundabout construction. MUT and DLT intersection types were found to be the least common the among intersections studied between the survey respondents. SPUIs were found to be the second most common facility type represented. Temporary signal was utilized more frequently for SPUIs than other facility types. This could be due to a need to relocate the intersection through the construction process. Only one survey respondent agency was responsible for more than 10 MUTs and two survey respondent agencies were responsible for more than 10 DLT intersections. These results show a dispersed number of each intersection type without any intersection type being unrepresented.

Survey participants were also asked about the number of maintenance projects performed through each intersection type, most prevalent method used through maintenance projects, and how frequently the most prevalent method was utilized (Table 4.2.1.3).

Table 4.2.1.3 Survey Respondent Answers Regarding Maintenance Projects

		Number of Intersections				Response Count
		0	1 to 5	6 to 10	Greater than 10	
For how many designs listed in question 2 has your agency performed maintenance projects (such as resurfacing, re-striping, etc.)?	Roundabout	19	18	4	5	46
	SPUI	28	9	3	1	41
	DDI	35	3	1	0	39
	RCUT	30	9	0	0	39
	MUT	31	6	2	0	39
	DLT	37	3	0	0	40
	answers					46
	skipped					1

		Complete Closure	Phased Construction with Partial Closures	Construct Temporary Runaround	Temporary Traffic Signal	Other	N/A	Response Count
What is the predominant method used by your agency during initial construction for each intersection type?	Roundabout	2	24	0	0	4	15	43
	SPUI	0	15	0	0	1	24	40
	DDI	1	10	0	0	1	29	40
	RCUT	0	13	0	0	1	25	39
	MUT	0	8	0	0	3	28	39
	DLT	0	6	0	0	0	32	38
	answers							43
	skipped							4

		Always	Almost Always	Sometimes	Rarely	N/A	Response Count
How frequently does your agency use each method mentioned in question 6 for maintenance projects?	Roundabout	5	24	2	0	14	44
	SPUI	2	13	1	0	25	41
	DDI	3	7	1	0	29	40
	RCUT	1	9	2	1	27	40
	MUT	2	8	1	0	29	40
	DLT	1	4	1	0	33	39
	answers						44
	skipped						3

Maintenance projects were observed to not be as prevalent as initial construction projects. Agencies have less experience with maintenance projects than initial construction projects. This could be due to the fact that many of these facilities are relatively new. However, each intersection type was found to have multiple respondents with experience in maintenance projects for each innovative geometric design studied. There is less variation in the method used for maintenance projects than for initial construction. This could be due to the fact that maintenance projects have less of an impact on the network. Similar to initial construction, roundabouts were observed to be the most common innovative geometric design experiencing maintenance projects. DLT intersections were found to be the least common in only having three respondents having one to three DLT intersections each. Survey participants were also asked what method is utilized most through maintenance projects in innovative geometric designs. Phased construction with partial closures was observed to be the most common method for maintenance projects, having 88% of the responses when excluding N/A responses. Phased construction with partial closure was found to be the only method “most frequently” utilized in DLT intersections. Complete closures were found to be utilized “most frequently” for some survey respondents in DDIs and roundabouts. Complete closures represented 10% of the DDI respondents and 11% of the roundabout responses when excluding N/A responses. None of the other intersection types were found to have an agency utilize complete closures “most frequently”. The use of temporary runarounds and temporary traffic signals were found not to be the most predominant method used in any intersection type. Responses of “Other” accounted for 13% of the responses through all intersection types when N/A responses were excluded and were observed through each intersection type except for the DLT intersection. These responses were stated by the survey participants to be temporary truck detours, temporary lane closure by flagman control, and moving operations. When survey participants were asked on the frequency in which the predominant method was used through maintenance projects, 75% of the responses were “Almost Always” while 16% of the responses were “Always” when excluding N/A responses. This result supports the notion, similarly to initial construction, that there is no one-size-fits-all method for maintenance operations through innovative geometric design intersections. This shows that MOT Phasing Diagrams should remain flexible for adjustments to fit the project scenario.

Survey participants were also asked how MOT plans were developed. Questions included what resources were used and what factors were considered when developing MOT plans. Table 4.2.1.4 shows the results of these two questions.

Table 4.2.1.4 Survey Respondents Answers Pertaining to Resources and Factors Utilized

What resources did you use to decide on the maintenance of traffic plans for your facilities? Check all that apply.		Percentage	Response Count
	MUTCD	91%	40
	State Design Manual	73%	32
	Experience/Knowledge	96%	42
	Other (please specify)	9%	4
	answered question		44
	skipped question		3
What factors did you take into consideration when determining the maintenance of traffic plans for your facilities? Check all that apply.		Percentage	Response Count
	Traffic Counts	93%	42
	Operating Speed	78%	35
	% Trucks	67%	30
	Availability of Alternate Routes	93%	42
	Land Use Access	56%	25
	Duration of Construction	89%	40
	Rural/Urban	51%	23
	Ped./Bike/ADA	56%	25
	Other (please specify)	7%	3
	answered question		45
	skipped question		2

The MUTCD and previous experience were observed to be the most highly utilized resource in having over 90% response rate for each. State design manuals were also found to be widely used in developing MOT plans through these intersection types. The responses classified as “Other” were stated to be standard plans and design standards of other states. Respondents indicated that they considered a variety of factors when developing MOT plans for innovative geometric designs. Traffic counts and availability of alternate routes were found to be the most widely used factors in being at an over 90% selection rate. Land use access, rural versus urban, and pedestrian, bike, and Americans with Disabilities Act (ADA) were found to be the least influential factors in having a near 50% response rate. The “Other” selections accounted for 7% selection among survey participants and were stated to include pavement type and day versus night work. These results indicate that traffic counts and the availability of alternative routes were the factors that most agencies consider while other factors depend on characteristics of the project site. Other characteristics taken into consideration could include proximity to local police or fire departments, an area hospital, or even a major shopping center.

Survey participants were asked if experience showed whether certain techniques for MOT performed less effectively than others. Respondents were given selection of complete closure, phased construction with partial closures, temporary runaround, temporary traffic signal, and other. Table 4.2.1.5 shows the results gathered from this question.

Table 4.2.1.5 Survey Respondent Answers Regarding Less Effective Techniques

		Percentage	Response Count
Did you find that certain techniques for maintenance of traffic were less effective than others?	Complete Closure	20%	6
	Phased Construction with Partial Closures	10%	3
	Construct Temporary Runaround	50%	15
	Temporary Traffic Signal	27%	8
	Other	17%	5
	answered question		30
	skipped question		17

The use of a temporary runaround generated the most concerns from respondents as it was selected as ineffective by 50% of respondents. This could be due to the requirement of additional right-of-way that a temporary runaround frequently requires and the resulting costs. Some agencies found the use of a temporary runaround to be cost effective when able to utilize temporary runaround for future use, such as an additional roadway, as well as when considering ease of construction. Phased construction with partial closures had the lowest selection rate at 10% while the "Other" selection was used by 17% of the respondents. The methods contained in the "Other" selection were stated to include placing truck traffic on local streets and utilizing long detours. Key findings determined through the survey are as follows:

1. "Phased Construction with Partial Closures" was selected as an initial construction method by 91% of the respondents.
2. "Complete Closure" was selected as an initial construction method by 13% of the respondents.

3. No experience was selected for maintenance projects by 74% of respondents. This is because many of these types of facilities are new and have not required maintenance.
4. “Phased Construction with Partial Closures” was selected as the maintenance project method by 87% of respondents.
5. “Complete Closure” was selected as maintenance project method by 3% of respondents.
6. “Experience/Knowledge” and the “MUTCD” were the selected as used resources by over 90% of respondents. “State Design Manual” was selected as a used resource by 73% of respondents.
7. There are many important factors to consider when developing MOT plans. “Traffic Counts” and “Availability of Alternative Routes” were selected as factors considered by 93% of respondents. “Operating Speed” and “Duration of Construction” were selected by 78% and 89% of the respondents respectively. “% Trucks” was selected by 67% of respondents while “Land Use Access” and “Ped./Bike/ADA” was selected by 56% of respondents. “Rural/Urban” was selected by 51% of respondents.
8. “Construct Temporary Runaround” was selected as a less effective technique by 50% of respondents and “Temporary Traffic Signal” was selected as less effective by 27% of respondents. “Complete Closure” was selected as less effective by 20% of respondents and “Phased Construction with Partial Closures” was selected as less effective by 10% of respondents.
9. Temporary runarounds are generally not suitable for MOT due to right-of-way and cost constraints
10. There is no one-size-fits-all method for constructing these types of facilities.

4.2.2 Interviews

Survey respondents as well as additional contacts generated from the survey process were asked to participate in an interview to share experiences pertaining to temporary traffic control through initial construction and maintenance projects for innovative geometric designs. Individuals from various DOTs, municipalities and consultant agencies participated in these interviews. Figure 4.2.2.1 shows the distribution of participants throughout the country.

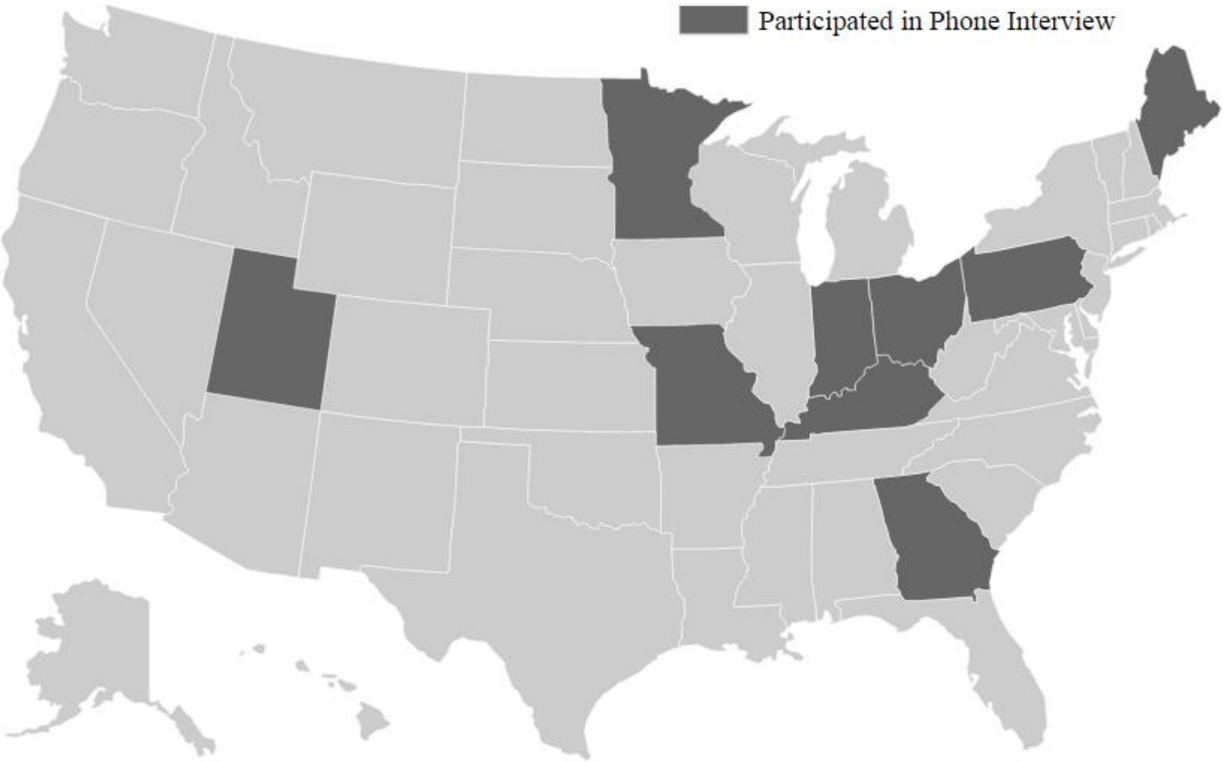


Figure 4.2.2.1 Distribution of interview participants by state

Table 4.2.2.1 shows the distribution between each agency type represented through interview participants. A majority of the respondents represented various state DOTs at 72%. The smallest percentage of participants was from counties at 7%. Consultants represented 21% of the phone interview participants while no cities were represented.

Table 4.2.2.1 Distribution of Agencies Represented by Phone Interviews

		Percentage	Interview Count
Agency Type Represented	State DOT	72%	10
	County	7%	1
	Consultant	21%	3
	Total		14

Interview participants were asked to share experiences pertaining to construction and maintenance of innovative geometric designs. This included providing any recommendations that may benefit transportation practitioners to implement these designs. Key findings of industry expert recommendations through the interview process are as follows:

1. Avoid using temporary movements through construction which would be considered an illegal movement for the final traffic movement configuration. If drivers are experienced with the final traffic configuration due to other intersections of a similar type in the area, this application of MOT could prove beneficial without increased risk of future illegal movements.
2. For DDI, if possible, construct curbing before construction is complete to ensure drivers travel the intersection correctly.
3. For MUT, make sure drivers know there is a median U-turn after the intersection.
4. Agencies have tried using innovative geometric designs for MOT setup, such as a quadrant interchange to avoid construction. Innovative geometric setups implemented for MOT could provide more effective work zone traffic management until construction is complete.
5. In roundabout construction, median cross-overs on legs prove useful on an as-needed basis.

6. For any innovative geometric design, doubling the number of channelizers used through the extents of the work zone can prove valuable in preventing drivers from weaving.
7. Sequential lighting can provide valuable aid to drivers through the work zone setup for both daylight and nighttime periods.
8. Final conversion of some of these facility types, such as DDI, should be done under full closure which should occur when traffic counts are lower, such as weekend periods. The conversion could occur either through the middle or at the end of the project.
9. Use of innovative contracting could be considered such as design build to allow contractors to determine methods used.

Additional findings through the interview process from interviewee opinion and recommendations include:

1. Other factors such as drainage, necessity of movements, and other situations can affect phasing.
2. Be cognizant of how to accommodate pedestrians.
3. With low speeds through the work zone, sharp angles in temporary traffic control are acceptable.
4. MOT plans should be continually reevaluated throughout the duration of the project.
5. Avoid the use of unwarranted temporary signals, because public pressure might make them permanent.

4.2.3 Project Plan Examples

Project plan examples provide more information on the details included in maintenance of traffic plans for each facility type such as construction phasing and work zone organization. Several industry experts sent project plans for projects involving innovative geometric designs. The example projects and findings from these plans are detailed in this section. In total, seven agencies provided project plans or information as examples or standard guidelines relating to MOT and construction phasing. Tables 4.2.3.1 shows the project plans and other information received from state DOTs, cities, and counties. Project plans were received from the City of Columbia, Kentucky Transportation Cabinet (KYTC), Minnesota DOT (MnDOT), MoDOT, Ohio DOT (ODOT), Omni Means, Washington County, Minnesota, Pennsylvania DOT (PennDOT), Utah DOT (UDOT), Crawford, Murphy and Tilly, New Mexico DOT (NMDOT), City of Tucson Arizona.

Table 4.2.3.1 List of Provided Projects Plans by Facility Type

Intersection Type	Received Plans	Project	Method Used	Notes
Roundabout	Columbia, MO	Clark Lane	Phased Construction with Temporary Runaround	Multiphase. Construct temporary by-pass prior to beginning modifications to existing roadway. Continue shifting traffic to newly improved roadway until project is completed.
		Clark Lane Phase II	Phased Construction with Temporary Runaround	Multiphase. Construct temporary by-pass prior to beginning modifications to existing roadway. Continue shifting traffic to newly improved roadway until project is completed.
		Mexico Gravel Road	Phased Construction with Partial Closure	Multiphase. Utilized temporary closures to construct roundabout and approaches one leg at a time, allow traffic as available. Place portable changeable message sign two weeks before construction to inform the public of closures.
		St. Charles Road and Lake of the Woods Road	Complete Closure	Place portable changeable message signs two weeks before construction to inform the public of closure.
		Vandiver Drive	Phased Construction	Multiphase with allowing original movements throughout construction. Project involved construction of new roadway connecting Mexican Gravel Rd. and Vandiver Dr.
	KYTC	Mt. Zion Road (Florence)	Phased Construction with Temporary Runaround	Multiphase. Construct new roundabout construction aside existing. Utilized temporary frontage roads to allow access as roundabout approaches and connections were constructed.

Intersection Type	Received Plans	Project	Method Used	Notes
Roundabout	KYTC	Johns Hill Road and University Drive	Phased Construction with Partial Closures	Multiphase. Construct new pavement prior to modifying existing road and shift traffic onto newly improved roadway as available.
	MnDOT	Highway 22 and Madison Ave. and Highway 22 and Adams St. (Mankato)	Full Closure	Two roundabouts at adjacent intersections were built in three phases using detour routes. In Phase 1, temporary access was constructed. In Phase 2, Highway 22 was closed between Bassett Dr. and Highway 14. Then construction of the roundabouts was started. In Phase 3, construction of roundabouts was completed, and temporary access was removed.
	MoDOT	Route 109 and Route 100, Route 109 and Pond Grover Loop Road (St. Louis County)	Phased Construction with Partial Closure	Two roundabouts were constructed, including one roundabout which replaced a signalized ramp terminal at a full diamond interchange (MO 100). In Phase 1, temporary pavement and permanent widening on MO109 were constructed. In Phases 2 and 3, a temporary signal and temporary pavement were used to construct the roundabouts in stages. In Phase 3, the WB MO 100 on ramp and Pond Grover Loop Road were closed. Phase 4 included the construction of the truck aprons, center islands, center splitter islands, and median.
		Route 171 and Route 43 (Jasper County)	Phased Construction with Partial Closure	Multilane roundabout that was converted from a signalized intersection. Phases 1 and 2 included full depth widening. A temporary signal was utilized. In Phase 3, the center island, curb, and truck apron were constructed. In Phase 4, the channelizing islands were constructed. Lane nearest the island under construction was closed at night.
		Route 63 and Route M (Ashland)	Phased Construction with Temporary Closures	Multiphase. Closed and constructed segments of the roundabout per phase. Flagging operation allowed for access to be maintained. Used nearby RCUTs to help maintain traffic.
	ODOT	SR 235 and SR 41 (Clark County)	Phased Construction with Partial Closures	Multiphase. Two legs closed throughout most of construction, detour used. Temporary pavement used for through movements.
	Omni Means	Shasta View Dr. and Old Arturas Rd. (Redding, CA)	Phased Construction	Multiphase. Temporary driveways had to be installed and 1 inch asphalt overlay placed at end of construction.

Intersection Type	Received Plans	Project	Method Used	Notes
Roundabout	Omni Means	I-5 and Deschutes Rd. (Anderson, CA)	Phased Construction with Partial Closures	Multiphase. Closed and constructed segments per phase. Existing/nearby roads used for detours.
	Washington County MN	CR 18 and 4th St.	Phased Construction with Partial Closures	Striping maintenance utilizing flagging operation.
		C.S.A.H. 15 and T.H. 96	Phased Construction with Temporary Runaround	Phased construction with partial roadway closure. Temporary runaround was constructed to allow for main road access and complete construction of roundabout.
		C.S.A.H. 19 and C.S.A.H. 22	Phased Construction with Temporary Runaround	Phased construction with partial roadway closure. Temporary runaround was constructed to allow for main road access and complete construction of roundabout.
		Roundabout Staging Typical	Phased Construction with Partial Closures	Temporary traffic control typical applications sheet for in-roundabout segment closures.
	PennDOT	Temporary Traffic Control Guidelines	Phased Construction with Flagging Operation	Temporary traffic control typical applications sheet for in-roundabout segment closures.
SPUI	KYTC	KY 237 and KY 18 (Limaburg)	Phased Construction with Temporary Runaround	Multiphase. Constructed temporary diversion prior to modification of existing roadway. SPUI is constructed adjacent to existing intersection and phasing is utilized to connect SPUI to existing roadways.
	MnDOT	I-494 at Lyndale (Richfield)	Phased Construction with Partial Closures	Multiphase. Bridge closed, alternate routes used. Through traffic allowed. Bypass ramp used in later phases. Traffic directed to ramps after construction, then back onto newly constructed main road.
	ODOT	WAR-75 at 63 (Monroe)	Phased Construction	Multiphase. Maintains complete access throughout construction, converting a conventional diamond interchange into a SPUI. Begins with widening bridge deck, followed by construction of left-turn ramps. Approaching roadways are widened and traffic is shifted to allow construction of opposite side, utilizing temporary a temporary traffic signal. Once complete, traffic is shifted to final configuration.

Intersection Type	Received Plans	Project	Method Used	Notes
SPUI	UDOT	Bangerter Hwy at 7800S (Salt Lake City)	Phased Construction with Temporary MUT	Multiphase. Temporary MUT used to maintain complete access throughout construction, converting a signalized at grade intersection into a SPUI. Begins with ramp construction, number of lanes decreased in all directions. Traffic diverted to ramps for construction. Once completed, traffic was shifted to final configuration.
DDI	Crawford, Murphy, and Tilly	I-65 and Worthsville Rd. (Worthsville, IN)	Phased Construction with Partial Closures	Originally designed as multiphase. Constructed second bridge adjacent to existing to serve as eastbound lanes in final layout. Constructed approaches to new bridge and once complete, all traffic is shifted to newly constructed bridge and reconstruction of existing bridge began. Once complete, traffic was shifted to final configuration.
			Full Closure	Switched to full closure because of changes in project conditions. Utilized detours to divert traffic during DDI construction.
	MoDOT	I-44 and Rangeline Rd (Joplin)	Phased Construction with Partial Closures	A full clover converted to DDI. In Phase 1 full depth outside shoulders on I-44 were constructed, and temporary outer ramp connections were built. In Phase 2, the center portion of the new I-44 bridge was constructed, temporary signals were activated, and outer ramp traffic was shifted to temporary connections. In Phase 3, the westbound portion of the new bridge and center islands were constructed, and permanent traffic signals were installed. In Phase 4, the eastbound portion of new bridge was constructed, the new ramps were connected, the permanent traffic signals were activated, and the remaining center islands were constructed. Phase 5 included the construction of permanent barriers, ramp islands, and sidewalks.
		US 60/160 (James River Freeway) and Kansas Expwy (Springfield)	Phased Construction with Partial Closures	In Phase 1, all median strips and islands were removed and, full depth pavement was constructed under the median strips and islands. In Phase 2, the southbound lanes on Kansas Expressway were constructed. In Phase 3, pavement and bridge repairs on the northbound lanes of Kansas Expressway were performed. In Phase 4, the medians were constructed. In Phase 5, the interchange was temporarily closed (right turns on and off ramps were allowed), islands were constructed, and traffic was switched to the DDI configuration.

Intersection Type	Received Plans	Project	Method Used	Notes
DDI	MoDOT	Route 65 and Battlefield Rd (Springfield)	Phased Construction with Partial Closures	Project is under construction in 2015. A temporary DDI configuration is being utilized.
DDI	NM DOT	I-25 and NM 14 (Santa Fe)	Phased Construction with Partial Closures	A partial clover converted to DDI. This project under construction in 2015. Phase 1 includes some ramp closures with temporary detours and temporary signals. Traffic on NM 14 reduced to one lane in each direction with crossovers. Widening for the DDI on NM 14 will be constructed under traffic with NM 14 traffic shifts. In Phase 2, detours on NM 14 utilized to allow for the demolition of an existing off ramp bridge structure. The I-25 off ramps constructed, and the DDI construction completed under one-lane NM 14 traffic shifts. In Phase 3, final paving, signing, and striping completed, and the DDI opened to traffic.
RCUT	MnDOT	US 52 and CR 66 (Vermillion)	Phased Construction with Partial Closures	The intersection was constructed in 2 phases. Traffic on CR 66 utilized a local road detour, and traffic on US 52 was reduced to one lane in each direction. In Phase 1, conflicting pavement markings were covered, and the CR 66 approaches were constructed. In Phase 2, the median construction was performed, and two U-Turns were constructed on US 52 on both sides of the CR 66 intersection. Then the left turn lanes and intersection islands were constructed.
	ODOT	Route 4B (Hamilton)	Phased Construction with Partial Closures	Multiphase with temporary side-roadway closures. Median U-turns and available west side of the future roadway were constructed first. Once the west side construction was complete, traffic was shifted onto the newly constructed roadway and work began on the east side. Once complete, all traffic was shifted to final configuration.
	MoDOT	US 63 and Route M (Atlanta)	Phased Construction with Partial Closures	The downstream U-turns were first constructed. Then, after completing construction of the U-turns and accommodating all movements, the median was closed. The median cross overs were fully closed for about 3 weeks to allow for the construction of improvements to the NB/SB left turns and the removal of the Route M through movement.

Intersection Type	Received Plans	Project	Method Used	Notes
RCUT	MoDOT	US 63 and RT B (Clark)	Phased Construction with Partial Closures	The downstream U-turns were first constructed. Then, after completing construction of the U-turns and accommodating all movements, the median was closed. The median cross overs were fully closed for approximately three weeks to allow for the construction of improvements to the NB/SB left turns and the removal of the Route B through movement.
		US 63 and Calvert Hill Rd./Hinton Rd. (Columbia)	Phased Construction with Partial Closures	In phase 1, right turn lane improvements and shoulder improvements were constructed. In phase 2, the right turn acceleration lanes were constructed. In Phase 3, the northerly and southerly J-turns were constructed. In phase 4, the median crossover was closed and offset lefts and median deceleration lanes were constructed. One lane in each direction on US 63 was closed with channelizers during construction
		RT 13 and 364 NE (Osceola)	Phased Construction with Partial Closures	In Phase 1, loons and side road entrances were constructed. Side road entrances were built one side at a time so that half of them remained open to traffic. In Phase 2, the median crossovers and turn lanes for the loons were constructed. Finally in phase 3, the median turn lanes and islands for intersection were constructed. The loons were not opened until new signs were installed.
MUT	Tucson, AZ	Grant Rd. and Oracle Rd.	Phased Construction with Partial Closures	In Phase 1, the center medians were removed, and temporary paving was placed in the median. In Phase 2, reconstruction of the eastbound lanes of Grant Rd. was performed. Phase 3 included the reconstruction of the westbound lanes of Grant Rd. In Phase 4, the north and south legs of Oracle Rd. were constructed. In phase 5, the median was constructed, signals were installed and activated at Oracle Rd. and the indirect left-turn intersections, and the final pavement lifts were placed.

Intersection Type	Received Plans	Project	Method Used	Notes
MUT	Tucson, AZ	Grant Rd. and 1st Ave./Stone Ave.	Phased Construction with Partial Closures	This project is currently being designed in 2015. The first two phases consist of partial construction in each direction. In Phase 3, the median areas will be constructed. Phase 4 includes minor paving and construction of curb and sidewalk areas. All paving within the traveled way must be completed on nights or weekends to minimize traffic impacts.
DLT	MoDOT	MO 30 and Summit Rd./Gravois Bluffs Blvd. (Fenton, MO)	Phased Construction with Partial Closures	Plans show DLT setup and footprint. Temporary traffic control was left to the contractor.
	ODOT	Austin Blvd. and OH 741 (Miamisburg)	Phased Construction with Partial Closures	Multiphase with temporary roadway closures. Left turns were constructed first and traffic was shifted to final configuration as available.

In total 19 projects were received relating to roundabout projects. The City of Columbia provided five project plan sets relating to roundabout intersections. These projects pertained to initial construction in which various methods were utilized which included phased construction with partial closure, phased construction with temporary runarounds, and full closure. In one set of plans, the City of Columbia constructed a roundabout while maintaining access by allowing two-way traffic through the roundabout during construction phases. It was determined that the general public were familiar with roundabout intersections due to the number of roundabouts in the area, and no increase in illegal movements were observed after final traffic configuration was adopted. KYTC provided example plans involving roundabout construction. The roundabout projects involved shifting traffic to newly constructed pavements as available. MoDOT provided plans relating to a roundabout construction project. This project involved construction of two roundabouts where intersections of a conventional diamond interchange existed. The roundabout construction example involved temporary lane closures in which flaggers were utilized to ensure proper flow of traffic. . Washington County, Minnesota, sent project plans pertaining to two roundabout construction projects and one maintenance project. For two of these roundabout construction projects, temporary runarounds were constructed to allow the complete construction of the roundabout and approaches. The maintenance project involved temporary closures with flagman operation in which through traffic of the main roadway was maintained. Washington Country, Minnesota also provided typical application sheets that show work zone phasing and temporary traffic control setup for roundabout maintenance through a two lane roundabout. This involves temporary lane closures through each leg and completing one quadrant per phase to limit effect on access. PennDOT provided traffic control guidelines used throughout the state which included temporary traffic control guidelines used through various single and multi-lane roundabout maintenance projects. The methods described include the organization of flagging operations through each scenario of roundabout construction. The scenarios include work zone setup when each lane of an approaching roundabout leg is closed and work zone setup for quadrant closures of a roundabout. Other agencies that provided roundabout sample plans include ODOT and Omni Means.

The Kentucky Transportation Cabinet provided a set of example plans involving SPUI construction. This project involved constructing a SPUI bridge adjacent to an existing at-grade intersection. One construction of the SPUI was complete, phased construction was utilized to construction SPUI approaches and connection to existing roadways. The Ohio DOT provided project plans pertaining to SPUI construction. The SPUI project plans involved phased construction while maintaining full access. For this project, the existing bridge was first widened to the final width and left-turn ramps constructed. Once all left-turn facilities had been constructed, a temporary traffic signal was placed near the final location in the center of the bridge. During this stage, right-turn facilities were constructed while right-turn movements utilized the existing ramps. Traffic was then shifted to one side of the bridge to allow for roadway widening. Once this was completed, traffic was shifted to the opposite side of the bridge to allow for the completion of the roadway widening. Additional SPUI project plans were received from MnDOT, ODOT, and UDOT.

Crawford, Murphy, and Tilly provided projects plans for the construction of a DDI. The project was first designed utilizing phased construction under traffic but was later changed to a full closure due to changes in project condition. The phased construction example involved building a separate bridge parallel to the original structure to serve as the eastbound lanes through the DDI final layout. This allowed for all traffic to be shifted to the newly constructed bridge while work was completed for the westbound bridge. Additional DDI plans were received from MoDOT and NMDOT.

ODOT provided project plans pertaining to RCUT construction. The RCUT example plan set utilized multiphase construction scheme with temporary minor roadway closures. Median U-turns were constructed first along with roadway widening to the west of the existing roadway. Once the western portion of the roadway widening had been completed, traffic was shifted to the newly constructed roadway, allowing for construction to begin on the opposite side. Once complete, traffic was shifted to the final intersection configuration. Additional RCUT plans were received from MnDOT and MoDOT.

Tucson, AZ provided project plans relating to MUT intersections. These plans utilize phased construction with partial closures in which the existing roadway is reconstructed and converted into a MUT intersection.

MoDOT provided plans relating to DLT construction. The DLT construction example involved the use of a full closure of the existing intersection and two detour routes to accommodate traffic flow. ODOT also provided project plans pertaining to DLT construction. The DLT plans involved phased construction with temporary roadway closures. Left-turn facilities were constructed first, and as new intersection movements were constructed, traffic was then shifted and movements reopened as available.

4.2.4 Construction Phasing and Maintenance of Traffic

This section presents the MOT Phasing Diagrams as well as discusses construction phasing for initial construction for each intersection type studied. These sheets were constructed using survey responses, interview findings, and project plan examples.

4.2.4.1 Roundabout

Roundabout intersection projects proved to be particularly challenging due to final geometry surrounding the initial intersection footprint. The initial construction phasing methods developed apply to both single lane and multi-lane roundabouts. MOT Phasing Diagrams were developed for two types of roundabout construction phasing methodologies. These include phased construction with partial closures and phased construction with temporary runaround.

MOT Phasing Diagrams was constructed for a case of retrofitting an existing conventional at-grade intersection into a single lane roundabout intersection through phased construction with partial closures. This method involves a four phase construction scheme. Figure 4.2.4.1.1 shows the initial configuration considered.

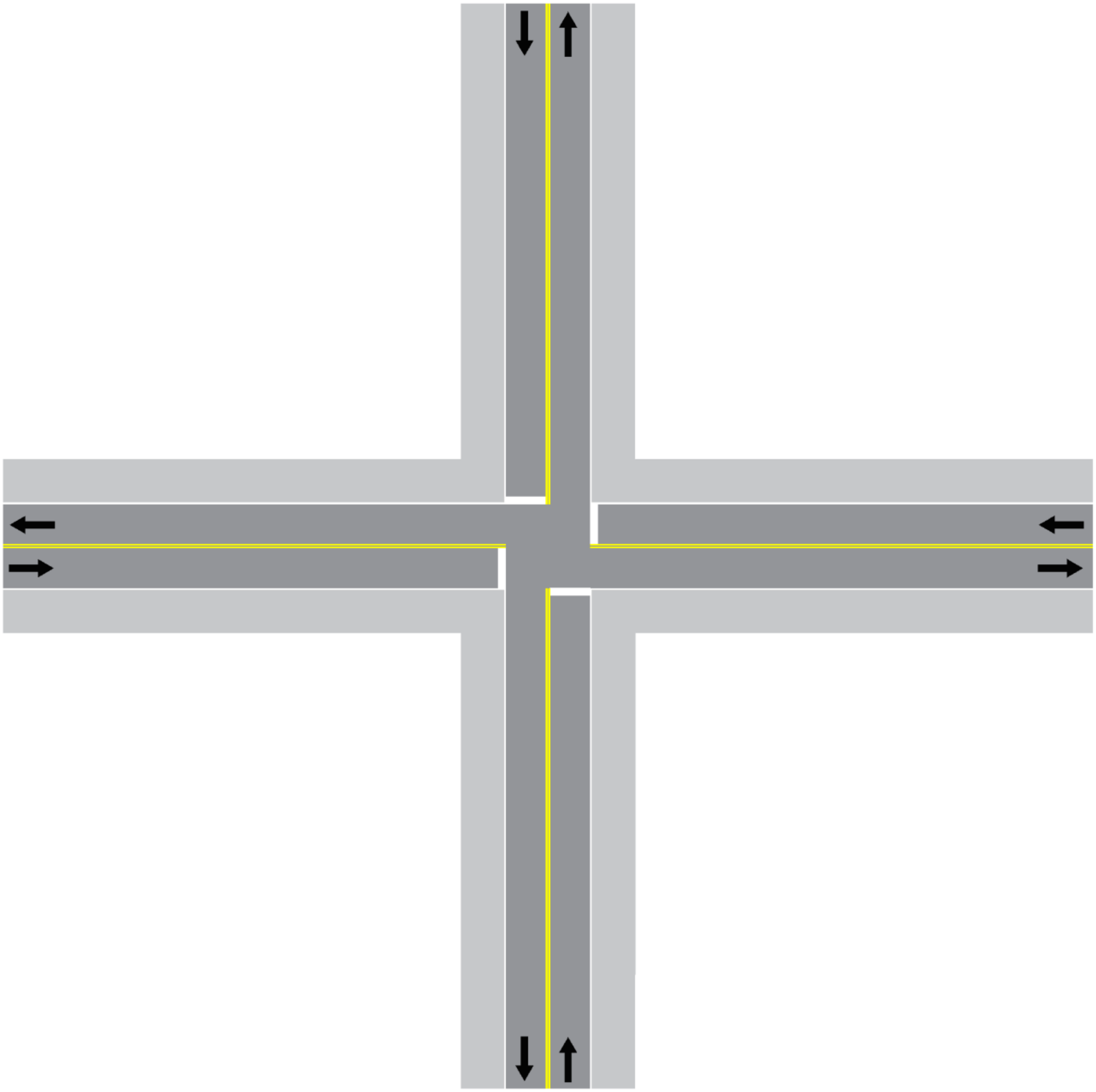


Figure 4.2.4.1.1 Roundabout phased construction with partial closures initial condition

Phase 1 of construction involves closing half of the intersection to allow construction of half of the roundabout. A flagging operation may be utilized to allow three of the four legs to remain open. The leg to be temporarily closed could be selected based on area constraints such emergency access and traffic counts. Figure 4.2.4.1.2 work area and MOT for this phase of construction.

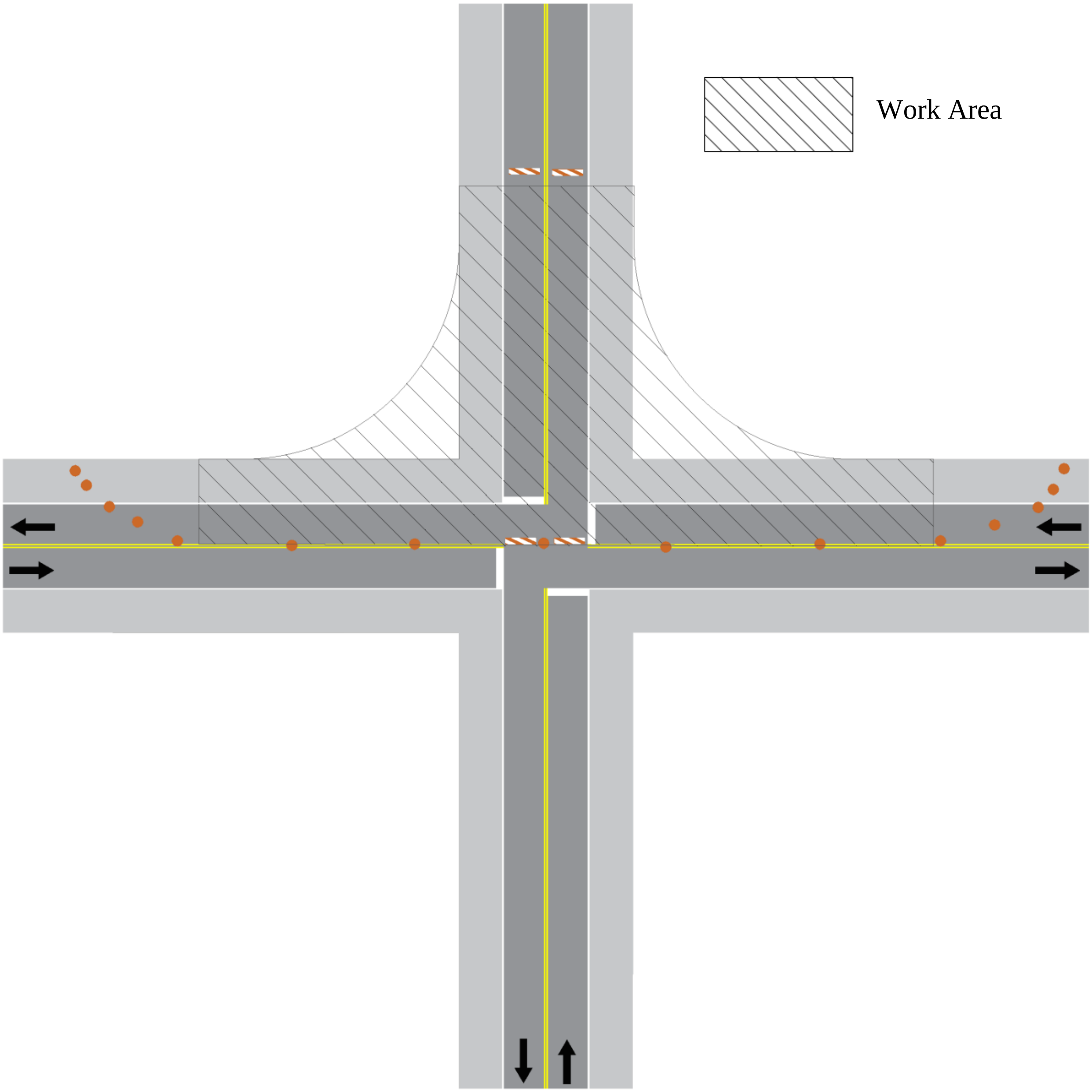


Figure 4.2.4.1.2 Roundabout phased construction with partial closures Phase 1

Phase 2 begins with opening the constructed half of roundabout to traffic as appropriate. One-quarter of the remaining existing intersection is then closed for roundabout construction. A flagging operation may be utilized to allow access through work zone. Figure 4.2.4.1.3 shows the work area and MOT for this phase of construction.

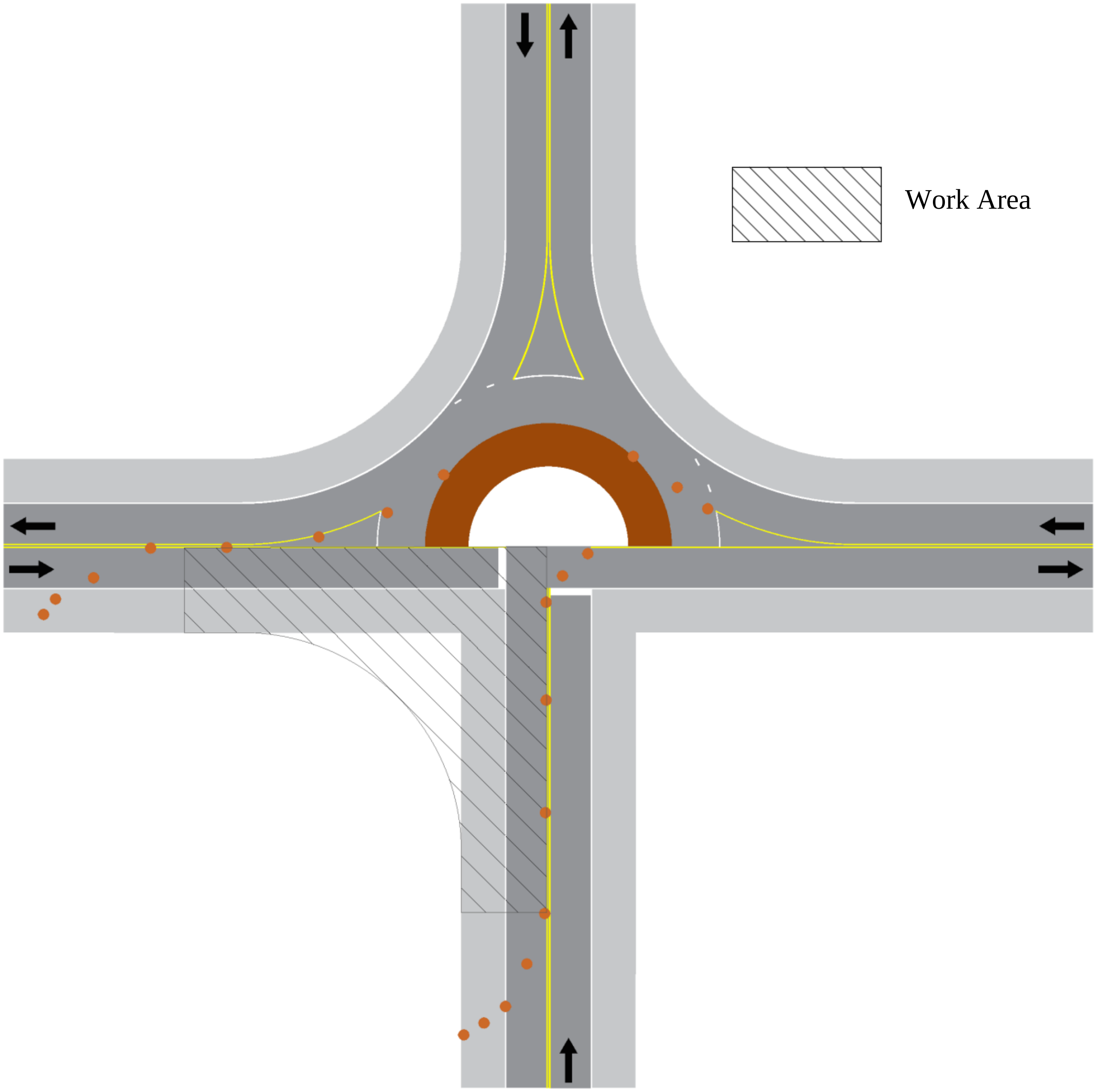


Figure 4.2.4.1.3 Roundabout phased construction with partial closures Phase 2

Phase 3 begins with opening the constructed quarter of roundabout to traffic. The remainder of existing intersection to be converted into roundabout configuration is then closed to allow final construction. A flagging operation may be utilized to allow full access through work zone. Figure 4.2.4.1.4 shows the work area and MOT through this phase of construction.

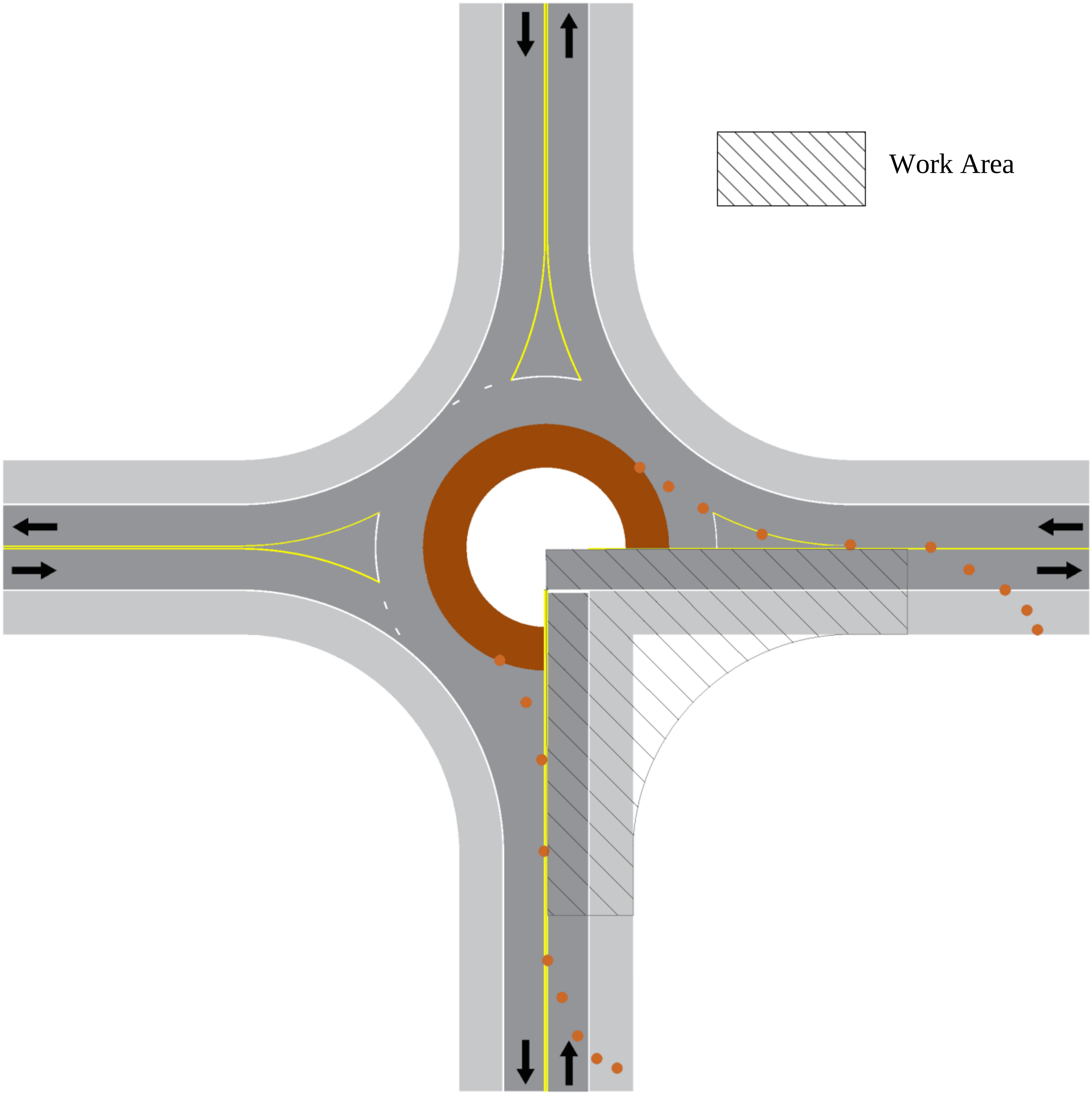


Figure 4.2.4.1.4 Roundabout phased construction with partial closures Phase 3

Once Phase 3 is complete, the temporary traffic control devices are able to be removed and the roundabout opened to the final traffic configuration. Figure 4.2.4.1.5 shows the final configuration of the roundabout setup considered.

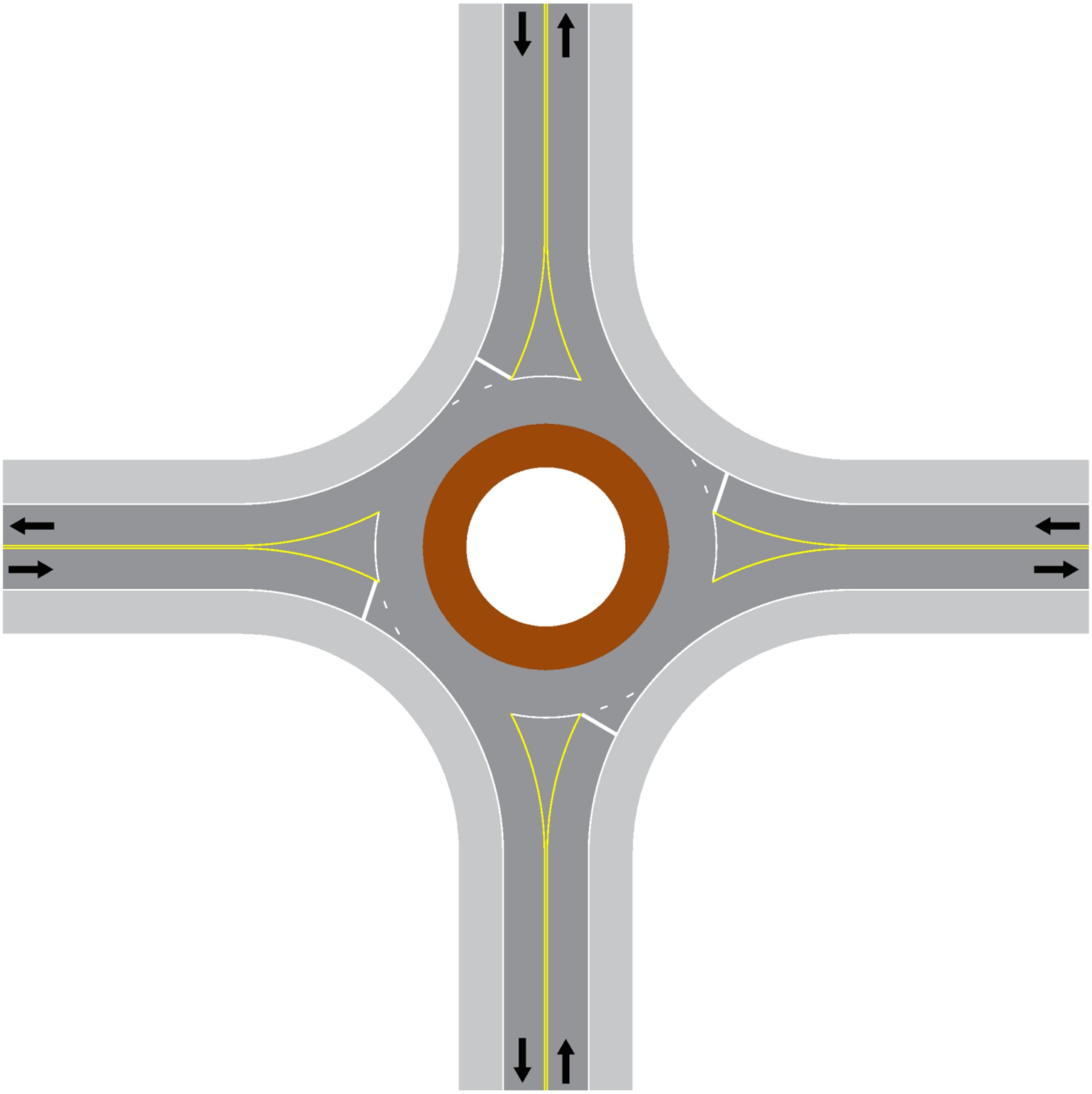


Figure 4.2.4.1.5 Roundabout phased construction with partial closures final configuration

This phasing organization mitigates closure to one roundabout leg for a single phase. The closure of certain legs may be considered based on traffic counts. Other phases may incorporate a flagging operation to allow full access among traffic movements (VDOT). Attention to proper signage and public outreach is important to ensure travelers do not mistake final roundabout configuration and make illegal turning movements.

An additional method that could be used to retrofit an existing conventional intersection into a roundabout intersection is through the use of a temporary runaround similar to the methods found in the Washington County, MN sample plans. Phased construction with the use of a temporary runaround involves three main phases. Figure 4.2.1.1.6 shows the initial condition of the conventional intersection.

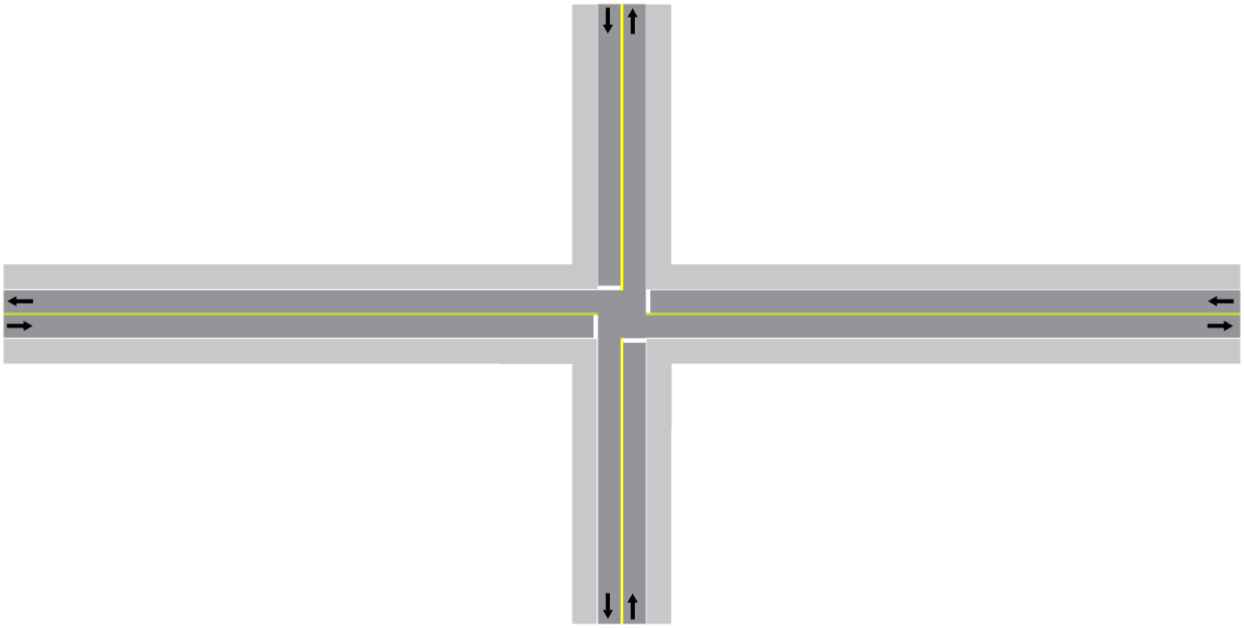


Figure 4.2.1.1.6 Roundabout phased construction with a temporary runaround initial condition

Phase 1 involves construction of the temporary runaround, considering movements needed to remain open through construction. This decision could be based on site considerations, such as emergency access or traffic counts. Figure 4.2.1.1.7 shows the work area and MOT for phase 1 of roundabout construction. Phase 1 does not result in any significant effect to traffic movements.

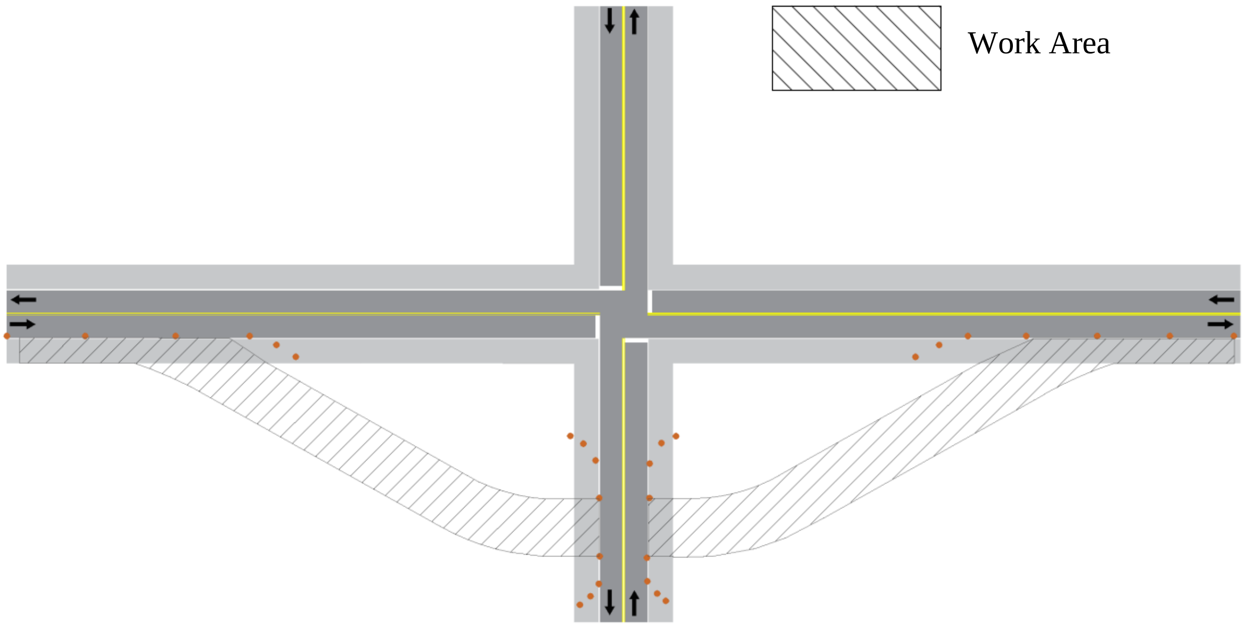


Figure 4.2.4.1.7 Roundabout phased construction with a temporary runaround Phase 1

Phase 2 involves diverting traffic to the temporary runaround, allowing full closure of intersection to be converted to a roundabout. The use of one temporary runaround results in a temporary closure of one leg of the existing intersection. Additional runarounds may be constructed to further allow access. Figure 4.2.4.1.8 shows the work area and MOT through this phase of construction.

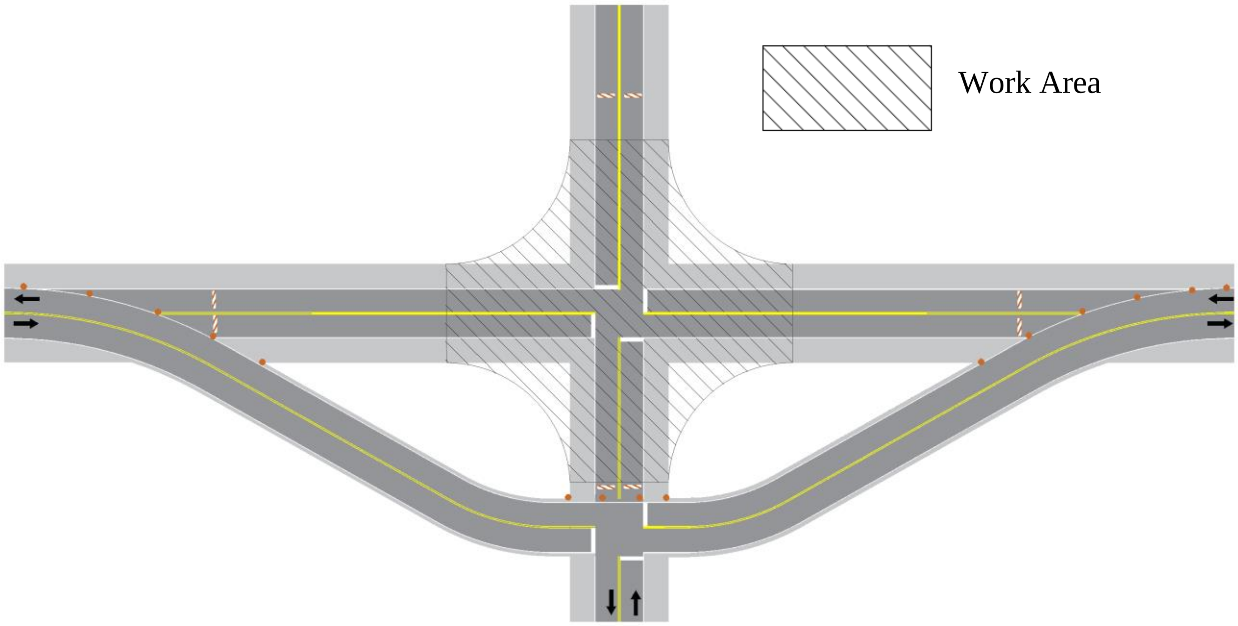


Figure 4.2.4.1.8 Roundabout phased construction with a temporary runaround Phase 2

Phase 3 begins once the roundabout construction is complete. Traffic is shifted onto the final roundabout configuration and deconstruction of the temporary runaround begins. Full access is allowed through Phase 3. Figure 4.2.4.1.9 shows the work area and MOT for this phase of construction.

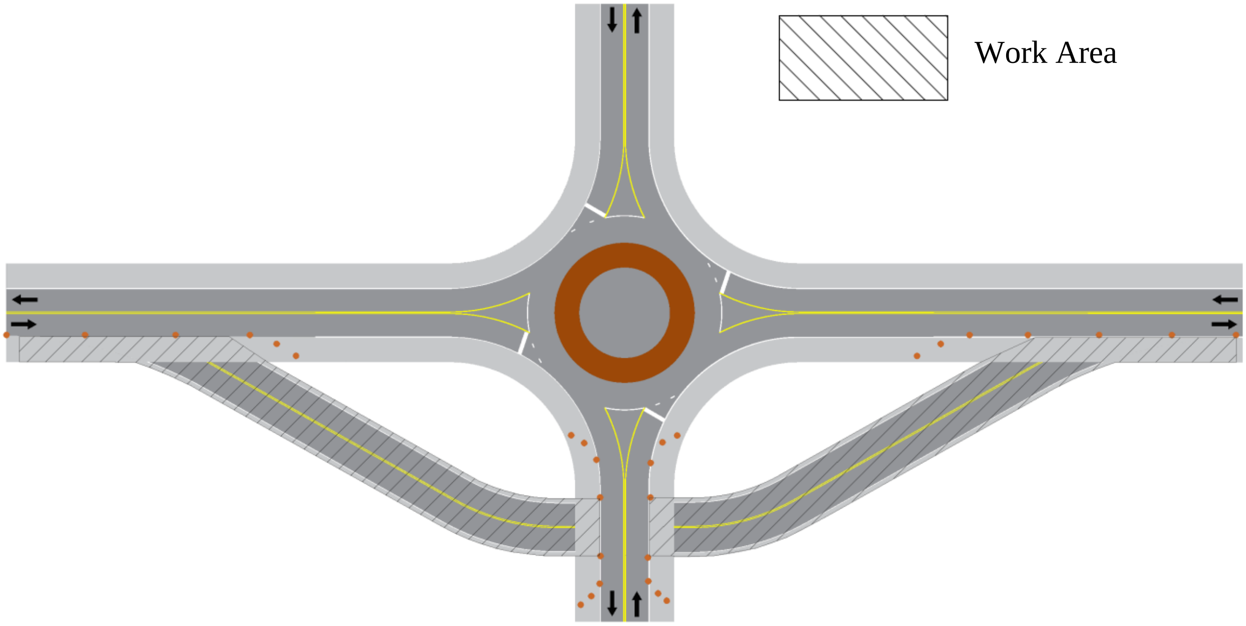


Figure 4.2.4.1.9 Roundabout phased construction with a temporary runaround Phase 3

The roundabout may be fully opened once the temporary runaround is deconstructed. Figure 4.2.4.1.10 shows the final configuration of the roundabout.

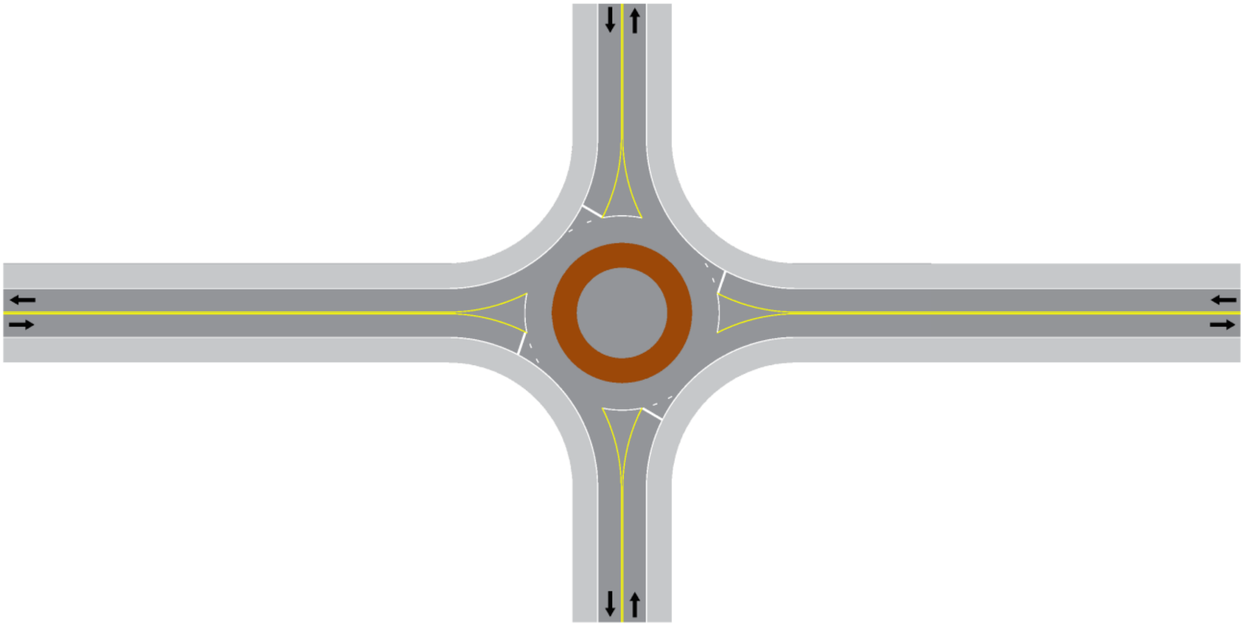


Figure 4.2.4.1.10 Roundabout phased construction with a temporary runaround final configuration

This construction phasing method allows for vital intersection movements to remain open while fully closing the existing intersection to expedite the construction process. The use of a temporary runaround provides a benefit of not requiring the usage of a flagging operation in order to maintain access. However, full closure may prove to be not as cost effective due to the construction of a bypass.

4.2.4.2 SPUI

SPUIs can typically be constructed from a conventional diamond interchange while maintaining full access for all movements. A phased construction scheme of five phases was developed utilizing ODOT SPUI sample plans as well as other DOT and phone interview experiences. Figure 4.2.4.2.1 shows the initial conventional diamond interchange considered.

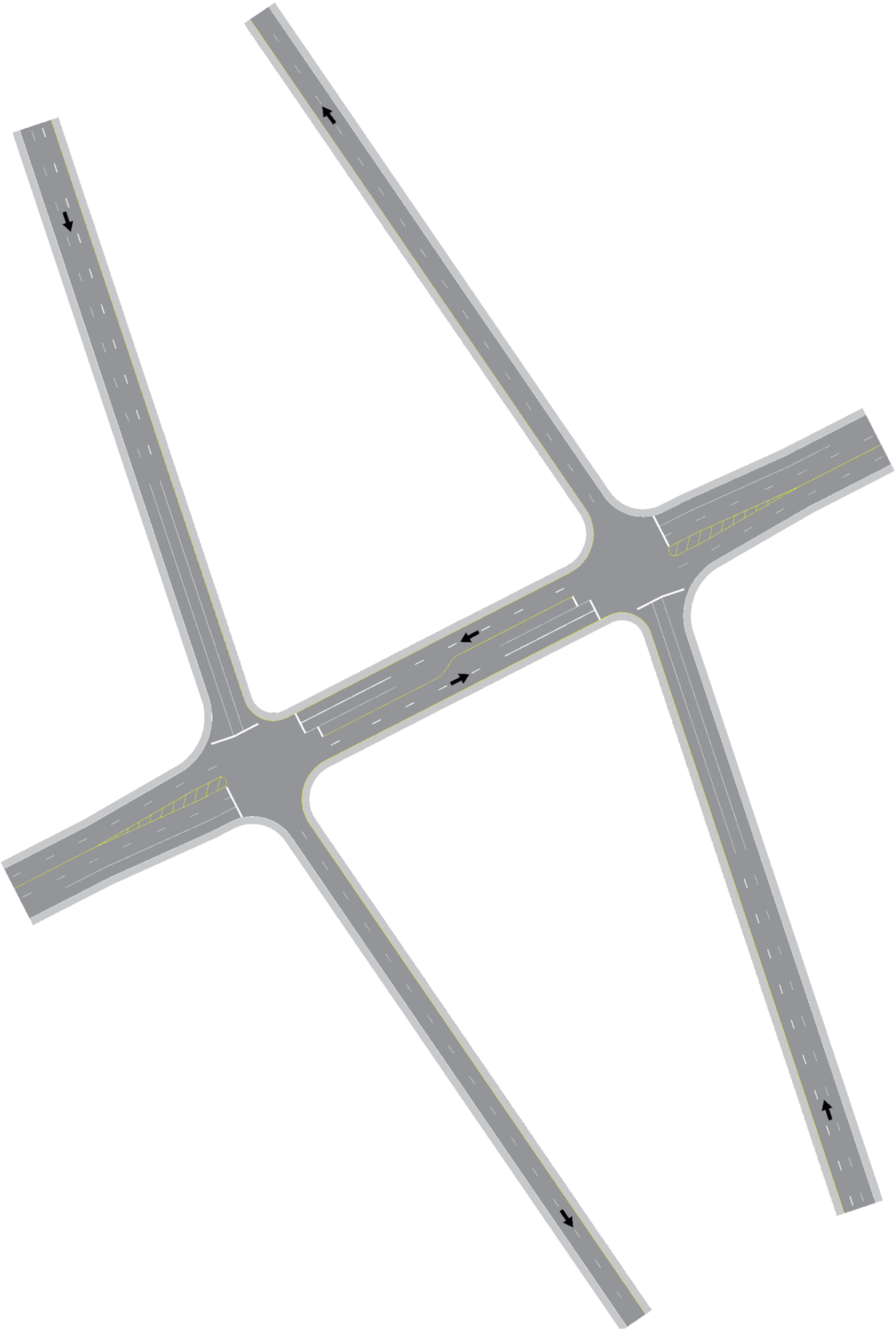


Figure 4.2.4.2.1 SPUI phased construction initial condition

Phase 1 involves the widening of the existing bridge to the final required width. This stage has little effect on bridge traffic due to barriers allowing travel to occur on adjacent lanes of bridge widening. Figure 4.2.4.2.2 shows the work area and MOT through this phase of construction.

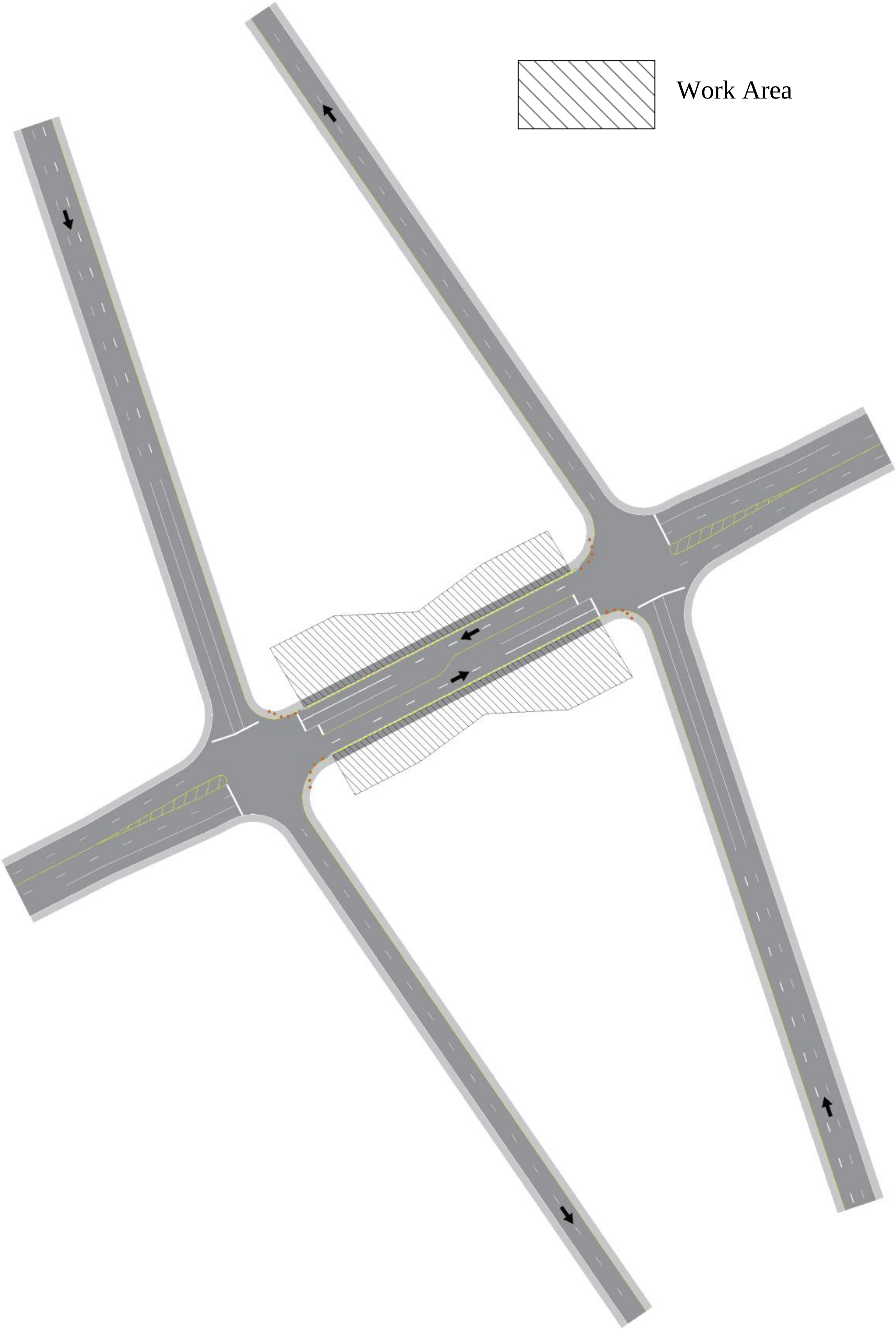


Figure 4.2.4.2.2 SPUI phased construction Phase 1

Phase 2 involves beginning construction of the left-turn ramps once the bridge widening is complete. This involves temporary closure of the innermost lane for both entrance and exit ramps. Figure 4.2.4.2.3 shows the work area and MOT through Phase 2 of construction.

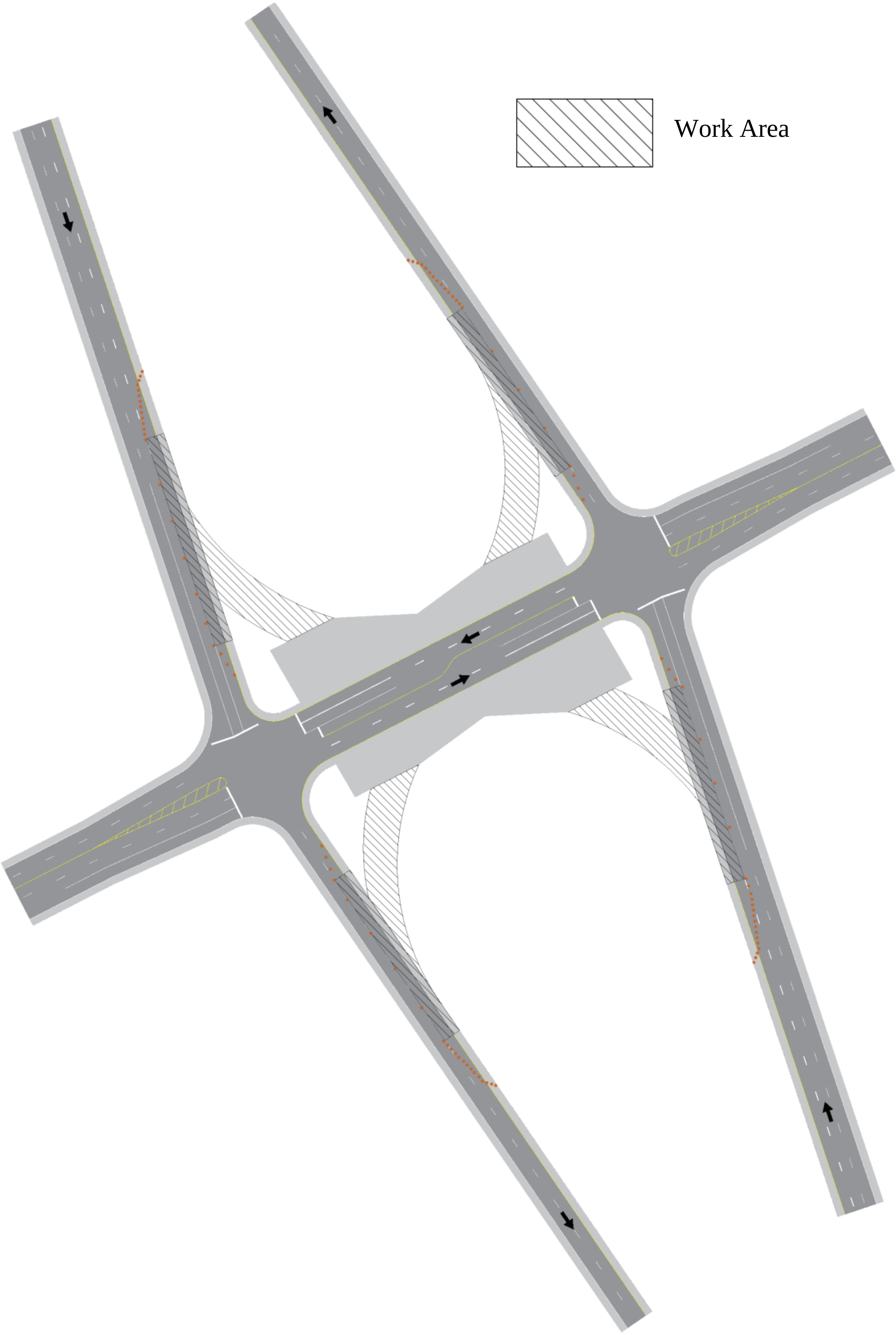


Figure 4.2.4.2.3 SPUI phased construction Phase 2

Phase 3 is divided into two sub-phases which involve construction of the connections to the newly constructed ramps and connections to the ramps constructed in the following phase. Phase 3a involves a temporary closure of one lane for the newly constructed ramps and existing ramps. During this phase, traffic is shifted to one-side of the bridge to allow for one side of the roadway widening to be constructed. The connection is finalized between the newly constructed ramps and the existing roadway. The existing intersection signals are removed and a temporary traffic signal is placed at the center of the bridge for the left turn and through movements, while right turning movements at the initial condition intersections are converted to stop control. Figure 4.2.4.2.4 shows the work area and MOT through Phase 3a.

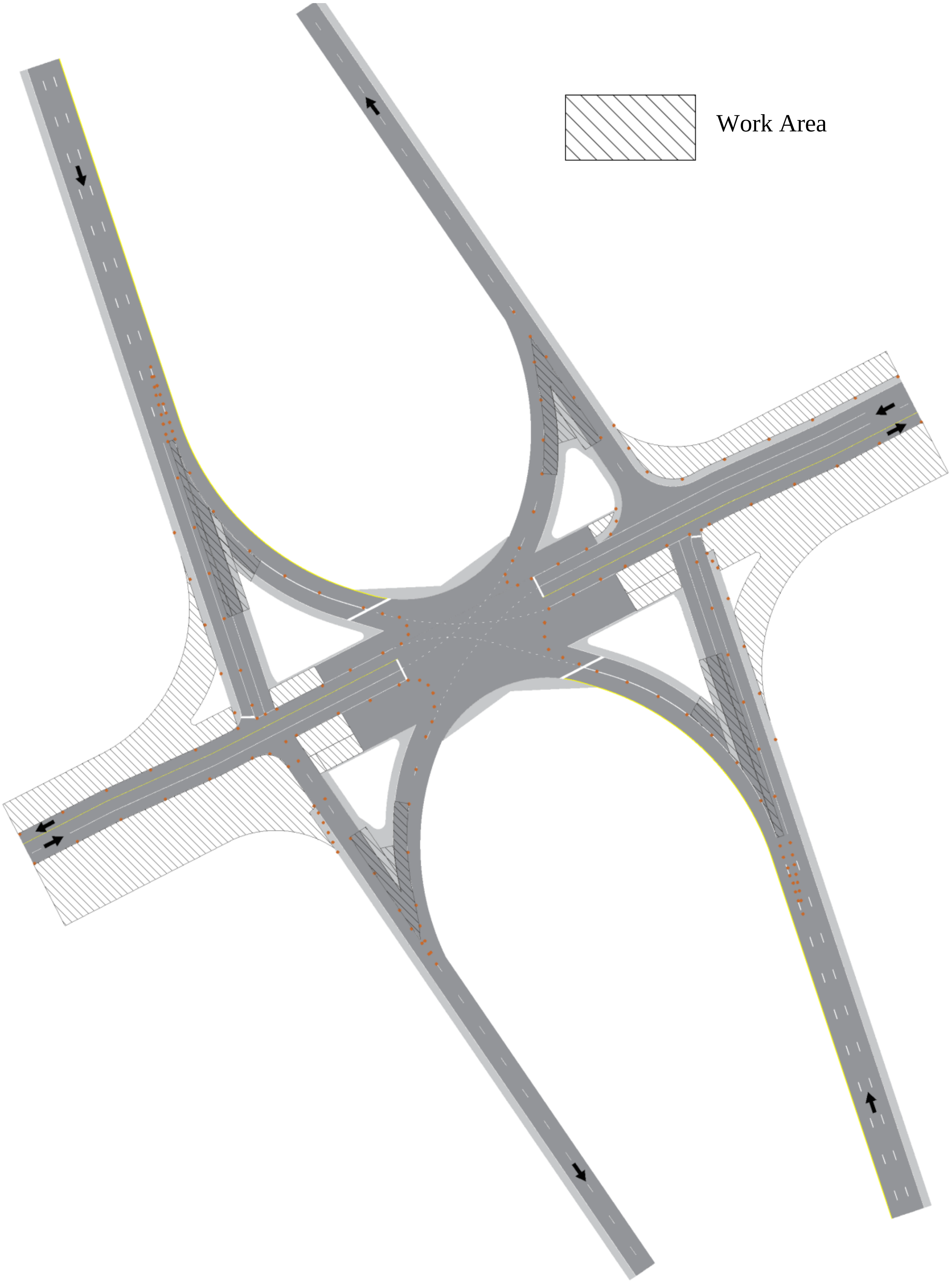


Figure 4.2.4.2.4 SPUI phased construction Phase 3a

Phase 3b begins once the connections between the left turn ramps and existing ramps. Right turn traffic is shifted onto the innermost lane of the existing ramps and construction begins for the right turn facilities. Throughout this phase construction is continued for the roadway widening available and the temporary traffic signal remains in the location previously placed. Figure 4.2.4.2.5 shows the work area and MOT through Phase 3b.

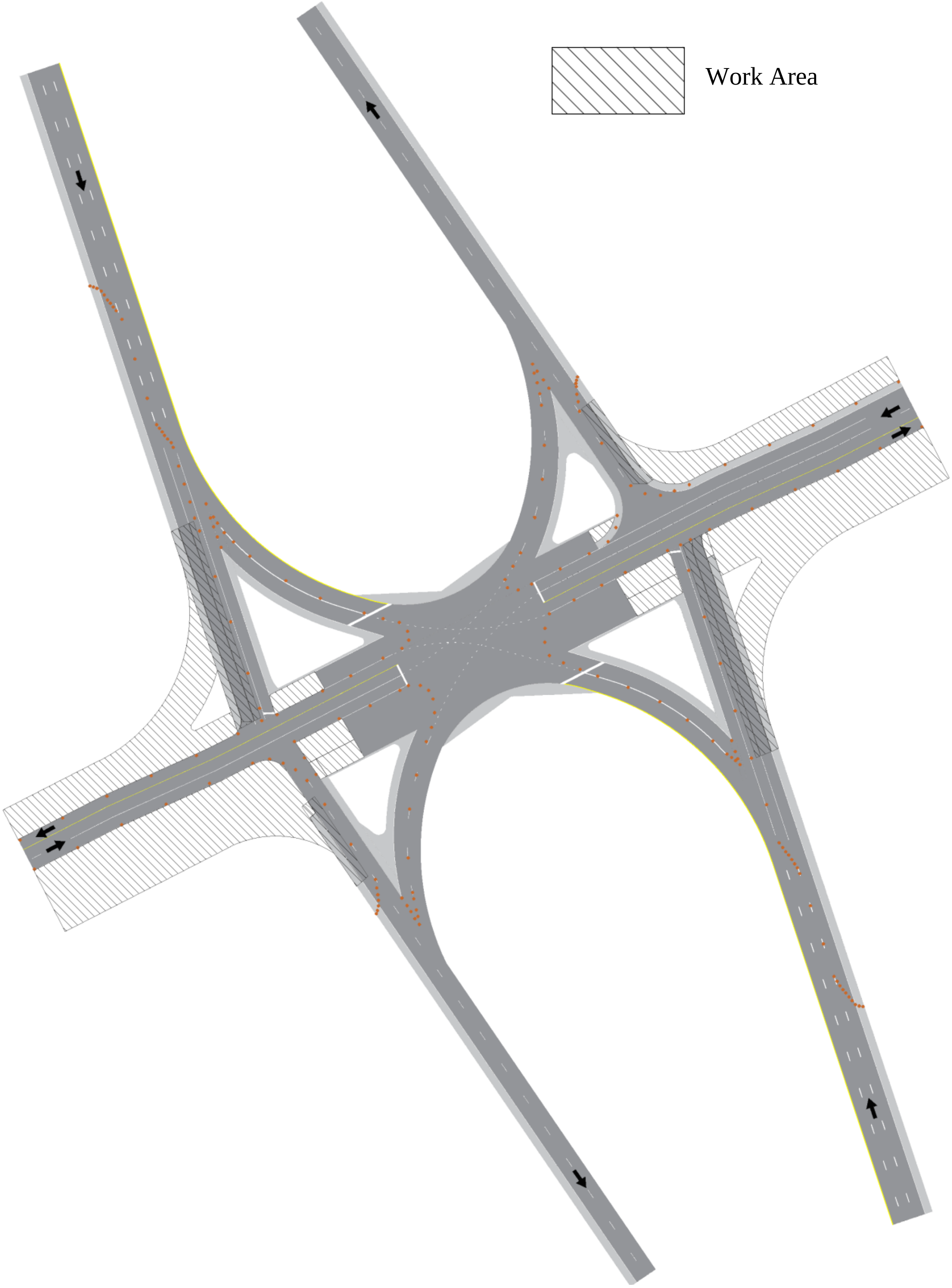


Figure 4.2.4.2.5 SPUI phased construction Phase 3b

Phase 4 begins once the turning facilities are complete for the SPUI. Traffic is shifted onto the final ramp movements and the cross-traffic lanes are shifted onto the newly constructed roadway. This allows for the widening of the opposite side of the roadway to commence. The temporary traffic signal is moved with this shift and the conventional diamond approaches are deconstructed. Figure 4.2.4.2.6 shows work area and MOT through this construction phase.

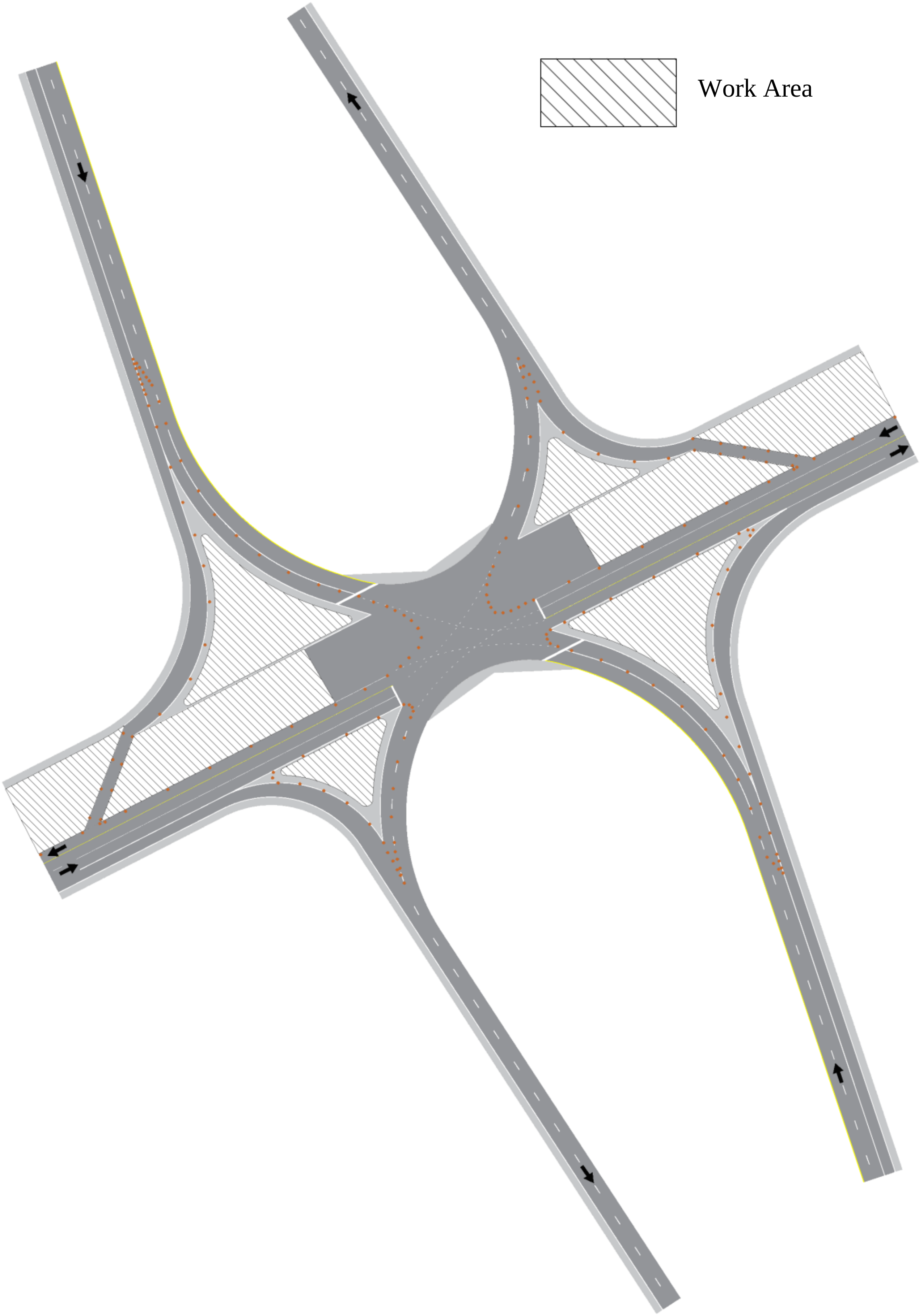


Figure 4.2.4.2.6 SPUI phased construction Phase 4

Once the roadway widening is complete, traffic is shifted onto the final SPUI configuration and the final signal control is installed. Figure 4.2.4.2.7 shows the final SPUI configuration.

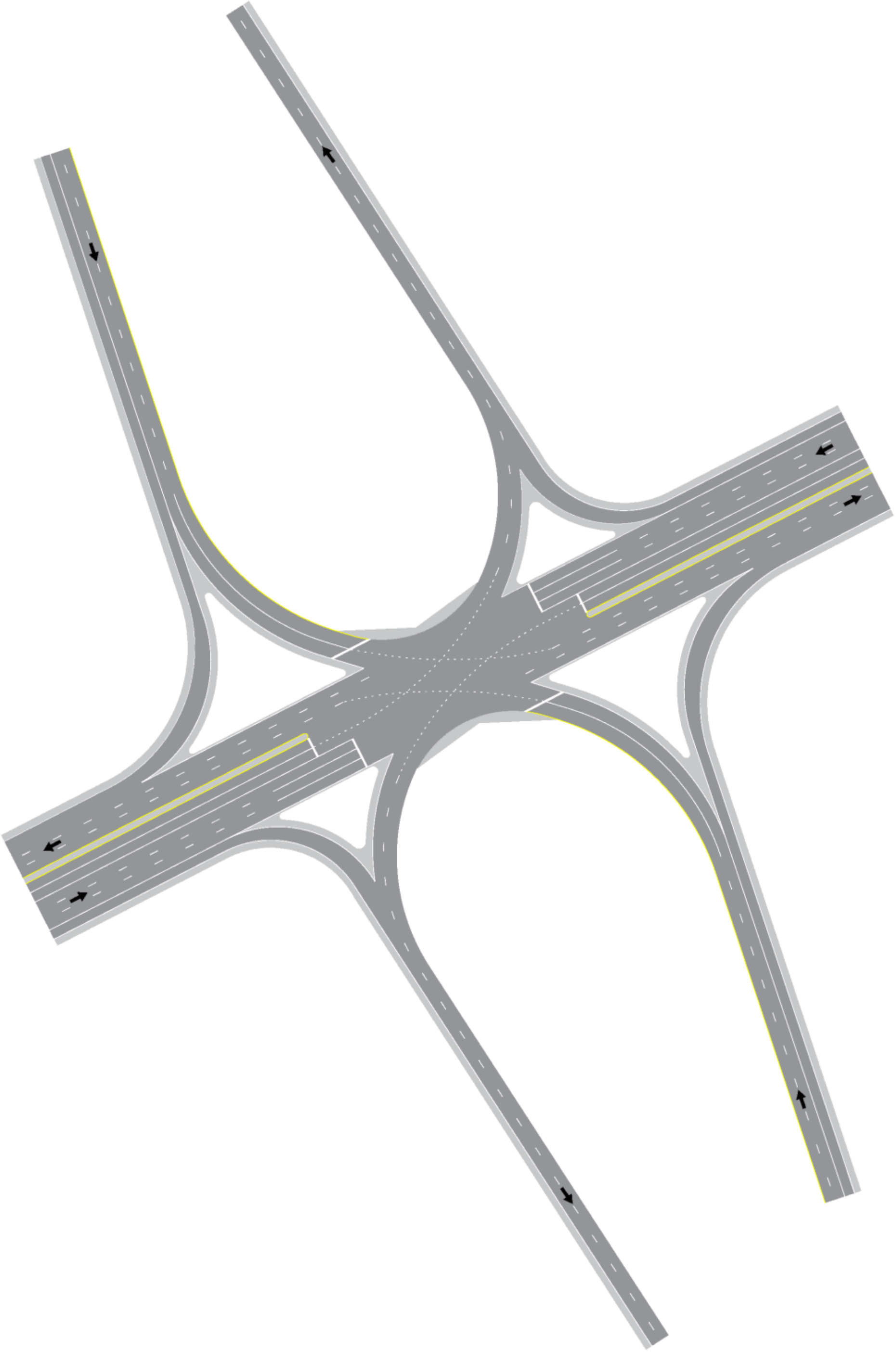


Figure 4.2.4.2.7 SPUI phased construction final configuration

This construction phasing method allows for a full retrofit from a conventional diamond interchange to a SPUI while maintaining full access. Shifting the traffic signals from the conventional diamond interchange setup to the SPUI location once the left-turn facilities are constructed allows for the full width of the bridge to be used for left-turn movements which provide space outside of the bridge for further construction.

4.2.4.3 DDI

DDIs can typically be constructed from a conventional diamond interchange while maintaining full access for all movements. A phased construction scheme for a DDI was developed utilizing six main phases. This scheme was developed based on experiences from MoDOT, Crawford, Murphy, and Tilly sample plans as well as industry expert phone interviews and Schroeder et al. (2014). Figure 4.2.4.3.1 shows the conventional diamond interchange considered.

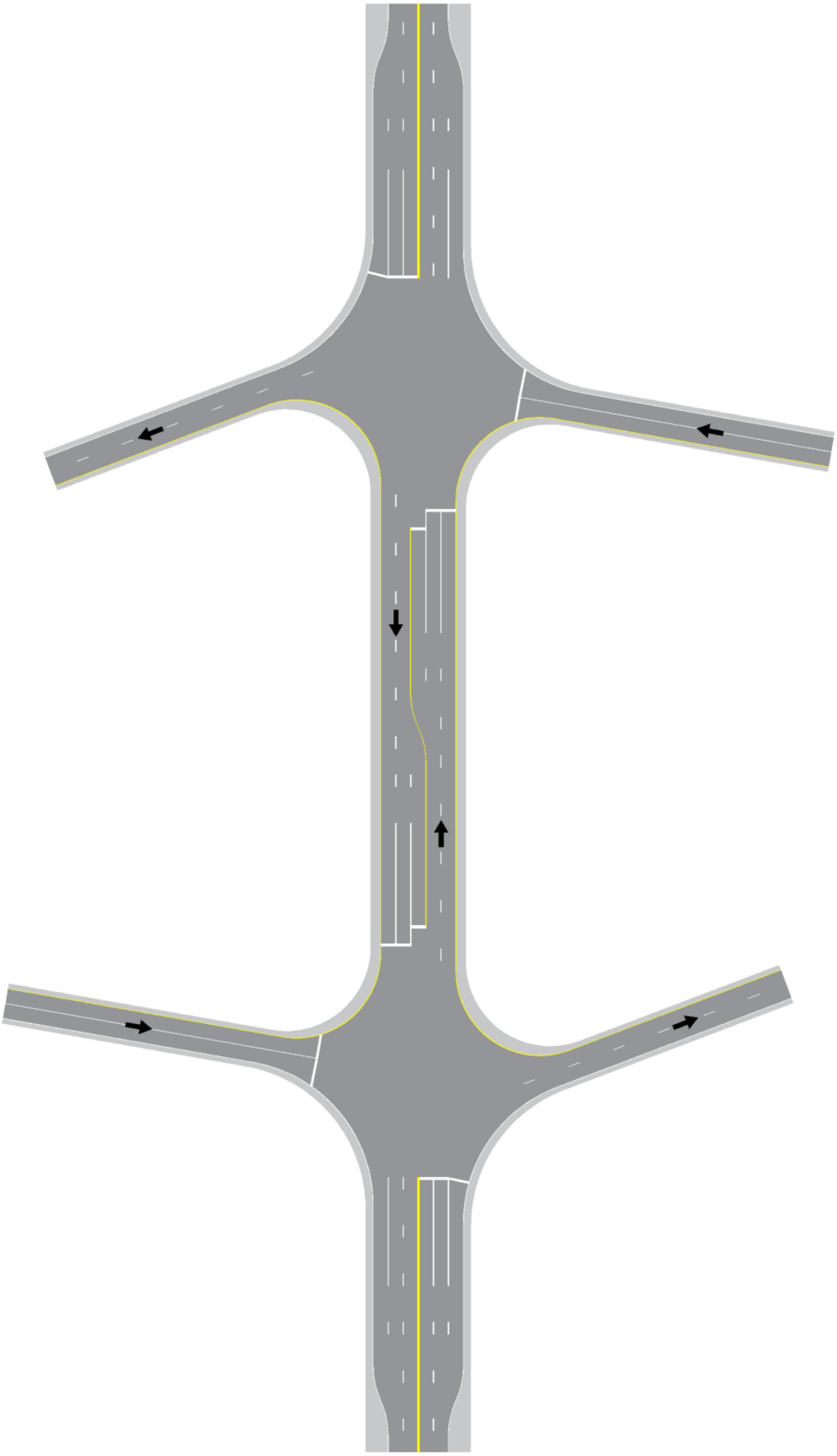


Figure 4.2.4.3.1 DDI phased construction initial condition

Phase 1 begins with construction of the bridge widening, if applicable, through the conventional diamond intersection. One benefit of a DDI interchange is that it does not require additional bridge cross-section when a pedestrian walkway is not constructed, however, the MOT Phasing Diagrams designed account for this construction of a pedestrian walkway. The staging methodology when a bridge widening is not required is similar to the MOT Phasing Diagrams designed without the additional cross-section. The section of crossovers falling outside of the existing roadway is constructed through Phase 1 for both scenarios. Figure 4.2.4.3.2 shows the work area and MOT through this phase of construction.

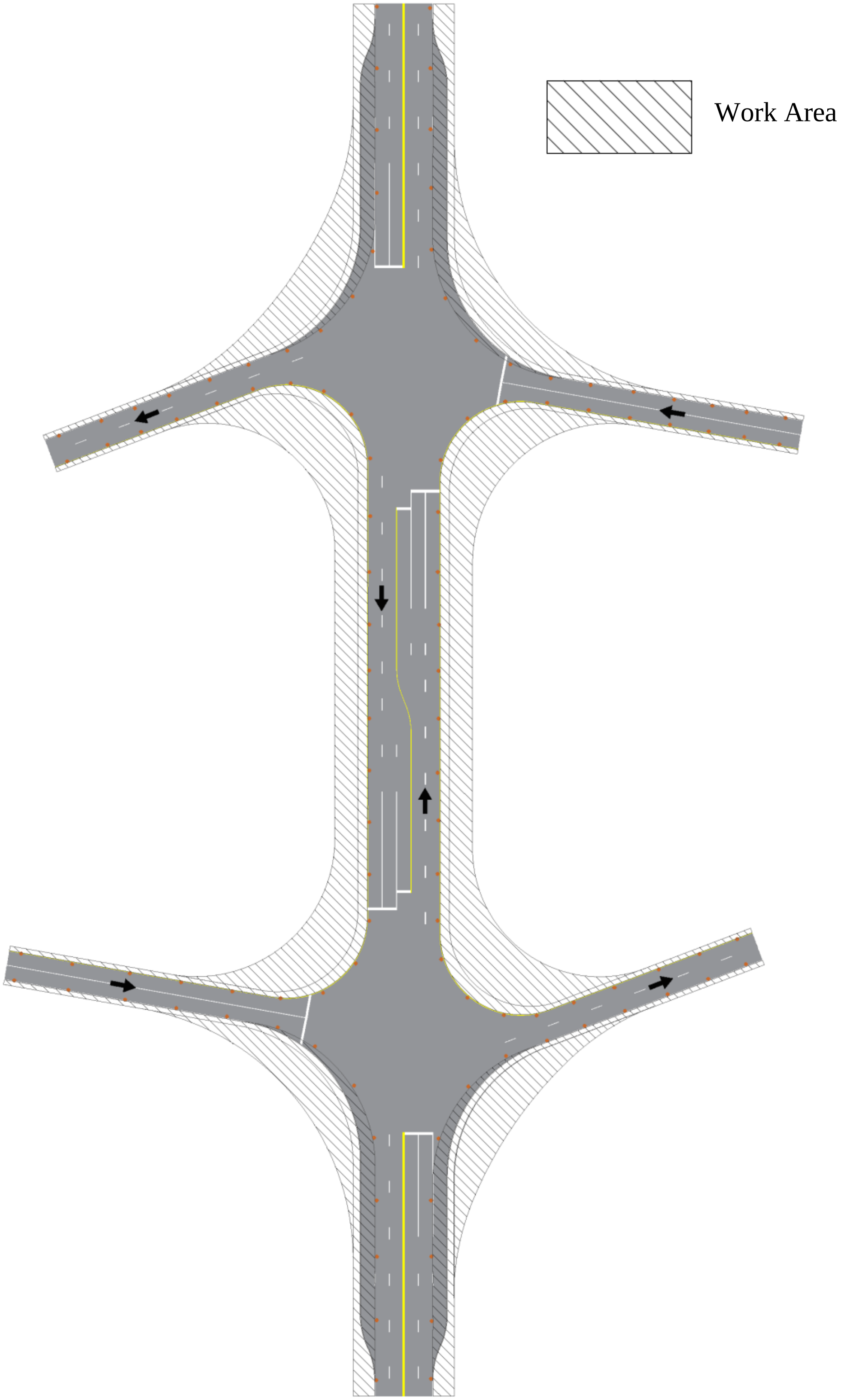


Figure 4.2.4.3.2 DDI phased construction Phase 1

Phase 2 begins with shifting the bridge deck traffic onto one side and beginning reconstruction of the bridge deck on the opposite side, if necessary. Construction of portions of crossovers outside of the existing roadway continues through Phase 2. Figure 4.2.4.3.3 shows the work are and MOT through this phase of construction.

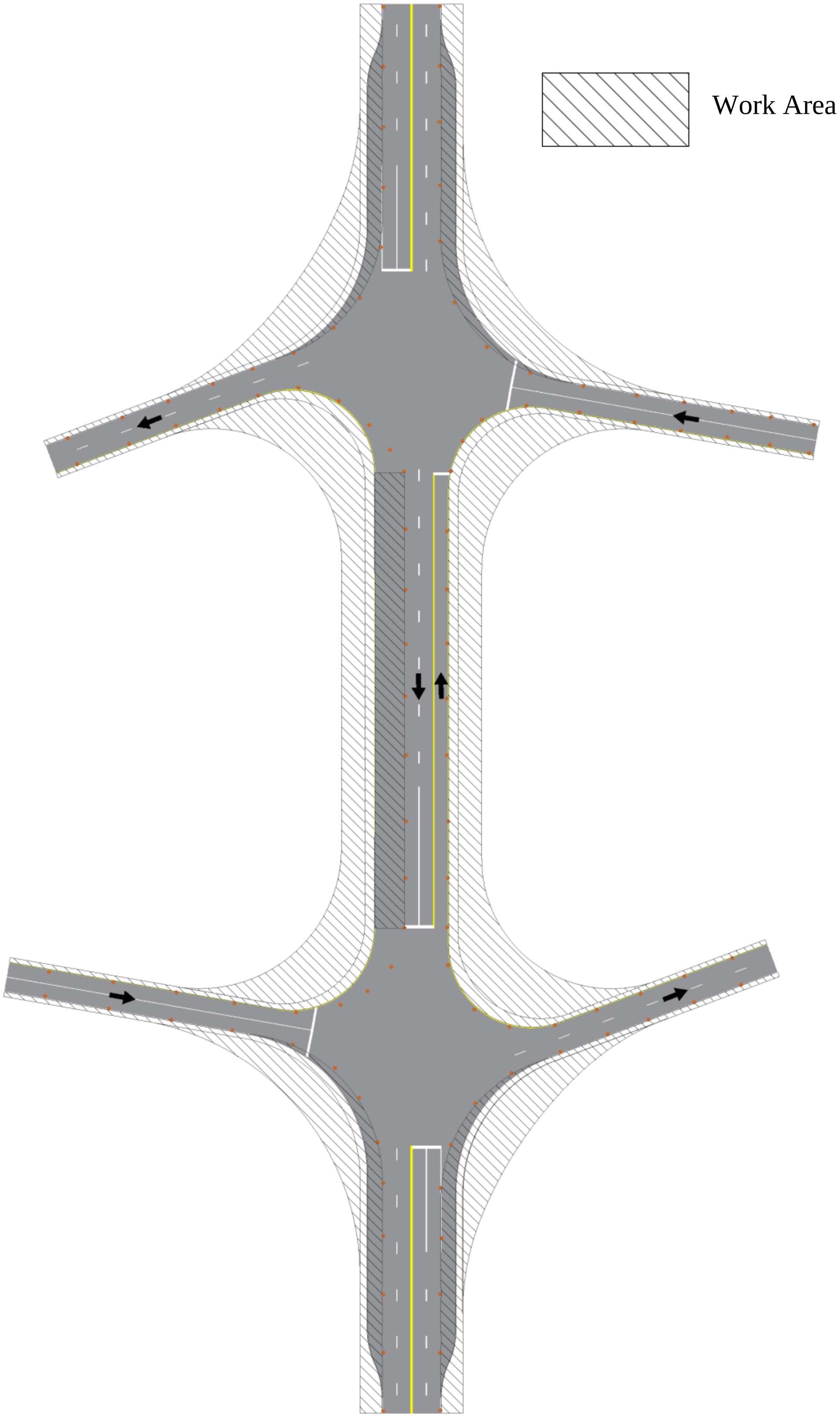


Figure 4.2.4.3.3 DDI phased construction Phase 2

Phase 3 begins once the construction of the existing diamond intersection widening is complete. One direction of traffic is shifted to onto the newly constructed bridge deck, leaving the opposite direction on the exterior of the existing bridge deck available for reconstruction. Reconstruction begins for the innermost lane and median on the bridge deck and approaching roadways. The widening of the existing bridge deck continues constructing throughout this phase. Figure 4.2.4.3.4 shows the work area and MOT through this phase of construction.

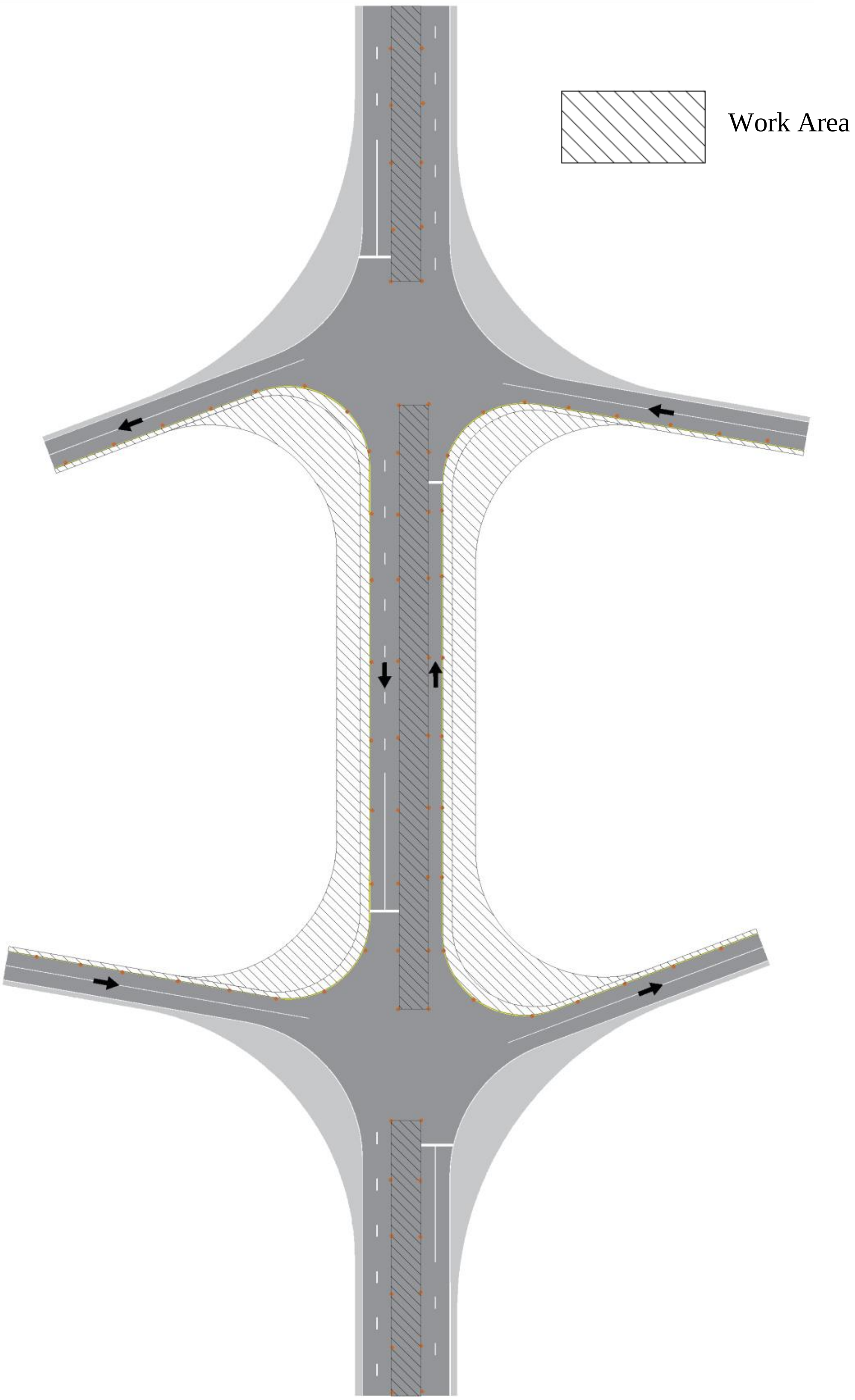


Figure 4.2.4.3.4 DDI phased construction Phase 3

Phase 4 involves shifting the bridge deck traffic from the existing bridge deck onto the newly constructed innermost lane. The bridge deck widening and construction of the medians through the bridge deck and approaching roadway is continued through Phase 4. Figure 4.2.4.3.5 shows the work area and MOT for this construction phase.

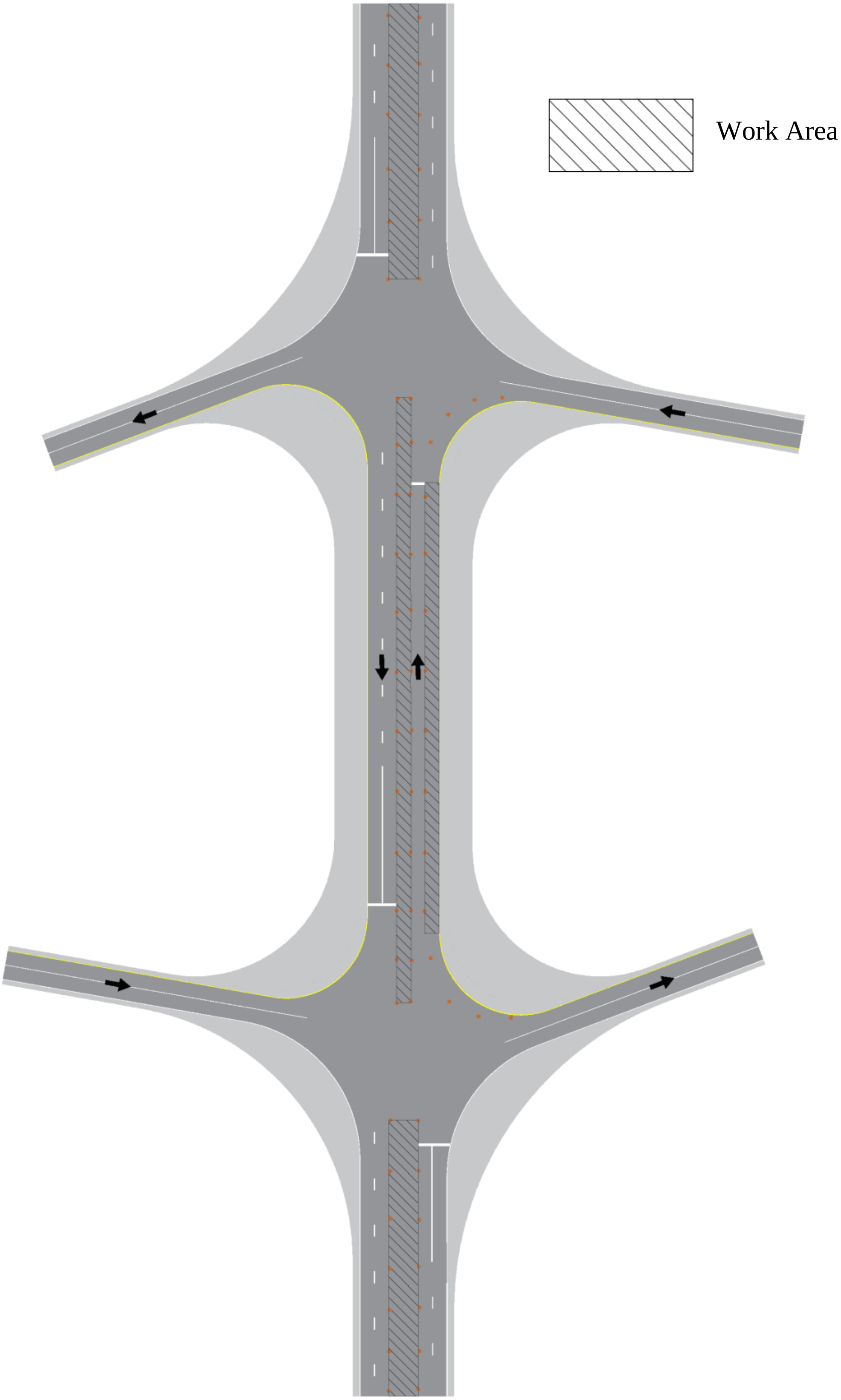


Figure 4.2.4.3.5 DDI phased construction Phase 4

Phase 5 begins once the bridge deck widening is complete. Utilizing temporary traffic control devices, traffic is shifted to final DDI configuration. This step requires a short complete closure of the interchange to set up the final DDI configuration with temporary traffic control devices. The final signal control is also constructed during this phase. This closure could occur overnight or during weekend periods to minimize effect on area traffic. Once traffic is shifted to the final DDI configuration, constructing the raised medians at each of the crossovers begins. Figure 4.2.4.3.6 shows the work area and MOT through this construction phase.

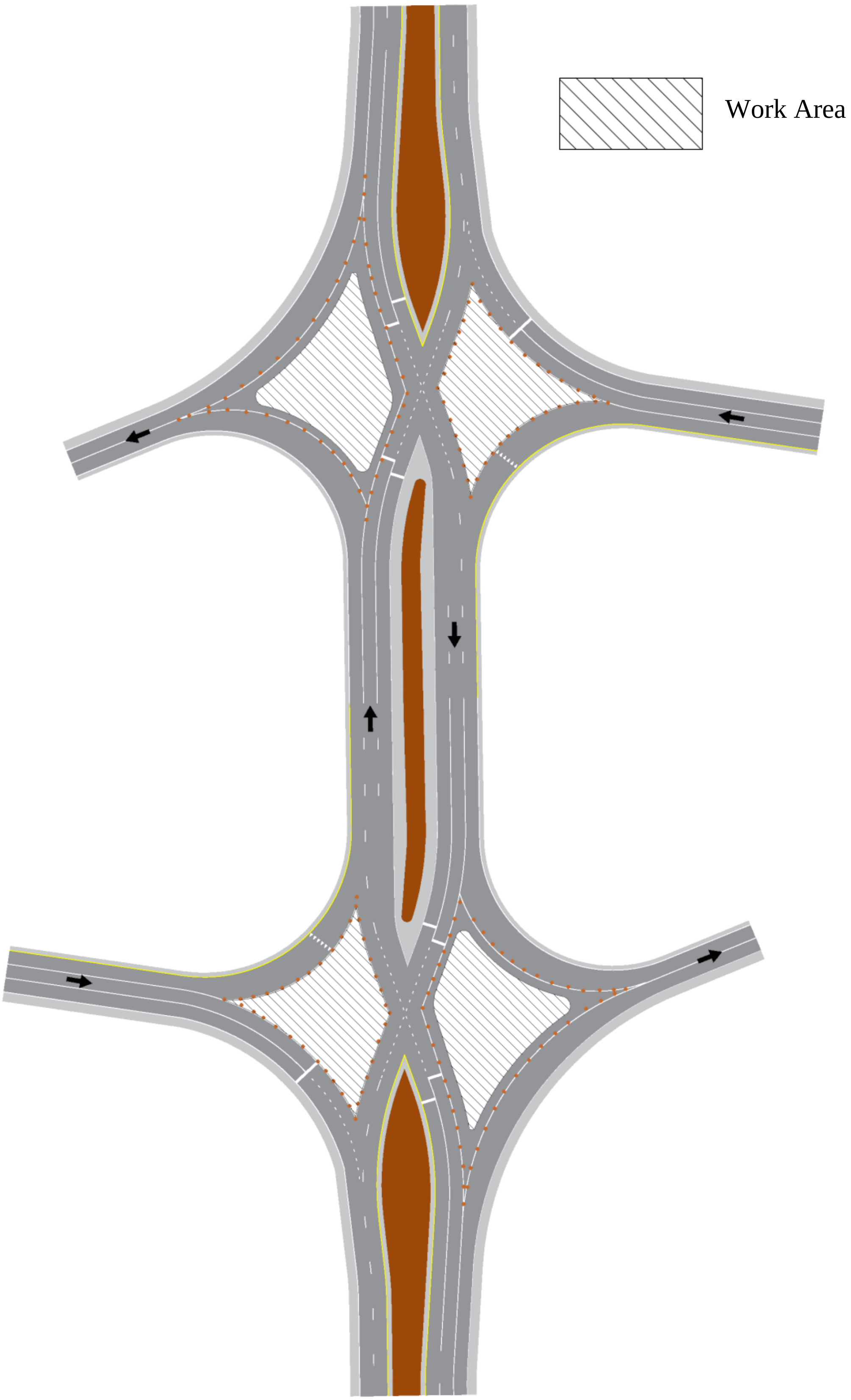


Figure 4.2.4.3.6 DDI phased construction Phase 5

Once the raised medians are constructed, fully open the DDI to the final configuration. Figure 4.2.4.3.7 shows the final DDI configuration.

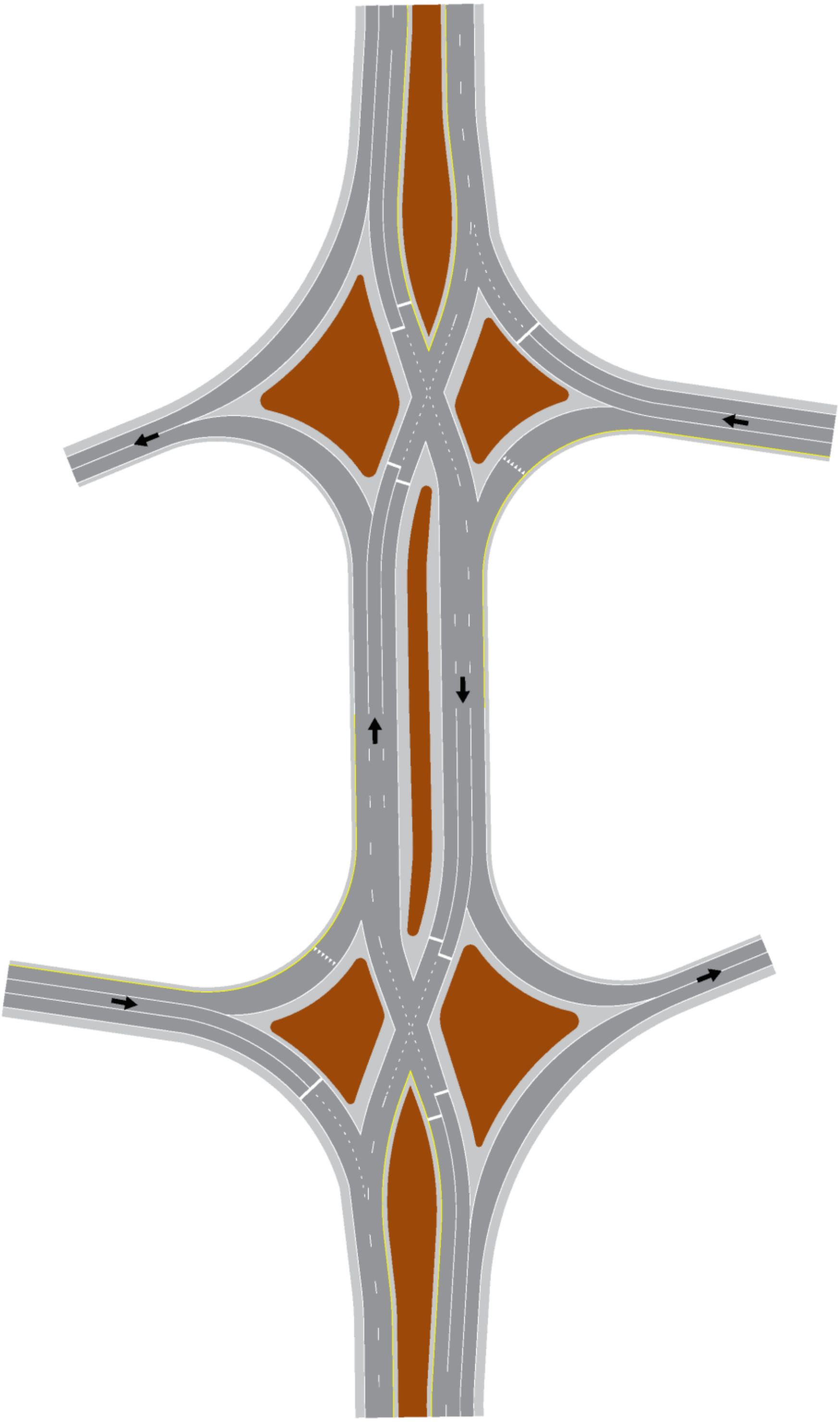


Figure 4.2.4.3.7 DDI phased construction final configuration

This six phase approach allows for the retrofit construction of a DDI while maintaining full access with the exception of short closures to shift traffic to DDI configuration. Deviations from this phasing scheme may occur due to initial intersection configuration, condition of existing infrastructure, etc. High importance should be placed on public outreach with regards to MOT and final DDI configuration to mitigate the risk of wrong way movements through construction.

4.2.4.4 RCUT

RCUT intersection retrofit construction is typically able to be completed while maintaining full access throughout construction. A phased retrofit construction scheme of converting an RCUT from a conventional at-grade intersection was developed utilizing three main phases. This scheme was developed utilizing Hughes et al. (2010) as well as DOT sample plans and industry expert interviews. Figure 4.2.4.4.1 shows the initial intersection considered. The MOT Phasing Diagrams depict an urban RCUT intersection, however, this construction phasing scheme is also applicable to rural setting RCUTs.

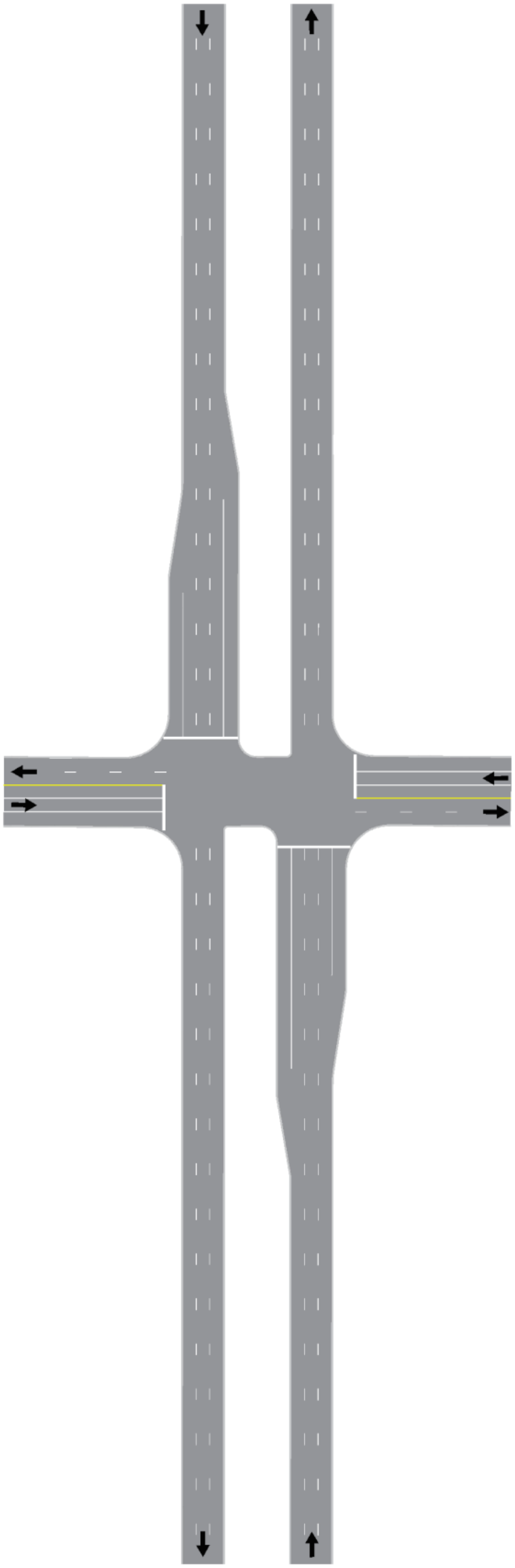


Figure 4.2.4.4.1 RCUT phased construction initial configuration

Phase 1 involves constructing the median U-turns on the main roadway. This phase is completed with little effect on traffic. Figure 4.2.4.4.2 shows the work area and MOT through this construction phase.

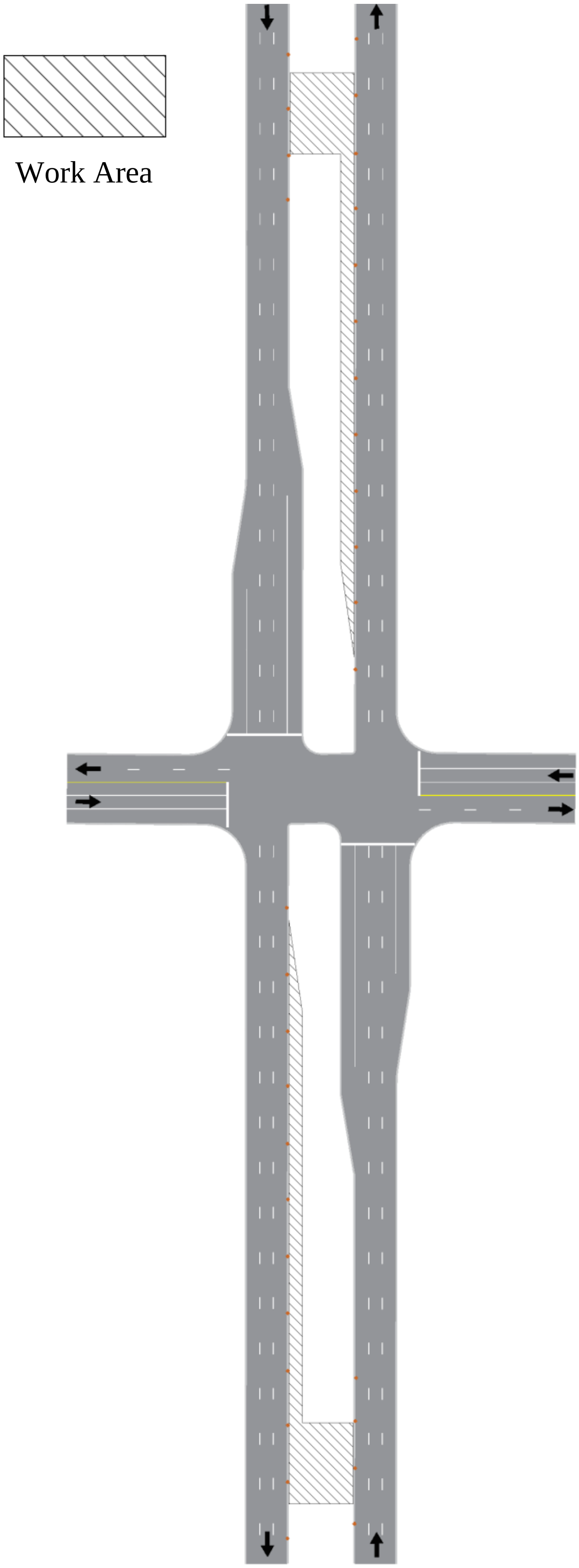


Figure 4.2.4.4.2 RCUT phased construction Phase 1

Phase 2 begins once the median U-turns are constructed. Traffic is shifted from the main roadway left-turning movements and minor roadway through movements onto the newly constructed median U-turns. Removing traffic from the intersection center allows for construction to begin on the RCUT intersection center and minor road medians. Figure 4.2.4.4.3 shows work area and MOT through this construction phase.

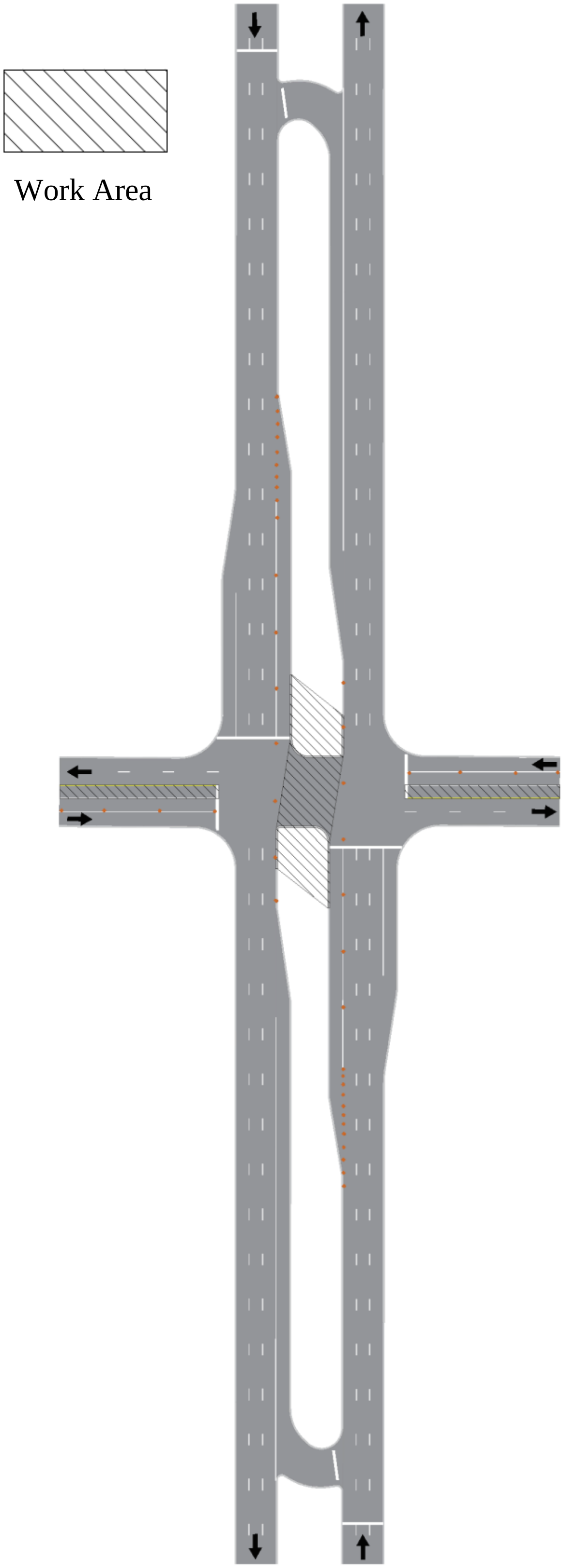


Figure 4.2.4.4.3 RCUT phased construction Phase 2

Once construction within the intersection center and minor roadway medians is complete, traffic is shifted onto the final RCUT configuration. Figure 4.2.4.4.4 shows the final RCUT intersection configuration.

This three phase process allows for the construction of the RCUT intersection while maintaining full access for all movements. Deviations from these MOT Phasing Diagrams could be caused by differing initial configuration, alignments, and other special circumstances.

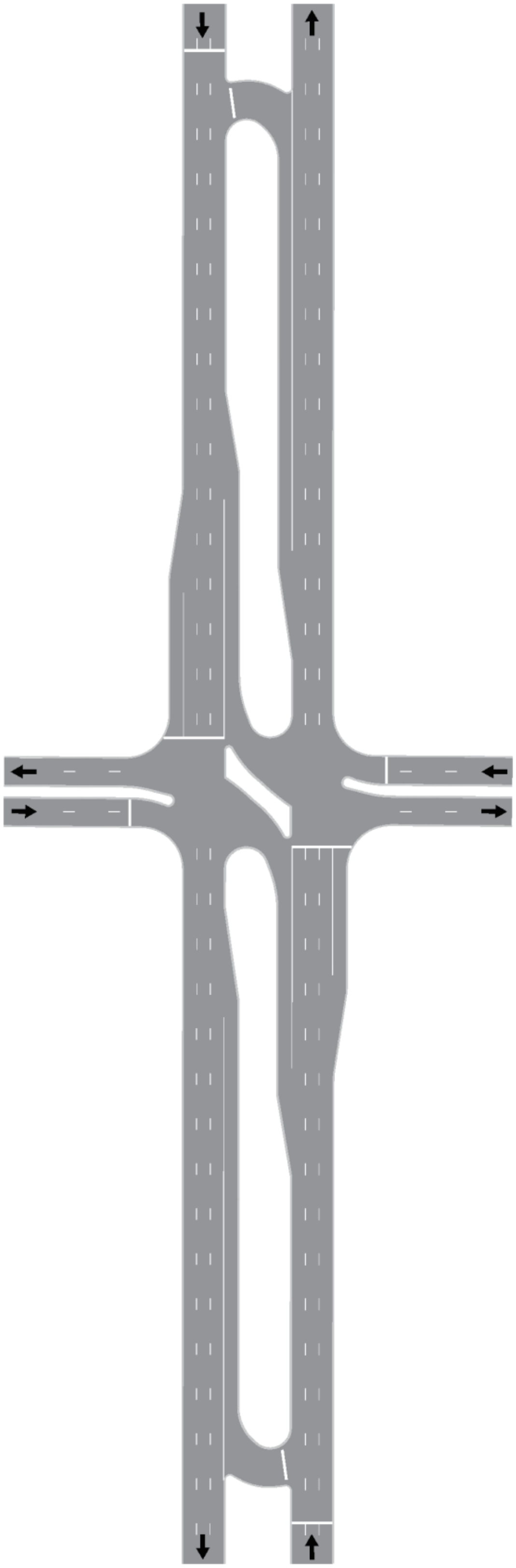


Figure 4.2.4.4.4 RCUT phased construction final configuration

4.2.4.5 MUT

An MUT intersection retrofit from a conventional at-grade intersection is able to be organized to maintain full access during construction. The MUT intersection retrofit construction from a conventional at-grade intersection type was developed utilizing three main phases. This scheme involves all legs of the intersection being converted into an MUT intersection and was developed utilizing Hughes et al. (2010) and industry expert interviews. Figure 4.2.4.5.1 shows the initial intersection considered.

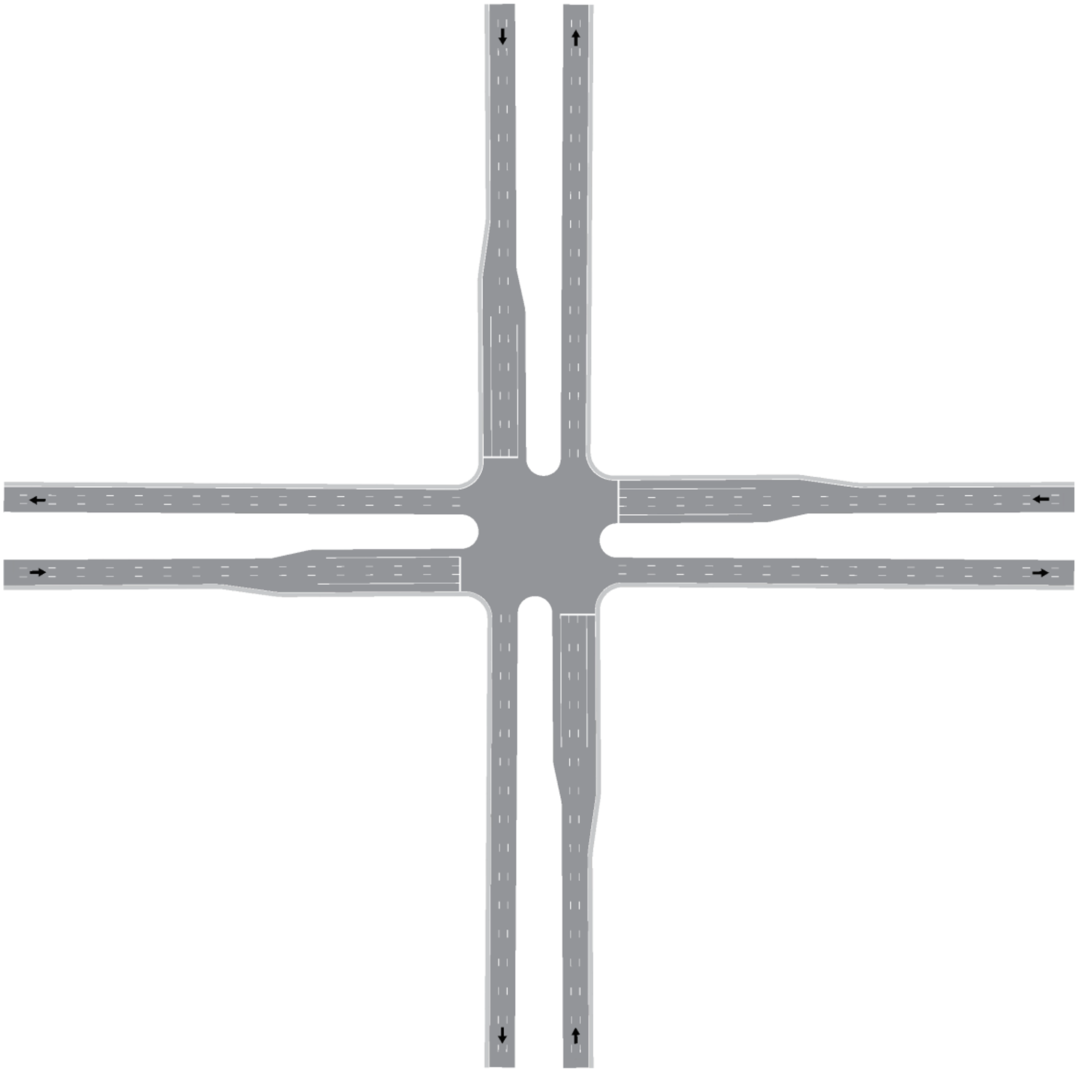


Figure 4.2.4.5.1 MUT phased construction initial configuration

Phase 1 involves constructing the median U-turns on the appropriate roadways. This construction has little effect on traffic and does not require a lane closure. Figure 4.2.4.5.2 shows the work area and MOT for this phase of construction.

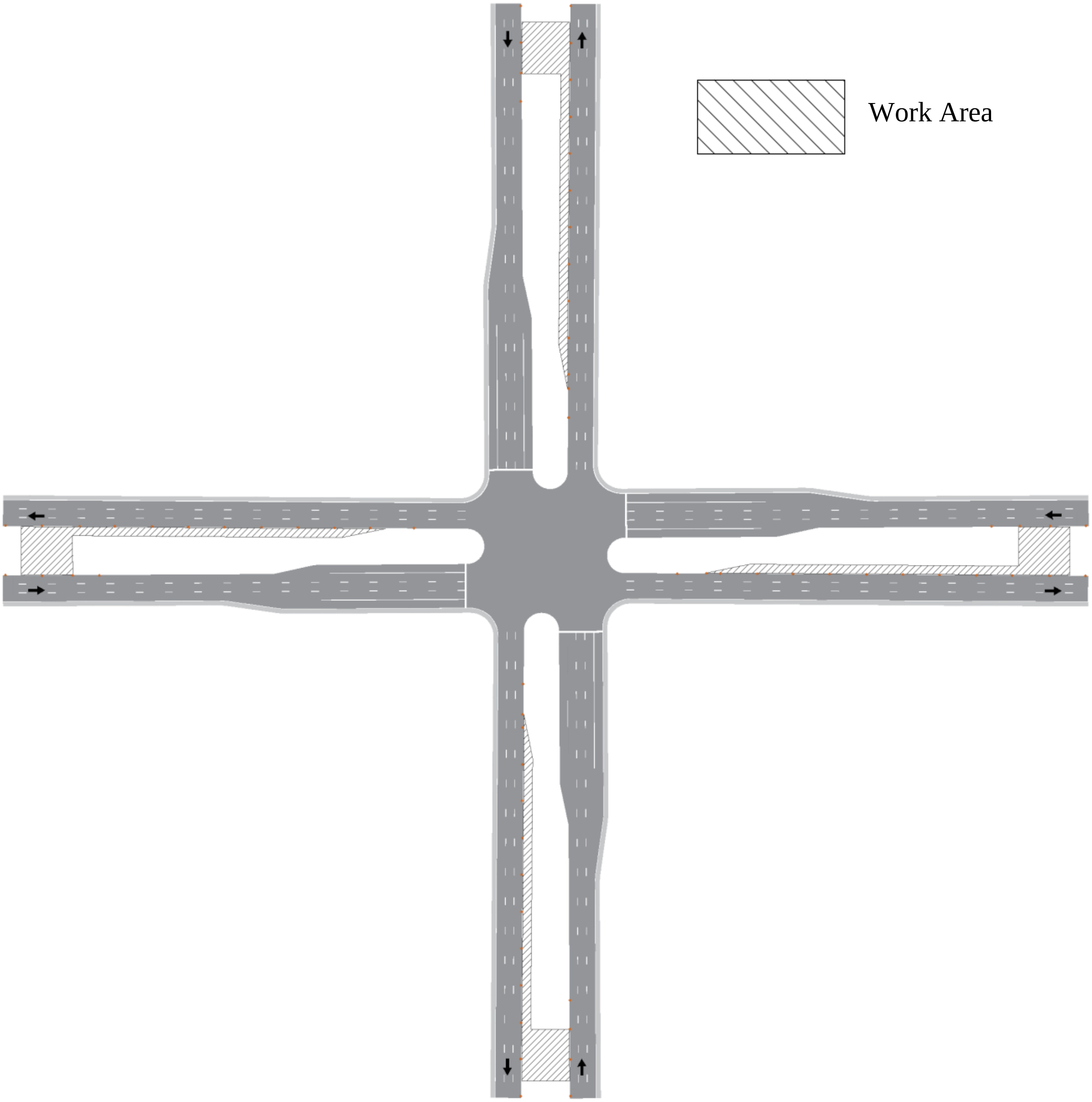


Figure 4.2.4.5.2 MUT phased construction Phase 1

Phase 2 begins once the median U-turns are complete. All turning movement traffic is shifted onto the median U-turns and removal of the intersection center and original left-turn bays begins. The change in intersection configuration may require a short full closure of the intersection to setup the temporary traffic control and ensure travelers acknowledge the change in configuration. Figure 4.2.4.5.3 shows the work area and MOT through this phase of construction.

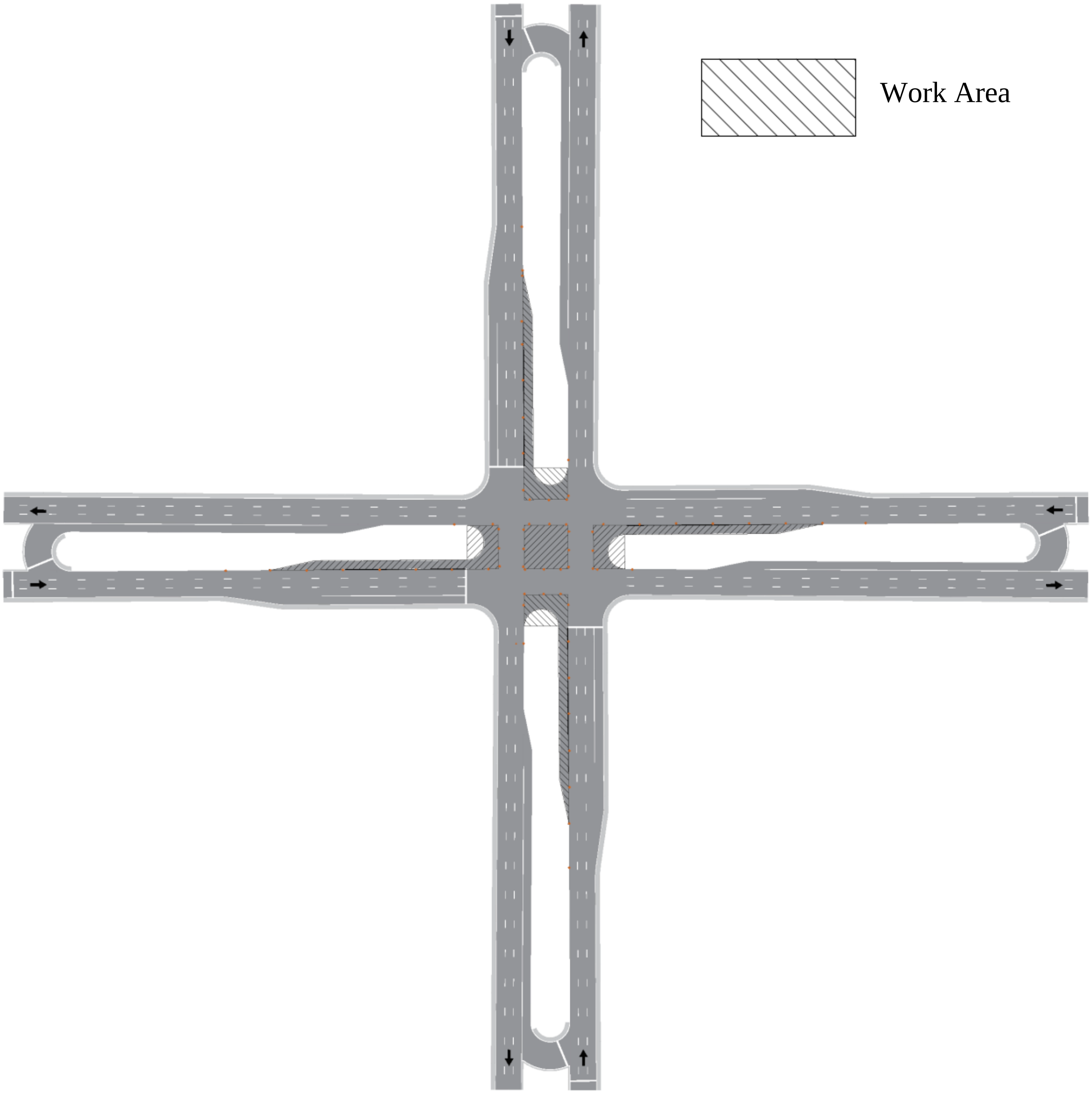


Figure 4.2.4.5.3 MUT phased construction Phase 2

Once removal of the pavement is complete, remove the temporary traffic control and fully open the intersection to MUT configuration. Figure 4.2.4.5.4 shows the final MUT intersection configuration.

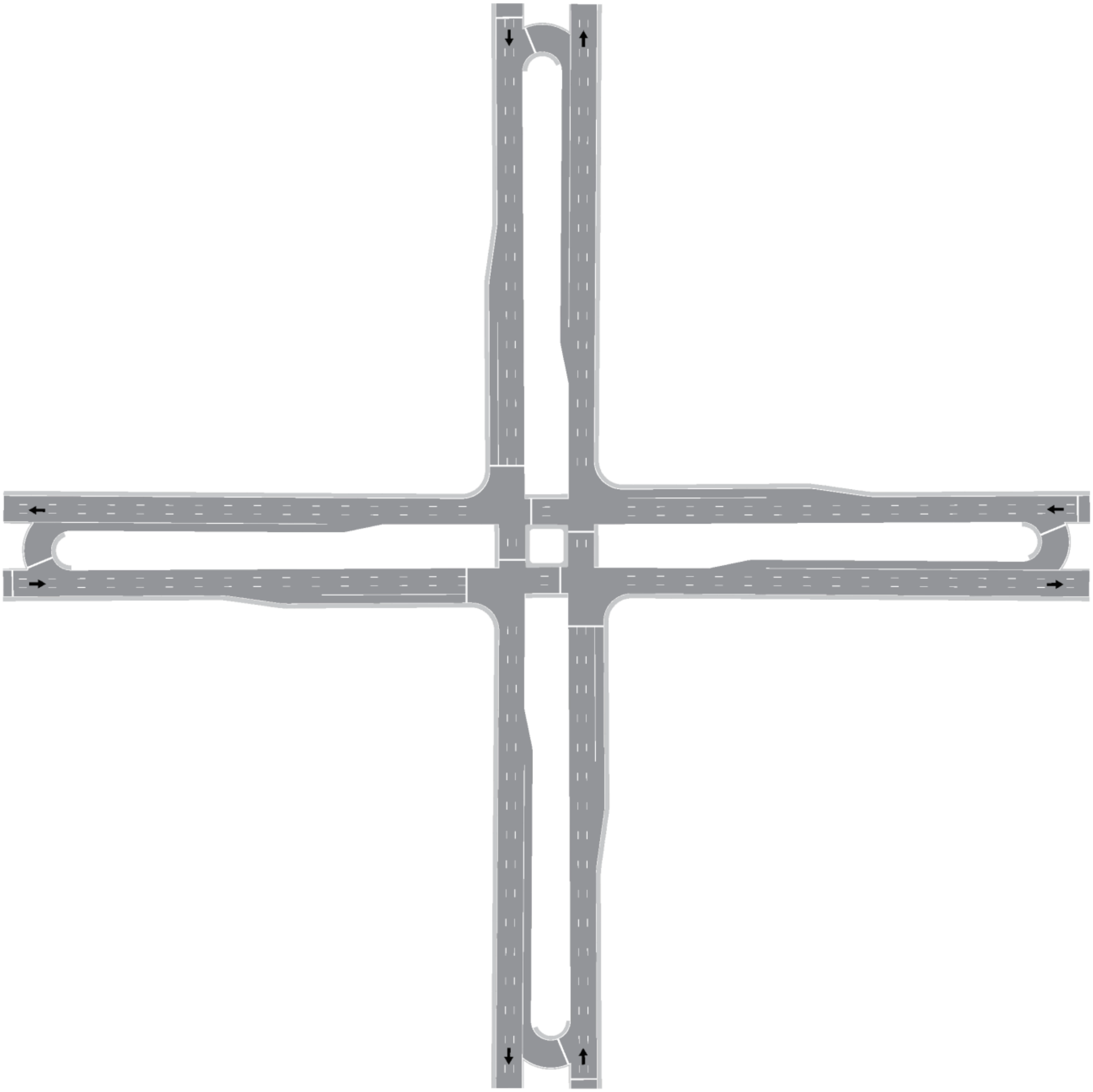


Figure 4.2.4.5.4 MUT phased construction final configuration

This three phase process allows for the intersection to be constructed while maintaining full access. For the MUT intersection, it is important to make sure drivers know of the median U-turn past the original left-turn point once median U-turns are utilized. This is accomplished through signage in advance of the intersection as well as through public outreach. Deviations from these MOT Phasing Diagrams could be caused by differing initial configuration, alignments, and other special circumstances.

4.2.4.6 DLT

DLT retrofit construction is able to be constructed while maintaining complete access through construction. The DLT intersection retrofit construction from a conventional at-grade intersection was developed utilizing four main phases. This phasing scheme was developed utilizing Steyn et al. (2014) as well as agency sample plans and industry expert interviews. Figure 4.2.4.6.1 shows the initial intersection configuration considered.

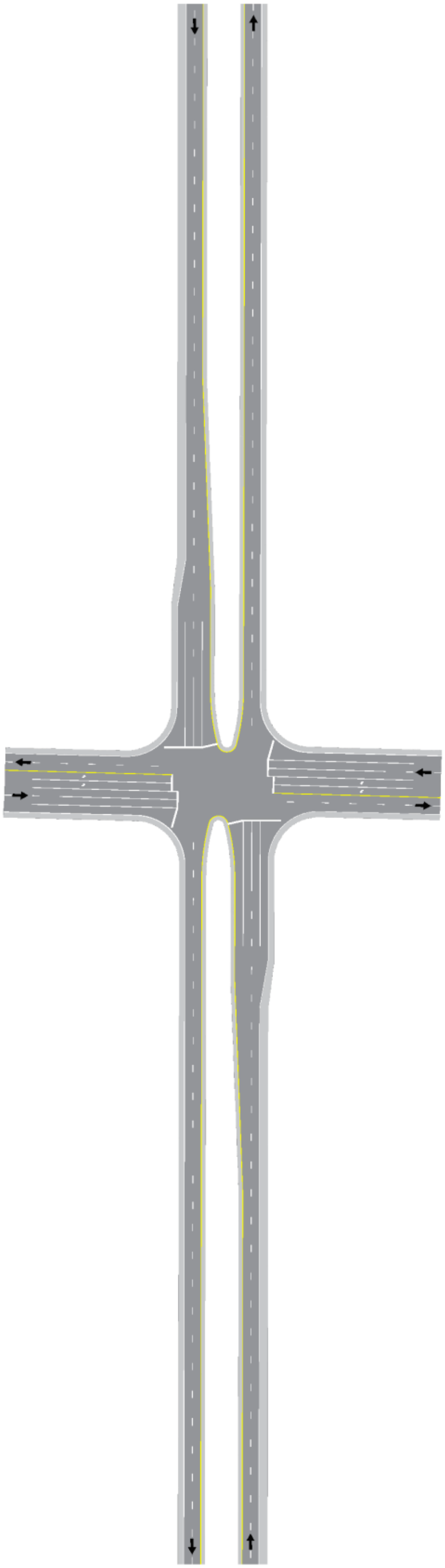


Figure 4.2.4.6.1 DLT phased construction initial configuration

Phase 1 involves construction of the minor roadway right-turn movements outside of the future left-turn bays as well as construction of the major roadway right-turn movements if applicable. This phase causes little effect to roadway traffic and does not require any lane drop. Figure 4.2.4.6.2 shows the work area and MOT through this construction phase.

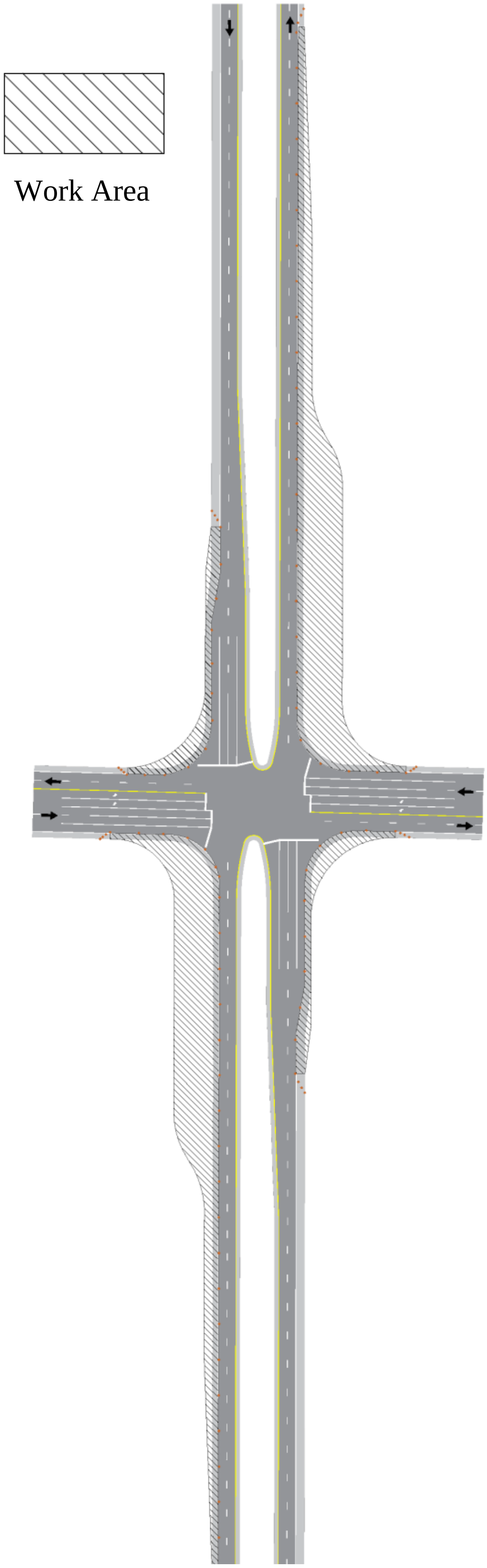


Figure 4.2.4.6.2 DLT phased construction Phase 1

Phase 2 involves opening the newly constructed right-turn movements to traffic and beginning construction of the displaced left-turn bays and cross-overs for the main roadway. Figure 4.2.4.6.3 shows the work area and MOT through this construction phase.

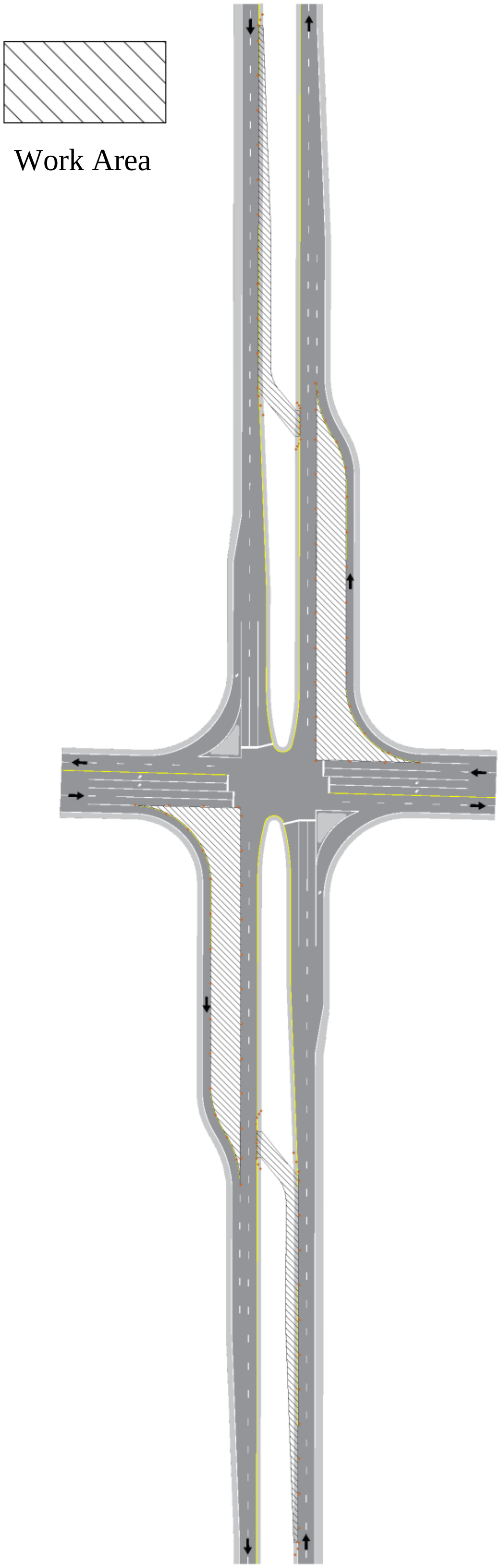


Figure 4.2.4.6.3 DLT phased construction Phase 2

Phase 3 begins once construction of left turn facilities is complete. Traffic is shifted to displaced left-turn bays and the original left-turn bays are closed at the original intersection. Pavement removal of the original left-turn movements is performed through this phase. Figure 4.2.4.6.4 shows the work area and MOT for this construction phase.

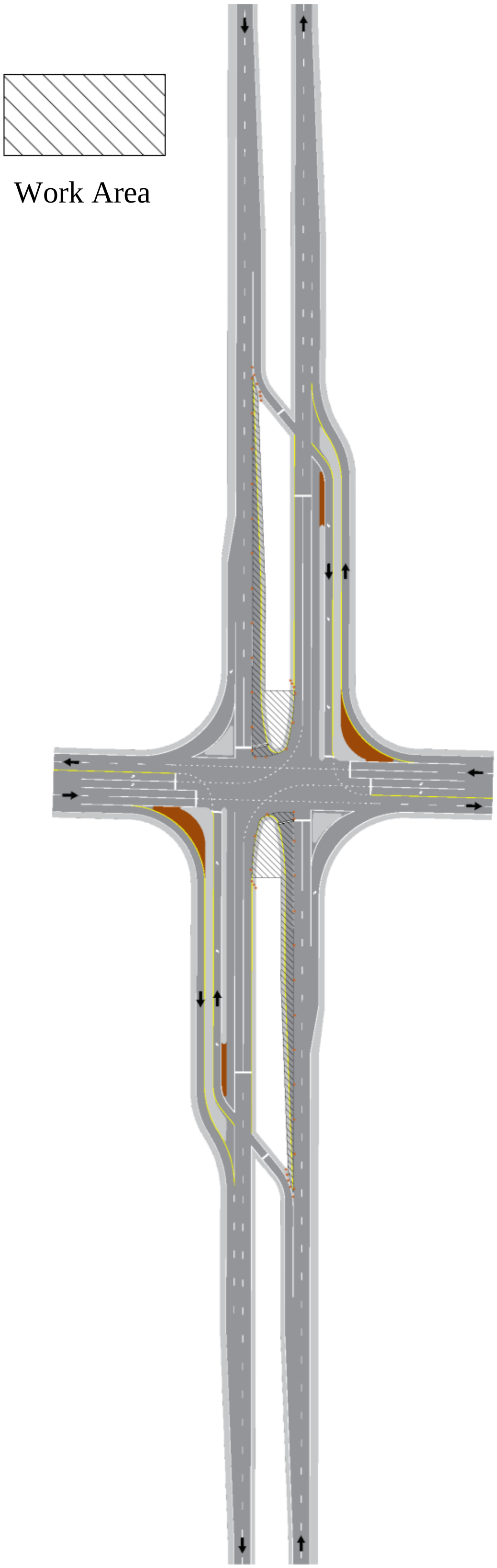


Figure 4.2.4.6.4 DLT phased construction Phase 3

Once the pavement removal and new configuration striping is complete, the DLT intersection is fully opened to the final traffic configuration. Figure 4.2.4.6.5 shows the final DLT configuration.

This six phase construction scheme allows for the retrofit of an existing at-grade intersection into a DLT intersection while maintaining full access throughout construction. Deviations from these MOT Phasing Diagrams could be caused by differing initial configuration, alignments, and other special circumstances.

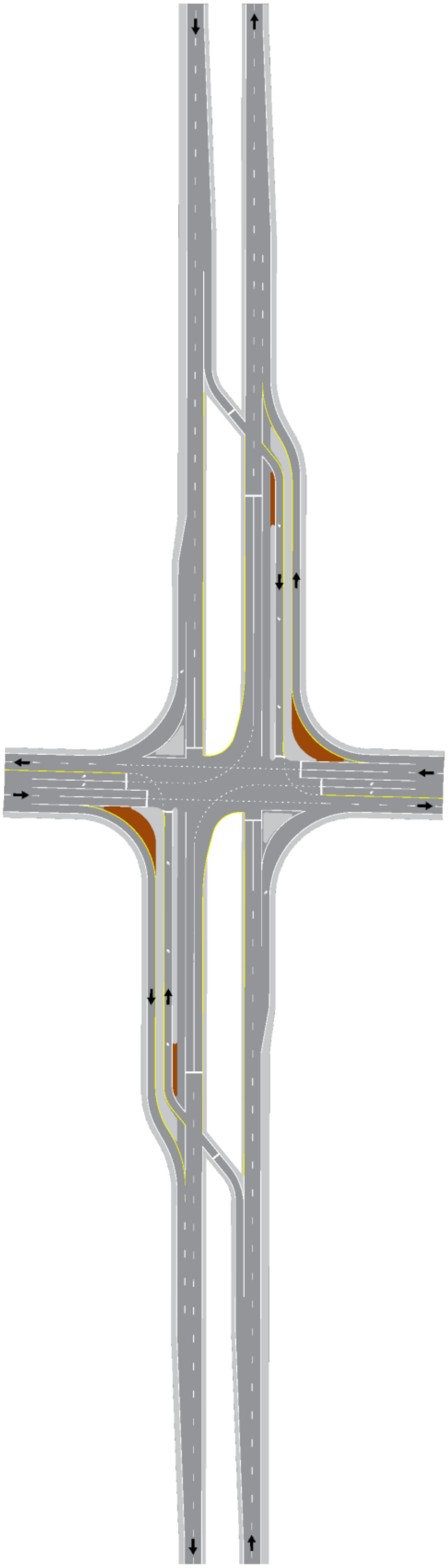


Figure 4.2.4.6.5 DLT phased construction final configuration

Chapter 5 Conclusions

This thesis focused on two emerging issues pertaining to work zone safety and operations in the transportation field. The first issue addressed deals with the increased distracted driving through mobile work zones. This is often due to texting while driving and overuse of cell phones, and is the main contributor to the increase in mobile work zone TMA truck collisions. The use of an audible warning system was explored to determine whether it could have a positive effect on warning travelers of the slow moving mobile work zone. The second issue addressed pertains to the growing use of innovative geometric designs as a solution to increasing traffic demands and greater constraining factors such as available funding. These intersections effectively handle traffic and are often much more cost effective than the conventional solution. The intersections of interest in this thesis include roundabouts, SPUIs, DDIs, RCUTs, MUTs, and DLTs. There is currently no guidance through the MUTCD on MOT for initial construction of these designs. This is a particularly pressing issue because the very nature of needing to implement these designs typically means that access is a necessity throughout construction, and therefore many transportation practitioners looking to implement these designs could greatly benefit from MOT Phasing Diagrams on initial construction MOT. This portion of the thesis aimed to develop these MOT Phasing Diagrams through determining current best practices reviewing existing literature and contacting agencies that have implemented such designs to gather both experiences and plans to use as a knowledge base.

5.1 Mobile Work Zone

The Alarm Device and DAS were found to be in compliance with national standards using sound level testing. The Alarm Device was found to have a tendency to be masked by background noise which included noise from the test highway through a spectral analysis. The

DAS was found to be much more distinct than the Alarm Device and was not found to be masked by background noises.

The most significant finding from the project was the analysis of average merging distances, standard deviation of merging distances, and average vehicle speeds. For mobile work zones, larger merging distances are a desirable driver behavior. Each audible warning system and setup was found to cause an increase in merging distance except for the Alarm Actuated setup. The DAS continuous setup experienced the greatest increase in merging distance. Standard deviation of the merging distances was used to determine uniformity between vehicles in terms of merging distance. The DAS Continuous setup was the only setup that led to a decrease in the standard deviation of the merging distance. A lower standard deviation of merging distance indicates that vehicles are merging in a more uniform manner. Lower vehicle speeds through the mobile work zone are also desirable. The DAS Continuous was the only audible warning system to see a decrease in vehicle speeds. Other non-ideal observations were recorded and determined to be important when evaluating driver behavior. Some undesirable driving behaviors were observed with the DAS warning setups. These behaviors include sudden maneuvers while using DAS Actuated setup, and vehicles travelling partially on the shoulder while using the DAS Continuous setup. However, it is unclear whether partial travel on a shoulder was caused by the presence of the mobile work zone alarm or the presence of the mobile work zone itself.

In terms of overall performance, the DAS Continuous application experienced the most significant results pertaining to average merging distance and vehicle speed while the main drawback was the tendency for some drivers to use the shoulder while passing the TMA truck. This could be due to drivers feeling to need to be more cautious of slow vehicles due to the message. For the DAS warning system, it is recommended to utilize a continuous application but other alarm sounds could further improve the results. For the Alarm Device warning system, recommendations include utilizing a more directed and distinct sound as well as a continuous operation. This could be explored through mounting a loud speaker as the Alarm Device. Through exploring alternative sounds for each system, improvements to various factors such as sound masking, localization, urgency, and attenuation could be addressed.

Recommendations for the actuation system include reducing the number of false alarms and false negatives. This could be addressed through utilizing a narrower band for actuation as well as improving horizontal and vertical curve tracking. Horizontal and vertical curves proved to be the most problematic for the actuation system to detect oncoming vehicles. Additional research opportunities relating to mobile work zones could also include further analysis of mobile work zone incidents through an analysis of crash reports.

5.2 Innovative Geometric Design

MOT Phasing Diagrams were developed for roundabout, SPUI, DDI, RCUT, MUT, and DLT intersections. These MOT Phasing Diagrams could serve as an aid to transportation practitioners looking to implement these designs through a retrofit construction from a conventional intersection while needing to maintain access throughout construction. Current practices throughout the United States were determined through literature review, survey and interview of industry experts, and by examining project plans. The MOT Phasing Diagrams were designed to serve as a starting point for transportation practitioners, but other factors must be considered when developing MOT plans for these types of designs. These factors include the level of experience that the drivers in the surrounding area may have with these types of designs, availability of detours, traffic counts, and anticipated impacts of a possible closure. Each of these factors aid in determining proper construction phasing and MOT methods. Key findings of this thesis through include:

1. Each facility type is capable of organized phased construction which involves little to no effect on movement access throughout construction.
2. Avoid using temporary movements through construction which would be considered an illegal movement for the final traffic movement configuration. If drivers are experienced with the final traffic configuration due to other intersections of a similar type in the area, this application of MOT could prove beneficial without increased risk of future illegal movements.
3. For DDI, if possible, construct curbing before construction is complete to ensure drivers travel the intersection correctly.
4. For MUT, make sure drivers know there is a median U-turn after the intersection.
5. Agencies have tried using innovative geometric designs for MOT setup, such as a quadrant interchange or MUT to accommodate left turns during the construction of a SPUI. Innovative geometric setups implemented for MOT could provide more effective work zone traffic management until construction is complete.
6. In roundabout construction, median cross-overs on legs prove useful on an as-needed basis.
7. For any innovative geometric design, doubling the number of channelizers used through the extents of the work zone can prove valuable in preventing drivers from weaving.
8. Sequential lighting can provide valuable aid to drivers through the work zone setup for both daylight and nighttime periods.

9. Final conversion of some of these facility types, such as DDI, should be done under full closure which should occur when traffic counts are lower, such as weekend periods. The conversion could occur either through the middle or at the end of the project. A short full closure period also ensures that drivers acknowledge the change in intersection configuration.

Additional findings through the interview process from interviewee opinion and recommendations include:

1. Use of innovative contracting such as design build could be considered to allow contractors to determine methods used.
2. Other factors such as drainage, necessity of movements, and other situations can affect phasing.
3. Be cognizant of how to accommodate pedestrians.
4. With low speeds through the work zone, sharp angles in temporary traffic control are acceptable.
5. MOT plans should be continually reevaluated throughout the duration of the project.
6. Avoid the use of unwarranted temporary signals, because public pressure might make them permanent.

Additional research opportunities through the innovative geometric design portion of this thesis could include further development of MOT Phasing Diagrams into MUTCD-like Typical Application sheets through including aspects such as signage.

References

American Association of State Highway and Transportation Officials (AASHTO). 2011. *A Policy on Geometric Design of Highways and Streets, 6th Edition*. Washington, D.C.

De Lorenzo, R.A., and Mark A. Eilers, M.A. 1991. "Lights and Siren: A Review of Emergency Vehicle Warning Systems." *Annals of Emergency Medicine*. Vol. 20, No. 12. p. 1331-1335

Federal Highway Administration. (FHWA). 2009. *Manual on Uniform Traffic Control Devices for Streets and Highways*. 2009 Edition Including Revisions 1 and 2. Washington, D.C.

Federal Highway Administration (FHWA). 2013. *Temporary Traffic Control for Building and Maintaining Single and Multi-Lane Roundabouts*. January, 2013. Federal Highway Administration. Washington, DC.

GoogleMaps. 2014. https://www.google.com/maps/, Accessed December 2014.

Ho, C. and Spence, C. Year. 2005. "Assessing the Effectiveness of Various Auditory Cues in Capturing a Driver's Visual Attention." *Journal of Experimental Psychology: Applied*. Vol. 11, No. 3, p. 157-174.

Hughes, W, Jagannathan, R, Sengupta, D, and Hummer, J. 2010. *Alternative Intersections/Interchanges: Informational Report. (AIIR)*. Report No. FHWA-HRT-09-060. Federal Highway Administration. Washington, DC.

LRAD Corporation. "LRAD Product Overview." http://www.lradx.com/site/content/view/15/110/. Accessed April 28, 2014.

Maddern, A., Privopoulos, E., and Howard, C. "Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations." Paper Number 3, Proceedings of Acoustics 2011. Gold Coast, Australia. November 2-4, 2011

National Institute for Occupational Safety and Health (NIOSH). 1998. *Criteria for a recommended standard: Occupational noise exposure*. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. Cincinnati, Ohio.

Niquette, Patricia. "Noise Exposure: Explanation of OSHA and NIOSH Safe-Exposure Limits and the Importance of Noise Dosimetry." [White Paper]. https://www.etymotic.com/pdf/er_noise_exposure_whitepaper.pdf. Accessed April 24, 2014.

Occupational Safety and Health Administration (OSHA). 1983. 29CFR1910.95 *Occupational Noise Exposure: Hearing Conservation Amendment*. Washington, D.C.

Phanomchoeng, G, Rajamani, R., and Hourdos, J. 2008. *Directional Sound for Long Distance Auditory Warnings from a Highway Construction Work Zone*. Report No. CTS 08-20. Center for Transportation Studies. Minneapolis, Minnesota.

Potter, R., Fidell, S., Myles, M., and Keast, D. *Effectiveness of Audible Warning Devices on Emergency Vehicles*. 1977. Report No. DOT-TSC-OST-77-38. United States Department of Transportation. Washington, D.C.

Tan, A.K., and Lerner, N.D. 1995. *Multiple Attribute Evaluation of Auditory Warning Signals for In-Vehicle Crash Avoidance Warning Systems*. Report No. DOT HS 808 535. United States Department of Transportation. Washington, D.C.

Schroeder, B, Cunningham, C, Ray, B, Daleiden, A, Jenior, P, Knudsen, J, Kittelson and Associates, Inc. (2014). *Diverging Diamond Interchange: Informational Guide. (DDI)*. Report No. FHWA-SA-14-067. Federal Highway Administration. Washington, DC.

Steyn, H, Bugg, Z, Ray, B, Daleiden, A, Jenior, P, Knudsen, J, Kittleson and Associates, Inc. 2014. *Displaced Left Turn Information Guide. (DLT)*. Report No. FHWA-SA-14-068. Federal Highway Administration. Washington, DC.

VDOT, (2011). *Virginia Work Area Protection Manual*. 2011 ed. Virginia Department of Transportation. Richmond, Virginia.

WisDOT, (2013). "*Roundabout Guide"* Wisconsin Department of Transportation, http://dot.wi.gov/safety/motorist/roaddesign/roundabouts/docs/guide-wisdotrab.pdf . Feb 4, 2015.