INSIGHTS INTO THE FIRST THREE DIVERGING DIAMOND INTERCHANGES IN MISSOURI

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by
Nicholas Ray Ressel
Dr. Praveen Edara, Thesis Advisor
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The undersigned appointed by the dean of the Graduate School, have examined the thesis entitled

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presented by Nicholas Ray Ressel,

for candidate for the degree of Master of Science in Civil Engineering,

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

_____________________________________________________________________________________

Dr. Praveen K. Edara

_____________________________________________________________________________________

Dr. Carlos Sun

_____________________________________________________________________________________

Dr. Timothy Matisziw
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ABSTRACT

This thesis aims to further the knowledge about diverging diamond interchanges (DDIs) by exploring several aspects of existing DDIs including performance measures, business surveys, bicycle and pedestrian issues found within a DDI, and compiling relevant existing literature. Several performance measures were examined to analyze current traffic flow levels at the Dorsett Road DDI in Maryland Heights, MO (St. Louis metro area). Access management was researched with an emphasis placed upon changes from previous interchange configurations and how they have affected businesses located in the direct vicinity of the DDI. Businesses located near the first three Missouri DDIs were surveyed for the first time to gauge perceptions of business owners. Results showed positive perceptions overall from business owners. Pedestrians and bicyclists can also be affected by this novel design. Two primary options are available to designers, a barrier protected center walkway or a perimeter based sidewalk. Previously only pedestrian planners had been surveyed, missing practical insights from everyday users not familiar with design intents. The majority of people surveyed preferred a center walkway, with ease of crossing from one side of the intersection to the other being the main reason.
1. INTRODUCTION

The diverging diamond interchange (DDI) or double crossover interchange is a relatively new interchange design in the United States, with Springfield, MO implementing the first DDI in 2009. What makes a DDI unique is that vehicles briefly crossover lanes, drive on the opposite side of the road on an overpass or underpass, allowing for free and unopposed left turns to the interstate/freeway. After crossing over or under the interstate/freeway another crossover is performed to correct the vehicles lane. Two phases are all that is required for each crossover intersection further cutting lost time due to signal changes.

Diverging diamonds were not invented in the United States however; they were first observed in France (Siromaskul 2010). Due to decreasing state transportation budgets and limited right of way available, alterative solutions were examined for potential cost savings for a variety of intersections. This led to the diverging diamond being considered as a potential interchange design in Missouri. The first DDI was previously designed and approved for Front Street in Kansas City, however, the Paseo Corridor construction project led to a delay in constructing this DDI. Springfield, Missouri opened the first DDI in the USA on June 21, 2009. Since then, Missouri has led the way with DDIs, there are currently five built, with more in the planning phases.

There have been several other states considering diverging diamonds. Utah was the second state to implement a DDI. The location of their first DDI is at I-15 and Main Street in American Fork, Utah. This area appears to be suburban, in between Salt Lake
City and Provo, creating a significant volume of interstate traffic. The interchange has four lanes in each direction and is an overpass with two separate bridges, a unique characteristic to this intersection. Three lanes are dedicated to through traffic, with one lane reserved for left turns in each direction. The additional overpass required is important because all previous DDIs have been retrofitted to existing structures, keeping the cost of a DDI much lower than other interchange options such as a SPUI. These specifications are different from Missouri’s DDIs. In Missouri all DDIs built have been either an overpass or underpass on a controlled access highway such as Interstate 44 or Interstate 270. Missouri DDIs have been retrofitted to previous roadways making them more attractive than SPUIs which would require additional bridge lanes creating high impact lane closures. The DDI option has minimized the construction impacts that would affect traffic flow on the interstates.

According to Federal Highway Administration (FHWA) (FHWA 2009) there are several situations that could favor a DDI. Generally speaking the DDI is most useful for freeway or interstate on ramp intersections. This is because a DDI is designed to handle heavy turning volumes and preferably lower through volumes. Several examples of prime intersections include medium to high volumes of off-ramp traffic making left turns, high traffic turning left for on ramps, or mid-level volumes of through traffic. Moreover if limited right of way exists, a DDI should be considered because it requires less right of way than a conventional diamond. All previously mentioned situations provide optimal situations for a diverging diamond.

Recently, (Chlewicki 2011) provided a comparison of diverging diamond intersections with single point urban interchange (SPUI) and conventional diamond
interchange (CDI). When comparing the DDI with a conventional diamond interchange, about two thirds of the time a DDI was operationally more efficient with costs favoring the DDI. If the costs are equal, the DDI outperformed the CDI 95% of the time. Furthermore, a DDI was found to operationally outperform a SPUI of the same cost. The researchers concluded that given the same amount of money the DDI will be a better choice.

1.1. Research Objectives

This thesis will look into several aspects of the DDI including performance measures, access management issues, and bicycle and pedestrian issues found within a DDI. Three DDIs are reviewed: a) Interstate 270 and Dorsett Road in Maryland Heights, Missouri, b) Interstate 44 and c) Kansas Expressway in Springfield, Missouri, and US Highway 60 and National Avenue also in Springfield, Missouri. Several performance measures have been examined to analyze the Dorsett Road diverging diamond in Maryland Heights with VISSIM a traffic simulation software program. Several signal timing strategies are tested against the performance measures for current traffic volumes as well as projected 2035 volumes. Access management was researched, for all three DDIs, with an emphasis placed upon changes from previous interchange configurations and how they have affected business located in the direct vicinity of the DDI. Additionally, analysis was performed on pedestrian and bicycle interactions with the Dorsett Road and the National Avenue DDIs. First a brief introduction about the safety and cost savings benefits associated with a DDI is provided to motivate research on this interchange design.
1.2. Safety Benefits of Diverging Diamond Interchange

Diverging diamond interchanges have proven safety benefits over alternative interchange designs. Figure 1 shows a diverging diamond and its 18 conflict points. A SPUI is illustrated in Figure 2 showing all 24 of its conflict points. Other comparisons can be made with the conventional diamond shown in Figure 2 which has 30 total conflicts. The most notable safety advantage for a diverging diamond is the reduction in the number of crossing points, a SPUI has eight crossing conflicts, and the conventional diamond has ten. As shown in Figure 1, a DDI only has two crossing conflict points.

Figure 1: Conflict Diagram DDI (MoDOT 2009)
Conventional diamond interchanges have 10 diverging and merging conflicts, providing a baseline for the advanced interchanges to improve upon. Diverging and merging conflicts for a DDI are eight each, the same as a SPUI, both of which are safety improvements over a conventional diamond.

Several theoretical safety benefits are listed in an FHWA Alternative Intersection: Informational Report (AIIR) (Hummer et al. 2010). Traffic calming is incorporated into the design with reduced speeds while sustaining capacity levels. Wrong way movements are eliminated from on ramps; however crossovers still have the opportunity for incorrect traffic direction.
Also included in Hummer et al. (2010) were the results from a driver simulation of the DDI. The simulation suggested that the DDI did not have substantial influence on drivers going the wrong way on crossovers when they were required to change over to the left side of the road. In addition, the number of red light runners was not statistically different from a conventional diamond interchange.
1.3. Cost Saving Benefits of Diverging Diamond Interchange

Monetary value is another primary reason departments of transportation (DOTs) choose a diverging diamond over other alternative designs. Several factors help determine whether or not a DDI can be the more economical design as opposed to other alternative intersection solutions. Some of these features are explored next.

Hummer et al. (2010) concluded that a four lane DDI performed at the same level as a six lane tight diamond interchange. Similarly, when a tight diamond needed eight lanes, the DDI only required six lanes, suggesting a substantial cost savings by either reducing bridge deck width or allowing for increased capacity on an existing bridge. This information is critical for the project bidding phase and should be carefully evaluated in the design phase to highlight the possible cost savings that a DDI offers because of the fewer lanes required.

In a study examining bottlenecks along urban arterials, Stanek (2008) found that a partial cloverleaf, having only one loop, would have similar right of way and construction costs, with lower capacity. A typical cloverleaf intersection would require more right of way costs than a DDI to provide similar capacity. Because of the large radius normally required, a cloverleaf may not even be feasible in a heavily urban environment, or could pose significant cost to acquire the necessary right of way. Therefore, the DDI is typically superior to the cloverleaf in terms of cost in urban areas.

Previously built displaced left turn intersection (DLT), also known as continuous flow intersections (CFI), are generally built in areas where right of way is not a problem, and to avoid grade separations, leading DLTs to be somewhat expansive in size. If a DLT were to be used as an overpass, it would be compressed and would be separated by
concrete barriers instead of grass medians. However, there are three total lane separations needed, two more than a DDI, likely adding to the overall width needed for an overpass. In conclusion, DLT is going to have similar right of way requirements, while probably needing a wider bridge than a DDI, leading to higher costs.

A single point urban interchange (SPUI) is an option that is often competing with the DDI. SPUIs have become a popular interchange in urban areas, requiring only one traffic controller for an intersection. The right of way necessary for a SPUI is not substantially different than for DDIs. However, SPUIs use more lanes than a DDI with equivalent throughput creating wider and costlier bridges.

The first Springfield DDI was chosen because “there was no need to widen (the interchange) or replace it” Don Saiko(Tang 2010). Designers were able to fit the DDI on the existing bridge structure. With bridge and land savings factored in, a difference of $7 million dollars was realized, jumpstarting national interest in DDIs (Tang 2010).

In Maryland Heights, an initial SPUI proposed would have cost $23 million while the DDI that was constructed cost $10 million, a savings of $13 million (MoDOT 2010b). The DDI option required less bridge structure, shorter in length, and did not require Dorsett Road to be lowered as much for bridge clearance. These factors resulted in shorter construction time and lower cost.

When looking at larger intersections, the savings appear to be even greater when compared with SPUIs. At the American Fork, Utah Main Street and I-15 interchange, a DDI was chosen as an alternative to a SPUI. This solution came about because of the design-build approach used to encourage innovation. A smaller bridge allowed for faster, easier, and more inexpensive construction. Cost savings from right of way and fill
resulted from the DDI allowing for a skewed interchange where a SPUI would need to be square with the interstate. Altogether, the DDI saved Utah Department of Transportation $20 million (ERP for Construction 2012).
2. LITERATURE REVIEW

2.1. Using simulation and other methods to evaluate the DDI concept

Because the diverging diamond is such a new concept in the United States, the available literature on research and implementation of the design is limited. One of the primary advocates of the Diverging Diamond interchange is Chlewicki. In Chlewicki (2003), he introduced the DDI concept at the second Urban Street Symposium in the United States. Since his seminal paper, additional research has been conducted by Federal Highway Administration (FHWA 2009) and Virginia Tech (Baredet al. 2005), a few state DOTs, and other practitioners across the country. These efforts are discussed in the next paragraphs.

Early research into alternate intersections was conducted by Bared et al. (2005) who analyzed a DDI and double crossover intersection using VISSIM. Their research showed the DDI to be far superior to a conventional diamond, especially for left turn movements DDI had twice the capacity of a diamond interchange. One other influential finding was that a four lane DDI rivals a six lane conventional diamond for traffic capacity.

A FHWA technical report (FHWA 2009) provides information about the DDI alternative intersection. Their report notes how the signals should operate in two phases and should be operated with either one or two signal controllers. Using VISSIM, the operational aspects of four interchanges were studied. Two DDIs and two conventional diamonds were evaluated with high and low flow scenarios. It was found that with high
flow, DDI performed better overall. For the lower flow scenario both designs performed similarly.

Siromaskul (2009) created basic guidelines for designers who are not familiar with the diverging diamond interchange. One important topic covered is the appropriateness of simulation software. SYNCHRO or HCS + are recommended for basic capacity, however Siromaskul recommends taking these results with caution. The preferred method though is a micro-simulation program such as VISSIM, which has the capability to replicate driver behavior, geometry, and traffic controls accurately for a DDI.

Another concern noted by Siromaskul (2009) is the location of nearby signals. The signals that are closest to the DDI can impede the traffic progression through the arterial. In their analysis a Single Point Urban Interchange was found to have better arterial progression than a DDI. However, in this thesis only the DDI is considered because of a lack of data for surrounding traffic signal volumes.

MoDOT released an initial report (2010a) following the completion of the first DDI in Springfield, MO. This report contained design guidelines for almost every aspect of a DDI. Several observations were made about the signal operations. When the off-ramp left turns are signalized, it creates a long clearance interval for the crossover through movements, which will then require greater yellow and all red times. These clearance intervals can be aided by dummy phases or overlaps. The dummy phase can be in the form of an extra few seconds of red time for the off-ramp, while the through movement is allowed to proceed. This is because the cars clear the crossover portion of the interchange first while the off-ramp turn lanes farther downstream require more time.
MoDOT reported that optimization with SYNCHRO proved to be ineffective and used field optimization for the signal timings.

Hummer et al. (2010) explored possible alternatives to a DDI. This study was conducted to remind designers that the DDI is not a magical solution to all congested interchanges. Several interchanges considered were median u-turn, superstreet, and contraflow left turn among others. The limiting capacity of each interchange type is compared, by Hummer et al., in a table with various turning movement scenarios. Another comparison made in this paper rates the performance of each intersection with respect to a DDI in various categories. Included in these categories are right-of-way, bridge size, conflict points, pedestrians, quality of progression, and unusual maneuvers. Hummer et al. concluded that no design proved superior in all categories. While the DDI was found to perform poorly for pedestrians and capacity, the DDI was found superior to all intersections based on the bridge width. Hummer et al. (2010) recommended exploring all alternative intersections when searching for a replacement for a conventional diamond based on their nature of being niche solutions.

Chlewicki (2010) conducted a study on the operational effects of a DDI. In his paper, methods are examined to determine proper signal timing schemes within a DDI and also including an extra signal outside the interchange. Several equations are created that are used to demonstrate signal progressions through a hypothetical DDI scenario. These results are then analyzed and the effects of signal spacing are discussed. Furthermore, it was found that the initial design of a DDI provided a good opportunity for optimizing signal progression due to his hypothesis that distance and design speed are found to be critical factors.
The first DDI implemented in Springfield, Missouri, at the intersection of Interstate 44 (I-44) and MO-13, is used as the example by Chlewicki (2010) for signal timings and progressions. Several guidelines are listed to aid with the design of a DDI. The cycle splits should be predetermined based on peak traffic volumes. A simple synchronization strategy for turning movements and cycle lengths is advised. Two design criteria that do not change, and are critical for initial design, are design speed and distance between signals. Once a DDI is built, the design speed and distance between crossovers will not change. Chlewicki (2010) also concluded that adding signals to the system would not necessarily lower system quality if proper planning is used with cycle lengths and bandwidths.

Xu et al. (2010) proposed a mathematical model to study the controlled delay for internal movements of a diverging diamond. In their research they compared the conventional method in chapter 16 of the Highway Capacity Manual’s delay calculation with a new approach they proposed. Two types of signal plans were evaluated: a) basic DDI and advance DDI phasing. Figure 3 shows the difference between basic DDI and b) advanced DDI signal phasing with the green arrows indicating movements controlled by signals. The base DDI only controls the two crossing conflict points and not the merging points created by on or off-ramp traffic, while an advanced phasing controls the off-ramp movements. Their results showed that for an advanced DDI signal, the proposed method was appropriate but for a base DDI, calculations didn’t match simulated results.
A performance review was conducted by Chilukuri et al. (2011) after the first DDI in the US was constructed in Springfield, Missouri. The purpose of this report was to validate initial reported results and gauge public perception, traffic safety, and operation of the interchange. Public perception studies showed positive results. Respondents to a survey by the authors reported traffic flow improved and delays were lower compared to the previous diamond interchange. Also there was good understanding of the interchange operations due to road signs, traffic calming island designs, and road markings, as reported in the survey.
The reduction in crash occurrences after DDI installation was attributed to the overall safety improvement achieved by DDI (Chilukuri et al., 2011). No additional types of crashes have occurred because of the new design, while a reduction in rear-end and left turn type crashes were observed. However, only one year of post-construction crash data was available at the time of the report and it was recommended that additional safety studies be completed when more data is available.

Chilukuri et al. (2011) established that during low flow periods, through movements experienced a greater travel time, due to reduced speed areas that are required for cross over areas. Nevertheless, traffic performance showed significant improvements from the previous design during heavy peak flows with shorter queue lengths and lower delays.

Furthermore, Chlewicki (2011) has examined whether or not a DDI should always be considered by designers. A critical lane volume method is used to determine the efficiency of several intersection configurations with a wide array of traffic volumes. The intersections studied include conventional diamond, single point urban interchange, and diverging diamond. Evidence suggested that given similar costs, DDI has superior operational aspects, for a majority of situations. Furthermore, a DDI was likely to be the best option when more lanes are required for an intersection. Designers are recommended to always consider a DDI initially and if there is an initial reason to eliminate it then no further investigation would be necessary.

Research has also been performed to establish a relationship between queue and storage bay length on overall intersection delay (Yang et al. 2011). In Yang et al. (2011), the queue length equations that were comparable with queue lengths results from
simulation. A calibrated model was also created to assess delays for a planning stage application. This model only requires degree of saturation, critical lane volume for each intersection, and maximum queue length to bay length ratio. Queue development on bridge correlated directly with operation of the DDI, making optimal bridge length crucial in the design phase.

**FHWA Alternative Intersection Selection Tool**

The alternative intersection selection tool of Bared et al. (2009) can use the volumes of traffic expected, analyze about a dozen intersection designs, and output the critical lane volumes for each design. Included in the interchanges are a Traditional Diamond, Partial Cloverleaf, Displaced Left Turn, Roundabouts, Median U-Turns, Diverging Diamond, and Single Point Urban Interchange. To judge the performance of critical points throughout the interchange Figure 4 shows acceptable configurations.

<table>
<thead>
<tr>
<th>Critical Lane Volume Sum</th>
<th>Acceptable Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1200</td>
<td>3</td>
</tr>
<tr>
<td>1200-1400</td>
<td>4</td>
</tr>
<tr>
<td>1400-1600</td>
<td>3</td>
</tr>
<tr>
<td>&gt;1600</td>
<td>20</td>
</tr>
</tbody>
</table>

**Figure 4: Critical Lane Volumes for Alternative Intersection Tool**

The existing PM peak hour traffic volumes have been entered for the Dorsett Road and Interstate 270 DDI, and the results are shown below in Figure 5. Also consider that the interchange is configured in the east/west direction, the north/south intersections have been eliminated from the results. The output ranks alternative intersections 1-10 and their adequacy for specified volumes. Results preferred Partial Cloverleaf, followed by Diamond, Displaced Left Turn, and Double Crossover Diamond. A Single Point interchange proved to be inadequate, with insufficient capacity.
If one looks at capacity for the interchange, Partial Cloverleaf performs the best at only 78.7% while a Double Crossover comes in at 99.6%. However the most critical location on this particular Double Crossover Diamond is the southbound right turn lane which in the field has 2 lanes but with this tool is only given 1 lane, leading one to believe there is adequate capacity.

Probably the most important consideration for choosing the design other than capacity would be cost. This interchange goes directly beneath I-270; therefore the number of lanes used has a high impact on the bridge width needed. The Diamond and Partial Cloverleaf interchanges will require 8 lanes underneath the interstate, while the Double Crossover and Displaced Left turn only need 6 lanes. Previously this underpass was six lanes. What this could have meant for MoDOT is that six lane options would not require new bridge construction, cutting costs significantly and allowing the road to stay open for traffic. The results of the Alternative Intersection Selection Tool are shown in Figures 6-9, displaying zonal capacities at critical locations in each interchange.
Figure 6: Tight diamond results from Alternative Intersection Tool
Figure 7: Cloverleaf Performance with Alternative Intersection Tool

Figure 8: Displaced left turn results from Alternative Intersection Tool
When MoDOT first decided to build a DDI for Front Street in Kansas City, they needed a method to test out their design before construction. This is when the Federal Highway Administration, (Bared et al., 2007), stepped in to build a 3-D model to simulate the intersection and drivers reactions. Approximately seventy drivers volunteered to drive the simulator. Responses to the DDI compared favorably to a conventional diamond. Results showed there was a 2% navigational error rate for the DDI versus a 2.6% rate for the conventional diamond and red light running was no more common with a DDI than a conventional diamond. Bared et al. (2007) concluded that a DDI will deliver many of the theoretically suggested safety benefits.
2.2. Reviewing Access Management Literature

Access management is an approach used by DOTs to improve corridor safety and access. When access management is deployed on a corridor, businesses may feel that their accessibility is compromised. In this thesis, accessibility refers to the ease of entry to and exit out of a business. Several methods are used to control access. When no access control is in place, drivers are free to make left, right, or through movements, and in urban areas often have two-way left turn lanes. For Missouri DDIs, median barriers creating right in right out (RIRO) and traffic signals are common control measures used. These median barriers are often present on busy arterial streets when private driveways are causing an increased number of conflicts.

Access management is a controversial subject because business owners may feel they are losing customers when their driveway is controlled (Vu et al. 2006). Primary incentives for introducing access control are safety and increased capacity without adding lanes, similar to how a DDI adds capacity without increasing bridge lanes. Access management is an important consideration with DDIs because of the optimal signal spacing required by design for a successful DDI, which can result in reconfigured adjacent signals. Some existing signals for the conventional diamond layout have to be spaced further apart during construction and old driveways might be converted to right in right out (RIRO).

A study was conducted by Vu et al. (2006) about whether or not access management is good for business, and how accessibility affects patronage. Surveys were given to businesses with access to the frontage road. Special consideration was taken to examine what type of access management a business had experienced previously and
how that related to their future opinion of the new control. Further insights found businesses with shared driveways or signals perceive a positive impact on patronage, while RIRO control was perceived as negatively effecting patronage. Another key finding in their research concluded businesses perceive a greater negative impact on patronage from congested traffic than because of added access management controls.

Previous research has studied how road spacing can impact annual crash rates (Rakha et al. 2008). In this study 186 access roads were used for data collection in the state of Virginia to test several models, including Poisson and least square, to estimate the number of crashes expected for a given road spacing. The distances analyzed for this study are off-ramp to first access road and the distance from access road to first intersection. Their research showed that an increase from 300 feet to 600 feet lowered crash rates by 50% and an overall decrease eight-fold from 0 feet to 1000 feet in access road spacing. When DDIs are installed, sometimes there will need to be a change in spacing between signals for optimization, therefore reevaluation of access roads is necessary to maximize safety and flow.

Additional research has been conducted to prioritize access management implementation (Schultz et al. 2009). Schulz et al. (2009) used 175 arterial roads in Utah classified by type of access management (median, signals per mile, access density, etc.), road and traffic characteristics (number of lanes, speed limit, etc.), and dependent safety variables (crash type, severity, etc.). Stepwise linear regressions were used to determine critical factors for a final equation. Lack of access management controls were shown in statistical analyses to be associated with increased crash rates and severity. A decision tree was used to provide a step-by-step system for determining access control measures.
needed. Several suggestions mentioned included planning for future growth, adding raised medians, and combining driveways to limit access points.

The FHWA AIIR (2010) suggests that transportation agencies maintain minimum spacing policies with regards to median openings, interchange ramps, and signal spacing distances. Because each interchange is different, local businesses should be dealt with on a case-by-case basis, especially when driveways will affect flow characteristics and signal operation.
2.3. Pedestrian and Bicycle Literature

MoDOT’s initial report (2009) discussed trade-offs with the two main options for sidewalks. Their preferred method when using overpasses is to channel pedestrians over the middle of the bridge between the two directions of traffic. When plans call for an underpass, structural supports might block a center sidewalk option leaving a perimeter walkway more feasible.

One option for designers is placing a sidewalk down the middle of the interchange as shown below in Figure 10. Benefits and drawbacks are inherently present. This design allows for a safe walkway with a concrete barrier on either side for protection. Pedestrians are protected by signal while crossing the through street with this configuration but still have to cross the free flowing on/off-ramps. There is only one sidewalk required for the bridge portion of the interchange, which can reduce costs. Lastly by having the walkway down the center it is possible to cross from side to side at either crossover.

![Figure 10: Springfield DDI with Sidewalk in middle of intersection (MoDOT 2009)](image)

Possible negative aspects include spacing with structural objects and pedestrians feeling comfortable. If the limited access road is crossing over, the overpass bridge may have structural columns in between opposing traffic lanes. Another issue is raised for
pedestrians feeling comfortable walking between lanes of traffic, if the crossing is narrow.

The alternative to the center walkway design is having the sidewalk on the perimeter of the intersection. As shown in Figure 11 below when an underpass is used there is likely to be structural columns at the mid-point of the bridge in between the traffic lanes preventing the necessary space for a sidewalk. This leads to a sidewalk being built around the perimeter of the intersection. One notable advantage for this design is that pedestrians are following the expected path for standard intersections. There are however several drawbacks to this design. Crossing points will not be signalized at free flowing on-ramps, possibly causing a decrease in flow. Even more dangerous though, could be the possibility of cars coming from the right side of a person, such as free flowing lefts, onto the interstate. Most built DDIs are in areas with low pedestrians but if high numbers are present, there could be a need for special signals to protect pedestrian crossings. This could create a loss in flow through the intersection.

![Figure 11: Maryland Heights DDI with sidewalk on perimeter of intersection (MoDOT 2009)](image)

The Geometric Design of Highways and Streets 2004 notes that pedestrians are unlikely to use special overpass or underpass facilities ruling those out from possible options as well as their higher costs. Other considerations are proper lighting and
eliminating glare screens to give pedestrians better sight lines which are commonly used for DDIs.

Hummer et al. (2010) found that pedestrians are not served as well in a DDI as other alternative intersections. This is because a pedestrian must cross traffic four times with two crossings under free flow traffic conditions. However, this is also the same for a SPUI, one of the primary competing intersections for state transportation departments.

Chilukuri et al. (2011) interviewed professionals with experience in bicycle and pedestrian planning. Approximately 55 percent of respondents thought pedestrian and bicycle movements were easier to make through the DDI than a standard diamond, with 21 percent believing they were more difficult, and 24 percent felt there would be no difference. When asked about the safety of a sidewalk down the center of the bridge, 53 percent said it was safer than perimeter sidewalks, 28 percent felt less safe than on a sidewalk outside of the roadway, and 19 percent believed the two options were equal.

Several opinion questions were asked with open responses. One dealt with safety of pedestrians in the DDI, the respondent felt safety was increased with the separated walkway for pedestrians. All four right turn lane crossings were not protected; however, in the future crosswalk controls could be installed. Upgrading the pedestrian facilities within the previous bridge structure provides substantial cost savings. The expert’s opinion about bike facilities was that daily bike commuters prefer their own path, such as a dedicated or shared lane on the roadway, and felt the speed differentials between walkers and cyclist could be a problem depending on future volumes.

Existing French diverging diamonds have chosen to put sidewalks on the outside of the roadway rather than in the center. On the following pages Figures 12 and 13 show
urban French DDI layouts. The third French DDI did not appear to have any crosswalks or accommodations for pedestrians.

Figure 12: Pedestrian Crosswalks in Versailles, France (Google Maps)
Figure 13: Crosswalks at LePerrux-sur-Marne, France (Google Maps)
3. METHODOLOGY

3.1. Performance Measures of Diverging Diamond

To analyze the operational aspects of a DDI further, a VISSIM simulation is conducted. The research is applied to the Dorsett Road and Interstate 270 intersection in Maryland Heights, MO. Both current (2010) and future (2035) scenarios are considered, with several performance measures evaluated and compared. The future scenario is used to test the longevity of this interchange design and explore timing characteristics of a DDI. VISSIM was chosen for its availability/common MoDOT practice and for its capabilities with respect to micro simulation.

VISSIM (2005) is a microscopic traffic modeling software, which can be used for a wide variety of transportation studies. One of the primary practices for VISSIM is signal timing and optimization. For standard intersections VISSIM is capable of creating an optimal signal timing plan when the number of vehicles and route choice are defined. There are also several options for creating signal plans, such as actuated or fixed time. What sets VISSIM apart from other traffic simulators is its psychophysical driver behavior modeling. Other models may use deterministic car following and constant speeds, which results in less complex simulations and lower quality analysis. What this means is the following car can think ahead and slow down when he reaches a perceived threshold of getting too close to the leading car. The driver then slows down to a defined comfortable distance and can begin accelerating again. All these factors make VISSIM a worthy tool for this experiment.
A SYNCHRO file was obtained from MoDOT containing traffic counts and timing plans for the PM peak which was used to create a VISSIM model. This SYNCHRO file only contains data about the diverging diamond, from crossover to crossover on Dorsett Road and Interstate 270 ramp counts. Currently MoDOT uses an actuated cycle of 100 seconds with a natural cycle of 50 seconds. There is an offset of 44 seconds between the two crossovers. Yellow times are set at four seconds for all traffic movements. Two different all red times are used by MoDOT 1.2 and 3 seconds but to improve driver behavior on the simulation, 3 seconds of all red time has been used for all phases. Within a DDI there are four phases, however, there are only two phases at each crossover, phase 1 and 2 split the cycle as do phases 3 and 4. All phases can be controlled by one controller. Pedestrians are given a cycle of 20 seconds which has not been considered for simulation because there are minimal pedestrians using the intersection (less than five per hour observed).

Performance measures collected for the DDI included number of stops, total travel time, average delay per vehicle, average number of stops, average speed, and total delay. Average delay per vehicle was then used to determine level of service (LOS). The primary consideration for this research was LOS but other measures were also considered in the discussion.

Several assumptions were used as a starting point for phase timings. The PM peak was used for traffic volumes. Because of conflicts, there are only two phases at each crossover and it is not possible to try alternative phase pairs. Right turns from off-ramps were controlled to minimize conflicts, however in field drivers make right turns on red. This seems to be a point of confusion mentioned by a business owner and
experienced by the author when travelling through the interchange. Off-peak, the cycle length observed in the field was approximately 60 seconds. Several offsets were tested between 10 seconds and 44 seconds. Many simulations were then run to get an idea of what cycle lengths provide optimal progression through the interchange. When calibrating the signal plans, an all red of three seconds was needed for traffic to clear the crossovers.

Numerous signal timing plans were considered for the I-270 and Dorsett Road interchange. The existing method of using detectors for actuated signals was tested with numerous cycle lengths. Additional green time differences were explored throughout the cycle length changes. Green times were adjusted by starting at a 50-50 split for phases then subtracting one second from phase 1 and adding one second to phase 2, and vice versa for phases 3 and 4, in an iterative process. Increases in phase 1/3 correlated with a decrease in phase 2/4 because of the assumed relationship of flow between crossovers. This was done for approximately 10 trials within each cycle length, while attention was paid to average delay per vehicle. Throughout this thesis this method will be referred to as the Iterative method.

There were also two special signal timings tried for each cycle length. One was based proportionally on the existing timings used by MoDOT found in their SYNCHRO file. This SYNCHRO scheme allotted 42% of the time for phase 1, 48% for phase 2, 62% for phase 3, and 38% for phase 4, which included 4 seconds yellow and 3 seconds all red. Assuming the engineers were visually estimating traffic while optimizing the traffic lights, one might conclude that the ratios of green time given could be applicable to other cycle lengths.
Another plan was devised using vehicles per hour per lane, flow, ratios of phases at each crossover. This was accomplished by adding up traffic volumes for phases, with attention to the number of traffic lanes. Then the flow of traffic moving through a set phase can be calculated at a given crossover. Both crossovers were considered independently for these proportions, but traffic often uses more than one phase, intertwining the crossovers to an extent. The resulting proportions were phase 1: 55%, phase 2: 45%, phase 3: 59%, and phase 4: 41% of the cycle length.

When average delay was increasing consistently from the lowest previously observed average delay, trials were halted and a new cycle length was tested. Average delay was used to determine the level of service the intersection was operating at. Level of service grades were taken from the 2010 Highway Capacity Manual and shown in Figure 14.

<table>
<thead>
<tr>
<th>LOS</th>
<th>Signalized intersection</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>≤10 sec</td>
</tr>
<tr>
<td>B</td>
<td>10 – 20 sec</td>
</tr>
<tr>
<td>C</td>
<td>20 – 35 sec</td>
</tr>
<tr>
<td>D</td>
<td>35 – 55 sec</td>
</tr>
<tr>
<td>E</td>
<td>55 – 80 sec</td>
</tr>
<tr>
<td>F</td>
<td>≥80 sec</td>
</tr>
</tbody>
</table>

Figure 14: Level of Service table

### 3.2. Access Management Business Surveys

There is one access control inherent with the DDI design, no through movements are allowed on off-ramps. To maintain only two signal phases, left and right turns from
the off-ramp are offset from the crossover, and the concrete medians channeling the turns will prevent any sort of through movement from the off-ramp. The only real issue with this limitation is that if a driver unfamiliar with the area exits at the wrong interchange there is not a direct path back onto the controlled access road. Instead, the driver must proceed through the interchange, make a U-turn, and travel back through one crossover to enter the controlled access road. This could make the DDI a less attractive option if the area has high tourist traffic, additional information from the new Branson DDI should help in this area. However, if a DDI is being compared with a SPUI as is often the case in Missouri, they both share this off-ramp through movement limitation.

When new diverging diamonds are fitted to existing conventional diamonds, new designs might be required to maintain good signal spacing as required by a DDI to preserve good flow through a DDI. This can sometimes mean changes limiting access to the roadway, such as right in right out or other control measures. The current standard for AASHTO crossroad access is 100 feet from the ramp terminal for urban areas. According to a study done for the Virginia DOT (Rakha et al. 2008), increasing the distance above AASHTO standards can result in improved safety. In the report, a distance from access road to first intersection, such as that in Maryland Heights, of 250 feet results in 7.35 crashes per million vehicle miles traveled (VMT). Whereas increasing the distance to 600 feet can reduce crashes 50%.

As diverging diamonds have been installed in Missouri, some of the roads in the immediate vicinity have been reconfigured to allow for better flow through the DDI. This is accomplished by spacing the crossroad stoplights farther from the crossovers at either end of the DDI. Traffic flows through a DDI can be heavily influenced by
surrounding intersections and proper spacing is necessary to ensure success for the DDI. This thesis attempts to evaluate what type of influence reconfiguring signal locations and controlling access has to existing businesses near DDIs.
3.2.1. Maryland Heights Interstate 270 and Dorsett Road Diverging Diamond Interchange Business Surveys

Before the diverging diamond interchange, a standard diamond interchange was in place. Existing outer roads on the east side of the interchange were relocated farther away from the DDI crossover. This was necessary to allow for vehicle storage and to create an optimal spacing for the DDI signal progression. Below are before and after photos of the interchange in Figures 15 and 16 that show the different signal locations.

Figure 15: Interstate 270 and Dorsett Road before DDI was constructed (Google Maps)
Figure 16: Maryland Heights after DDI construction blue arrows point to stop bar location for traffic signals (Google Maps)

The change in the north outer road (Old Dorsett Rd.) affected several of the businesses from an access standpoint. Before the construction, Papa Johns and two neighboring restaurants had an entrance without a stoplight. There are also two hotels right off of the interstate on Old Dorsett Road that were contacted. Progress Parkway was the road directed south from intersection A, its name has been moved to the southbound road at intersection B and the south road at intersection A is now called Investment Drive. Just out of this picture there has been a roundabout created where Progress Parkway connects with Investment Drive, minimizing the impact of changing the intersection location from A to B for cars travelling westbound on Dorsett Road.

Because the flow rate through a diverging diamond can be improved by the spacing with adjacent intersections, sometimes the existing intersections are changed to improve flow. As previously shown through the figures, most of the DDIs in Missouri
have included a change in the surrounding approaches. While changing the approaches, some driveways may have their access to the roadway changed. A survey was created for local businesses to gage their opinion of the new diverging diamond interchange.

This intersection is the dividing line between residential housing to the west and commercial zone east of the interchange. Investment drive leads to a large Edward Jones office as well as Westport Plaza Shopping center. On Dorsett Road east of the interchange, there are several hotels and restaurants and also the post office for Maryland Heights. West of the interchange, apartment complexes and homes are located just off of Dorsett Road.

3.2.2. Springfield – I-44 and Kansas Expressway Diverging Diamond Interchange Business Surveys

The first diverging diamond constructed in Springfield had two adjacent intersections that were changed to help accommodate the DDI. I-44 is the road running east/west, while Kansas Expressway is going North/South. Orange circles shown below in Figure 17, depict previous locations for stoplights that have been removed for the new design. These two signalized intersections that were moved also happened to be driveways for two large retail stores and several small businesses surrounding them. On the southern half of I-44 (A) is a large Walmart store whose main driveway was changed for the new design. The north side of the I-44 (B) is home to a Lowe’s home improvement store with a large parking lot and a pair of gas stations. With the rearrangement on the north side of the interstate, one can reasonably assume that there is
better access to Lowe’s and the gas stations are located right next to the signalized intersection compared to the old outer road.

Figure 17: I-44 and Kansas Expressway Springfield green arrows point to stop bar for traffic signal (Google Maps)

Only two of the businesses at this location were available for surveys as a result of time passing since completion of the interchange. There were several reasons that this intersection was not an ideal candidate for surveys. One reason was that it is now two years old leading to some changes in managerial positions. Some of the managers were not working at the business around the time of the change in design and were unable to
contribute to the survey. Further consideration should be made as to what is a reasonable time table for the DDI to affect a business. Drivers generally become acclimated to the new design after driving through the interchange several times. Access management will always be an issue but relief of traffic congestion will be felt most during the first 6 months to the businesses. A final issue encountered when attempting surveys for this location was businesses closing or being bought out by another company especially several gas stations.

3.2.3. Springfield – US 60 and National Ave. Diverging Diamond

Interchange Business Surveys

Shown below in Figure 18 is the layout of US 60 and National Avenue before the Diverging Diamond was constructed. The horizontal road is US 60 which is crossed over by National Avenue with an overpass. Previously the overpass had five lanes, two in each direction with a split turning lane for on-ramp left turns. North of the interchange is Cox Medical Center south, a large hospital which contributed substantial payments for the rehab of this intersection. A small commercial zone exists on the southern side of the interchange with mostly restaurants.
Below, one can see an aerial photo after the DDI conversion in Figure 19. The biggest access control change made for this interchange was creating a right in right out entrance to the hospital with a tunnel going underneath National Avenue for northbound traffic. Previously there were left turns allowed but a median blocked through movements. Surveys were compiled for three businesses around the newest Springfield DDI. Two of the respondents were restaurants with the other being a bank.
3.3. Non-Motorized Transportation Issues within the Diverging Diamond

Previously there has been little research done with regards to pedestrian preference in a Diverging Diamond Interchange. As mentioned before, MoDOT considers the positive and negative aspects related to each possible configuration when designing the intersection; however, there has not been much research into how
pedestrians react to the changes brought about by this complex interchange. Changes to pedestrian walkways may not always be intuitive to users and safety levels may not necessarily decrease. The DDI creates a situation where pedestrians have to look right before crossing putting them at risk for bodily harm. Conversely, a DDI can produce a safe island walkway increasing safety. A survey was created to try and gauge pedestrian and bicyclist reactions to this complex new interchange. To view complete list of survey questions please see Appendix B.

Bicyclist can also be affected by the DDI. Certain states such as Oregon would require bike lanes to be included while others anticipate bikers using sidewalks. MoDOT allows bicyclists the option to ride on the road in traffic lanes or on the sidewalk. In Maryland Heights, approaching the DDI there are signs to alert drivers to share the road with bicyclist. This issue also likely coincides with city expectations and plans for development. Different cities have different policies about promoting cycling, which in Missouri is the likely factor for determining bicycle priorities. To accommodate a bike lane in both directions, approximately one traffic lane would have to be sacrificed.
3.3.1. Maryland Heights Interstate 270 and Dorsett Road Diverging Diamond Interchange an Underpass with Perimeter Sidewalks

To get a basic overview of the intersection one can look at Figure 20 below. I-270 is the existing gray road running north south while Dorsett Road is black running east west. There are two possible paths for pedestrians through this interchange, the north sidewalk or the south sidewalk. No crosswalks are available to move from the north side of the interchange to the south side. To accomplish this, one must walk to the next signal in either direction. The first signal to the west is a third of a mile away from the crossover. On the east side of the intersection, a more reasonable 650 feet is the distance from the crossover to the nearest crosswalk. Pedestrians might be more likely to cross free flowing traffic than to walk additional distance to use a crosswalk.

![Figure 20: I-270 and Dorsett Rd. DDI (MoDOT 2009)](image)

Two trouble spots are circled in pink to call attention. First, on the left side of the image one can see that there is no sidewalk from this portion westward. This forces a pedestrian to either walk in the grass or switch to the opposite side of the road. Another issue, possibly because of the construction is the planned crosswalk has not been painted yet. During the morning rush hour there were a substantial number of cars turning right
onto Progress Parkway and currently with no crosswalk pedestrians are left vulnerable to traffic.

Bicycle facilities for this interchange appear to be the sidewalk or shared lane with cars, which is consistent with adjacent intersections and roadway. There appears to be enough space for possible bike lane addition in the future because there is nearly a full lane of available space between the road and center divider on each side between crossovers.

DDIs provide a unique crossing situation in the USA, where pedestrians need to look left when crossing on-ramp left turn lanes. Designers have a solution shown in Figure 21 also commonly used in London, UK, where tourist pedestrians are not used to looking for traffic in different directions.

![Look left on crosswalk at Maryland Heights DDI](image)

**Figure 21:** Look left on crosswalk at Maryland Heights DDI
3.3.2. Springfield US 60 and National Ave. Diverging Diamond

Interchange Protected Center Walkway

This intersection is an overpass with National Avenue passing over US 60. On the north side of this interchange is a large hospital complex (Cox Hospital) that stretches a third of a mile until the next intersection. South of the interchange are restaurants, hotels, and small businesses. In the authors opinion there is a large gap where this interchange is that not many people cross on foot. Pedestrians and bicyclists have a protected walkway down the center of the interchange with concrete barriers on either side. For Missouri one sidewalk down the center of the overpass appears to be the preferred design for an overpass DDI. Having the sidewalk down the middle can allow for a retrofit of an existing single turn lane bridge into a higher capacity DDI. As shown below in Figure 21 the sidewalk starts out on both sides of the intersection then at the first crossover, a pedestrian will cross to the center of the roadway to pass over the highway. When the pedestrian reaches the second crossover they have the choice to cross to either side of the road. In Figure 22 the sidewalk has been highlighted with a red, green, and blue line. The red represents the sidewalk, blue shows crosswalks that aren’t protected, and green denotes crosswalks with pedestrian actuators. One preference noticed at several of the DDIs is that MoDOT seems to prefer leaving on-ramp right turns in a free flowing state, not offering an actuator for the crosswalk. Pedestrians are expected to make a single lane crossing to a protective island and from personal experience there is no problem making this crossing. There are plenty of gaps in the morning traffic and it is not a great distance to cross.
Figure 22: US 60 and National Ave. DDI arrows indicate stopping locations for cars at signal (Google Maps)
4. RESULTS AND DISCUSSION

4.1 Performance Measures of Diverging Diamond

Diverging diamond interchanges are unique in that they only have two phases per cycle. This unique trait is examined by collecting performance measures for two different VISSIM simulations. One simulation used the volumes from 2010 and another used future volumes for 2035. Vehicle counts were only available for the DDI portion of the Dorsett Road corridor during the PM peak, adjacent signals were not modeled in VISSIM because vehicle counts were not available. Traffic volumes are inclusive of all vehicles regardless of origin for the DDI. Many simulations were run with different cycle lengths for the PM peak hour volumes.

The VISSIM model was set up using a SYNCHRO file, which included signal timings, vehicle counts and route choices provided by MoDOT. A Google map was used to design the interchange in VISSIM. VISSIM’s urban driver behavior has been chosen for all links because the intersection is in a heavily urbanized area within St. Louis County. A set speed range of 29-35 mph was used for the intersection with reduced speed zones set throughout curves to simulate the design intentions. MoDOT plans for the DDI (MoDOT 2010a) show a speed limit of 30 mph for cars travelling through the interchange and 35 mph for cars approaching the interchange. The reduced speed values used for turning movements were 18.6 – 21.7 mph for cars and heavy goods vehicles
(HGV), in alignment with MoDOT’s desires to move vehicles through the DDI crossovers at 20mph and turns at 15mph (MoDOT 2010a). A vehicle composition of 98% cars with 2% HGV were assumed, no data was available.

The volumes used for the present simulation are shown below in Table 1. These volumes were obtained from MoDOT for 2010. The PM peak hour volumes showed traffic heavily favored movements towards the west side of the interchange. For example the Dorsett through movements are 320 eastbound versus 620 westbound. When comparing the off-ramp traffic, approximately 63 percent of exiting traffic has a final destination on the west side of the interstate. Table 2 shows the estimated volumes for 2035. These volumes were generated by using a growth rate of one percent per year, based off of a conservative estimate used by Chilukuri et al. (2011). The result is an increase in all travel time measures.

Table 1: 2010 PM Peak hour Volumes

<table>
<thead>
<tr>
<th></th>
<th>Eastbound (veh/hour)</th>
<th>Westbound (veh/hour)</th>
<th>Northbound (veh/hour)</th>
<th>Southbound (veh/hour)</th>
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</thead>
<tbody>
<tr>
<td>Left Turn</td>
<td>390</td>
<td>725</td>
<td>720</td>
<td>505</td>
</tr>
<tr>
<td>Through</td>
<td>320</td>
<td>620</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>Right Turn</td>
<td>400</td>
<td>775</td>
<td>385</td>
<td>785</td>
</tr>
</tbody>
</table>

*n/a because through movements are not allowed in DDIs for off-ramps
Table 2: 2035 PM Peak hour Volumes

<table>
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<th></th>
<th>Eastbound (veh/hour)</th>
<th>Westbound (veh/hour)</th>
<th>Northbound (veh/hour)</th>
<th>Southbound (veh/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Turn</td>
<td>476</td>
<td>885</td>
<td>878</td>
<td>616</td>
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<tr>
<td>Through</td>
<td>390</td>
<td>756</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>Right Turn</td>
<td>488</td>
<td>946</td>
<td>470</td>
<td>958</td>
</tr>
</tbody>
</table>

*n/a because through movements are not allowed in DDIs for off-ramps

Four major phases are used for a DDI. The through movements at each crossover correspond with an off-ramp turn in the opposing direction. As shown below in Figure 23, one can see where the west bound through signal number two is paired with northbound right turns. Similarly, eastbound through signal number one is matched with northbound left turns. Although there are four phases listed, at each crossover the cycle is split in two phases and all phases can be operated with one signal controller. For this particular intersection a pedestrian phase can be served sufficiently with corresponding red phases.
Figure 23: Traffic signal phases for Interstate 270 and Dorsett Road,

Basic overview of the interchange:

- Distance between crossovers is about 515 feet on Dorsett Rd.
- Dorsett Rd. has 3 lanes leading up to interchange but goes to 2 lanes after on-ramp left turn lanes diverge
- Interstate 270 southbound has roughly 1000 feet of storage for left and right turns, around 350 feet from the signals there is a third lane that is shared between left and right turns.
- Northbound off-ramp has 920 feet of storage, with 485 feet being 3 lanes and the previous 435 feet single lane storage
- Northbound and southbound on ramps merge from 2 lanes initially to 1 before reaching I-270
There are two critical points on the off-ramps where traffic can begin to backup. The problem area in the morning is coming off of southbound I-270. Starting out there are only two exit lanes which expand to three closer to the stoplight. When cars waiting to make left turns exceed the storage bay limit, cars turning right are also blocked from turning. Then instead of four storage lanes for turns on the southbound I-270 exit ramp there are only two, creating a large queue. Similarly during the PM peak, there is high demand from left turning vehicles with phase 1 and through cars from phase 2. There is approximately 280 feet of three lane roadway between the stop bar for phase 3 and where cars exit from northbound I-270 making a left turn onto Dorsett Road. This was the critical area for the entire intersection. When the signals were timed poorly, traffic from phase 2 would back up at this point and block the cars from phase 1 from being able to turn left onto Dorsett until the queue had dissipated. Under heavy queues, traffic making a left turn onto the southbound I-270 ramp also would be disrupted. Similar situations arose on east bound Dorsett Road for cars exiting left at phase 3 but not as extensively because phase 4 does not have nearly as many through cars.

As one might expect, with the growth in traffic demand the signal times must also evolve. If one examines the same signal timing for both 2010 and 2035, there are differences in all performance measures recorded. There were also more simulations that did not allow all vehicles to pass through the interchange.

To develop an optimal signal time for a diverging diamond, optimization must be done manually; VISSIM is currently unable to minimize delays for this intersection. The strategy consisted of starting with the existing SYNCHRO file and sample field signal timings. The actuated cycle used by MoDOT has a maximum cycle time of 100
seconds and a natural cycle length of 50 seconds. Various cycle lengths between 40 seconds and 100 seconds were simulated with fully actuated signal controllers. Additionally, three different offsets were tested, 10, 20, and 44 seconds. Twenty seconds was the time needed to drive from one crossover to the other in field, 44 seconds were given in the SYNCHRO file as part of a corridor plan, and after testing several other offsets 10 seconds was selected as the other option.

There were three signal timing methods tested in the simulation, green time percentages are shown in Figure 24. First the cycle length was divided equally between two phases then a base run was completed. For example with a 40 second cycle both phases would have 20 seconds. After that, one second was added to one phase and one second was subtracted from the opposing phase. This was an iterative process, referred to as Iterative method that ended when there was a noticeable increase in average delay per vehicle. Another method tested was determining the percentages of green time from the SYNCHRO file and using them with different cycle lengths. Similarly, the percentage of flow (vehicles per hour per lane) for each phase was calculated and given a corresponding percentage of green time at that crossover, throughout the cycle lengths tested.
The existing signal timing found in the SYNCHRO file is Phase 1: 42 seconds, Phase 2: 58 seconds while Phase 3 has 62 seconds, and Phase 4 38 seconds. This results in a total travel time of 116 hours with an average delay per vehicle of 32 seconds. The average number of stops per vehicle was 0.76. These results can be used to determine if a given timing plan is better or worse than what is in place.

Generally the shorter cycle lengths produced lower average delay per vehicle for the 2010 volumes. When comparing the best timing for a cycle of 100 seconds, average delay per vehicle is 30.6 seconds, while the shortest cycle length simulated of 40 seconds produced an average delay per vehicle of 20.1 seconds. However, the worst overall average delay per vehicle was found for a cycle of 40 seconds with a five second error in timing. The best was a 40 second cycle length with times of 18 and 22 seconds for phase 1 and 2, as well as 24, and 16 seconds for phase 3 and 4 at the other crossover. The short cycle works well at serving all traffic, thereby minimizing the average delay for all vehicles. However, the number of stops and average stops are lower when using a longer cycle length such as 90 seconds. When the cycle is 90 seconds, there is enough
time for most of the northbound off-ramp cars making left turns to make it through the crossover without having to stop. This does not happen with short cycle lengths. If there is much of a queue already at the crossover for phase 3, it can take several seconds to dissipate and limit the number of left turning cars from phase 1. Travel time through the intersection also limits synchronization with a short cycle length.

When comparing the signal timing strategies, the Iterative method resulted in a lower average delay per vehicle for every cycle length tested for 2010 volumes. Additionally, this method outperformed the existing timing plan for every cycle length tested. The next best strategy was using the existing signal timing plan’s green percentages and applying them to other cycle lengths. Figure 25 shows the best result for each timing method for all cycle lengths using 2010 volumes.

<table>
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<tr>
<th>Method</th>
<th>Φ1</th>
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<th>Φ3</th>
<th>Φ4</th>
<th>Total Cycle Length</th>
<th>Total Travel Time (h)</th>
<th>Num. of Stops</th>
<th>Avg Delay / vehicle (s)</th>
<th>Avg Stops</th>
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</table>

Figure 25: Simulation Results, the best timing plan for each method using 2010 volumes

Although the Iterative method performed very well there are limitations. A leading concern would be time constraints for producing a signal timing plan. Repeating the simulations over and over for an increment of one second is time consuming, especially if one considers several different timing plans for an intersection throughout the day. Additionally this Iterative method is only being used on an isolated
intersection, adding surrounding corridor signals might complicate the usage of this method.

Simulation with the existing timing percentages created timing schemes that were average throughout most cycle lengths, never the best or worst. Unexpectedly, all cycle lengths other than 100 seconds produced lower average delay than the field timing plan. These decreases in average delay started at 10% and dropped to 40% for the best timing plan using the proportions found with existing green times. The number of stops fluctuated throughout the cycle lengths but was worst during the 100 second cycle. Using this method still requires engineers to optimize signals in the field first, lowering efficiency but providing improved timings. In the future field optimization could be done first, then apply the resulting timing plan to different cycle lengths for VISSIM simulations to test for improvements.

The final method that was tested is also one of the simplest methods. If a specific phase of a traffic signal has 80% of the traffic flow, one would likely assume that phase should get the majority of the green time assuming everything else being equal (e.g., saturation flow rates). Therefore a scheme was devised which gave all traffic movements their share of green time based on their percent of total traffic at that crossover. After completion of the simulation, this method returned poor results. Average delays per vehicle were only good for a cycle length of 80 seconds, other cycle lengths returned results that were equivalent to the stopping point on the iterative method. This method would be the easiest of the three to implement in future timings and gives a good estimation for the amount of effort required.
When considering future volumes, a one percent growth rate per year has been used with the DDI layout unchanged from the current configuration. Contrary to the 2010 timing plans, longer signal cycles perform better overall than shorter cycle lengths. Changes in the signal timing plan, even a second one way or the other can make a difference of several hours in total travel time through the intersection with the increased traffic volumes. The level of service in with future volumes is at best C with some plans resulting in a level D. Still there are many scenarios in which all vehicles are unable to traverse the intersection successfully during simulation.

The Iterative method produced the best results of all tested methods shown in Figure 26. The optimal cycle length for minimizing total delay was 70 seconds; phase 1 was given 33 seconds, phase 2: 37 seconds, phase 3: 37 seconds and phase 4: 33 seconds. This resulted in an average delay per vehicle of 25 seconds leading to a total delay of 47.4 hours. The number of stops are third lowest among all simulations, suggesting that this is a good plan for all measures. Using flow rates proved ineffective in 2035 with no cycle lengths allowing all cars to pass through the interchange.

<table>
<thead>
<tr>
<th>Method</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>Total Cycle Length</th>
<th>Total Travel Time (Hours)</th>
<th>Numb of Stops</th>
<th>Avg Delay / vehicle (s)</th>
<th>Avg Stops</th>
<th>Avg Speed (mph)</th>
<th>Total Delay (h)</th>
<th>LOS</th>
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<td>33</td>
<td>37</td>
<td>37</td>
<td>33</td>
<td>70</td>
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<td>5093</td>
<td>25.08</td>
<td>0.748</td>
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<td>47.4</td>
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<td>35.9</td>
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<td>17.4</td>
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**Figure 26: Simulation results for 2035**

Using the Iterative method worked well with the increased volumes for 2035. The other two methods were not as successful because there was no margin for error. If the timing was off by one second in a phase, then all vehicles may not traverse the
interchange in the hour of simulation. All timing plans that had cars unable to traverse the interchange were considered invalid. However, with the Iterative method, small adjustments could be made to timing schemes when nearly all of the vehicles were able to pass through the interchange. One critical issue with the DDI when volumes are increased to 2035 levels is how to properly time phase 3, because the volume of cars from phase 1 and 2 that are going westbound on Dorsett Road have a tendency to back up because of the high volumes. When cars travelling through on westbound Dorsett get to the crossover signal sometimes there is enough volume that stopped cars are delaying left turns from the northbound off-ramp. This can create a safety problem, where not all of the cars will make it through the intersection before the end of the simulation because phase 1 and phase 2 are competing for green time. If there is not already a hierarchy for the interstate exits to limit spillover onto the interstate, it could be necessary in the future to set a priority for phases. Flow westbound on Dorsett Road is likely to affect the entire corridor. Often times during simulations, vehicles are backed up to the intersection immediately east of the DDI, creating another issue with balancing storage of the off-ramp against storage for through movements on Dorsett Road.

In the future if the number of pedestrians increases there might be a need to account for more time during pedestrian crossings. This could be a concern at the crosswalk that crosses Dorsett Road’s left turn onto southbound I-270. A queue typically builds up while phase 2 is green and slowly dissipates during phase 1 never allowing a gap for an unprotected crossing. Cycle times longer than 100 seconds could work with properly offset adjacent signals. However, this was unable to be tested due to a lack of data.
4.2 Access Management Business Surveys

For this study, only businesses that were directly impacted from the construction of the new interchange or the change in design were contacted, within a third of a mile or less away from the interchange. Surveys were collected from July 11, 2011 to August 2, 2011. The DDIs were opened: a) Springfield I-44 and N. Kansas Expressway June 21, 2009, b) Springfield US60 and National Avenue July 12, 2010, and c) Maryland Heights I-270 and Dorsett Road October 17, 2010. This gave a minimum of nine months for businesses and managers to feel impacts from the DDI. The majority of surveys were completed by phone. Surveys lasted less than three minutes enticing managers to participate with minimal impact to their schedule. One manager was also contacted in person during a site visit. Businesses ranged from local restaurants to large retail stores. Twelve surveys were collected overall out of 22, giving a response rate of 55%. Responses were received from all three of the DDIs in Missouri but more from the Maryland Heights and National Avenue Springfield location. Their recent completion lead to more of the managers still working that had witnessed the previous interchange. To see the list of questions used for the survey see Appendix A.

The following graphs, Figures 27-35, represent questions asked during the business survey. They summarize business responses for all three DDIs surveyed, Maryland Heights I-270 and Dorsett Road, Springfield US 60 and National, and Springfield I-44 and N. Kansas Expressway. All questions had responses from twelve businesses except one.
Starting with Figure 28, one can see that one business lost accessibility to their business as a result of the DDI. With the DDI design, the median barrier shown in Figure 27 extends farther than the previous design, allowing about 3 car lengths of storage before the driveway. The manager noted that it was hard to make left turns into their business after the DDI conversion.

*Figure 27: Dorsett Road and I-270 median barrier obstructing starred driveway*

Next managers were asked about losing property for the DDI to determine if that affected their view of the design overall. The results are shown in Figure 29. Only one manager reported losing any property but stated an equal piece of land was given by MoDOT in exchange, resulting in a neutral response. Next, businesses were asked if they noticed a change in customers after the DDI was built. Figure 30 shows that eight businesses experienced no change or were neutral and four businesses had noticed a change. Immediately following that question was whether the change was positive or negative, shown in Figure 31. Four businesses replied with increases and eight stated their business patronage was neutral.
Managers were asked if they had heard customer complaints about the interchange to capture public feedback about the interchange design. Only 11 managers responded to this question and Figure 32 shows six had not and five had heard customer complaints. The next question was about a business’s suppliers and if they had any comments. This question was formulated to catch any issues larger vehicles were having with the DDI. One can see in Figure 33 that there was one negative comment along with 11 neutral or positive remarks.

Participation in public meetings was included in the survey to determine if businesses were more likely to appreciate new designs after having a chance for their input. Figure 34 shows that four businesses participated in public meetings and eight did not. All businesses that participated in public meetings had positive views of the DDI. Figure 35 shows businesses satisfaction with the current design, eleven were and one was not satisfied with the design. The unsatisfied manager also felt that they had lost access to their business and a loss in customers.
Do you think you lost accessibility to your business as a result of DDI

Figure 28: Pie Chart for business accessibility question

Did you lose property for new interchange

Figure 29: Pie Chart about Property Loss for DDI
Have you noticed a change in customers since the new design

Neutral 2
Yes 4
No 6

Figure 30: Pie Chart for change in customers

Positive or Negative change in Business

Neutral 8
Positive 4

Figure 31: Pie Chart change in business after DDI
Figure 32: Pie Chart for customer complaints after DDI

Figure 33: Pie Chart business suppliers comments
Participate in Public Meetings

Yes 4
No 8

Figure 34: Pie Chart for participation in public meetings for DDI

Are you satisfied with current design

Yes 11
No 1

Figure 35: Pie Chart for satisfaction with DDI design
Finally managers were asked overall how the DDI has affected their business. The author would consider positive and neutral to be good outcomes showing that the DDI does not hurt a business and negative to be an argument against DDIs. In Figure 36 one can see eleven businesses felt positive or neutral about the DDI while one business had a negative view overall.

![Pie Chart overall rating of DDI on business](image)

**Figure 36: Pie Chart overall rating of DDI on business**

These surveys do not capture all elements leading customers to a business, destination choice could be affected by congestion or lack of congestion associated with a DDI. Compiling a destination choice survey would provide more information from
customers. A destination choice survey of customers could then be compared with business perception to draw stronger conclusions in future research.

In the future businesses could be contacted in a before/after survey about impacts of the DDI. Timing is also very important; manager turnover can affect the sample size if surveys are not obtained in within the first six months of DDI operation. Large sample sizes may only be possible with ten DDIs because each DDI affects a unique number of businesses. Additionally, not all businesses will likely respond
4.2.1 Maryland Heights Interstate 270 and Dorsett Road Diverging Diamond Interchange Business Surveys

Overall the feedback from business owners in Maryland Heights was very good. All of the managers stated that the new interchange relieved congestion and they were happy with the interchange overall. Only one manager complained that the interchange had hurt their business but also offered that she liked the DDI overall. The manager mentioned that it was harder for customers to access her business and felt the DDI negatively impacted business. Other responses ranged from good to satisfactory. Three businesses stated that they had noticed a change in the number of customers. All three reported positive increases in the amount of business they were seeing because of the DDI. A pizza delivery service, a family oriented restaurant and a hotel chain were the businesses that reported these positive changes.

There were no reports of losing property to the interchange as in eminent domain. Substantial reconfigurations were completed for this interchange and one might expect some sort of eminent domain to have been used. Nevertheless, businesses that were most likely to have been affected by the roadway changes were available for contact and had positive opinions about the interchange upgrades. Slightly more surprising was that only one manager reported participating in the public meetings and this manager’s property was not directly impacted by construction.

After reviewing Google Streetview, it appears that there was a gas station and Waffle House that sat where the new Old Dorsett Road intersects Dorsett Road. These could be the businesses that were lost for construction of the DDI and were unavailable for comment. One solution MoDOT may have used could have been to purchase some
land from business owners who did not mind relinquishing it. Many of the businesses did have a small buffer between the road and their building which probably prevented major impacts. MoDOT appears to have optimized construction of Old Dorsett Road (northeastern outer road) in existing right of ways as much as possible.

Businesses reported mixed opinions when asked about accessibility. The primary negative concern was reported from a new business owner who reported problems customers had with turning into their business. However, it is important to note that the business owner had purchased the restaurant after construction had been started and was not aware how the previous configuration affected the entrance way. While the business was not located directly off of Dorsett Road, the driveway was only 250 feet from the crossover signal. When heavy traffic was present it could become difficult to turn in from westbound lanes because stored cars from the eastbound crossover signal were backed up. Another restaurant reported construction work creating problems, but the final design was not affecting accessibility.

As alluded to previously, all businesses that reported a change in business had a positive increase in business. Three of the managers contacted noticed a positive change in customers since the new interchange was completed. All of these businesses were directly impacted by the change in design. One business was based on pizza delivery and found that the better traffic situation allowed for more customer carry outs. The other restaurant had reported accessibility issues during construction but noticed more customers after construction was complete. Positive reviews from businesses about DDI implementation should help DOTs with future DDI construction.
Complaints have been heard by three out of seven managers from customers. One concern raised by a hotel manager was that roughly two out of fifteen guests said the design was confusing. One could say this is the largest drawback to a DDI, drivers not being familiar with the design, which can be expected. Novel interchanges can require several trips through the interchange to become acclimated and media campaigns are only targeted at local drivers. Furthermore, the guests of a hotel are likely from out of town and not used to seeing such a design. Another manager had customers state that it was hard to turn in to their location and this complaint corresponded with the manager’s overall opinion of the interchange. Finally one manager noted a few general complaints about the interchange.

No managers had received any complaints or comments from their suppliers. Only one business had sent a manager to a MoDOT meeting, who reported an overall satisfaction with the interchange design. Overall satisfaction with the interchange was high; every manager reported that they or their business was satisfied with the current design.

When asked what they like most about the interchange managers responded:

- The fact that there are less traffic jams, westbound used to be really bad and would take several lights to get through
- Whole thing, different design that is new
- Flow of traffic is better
- More of an attraction, looks better
- Controls traffic better

What they dislike the most?

- Our entrance/exit is not ideal
- All the traffic lights
- Nothing
• Confusing for first time drivers
• Uncertainty about right on reds for off-ramps

The business surveys have a bit more to do with how well a media campaign worked on public perception and how much a particular DDI changed due to signal relocation. However these are critical elements to the success of a constructed DDI. If the public does not perceive the DDI to be positive then the DDI will not be a strong candidate for the next intersection in an area that could benefit from it. DDIs require special spacing between adjacent intersections and crossover. This requires some of the adjacent signal roads be relocated to maintain an optimal progression through the corridor. This can be a very delicate process with local businesses and has the possibility to create fierce opposition to a DDI.

Businesses in Maryland Heights seemed receptive overall to the increased performance of the DDI after construction over a standard diamond. Even the business owner that felt a negative impact on their business due to the DDI was satisfied with the current design and experienced shorter travel times through the intersection. This business was already sharing a driveway and did not receive any access control measures but was located near a crossover. This was different from the findings of Vu et al. (2006), who found that businesses with shared driveways or traffic signals often had positive perceptions of patronage, while those with right in right out controls were considered negative influences on business.
4.2.2 Springfield – I-44 and Kansas Expressway Diverging Diamond

Interchange Business Surveys

Responses received from the first Springfield DDI were both positive overall. Although there was not much research done at this location, two very prominent businesses were reached. Neither business expressed a loss in accessibility due to the new interchange nor did they lose any property for the DDI. McDonald’s reported no change in the number of customers while Walmart was unsure because a new store had been constructed nearby. McDonald’s had noticed people complaining about the interchange while it was still new, whereas Walmart reported that everybody liked the interchange. The suppliers to Walmart commented that they liked the new design because traffic moves faster. Walmart was one of the few businesses surveyed that did have somebody from management attend a MoDOT meeting about the new design. McDonald’s did not think that anyone went to the meetings. Both were satisfied, and Walmart was “very satisfied”. Between the two businesses when asked what they liked most stated:

- Easier to get through north and south with less tie ups than before
- Seems easier to get on and off the interstate
- More convenient overall

When asked what they liked least about the new intersection they responded:

- Hard for people from out of town to understand
- Stoplight was moved to the south side of store instead of directly in front of Walmart but not a major issue.

Both managers thought that the DDI had positively impacted their businesses overall.
Around Interstate 44 on North Kansas Expressway, most of the businesses are sharing driveways. Walmart is nearby and has two driveways, one closer to the DDI allows for right turn exits but left turn entries, and a signalized exit farther from the DDI. There are several businesses on Walmart’s side of the road, including McDonald’s, which are sharing driveways. According to Vu et al. (2006), this would make these businesses more likely to report positive perceptions of the interchange, which they did. On the east side of North Kansas Expressway, businesses have unrestricted access and the previous stoplight location was for the outer road. When the stoplight intersection was relocated farther south of the DDI, Golden Coral gained a signalized entrance and exit opposite of Walmart.

4.2.3 Springfield – US 60 and National Ave. Diverging Diamond Interchange Business Surveys

The majority of responders for this location were positive. This location already had a substantial amount of access control and there were no traffic lights in the immediate vicinity of the interchange. On the north side of the interchange only the CoxHealth hospital had a driveway within a third of a mile. Unfortunately hospital representatives were not available for the survey, although one would assume they are satisfied with the design considering they contributed millions of dollars to the project. South of US 60, there are two collector crossroads for all of the business traffic, with two right in right out (RIRO) driveways between them. East Kingsley Street is closest to the DDI and does not have signalized control but allows for left turns in or out, which is the
same as before the DDI. With the limited change at this intersection because of the DDI, the impacts to business should not be as substantial. Most of the businesses have combined driveways or are connected to National Avenue by a collector road.

The businesses that responded to the survey were within the first cross road E. Kingsley Street. Two of the managers were satisfied with the current design, while one found the design confusing and unnecessary. None of the managers contacted had lost any land to the DDI, although one lost a strip of land on one side and gained an equal amount on the other side. They reported no loss in accessibility for the customers. One restaurant noticed a positive increase in customers after construction of the DDI while the other restaurant and bank felt no change occurred in the number of customers.

Customers will often state their opinion to people working at a particular business and these particular managers had several complaints they had heard. One stated that older drivers were having issues adjusting to the design. Another manage commented similarly about elderly drivers and had seen two cars go down ramps the wrong way. Suppliers for one business had to adjust their exit to several right turns instead of making a left onto National Avenue. The two businesses with the more positive view of the new interchange had a representative at the MoDOT meetings. This is a valuable correlation for DOTs illustrated that being able to control the message, accept input, and show the public how a different option will improve traffic can result in more support from business owners.

Only three businesses responded to the survey for this location making it hard to draw meaningful conclusions. However, two out of three business owners were satisfied with the current design, while one found the design to be unnecessary. This manager that
was not satisfied with the design had not been to any MoDOT meetings, increasing the chances that he did not understand the benefits the DDI provided over other options, demonstrating the importance of educating the public.

When asked what they liked most about the DDI managers responded with:

- DDI increased traffic flow
- Can make left turn during rush hour much easier
- Traffic goes through faster than before

What did the dislike the most about the DDI:

- Does not like getting caught at the signals, felt they should make it through the DDI once they start
- Curves more than the other DDI in Springfield seems dangerous in winter weather conditions
- Seems unnatural, contributes to traffic problem because people don’t understand it

Generally speaking, two managers felt the DDI had a neutral impact on their business and one felt a positive impact because of the DDI. Research from this intersection showed that improving traffic flow can have a positive impact on businesses. If a DOT can demonstrate how the DDI will improve traffic flow and that improved traffic flow will increase business patrons early on, business owners might be more supportive of designs they are unfamiliar with.
4.3 Non-Motorized Transportation Issues within the Diverging Diamond

In a general overview of walking and biking, there is not much of it going on in DDIs studied in this thesis. Most DDIs are built for access controlled highways or interstates. That alone cuts down the number of destinations available to a pedestrian or bicyclist moving through this interchange. More complex issues for trip generation could be related to differences in land use from one side of an interstate to the other and the general separation an interstate creates between two different sides. Two different DDIs are studied, one overpass and one underpass. Six surveys were obtained, four pedestrian and two cyclists. Because of the sample size the results of the survey are discussed with relation to issues found within each DDI alternative.

The most likely candidate for pedestrian crossing at Missouri DDIs has to be the center sidewalk, which has been installed at four out of five DDI locations in the state, including two new locations since the start of this research. The advantages and disadvantages are reviewed through pedestrian and bicyclist surveys in the following sections.

4.3.1 Maryland Heights Interstate 270 and Dorsett Road Diverging Diamond Interchange an Underpass with Perimeter Sidewalks

On August 5th a site visit was made from approximately noon until 1:30 PM. Two pedestrians and a bicyclist were observed using the interchange. There was construction occurring on the north sidewalk that consisted of pouring concrete for the sidewalk. Nevertheless, one pedestrian was seen using the north sidewalk and possibly part of the closed traffic lane for construction to cross the interchange. The bicyclist
observed was travelling westbound on Dorsett Road with the flow of traffic. Upon reaching the second crossover he took the sidewalk across this signal and continued to ride against traffic in the eastbound lane because there is no sidewalk on the southern side of Dorsett Road after the interchange. Pedestrians and cyclists at this location were not afraid of traffic and that showed through their interactions with the DDI.

Another field visit was made on August 8th to the Maryland Heights diverging diamond interchange for the morning peak hour commute as recommended by a construction worker. From 7:00 AM until 9:00 AM there were approximately nine pedestrians and zero bicyclists. Five were walking on the north sidewalk and four used the south sidewalk. Two pedestrians were observed crossing the six lanes of traffic on the outside of the intersection to reach the opposite side of the road. This is a result of the crosswalk being too far away from where pedestrians are interested in crossing. When the nearest cross walk is approximately 200 yards out of the way the pedestrian will cross at the point most convenient to them.

Only a couple of interviews were obtained for this intersection. There was great difficulty in observing pedestrians and being on the right side of the road to survey. One responder had only walked the interchange once since the construction. When asked whether signage was sufficient for safe crossing, the pedestrian was not convinced there was enough. However, they felt safer crossing through the DDI than the previous diamond. Next the person said they felt uncomfortable enough with the new design to change their walking habits. They referred to the channelized walkways as a “mouse trap”. The crosswalks did not seem unsafe because of traffic coming from unexpected
directions, they said the grooves helped. This person felt that more pedestrians used the sidewalks with the old configuration.

Overall this survey respondent was inconsistent at best. As one might expect, the educational material was focused on cars moving through the intersection and pedestrians are left to learn by experience, which is reasonable considering the number of pedestrians using the intersection.

As alluded to in the previous paragraphs there are a few observations concerning this interchange and pedestrians. First of all there are relatively low numbers of pedestrians. A construction worker who was interviewed reported seeing maybe 6-10 pedestrians in a given morning. Then three were counted at midday and if one assumes 6-10 pedestrians will return home in the evening there are around 30 pedestrians total per day with only 10-14 being unique for surveys. Additionally observing new pedestrians would seem unlikely except on weekends. The composition of pedestrians appears to be commuters that live close by and work at businesses adjacent to the DDI. Bus stops are located on either side of the interchange limiting that possibility of pedestrian usage.

The right turn lanes from Dorsett Road onto I-270 do not have pedestrian actuators, requiring pedestrians to cross free flowing traffic. Pedestrian actuators at other crossings in the DDI were not fully understood by several interviewees who thought the actuators did not work. The pedestrians were expecting the actuator to work faster and therefore just crossed during traffic gaps.
4.3.2 Springfield US 60 and National Ave. Diverging Diamond Interchange Protected Center Walkway

A field visit was taken on August 11, 2011 from 8:30 until 10:00 AM to observe the morning peak hour and survey pedestrians. Throughout this time period three bicyclists and three pedestrians were observed. Two of the bikers used the center sidewalk, while one used the right-hand lane of traffic to get through the intersection. One bicyclist who was riding on the road moved to the protected sidewalk for the crossover portion of the DDI and one rode on the sidewalk the entire time. One of the pedestrians was a jogger who ran about twice a week through the DDI. The other pedestrian interviewed was a construction worker from the hospital that took three smoke breaks a day in the center walkway of the DDI (off of hospital grounds). He reported rarely seeing anybody else walk through the intersection.

Another interesting comment made by a bicyclist was that previously he had been riding on Fremont Street, which is one block east and runs parallel to National Avenue, but since the diverging diamond opened he began using National Avenue to ride to work. He also mentioned that Fremont was crazy and felt much safer riding on National through the diverging diamond. He used the protected center sidewalk instead of riding in the traffic lanes. Another bicyclist used the road only supporting the expected behavior suggested by planning professional’s interviewed in Chilukuri et al. (2011).

Below in Figure 37 is a view from a pedestrian’s perspective of the center island walkway. This is a plan view from the first DDI in Springfield. By looking at this one can see how a pedestrian is protected with concrete barriers on either side of the center
walkway. There are also raised bumps for ADA compliance at the edge of the sidewalk before the crosswalk.

Figure 37: Pedestrians view of crosswalk to concrete barrier protected center walkway (MoDOT 2010a)
5 CONCLUSION

The diverging diamond interchange has proven to be a valuable alternative to existing interchange designs because of the cost savings. However, if there were not safety and operational benefits associated with a DDI, it would not be as attractive of an option as it is. This thesis has attempted to bring together valuable pieces of literature about DDIs while also exploring new topics associated with the DDI.

This research found that while field optimization, currently used by MoDOT, for a DDI has been successful, signal timing plans can be improved with simple methods tested in this thesis. These methods can easily be investigated using a traffic simulation software program such as VISSIM. Three different methods were tested: an Iterative method, one that uses traffic flow percentages, and by trying different cycle lengths with the existing field optimized green time ratios. The optimum timing plans were found using the iterative process for every cycle length tested on present 2010 volumes and future 2035 volumes. Still, the other methods give a good starting point for the iterative method. Average delay per vehicle was reduced 94% and the level of service was improved from level C to B. This was done by changing the cycle length from 100 seconds to 40 seconds for the 2010 traffic volumes. With 2035 volumes, the intersection is near its capacity and signal timing becomes much more delicate. A change in timing of one second either way can result in the intersection failing from a capacity standpoint. The current timing plan would not allow all vehicles to pass through the intersection. Shortest cycle lengths that performed well with 2010 volumes also were ineffective.
Mid-range cycles such as 70 seconds returned lowest average delay, level of service, and maximum speed. While a 100 second cycle produced the lowest number of stops and provided the best performance measures. Unlike the 2010 simulation, 2035 has a level of service of C at best, with several timing schemes providing level of service D while still allowing all cars to pass through the DDI.

Surveys were created for businesses surrounding the DDI. The survey was formulated to gauge businesses’ opinion about how the diverging diamond interchange affected their business. One business out of the twelve surveyed had a perceived loss of accessibility due to the DDI. This business was satisfied with the design but felt a negative overall impact from the DDI. Eleven out of twelve businesses had a positive or neutral effect on their business. Vu et al. (2006) found a strong link between improving traffic flow and business. Throughout the surveys this was confirmed, even the manager that lost business was satisfied with the designs improvement on traffic congestion. Most businesses will accept new solutions that increase traffic efficiency. In the future more in depth economic studies could be used as evidence to new areas that have not experienced a DDI.

Non-motorized issues such as cyclist and pedestrians have not received significant attention for DDIs. Previous surveys consisted of interviewing bicycle experts and planners about the interchange. The survey in this research attempted to gain new public feedback from day to day users of the DDI who are less familiar with design intentions. Both an overpass with a center protected sidewalk and underpass with perimeter sidewalks were studied and surveyed. Future research could be done to create a better method for pedestrians to cross the through street of the diverging diamond intersection.
This is especially true for perimeter based sidewalk systems used similar to the St. Louis Dorsett Road interchange. At the St. Louis interchange there was enough room outside of the sidewalk for bikers to use as a bike lane and one person was observed doing this. Previous planning around the interchange can determine whether or not there is a sidewalk leading up to the interchange because some sidewalks ended after the DDI. When the perimeter sidewalk is used, creating ways to cross from side to side within the interchange would be a safety improvement. Currently most pedestrians choose to cross free flowing traffic lanes instead of travelling farther to use a crosswalk.

One of the drawbacks to having barricades around a center sidewalk was that the pedestrian might not feel comfortable. After surveying, the author can conclude that pedestrians and cyclists perceive the barricades to be safe. A cyclist was witnessed changing from the road onto the sidewalk for the overpass to use the barrier protected sidewalk. Another cyclist reported he previously used a parallel road to get to work but now that the DDI was built he felt it was much safer and used the sidewalk to traverse it.

More research into the best sidewalk design can be done when more pedestrians are present; currently there are very few pedestrians at the studied DDI locations. There will inevitably be different pedestrian and bicycle behavior throughout the different parts of the country. In Missouri’s cases, bicyclists are not as prevalent, and drivers are not as used to sharing the road, which can make cyclists more likely to use the protected sidewalk through a busy interchange for safety. When more cyclists are present that prefer to ride in bike lanes the traffic flow could be impacted.

In the future, more comprehensive studies of built DDIs should help answer questions about the performance, safety, and cost of DDIs. If the positive word of mouth
reviews are confirmed DDIs could become popular cost saving interchange solutions. Positive reviews from DDI implementation should help DOTs in the future when new solutions are discovered in the design stage.
REFERENCES


Appendix A
Diverging Diamond Business Survey about Access Management

Date:

Call or In Person

Business:

1) Do you think you lost accessibility to your business as a result of the new interchange? Yes / No
2) Did you lose any property for the new Diverging Diamond Interchange? Yes / No
3) Have you noticed a change in the number of customers since the new interchange? Yes / No
4) Was that change + or –?
5) Have customers complained about the DDI? Yes / No
6) Do your suppliers have any complaints or comments? Yes / No

What are they?

7) Did you participate in any public meetings?

8) Are you satisfied with the current design?
9) What do you like most?

10) What do you dislike most?

11) Do you think the DDI has affected your business positively or negatively overall?
Appendix B
Diverging Diamond Bike/Pedestrian Survey

Date:

Pedestrian or Bicycle

Location:  Springfield 1  Springfield 2  Maryland Heights

1) How often do you walk or bike through this intersection? (daily, once a week, etc.)

2) Do you think there is sufficient amount of signage to help pedestrians safely cross?

3) Do you feel safer crossing the lanes now than before?

4) Has the new design changed your walking habits?
   a. If so how?

5) Do the crosswalks seem unsafe to use because you have to look for traffic in the wrong direction?

6) Have you noticed many other pedestrians using the sidewalks?

7) Do you feel comfortable and safe using the current sidewalk?

8) Would you prefer to walk down the middle or outside of the traffic lanes?

9) What improvement would you make?

10) Biker: Would you prefer riding a bike lane or the sidewalk?