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UDOT DIVERGING DIAMOND INTERCHANGE (DDI) OBSERVATIONS AND EXPERIENCE

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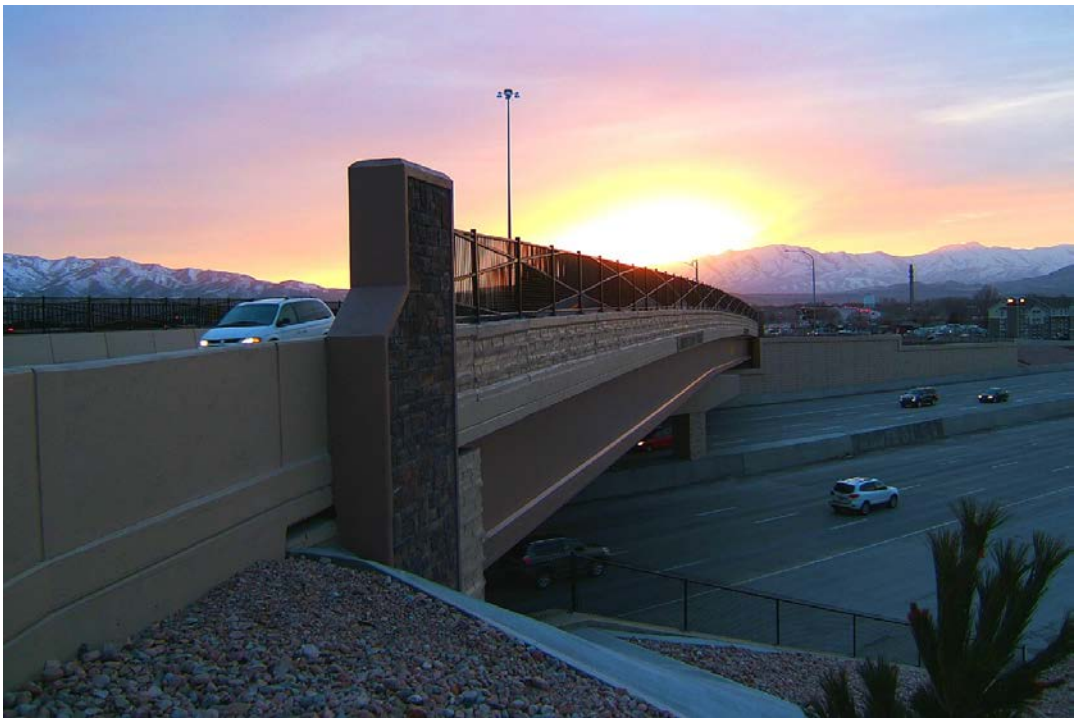
April 2012

UDOT Diverging Diamond Interchange (DDI) Observations & Experience



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16. Abstract

This report presents the results of a functionality evaluation, by the I-15 Utah County Corridor Expansion (CORE) traffic team, of the first Diverging Diamond Interchange (DDI) in Utah, located at the intersection of American Fork Main Street (Pioneer Crossing) and I-15. The Pioneer Crossing DDI was opened to traffic in August 2010. This evaluation incorporates a review of population trends, traffic patterns, detoured traffic, and design features to understand how this new interchange operates for the traveling public. In general, this evaluation determined that the application of a new-construction DDI at this location resulted in better than expected traffic operation. Since the completion of the Pioneer Crossing DDI analysis, three other DDIs have been opened to traffic within Utah with differing site conditions and geometric provisions. Two of the DDIs were retrofits of previous conventional Diamond Interchanges. One was a new construction completed for the I-15 CORE project. The other three installations have added valuable insight to the traffic characteristics that influence the DDI design so that future DDIs can be even more successful. An observational study was completed at each of the new DDIs in Utah, and key characteristics were recognized for working well or not working well with the DDI design. These characteristics and conclusions from the study of the four DDIs currently in Utah are provided as lessons learned for use on future projects. Overall, the four DDIs have proven effective as viable interchange options at these locations.

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Executive Summary

The I-15 CORE traffic team was asked to evaluate the functionality of the first Diverging Diamond Interchange (DDI) in Utah located at the intersection of American Fork Main Street, also known as Pioneer Crossing, and Interstate 15 (I-15) in Utah County. This evaluation incorporates a review of population trends, traffic patterns, detoured traffic and design features to understand how this new interchange operates for the traveling public. In general, this evaluation determined that the application of a DDI at this location resulted in better than expected traffic operation.

Population growth has increased in northern Utah County over the last 10 years. In addition to population growth, commercial development has increased. Most of the population growth has occurred on the west side of I-15 to the north of Utah Lake leading to the construction of Pioneer Crossing and the Diverging Diamond Interchange (DDI) at I-15 and American Fork Main St.

When the Pioneer Crossing DDI opened in August of 2010, a shift in east-west travel was observed between Lehi Main Street and Pioneer Crossing. Traffic volumes on Lehi Main St decreased by approximately 5,500 vehicles per day (a 23 percent decrease), while volumes on Pioneer Crossing increased by approximately 10,200 vehicles per day.

The original Access Justification Report (AJR) for the DDI documented the proposed changes to the interchange and projected the impacts these changes would have on traffic both on opening day and in the future (2030). Actual opening day (2010) traffic counts were collected and compared to traffic volumes used in the AJR. This comparison showed that some of the opening-day turning-movement volumes within the DDI were relatively close to the 2030 volumes that were projected for use in the AJR. At current volumes, the DDI is functioning as intended with minimal delay and high mobility. The DDI and the surrounding intersections are operating within, and in some cases, better than expected levels of service, as reported in the AJR.

There may be concern that the interchange will fail sooner than expected due to the increased in observed traffic volumes. Throughout 2011, the I-15 CORE traffic team has been given the opportunity to evaluate the operation of the DDI under varying traffic patterns associated with incident management and detour traffic associated with freeway reconstruction. The DDI has been used to divert traffic off I-15 for three separate full I-15 night time closures, and was vital to the State Street detour for several day time closures; including two pothole repair operations and two separate paving operations that lasted 19 and 15 days each. The DDI has also proven effective in diverting traffic off I-15 and onto State Street due to backups from incidents such as stalled vehicles or crashes. Field observations during each of the closure events have indicated that traffic flow at the DDI was not hindered with the increased directional traffic but was proven as an effective traffic management tool in diverting traffic off I-15.

Since the completion of the Pioneer Crossing DDI analysis, three other DDIs have been opened to traffic within the State with differing site conditions and geometric provisions. Two of the DDIs were retrofits of previous conventional Diamond Interchanges. One was a new construction completed for the I-15 CORE project. The other three installations have added to the valuable insight to the traffic characteristics that influence the DDI design so that future DDIs can be even more successful. An observational study was completed at each of the new DDIs in the State and key characteristics were recognized for working well with the DDI design. These characteristics include the following:

1. Directional traffic flow with either high demand from the interstate to the cross-street or across the interchange with lower exiting volumes work well with a DDI. For example:
    a. I-15 at 500 East in American Fork
    b. I-15 at Pioneer Crossing in American Fork
    c. I-15 at Timpanogos Highway in Lehi
2. Left turn lanes on the cross-street help to separate turning traffic from through traffic to improve overall operations of the interchange. For example:
    a. Heavy left turn volumes from the cross-street to the interstate on-ramp in conjunction with heavy cross-street through traffic benefit from having left turn lanes develop in advance of the approach cross-over signal.

i. I-15 at Pioneer Crossing in American Fork
ii. I-15 at Timpanogos Highway in Lehi (Westbound)

b. Medium left turn volumes from the cross-street to the interstate on-ramp in conjunction with heavy cross-street through traffic benefit from having a left turn lane develop under or over the structure between the off and on-ramps.
    i. I-15 at Timpanogos Highway in Lehi (Eastbound)

From the observational study at each of the new DDIs in the State, key traffic characteristics were also recognized for not working well with the DDI design. These characteristics or disadvantages include the following:

1. Heavy traffic demands at the freeway exit and the cross-street simultaneously result in congestion associated with vehicles needing to be stored between the two cross-over signals.
    a. SR-201 at Bangerter Highway in West Valley City. Since this interchange was a retrofit, the ability to provide left turn storage on the existing structure was limited.
    b. In general, a DDI is limited to one of two phasing strategies: emphasized coordination to the off-ramp left turn movement or emphasized coordination of the through traffic movement across the interchange. If both movements are heavy, the overlap of queues can be difficult to overcome during peak periods without sufficient capacity.
2. Coordination of the DDI with adjacent signals is not easily done. Most DDIs need a lower cycle length than the adjacent signals. This may result in a vehicle having to stop at both the off ramp terminal and the next adjacent signal.

Based on general observations of each of the DDIs in Utah, the following conclusions were made:

- Each location should be studied and evaluated using appropriate traffic modeling and engineering principles.
- From a signal timing perspective, a DDI can be optimized to better accommodate cross traffic, or left turning traffic from the off ramps. As a result, DDIs are often

best suited for locations with high demands on the off-ramps or the cross-streets, but not both simultaneously.

- A key success to the overall operation of a DDI is weaving movement. Lane utilization issues can be overcome through properly designed auxiliary lanes that develop in advance of the cross-over intersections. These lanes should include the appropriate advanced guide signing.
- The striping, signing, traffic signal and roadway design should be as uniform as possible between DDIs to meet driver expectancy and optimize the overall efficiency of the system.

In conclusion, under the right circumstances a Diverging Diamond Interchange can be an effective interchange option. The DDI at I-15 and American Fork Main St has performed well from a traffic standpoint and is expected to continue to perform well for years to come. Additional DDIs around the State have also proven effective as viable interchange options. Lessons learned on the current DDIs will help to improve any future DDIs considered throughout the State.

1 Introduction

The I-15 CORE traffic team was asked to evaluate the functionality of the first Diverging Diamond Interchange (DDI) located at the intersection of American Fork Main Street also known as Pioneer Crossing and Interstate 15 (I-15) in Utah County. This evaluation incorporates a review of population trends, traffic patterns, detoured traffic and design features to understand how this new interchange operates for the traveling public.

The need for a major east and west route in northern Utah County has grown exponentially in the past ten years. Prior to the construction of Pioneer Crossing Lehi Main Street and American Fork Main Street experienced major delays for drivers on either side of I-15. Much of the growth west of I-15 in Utah County came without major improvements to the transportation system. Lehi Main Street, a two lane facility, was the primary route to and from I-15 for thousands of drivers living in northwest Utah County. Lehi Main Street was saturated with traffic every day for hours at a time. Lehi Main Street could not sustain the increases in traffic spurred on by increased land development. The opening of Pioneer Crossing dramatically changed the dynamics of traffic flow on the northwest end of Utah County. Pioneer Crossing now offers an alternative access to drivers living west of I-15 in Lehi, Saratoga Springs, and Eagle Mountain. Pioneer Crossing is an attractive route for drivers headed to or coming from I-15. Higher speeds and properly spaced traffic signals along Pioneer Crossing allow drivers to get to I-15 more quickly than Lehi Main Street.

A 2008 Access Justification Report (AJR) for the Federal Highway Administration was created which outlined the need for construction of the Pioneer Crossing /American Fork Main Street Interchange at I-15. Through the competitive design-build bidding process the Diverging Diamond Interchange (DDI) was chosen (as an alternative technical concept to a single point urban interchange) as the interchange type that would be best suited for the American Fork Main Street Interchange. This report compares the vehicle volumes and distributions that were projected in the AJR and what has been observed since the DDI has opened to the public. This report documents an evaluation of the effectiveness of the DDI at American Fork Main Street now that the interchange has been in operation since August of 2010.

Since the American Fork Main Street DDI opened, three other DDIs have been built by the Utah Department of Transportation (UDOT):

- SR-92 (Timpanogos Highway) & I-15 in northern Utah County was opened to live traffic in the early fall of 2011.
- SR-201 & Bangerter Hwy in Salt Lake County was opened to live traffic in late October of 2011.
- 500 East & I-15 in American Fork was opened to live traffic in early November of 2011.

The I-15 CORE traffic team made observations at all four of these DDIs regarding the overall effectiveness and operation of DDIs. This report primarily focuses on the analysis of the DDI at American Fork Main Street; however observations and findings collected from all four DDIs within the State are summarized and identified in this report.

2 American Fork Main St DDI Population Trends & Travel Demand

When comparing both the population trends and traffic volumes used in the AJR to the existing conditions found today, a few differences were discovered. This chapter outlines and attempts to explain the reasoning for those differences.

2.1 Northern Utah County Population Growth

Populations of American Fork, Lehi, Saratoga Springs, and Eagle Mountain were collected from the United States Census Bureau for the years 2000 and 2009 to show the population growth for each city. Trips originating from or destined for these cities influence traffic demands along Pioneer Crossing. With American Fork City to the east of the I-15 corridor, the American Fork Main Street Interchange is a key regional access point for citizens and businesses in American Fork. Pioneer Crossing bisects the southern portion of Lehi City and as a result is an important transportation corridor for Lehi City, as well. Pioneer Crossing terminates at Redwood Road in Saratoga Springs, north of much of Saratoga Springs' residential population making Pioneer Crossing an attractive route to and from I-15 for these residences. Pioneer Crossing is conveniently located to accommodate traffic traveling to and from Eagle Mountain. From where Pioneer Crossing ties into Redwood Road, trips traveling to and from Eagle Mountain can either use SR-73, Eagle Mountain Boulevard or Pony Express Parkway.

The United States Census Bureau estimated the population of Lehi City to be 19,028 in the year 2000. In 2009, the Bureau estimated the population to be 41,680. This equated to an average growth of 13.2 percent per year. The population used for the AJR used a population of 36,885 in 2007 which was consistent with the observed growth rate. Figure 2-1 below shows the populations in 2000, 2007 (used in AJR), and 2009.

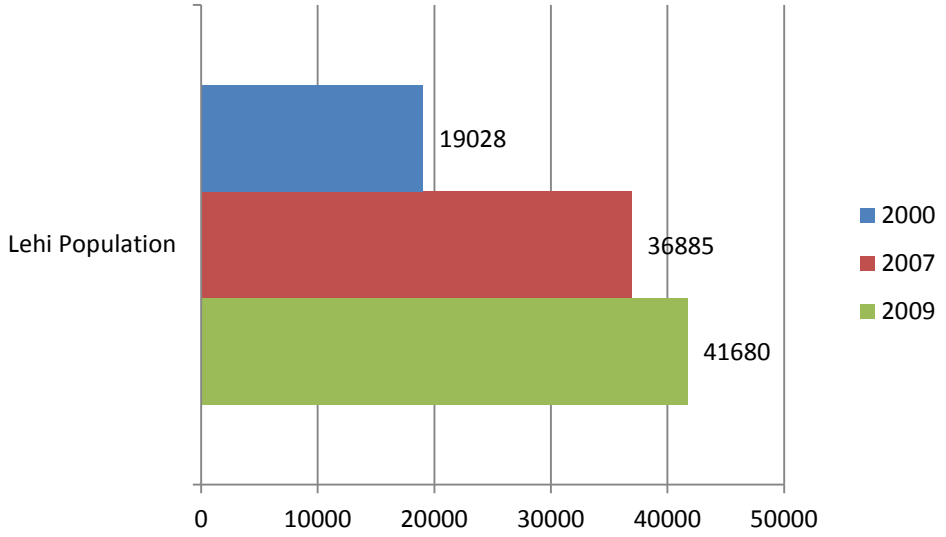

Figure 2-1. Lehi City Population Growth.

In the year 2000, the United States Census Bureau reported American Fork City as having a population of 21,941. In 2009, the Bureau estimated the population to be 26,627. This equated to an average growth of 2.4 percent per year. The population used for the AJR used a population of 26,472 in 2007, which has an average growth rate of 3 percent. This was larger than the growth rate actually observed. Figure 2-2 below shows the populations in 2000, 2007 (used in AJR), and 2009.

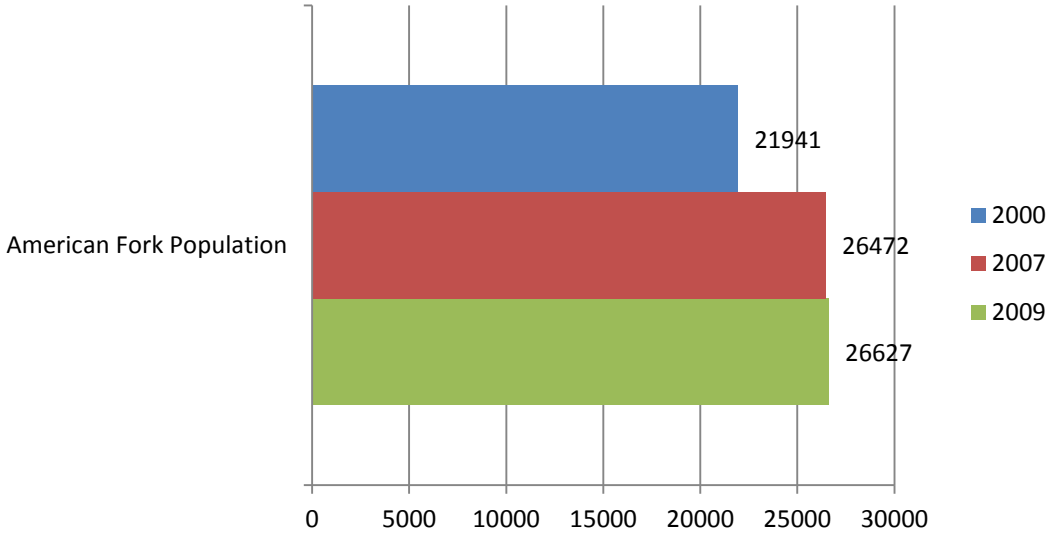

Figure 2-2. American Fork City Population.

In the year 2000, the United States Census Bureau reported Saratoga Springs as having a population of 1,028. In 2009, the Bureau estimated the population to be 12,584. This equated to an average growth of 125 percent per year. The AJR did not specifically report the population assumed for Saratoga Springs within this same timeframe. Figure 2-3 below shows the population in 2000 and 2009.

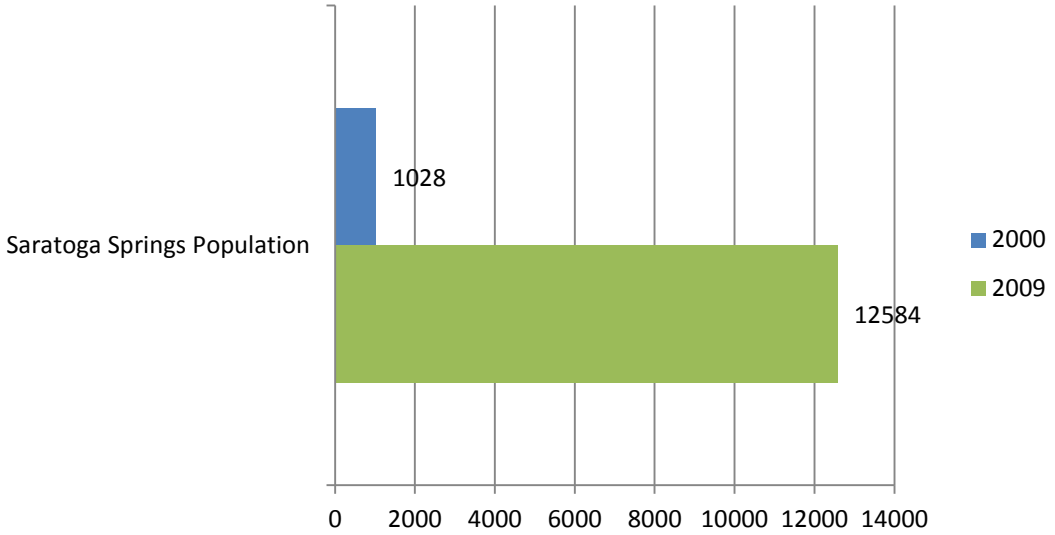

Figure 2-3. Saratoga Springs City Population Growth.

In the year 2000, the United States Census reported Eagle Mountain having a population of 2,157. In 2009, the population was estimated to be 18,960. This equated to an average growth of 87 percent per year. The AJR did not specifically report the population assumed for Eagle Mountain within this timeframe. Figure 2-4 below shows the populations in 2000 and 2009.

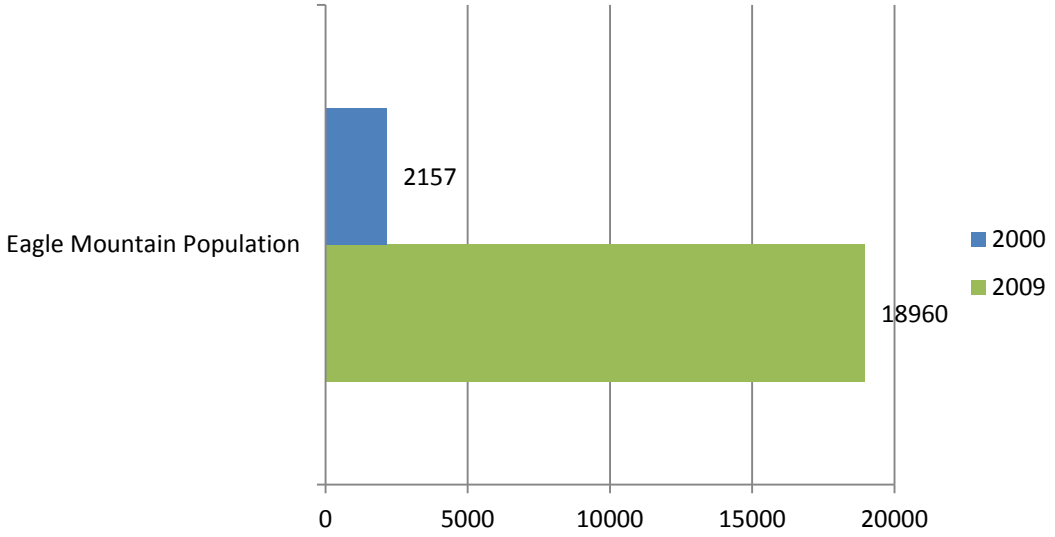

Figure 2-4. Eagle Mountain City Population Growth.

While new housing construction has waned as a result of the current housing market conditions, additional growth in the future is expected. Many farms in West Lehi, Saratoga Springs, and Eagle Mountain are likely to be replaced by housing and commercial developments over the next 20 years. However, growth rates seen in Lehi, Saratoga Springs, and Eagle Mountain in the past 10 years are not likely in the future. The population growth trends outlined above show the need for the construction of Pioneer Crossing and the associated DDI.

2.2 Commercial Development near the American Fork Main St DDI

The area around State Street (US-89) between American Fork Main Street and Lehi Main Street is full of commercial property. Figure 2-5 shows this commercial area outlined in red. This area attracts people from the greater northern Utah County region. The commercial area includes many big box stores that generate traffic in the surrounding area. This area is also home to many strip-mall type stores, restaurants and a large movie theater. Many patrons of this commercial shopping area will pass through the Pioneer Crossing DDI to access these businesses from the residential areas west of I-15. In addition, an increase in development has occurred, specifically in the area on the south leg of the Kawakami and American Fork Main Street intersection attracting more people to the area around the DDI.

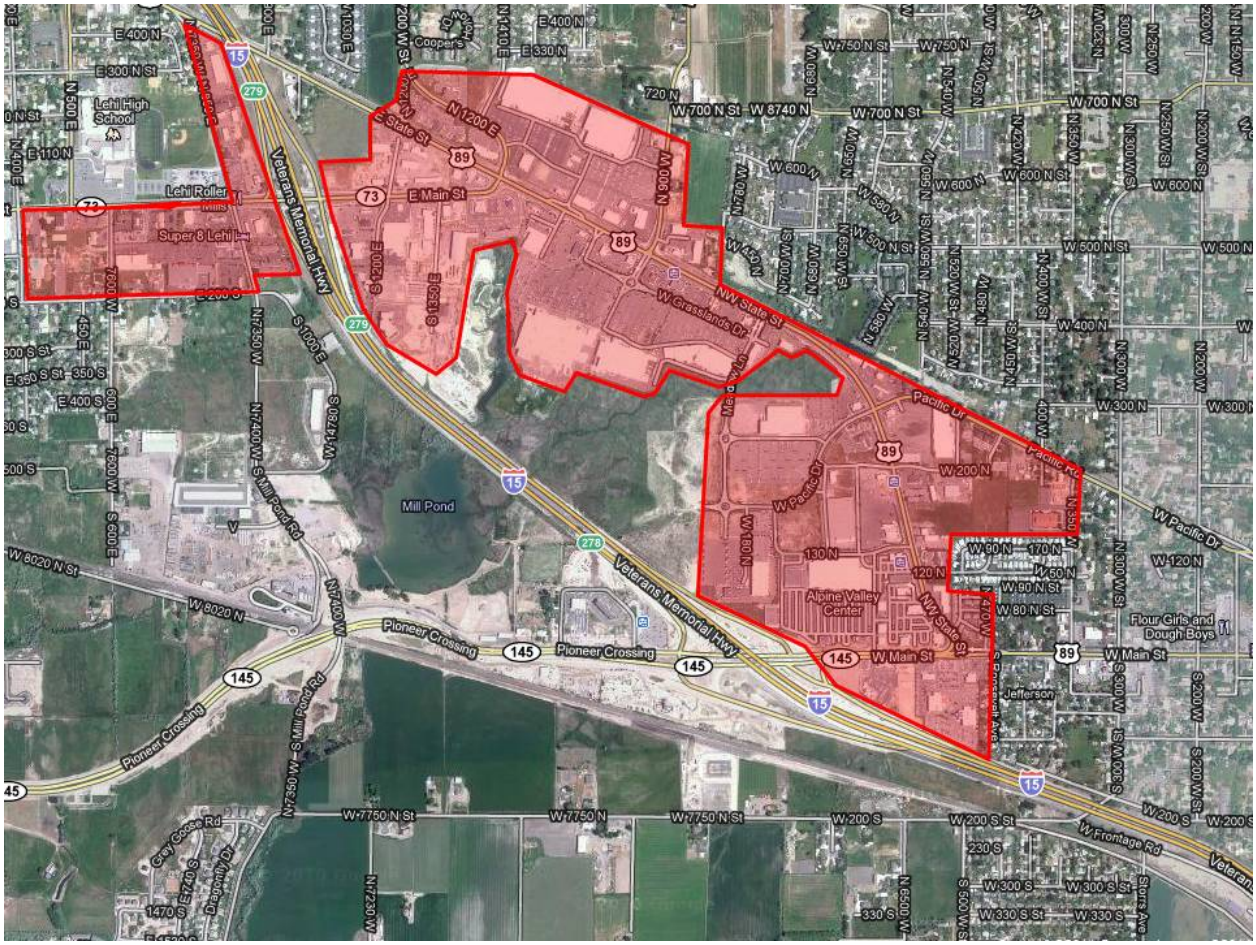

Figure 2-5. Commercial Property near the Pioneer Crossing DDI.

2.3 Public Transit near the American Fork Main St DDI

Currently, there are no UTA bus routes that connect Eagle Mountain, Saratoga Springs, or west Lehi to I-15. The only bus route on the west end of Utah County runs up Redwood Road and into Salt Lake County. There are no viable transportation alternatives to cars for residents of West Lehi, Saratoga Springs, or Eagle Mountain. Park and rides are located near the freeway for passengers traveling north or south on I-15. Each park and ride lot is currently heavily utilized.

2.4 Travel Demand Modeling for the American Fork Main St DDI

The 2030 traffic volumes used in the AJR were developed using the Mountainland Association of Governments regional travel demand model. A comparison of the current traffic

volumes to the 2030 projected traffic volumes indicates that the initial impact of Pioneer Crossing was underestimated in the AJR. This does not necessarily negate the quality of the travel demand model used. There was a larger shift than expected to Pioneer Crossing. Reasons for this large shift stem from convenience and quality of the newly constructed route. As additional alternative east/west routes are developed, travel on those routes will become more convenient. Roadway improvements that are planned or under construction will result in a shift to the best route for individual travel patterns as those improvements are completed. In essence, the regional travel demand remains the same but the demand for each facility will depend on the ease and convenience of use.

2.5 Existing ADT & Travel Demand Shifts after opening Pioneer Crossing

In an effort to better understand how the Pioneer Crossing facility impacted the regional travel patterns, traffic counters were placed out along Lehi Main Street one week before and one week after Pioneer Crossing was opened. This data collection effort showed that there was a 23 percent decrease in east/west traffic, or about 5,500 vehicles per day, on Lehi Main Street once Pioneer Crossing was opened. Traffic counts from permanent count station 407 maintained by Systems Planning and Programming along Redwood Road near Camp Williams decreased by about 500 vehicles per day after Pioneer Crossing was opened indicating a shift in travel patterns to access I-15 via Pioneer Crossing. Traffic counters on Pioneer Crossing between Mill Pond Road and I-15 counted a daily traffic volume of about 21,800 vehicles per day after the project opening. Prior to the DDI, traffic on American Fork Main Street in 2008 west of the southbound ramps was about 11,600 vehicles per day. Remaining is a total of about 4,200 vehicles per day currently using Pioneer Crossing that would have come from a combination of new trips and shifts from roadway facilities other than Lehi Main Street and Redwood Road. These additional trips may also represent trips that did not normally occur previously due to inconvenience prior to the new interchange and roadway being built. Figure 2-6 shows the traffic shift that occurred after Pioneer Crossing was opened.

Figure 2-6. Traffic Shift after Pioneer Crossing Opened

2.6 Existing Turning Movement Counts at the American Fork Main St DDI

In order to develop a model of the DDI interchange to represent existing conditions, PM peak turning movement counts were collected at key intersections. Key intersections include American Fork Main Street Interchange, Kawakami/Main Street, and US-89/Main Street. The turning movement counts that were collected in 2011 were compared to 2030 projected volumes. The 2011 and 2030 peak hour volumes for the DDI, Kawakami and Main Street, and State Street and Main Street are provided in Figures 2-7 and 2-8.

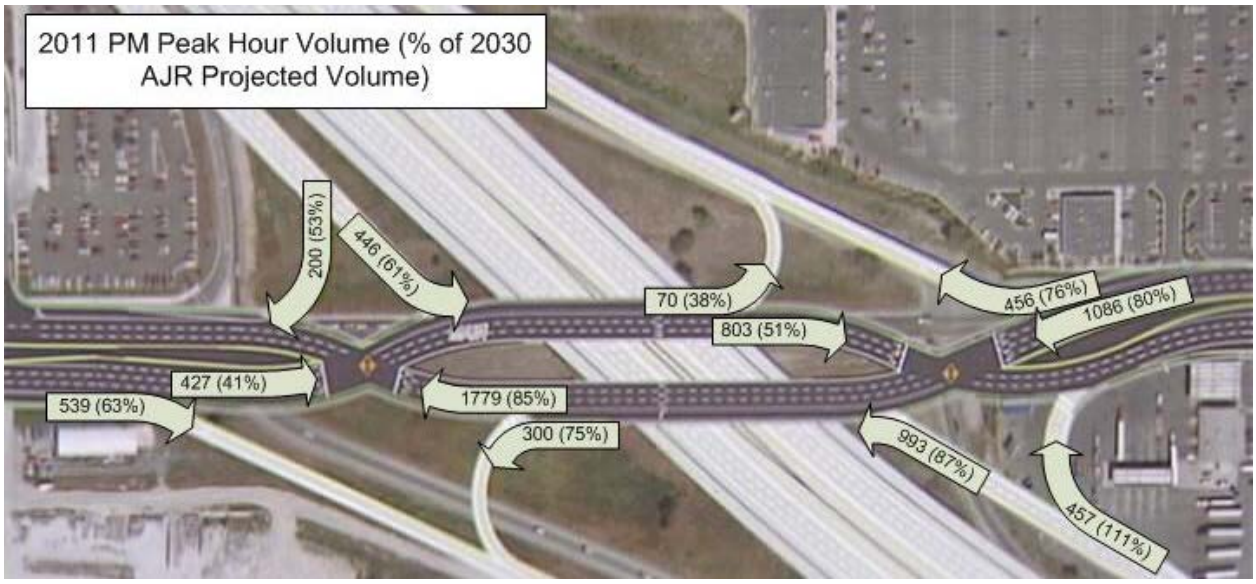

Figure 2-7. 2011 Peak Hour Volumes for the DDI.

Figure 2-8. 2011 Peak Hour Volumes for Kawakami & US-89.

3 American Fork Main St Post-Construction DDI Traffic Operations

The DDI at Pioneer Crossing has been fully operational since August of 2010. The DDI has operated effectively without failure during that time. It has also been used on four occasions to detour traffic around full freeway closures and two daytime I-15 detour routes needed for pothole repairs when I-15 was reduced to 1 lane in the southbound direction of travel. The DDI has proven effective for incident management detour routes. This chapter discusses changes made to the DDI since the opening day to optimize the operations and safety of the interchange. The overall effectiveness of the DDI interchange is discussed below. In addition, the effectiveness of the DDI as an incident management option is also discussed below.

3.1 Post Construction Improvements to the American Fork Main St DDI

Several changes were made to the DDI after the DDI opened to the public. These changes were to improve efficiency and safety of the interchange. The Federal Highway Administration (FHWA) visited the Pioneer Crossing DDI and made some observations of the site concerning safety and visibility. UDOT made several changes to signing as a result of some of the comments received by the FHWA.

Visibility of both the northbound ramps and the southbound ramps from the signal cabinet is obstructed by the vertical curve over the bridge structure. To accommodate this lack of visibility, a signal board with colored light indications was installed in the signal cabinet so that a signal timing engineer can see all the traffic signal indications at the interchange while standing at the signal cabinet to facilitate adjustments to the operations of the signal. Figure 3-1 shows the signal board installed in the signal cabinet.

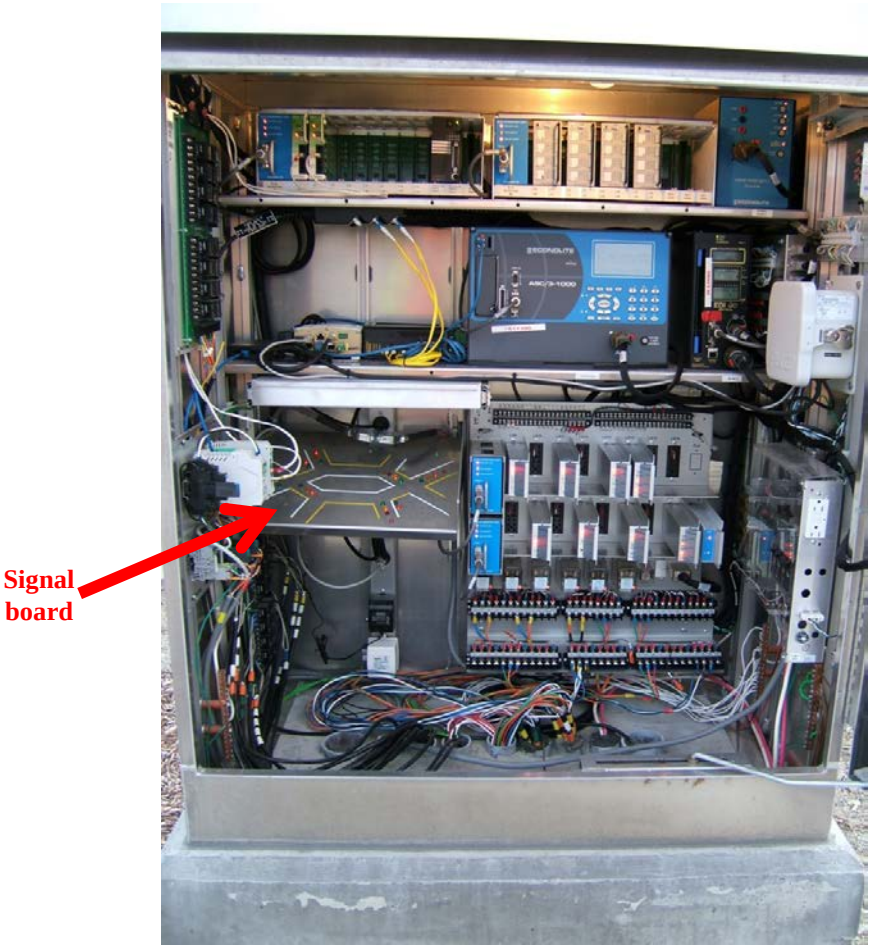

Figure 3-1. Signal Cabinet Pioneer Crossing DDI.

CCTV cameras were also added at both the northbound ramp and the southbound ramp to allow operators at the UDOT TOC to manage issues or incidents on the DDI.

Additional vehicle detectors using radar detection were added by the TOC after the initial design to increase safety for vehicles passing through the DDI. The detection devices were added to the crossover areas to ensure that all vehicles are cleared out of the crossover areas before the green from the conflicting movements were allowed to turn. This detection was not included in the initial design but was added after final construction in an attempt to further improve safety. This clearance detection extends the all red time until the crossover area cleared of any conflicting vehicle movements. The clearance detection is intended to prevent head-on/ right angle collisions at the crossover point from vehicles entering the intersection at the start of the red.

3.2 Signal Timing Optimization at American Fork Main St

Signal timing has been optimized to improve the efficiency of the interchange. Currently, the signal operates in free mode (signals are actuated by vehicles only with no set cycle length and therefore are not coordinated with adjacent signals). The signal currently operates in the peak hour without any cycle failure (when vehicles in a queue are unable to clear the intersection in a single green light sequence).

When the signal timing was modeled for the AJR report, the signal used only two phases. The large cross over distance was not accounted for in the initial signal timing. Currently, the signal operates with a complex ring-barrier setup where the northbound ramps and the southbound ramps work independently but can be coordinated to work as one. Both the northbound ramps and the southbound ramps operate using a single signal controller.

When vehicle volumes increase, the signals on the DDI can be coordinated to allow for greater traffic flows for certain movements. Doing this allows for greater vehicle flow of the main movements while potentially increasing the delay for the minor movements.

The vehicle delay was minimized at this intersection further by improving signal coordination with the adjacent intersections. A preliminary overview of the next three intersections to the east found inconsistent cycle lengths and in turn lack of coordination between signals. Kawakami & Main St was running at 120 second cycle length, State St & Main St was running at 130 second cycle length, and 300 W & Main St was running a variable cycle length (i.e., running “free”). Traffic signal timing adjustments were recently made to correct such inconsistencies and have improved vehicle progression through this area, thereby decreasing vehicle delay at the DDI.

3.3 Incident Management with the DDI at American Fork Main St

The DDI has been successfully used for incident management and detour purposes. The DDI has been used to divert traffic off I-15 for three separate I-15 closures and was a vital detour for several day time closures; including two pothole repair operations and a paving operation that lasted 19 consecutive days.

In two instances (southbound on October 15 and northbound on November 1), traffic was detoured through the DDI at American Fork Main St for full freeway closures. The southbound detour began at American Fork Main Street, took traffic south along State Street to 2000 West,

then back to I-15 on Pleasant Grove Boulevard. The northbound detour used the same route in reverse. Operations at the DDI ran smoothly allowing traffic queues to clear shortly after the closure began. At the time, only a single lane was open on the DDI southbound ramp. Delays to drivers were held under 19 minutes for each closure, most of that delay came from the detour route and not the capacity of the DDI. An additional lane on the southbound ramp would have cleared traffic even faster.

Concrete paving operations for I-15 CORE reconstruction began in the summer of 2010, extending into fall and winter. Paving restrictions were implemented first for southbound I-15 through American Fork and Pleasant Grove. Southbound traffic lanes were restricted to three lanes for 15 days in October. The paving operation shifted to the northbound lanes where traffic was restricted to three lanes for a total of 19 days in October and November. The northbound restriction occurred in two increments due to equipment failure. Mainline was again restricted to three lanes in December for paving plugs at Pleasant Grove Boulevard.

During the winter 2010-2011 pothole repairs, the reduction to a single lane on I-15 resulted in a maximum queue of four-and-a-half miles (back of queue reached 100 East in American Fork) with a maximum delay of 60 minutes for southbound drivers on I-15. Maximum delay along State Street to make the parallel trip was measured at 40 minutes. State Street was observed to have some excess capacity, evidenced by the fact that there were no cycle failures occurring (the vehicle queues were clearing during every green signal indication period). The DDI was instrumental during these impacts as a diversion point to I-15. The interchange managed the increased demands with minimal delays and no queuing back to I-15 along the off-ramp. For each of these daytime closures, traffic on mainline I-15 backed for miles. Pioneer Crossing became vital in diverting traffic away from I-15 and onto State Street. Personnel from the I-15 CORE Traffic Team were utilized in the field to optimize traffic operations, in addition to support from the UDOT TOC. Drivers southbound on I-15 were informed of heavy delays ahead on overhead VMS signs in Salt Lake County, supplemented by the southbound overhead VMS just south of Point of the Mountain and with portable VMS at 1200 West Lehi and at American Fork Main Street. The Point of the Mountain overhead VMS and the two portable VMS strongly encouraged drivers to leave I-15 and utilize State Street. Efforts to get drivers to divert were successful, but there was definitely reluctance on the part of drivers to leave the

mainline (despite the message indicating "Heavy Delays Ahead"). The I-15 CORE PI Team also provided messaging to radio stations to encourage diversion to State Street. The DDI again proved its effectiveness in managing heavy directional traffic situations.

The DDI has also proven to be effective in diverting traffic off I-15 onto State Street due to backups from incidents such as stalled vehicles or crashes. On numerous occasions, southbound I-15 traffic has backed beyond American Fork Main Street. When this happens, traffic tends to exit the freeway at American Fork Main Street onto State Street. Special timing plans with increased signal cycle lengths have been placed along State Street to allow greater southbound capacity for traffic diverting down State Street. For traffic incidents, the DDI handles itself well. Even with large diversion off I-15, the DDI is capable of handling the traffic without having to increase the signal cycle length. The DDI has proven an effective traffic management tool in diverting traffic off of I-15.

3.4 Overall Efficiency of the American Fork Main St DDI

An existing VISSIM model from the AJR report was modified with existing conditions and geometry. The model included the DDI and the two intersections to the east. Traffic volumes and routes were changed in the model to reflect current traffic conditions. The traffic signals in the model were set up to operate in the same way that the signal operates in the field.

Data analysis zones were set up to collect several Measures of Effectiveness (MOE) to compare operation to 2008 and 2030 projected conditions as outlined in the AJR. The MOEs collected from the model included peak hour vehicles served, delay (sec/veh), and maximum queue. The average values for multiple simulation runs are provided in Table 3-1.

Table 3-1. VISSIM Analysis Measures of Effectiveness

	2008 Pre-DDI Conditions			2030 AJR With DDI Projected Conditions			2011 Post DDI Construction Conditons		
Intersection Operation	Peak hr veh serv	Delay (sec/ veh)	Max. queue	Peak hr veh serv	Delay (sec/ veh)	Max. queue	Peak hr veh serv	Delay (sec/ veh)	Max. queue
SB Ramps & Pioneer	2077	21.8	1121	4544	24.3	407	3197	16.3	382
NB Ramps & Pioneer	2832	15.8	1111	4582	31.1	1124	3443	20.7	332
Kawakami & Main	2450	7.9	1001	4211	12.0	260	3057	22.1	419
US-89 & Main	3420	24.1	2560	4908	36.8	1108	3441	33.1	736
Network	12002	16.2	2560	22846	25.7	1124	16081	17.1	736
	Ave Pk Hr	Pk 15 min	Pk 15 min	Ave Pk Hr	Pk 15 min	Pk 15 min	Ave Pk Hr	Pk 15 min	Pk 15 min

Level of Service (LOS) is a term used by the Highway Capacity Manual (HCM) to describe the traffic operations of an intersection, based on congestion and delay. LOS ranges on a scale of LOS A (no congestion or delay) to LOS F (gridlock conditions with extreme congestion and delay). For urbanized intersections, LOS D is generally considered acceptable. When intersections reach LOS E, the intersections are running at or near full capacity. Table 3-2 provides the LOS criteria for signalized intersections.

Table 3-2. HCM Level of Service Criteria for Signalized Intersections.

Level of Service	Average Control delay (s/veh)
A	0 - 10
B	> 10 - 20
C	> 20 - 35
D	> 35 - 55
E	> 55 - 80
F	> 80

(Highway Capacity Manual 2000)

For each of the intersections, delay was calculated with VISSIM and compared to the HCM LOS table for each of the study years; 2008(AJR pre-build), 2011 (observed), and 2030 (AJR projected). An overall delay was also calculated for the entire network in the model. Table 3-3 shows the delay and LOS for each of the intersections in the network. The current LOS for each intersection shows an acceptable amount of delay. The network has a LOS B, which is a relatively small delay. Kawakami and Main Street had a decreased LOS from A to C. One of the reasons for this is because the original model did not take into account the new development that was added to the south of the intersection. In addition, the amount of traffic accessing northbound Kawakami was larger than expected. This signal still operates within an acceptable LOS.

Table 3-3. Level of Service for Key Intersections

	2008 Pre-DDI Conditions			2030 AJR With DDI Projected Conditions			2011 Post DDI Construction Conditons		
Intersection Operation	Peak hr veh serv	Delay (sec/ veh)	LOS	Peak hr veh serv	Delay (sec/ veh)	LOS	Peak hr veh serv	Delay (sec/ veh)	LOS
SB Ramps & Pioneer	2077	21.8	C	4544	24.3	C	3197	16.3	B
NB Ramps & Pioneer	2832	15.8	B	4582	31.1	C	3443	20.7	C
Kawakami & Main	2450	7.9	A	4211	12.0	B	3057	22.1	C
US-89 & Main	3420	24.1	C	4908	36.8	D	3441	33.1	C
Network	12002	16.2	B	22846	25.7	C	16081	17.1	B
	Ave Pk Hr	Pk 15 min	Pk 15 min	Ave Pk Hr	Pk 15 min	Pk 15 min	Ave Pk Hr	Pk 15 min	Pk 15 min

Even though differences existed between the original AJR operations and the actual observed conditions, the DDI has proven to be an effective interchange alternative. Comparing the peak hour vehicles served between the observed 2011 conditions and the projected 2030 volumes, there is sufficient capacity to accommodate approximately 2 percent growth per year at an acceptable LOS in the year 2030 as concluded in the AJR.

4 Successes of Diverging Diamond Interchange Designs

Since the opening of the American Fork Main St DDI, the SR-92 Project in northern Utah County opened another DDI to live traffic in the fall of 2011. UDOT Region 2 opened a third DDI in October of 2011 at SR-201 and Bangerter Hwy. In November of 2011, the I-15 CORE Project opened a DDI at 500 East in American Fork (see Figure 4-1 below). Based on observations of traffic at all four of these Diverging Diamond Interchanges, a number of successes were identified that should be carried forward on future interchanges of this type.

Figure 4-1. 500 East American Fork DDI - November 2011

4.1 Traffic Modeling and Traffic Analysis of a DDI

Micro-simulation models need to be used to help identify potential problems in advance of construction. Sufficient data is necessary to correctly calibrate and model the interchange and surrounding roadway network accurately. Since each location is unique, traffic engineers and planners should identify local traffic patterns and conditions in order to reflect those in the model. The model can then be used to develop solutions to mitigate potential congestion. For example, DDIs can be sensitive to heavy weaving movements through the interchange and the surrounding roadway network. Engineers and modelers should make sure the model accounts for the local origin-destination patterns observed in the field or expected in the future. This should include a review of adjacent cross-streets or access points for large developments along the arterial street that are within close proximity of the interchange. The traffic model should reflect real traffic conditions as close as possible.

4.2 Directional Traffic Demands at a DDI

DDIs are not a fix all solution for every interchange. UDOT should evaluate the alternatives available and implement the best one. As a general rule of thumb, DDIs are typically well suited for interchanges with directional traffic flows with either high demand from the interstate to the cross-street with low to moderate cross-street traffic, or high demand across the interchange with lower left-turn exiting volumes from the interstate. Some specific examples of high left turn traffic from the ramp to the cross-street where traffic flows smoothly with minimal delays includes the following locations:

1. I-15 at Pioneer Crossing in American Fork
2. I-15 at 500 East in American Fork
3. I-15 at Timpanogos Highway in Lehi

Additional observation at the new DDI at SR-201 & Bangerter Hwy in West Valley City resulted in the conclusion that if heavy traffic demands exist at the freeway exit and the cross-street simultaneously, a bottleneck may still result. This project was a retrofit, and as a result, the ability to provide left-turn storage on the existing structure was limited. The retrofit was a minor improvement that simply eliminated the left-turn phasing from the signals. The addition of left-turn lanes in advance of the cross-over intersection may improve the overall weaving and

lane utilization issues observed on the cross-street at this location. Much of the congestion at this location was associated with vehicles needing to be stored between the two cross-over signals.

4.3 Signal Timing of a DDI

In general, a DDI is limited to one of two phasing strategies: emphasized coordination to the off-ramp left-turn movement or emphasized coordination of the through traffic movement across the interchange. If both movements are heavy, the overlap of queues can be difficult to overcome during peak periods without sufficient capacity.

Instead of running excessively long clearance intervals (yellow and all-red times), the signal team at the UDOT TOC came up with a phasing strategy to use a few "dummy" phases in order to optimize the efficiency of the interchange. The use of these "dummy" phases allows the crossover signal to change over to the next phase in an efficient manner while the off-ramp traffic waits for a green light after a red light clearance interval. This allows crossing vehicles to clear the off-ramp intersection as well as the cross-over intersection prior to permitting the off-ramp traffic to proceed.

Most DDIs need a lower cycle length than the adjacent signals. As a result, the interchange signals at DDIs are run in coordination with each other usually at half the cycle length of the adjacent system. In fact, signal engineers have found that some of the DDIs operate best in "free" mode, or in other words based on actual demands from the signal detectors. This may result in vehicles having to stop at both the off ramp terminal and the next adjacent signal.

4.4 Lane Utilization Approaching the DDI

Lane utilization is critical to the traffic operations in and around any interchange. Each traffic movement should be appropriately analyzed to establish the proper number of lanes and storage length needs to accommodate traffic at an acceptable level of service. If one lane of any one traffic movement is over utilized, the efficiency of that movement decreases. Two keys to overcoming lane utilization issues at DDIs include adequate advanced guide signing approaching the interchange and the appropriate development of auxiliary lanes for heavy traffic movements. Spacing of adjacent signals with large traffic generators has an impact on the lane utilization through a DDI.

At both the American Fork Main St DDI and the SR-92 DDI, overhead advanced guide signing is used to notify drivers regarding the appropriate lane utilization and destinations along the arterial cross-street. These overhead signs provide advanced warning prior to the final decision point with regards to which lane drivers need to use in order to arrive at certain destinations. The SR-92 Project used arrow-per-lane overhead guide signing, while the American Fork Main St Project simply used cantilever structures communicating the proper access to northbound and southbound I-15. The arrow per lane signs do require a sign bridge, but clearly communicate all movements and destinations provided through the interchange.

Left-turn lanes on the cross-street in advance of the cross-over signal help to separate turning traffic from through traffic to improve overall operations of the interchange. For example, heavy left-turn volumes from the cross-street to the interstate on-ramp in conjunction with heavy cross-street through traffic benefit from having left-turn lanes develop in advance of the approach cross-over signal. The benefit of having this additional lane to mitigate weaving and lane utilization issues within the traffic stream is apparent at the following locations:

1. I-15 at Pioneer Crossing in American Fork
2. I-15 at Timpanogos Highway in Lehi (Westbound)

Medium left-turn volumes from the cross-street to the interstate on-ramp in conjunction with heavy cross-street through traffic benefit from having a left-turn lane develop under or over the structure between the off and on-ramps. An example of this is the DDI at I-15 and Timpanogos Highway (SR-92) in Lehi in the eastbound direction.

The development of turn auxiliary lanes for the on-ramps in advance of the cross-over intersections along the arterial cross-street allows for smoother flow of traffic for each movement through the interchange. Overhead signs can be used where these lanes develop with the appropriate arrows to clearly communicate the appropriate lane for drivers to be in. These turn lanes provide added capacity through the cross-over intersections, particularly if they can be developed in advance of the interchange. Extra auxiliary lanes through the interchange help prevent the on-ramp traffic from being impeded by queued vehicles at the cross-over intersections.

Auxiliary lanes should not be overlooked in the design of a DDI, as traffic can be very sensitive to weaving maneuvers. A current standard does not exist for weaving analysis on

arterial systems, only on freeways systems. Perhaps future studies and research should be done to determine the best way to measure weaving on arterials and develop standards for future designs. A simple solution would be to develop a minimum auxiliary lane length standard for DDI interchanges.

4.5 Striping throughout the DDI

In general, striping for a DDI should be standardized to maintain consistency, uniformity, and efficiency. Through pavement arrows used at the cross over intersections help emphasize the fact that turning movements are prohibited within the intersection. At DDIs opened to traffic a large pavement through arrow has been placed centered in each lane entering the cross-over intersection (typical arrow with 12 inch striping), followed by a standard pavement arrow centered in each lane on the receiving side of the intersection. In addition to the pavement arrows, extension skip pavement markings through the cross over intersections help emphasize the need to go straight.

Another key success to the striping is the placement of extension skip pavement markings for the left turn lanes from the off ramps. Where left turn auxiliary lanes exist for traffic on the cross-street to access the on-ramps, extension skip pavement markings were provided for the left turn lanes on the off-ramps directing them around the auxiliary lane allowing vehicles to avoid getting right back on the freeway and also thereby avoiding an unnecessary weaving maneuver. This striping is especially critical for dual left turn lanes from the off ramp.

4.6 Traffic Signal Heads placement within the DDI

Type 2 traffic signal heads (red ball, yellow & green arrows) should be used for signalized right turn movements, not Type 3 (red, yellow and green arrows). Type 3 heads do not allow for vehicles to turn right on a red light. This greatly reduces efficiency and may be necessary if pedestrians were permitted to cross the street within the interchange area.

Due to driver expectancy, Type 3 signal heads should be used for all left turns for the time being. In the future, UDOT may consider using Type 2 heads with the appropriate signing to permit left turns on red to improve efficiency. Since left turn movements on red are counter intuitive, there may some safety implications that need to be considered.

Either Type 1 or Type 2 signal heads (with up arrows) may be used for the through movements at the cross over intersections. The Type 2 heads help reiterate the need to go straight through the intersection and that turning maneuvers are not permitted. Designers should also make appropriate considerations for the placement of nearside signal heads for cross-over intersections to ensure adequate advanced notice, etc. For example, the vertical alignment of the bridges of the American Fork Main St structure makes it difficult to see the next cross-over signal until one is on the bridge itself. Additional nearside signal heads could help improve the visibility of the approaching signal.

4.7 Cross-Over Intersection Design Considerations

Since one of the keys to success of the DDI is the ability to coordinate the signal timing of the two cross-over signals, the ability to coordinate those signals with one another is directly related to the distance those signals are apart. A good rule of thumb for the spacing between the two cross-over intersections is about 800 to 1,000 feet. This provides sufficient space for queue storage and the ability to move traffic through the system.

The approach angle for cross-over intersections of a DDI should be 30 degrees or greater. There should be a balance between providing a smooth transition through the cross-over and meeting driver expectancy of a square intersection. If the angle is too flat, drivers may be confused and run down the wrong side of the road.

Barrier should be placed with sharp angles at the corners of the cross-over intersections where right turns are to be prevented. These sharp edges, as opposed to the normally rounded corners, help emphasize the need to go straight. Once traffic is on the opposite side of the road, barrier should separate traffic and if possible block the view of oncoming headlights and traffic.

4.8 Access Management Approaching the DDI

Access management is an important principle to maintaining capacity and safety of UDOT's arterial systems. The nature of a DDI effectively lengthens the influence area of the interchange due to the shape of the interchange itself. Minimizing access points within the interchange and influence area of each of the cross over intersections improves traffic flow through the arterial cross-street and also minimizes conflict points along the route.

The American Fork Main St DDI Project consolidated a number of access points. For example, a right-in right-out access from the Target shopping center on the northeast quadrant of the interchange was converted into a right-in access only. Access out of the same shopping center was consolidated into a new traffic signal at Kawakami Dr which was shared with access to and from new development on the southeast quadrant of the interchange as well. On the west side of the freeway, two previous full movement accesses were consolidated into a single full movement access and a right-in right-out access.

At the SR-92 DDI, UDOT closed the northbound and southbound through and left turn movements at Thanksgiving Way, the frontage road on the west side of I-15. The traffic signal was removed from this intersection and the access was converted into a right-in right-out access only. A new traffic signal was installed further to the west at Ashton Blvd to consolidate the access to SR-92. The east frontage road was modified from a full access to a right-in right-out access to provide more safe and efficient operations through the interchange.

The SR-201 and Bangerter Hwy Project did not consolidate any access points, however access along Bangerter Hwy was already very well restricted due to the classification of that roadway facility.

5 Conclusions

Population growth has increased dramatically in northern Utah County over approximately the last 10 years. Most of this growth has occurred on the west side of Interstate 15 to the north of Utah Lake. The growth in this area led to the construction of Pioneer Crossing and the Diverging Diamond Interchange at I-15 and American Fork Main St. In addition to population growth, commercial development has increased, especially around the new interchange itself.

The increase in land development brought an increase in traffic demand to the area. When Pioneer Crossing opened, traffic volumes on Lehi Main St decreased by 5,500 vehicles per day (a 23 percent decrease). At the same time, volumes on Pioneer Crossing increased by 10,200 vehicles per day.

The original Access Justification Report (AJR) for the DDI documented the proposed changes to the interchange and projected the impacts these changes would have on traffic both on opening day and in the future. While the existing turning movements within the DDI indicate the rapid approach to the 2030 volumes used in the AJR, there is no immediate need for concern. At current volumes, which in the westbound direction are at or near 2030 volumes, the DDI is functioning as intended with minimal delay and high mobility. The DDI and the surrounding intersections are operating within, and in some cases, better than expected levels of service. The DDI can handle additional traffic without being over burdened.

Signal timing was optimized to improve the efficiency of the interchange. When the signal timing was configured for the AJR report, the signal used only two phases. Currently, the signal operates with a complex ring-barrier setup where the northbound ramps and the southbound ramps work independently but can be coordinated to work as one. Both the northbound ramps and the southbound ramps operate using a single signal controller. When vehicle volumes increase, the signals on the DDI can be coordinated to allow for greater traffic flows.

The DDI has been successfully used for incident management and detour purposes. The DDI has been used to divert traffic off I-15 for three separate I-15 closures and was a vital detour for several day time closures; including two pothole repair operations and a paving operation that lasted 19 consecutive days. The DDI has also proven to be effective in diverting traffic off I-15 onto State Street due to backups from incidents such as stalled vehicles or crashes. Even with large diversion off I-15, the DDI is capable of handling the traffic without having to increase the signal cycle length. The DDI has proven an effective traffic management tool in diverting traffic off I-15.

The DDI at I-15 and American Fork Main St has performed very well from a traffic standpoint and is expected to continue to perform well for years to come. Since the opening of the American Fork Main St DDI, UDOT has opened three other DDIs: SR-92 & I-15, SR-201 & Bangerter Hwy, and 500 East in American Fork & I-15. Based on observations of traffic at all four DDIs in Utah, a number of successes were identified that should be carried forward on future interchanges of this type. The following are recommendations regarding the design and construction of DDIs:

- Each location should be studied and evaluated using appropriate traffic modeling and engineering principles.
- From a signal timing perspective, a DDI can be optimized to better accommodate cross traffic, or left turning traffic from the off ramps. As a result, DDIs are best suited for locations with high demands on the off-ramps or the cross-streets, but not both simultaneously.
- A key success to the overall operation of a DDI is weaving movement. Lane utilization issues can be overcome through properly design auxiliary lanes that develop in advance of the cross-over intersections. These lanes should include the appropriate advanced guide signing.
- The striping, signing, traffic signal and roadway design should be as uniform as possible between DDIs to meet driver expectancy and optimize the overall efficiency of the system.

In conclusion, under the right circumstances and conditions a Diverging Diamond Interchange can be an effective interchange alternative and has many advantages to other

interchange types. The DDI is just one of the tools in UDOT's toolbox to meet traffic demands. Careful consideration should be taken in deciding which tool to use for each specific location.

Additional study of the DDI is recommended to better determine the overall sensitivity of specific traffic patterns and volumes to provide more definitive conclusions. Future studies and research should be done to determine the best way to measure weaving on arterials (as opposed to just freeways) and develop standards for future designs since current standards do not exist.