Frontage Roads and DDIs, an Atypical Pairing

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Executive Summary

The acceptance and rapid installation of Diverging Diamond Interchanges (DDI) across America is resulting in the realization of operational and construction cost savings benefits for many agencies and jurisdictions. As DDIs are considered for more locations, agencies have encountered their limitations; however, innovative DDI designs that incorporate site specific features are giving locations with perceived fatal flaws new life. Highways with existing frontage roads have often resulted in the elimination of a DDI as a viable interchange configuration. However, innovative designs have been able to accommodate one-way frontage road movements within DDI interchanges. Texas has successfully constructed DDIs with existing one-way frontage roads by utilizing separated left-turn movements to connect the frontage road traffic without entering the main arterial and by fitting frontage roads under overcrossings of the cross street through merging and weaving configurations with the on and off-ramps. One of the more innovative ways to solve the one-way frontage road challenge is to evaluate opportunities for offsetting the frontage roads and adding a turn pocket synchronized with the two phase signals at the DDI intersection terminals. This application creates a direct connection for a one-way frontage road system while maintaining a level of service (LOS) at the interchange, the 2-phase signal advantages throughout, and the avoidance of grade separating the frontage roads from the rest of the interchange. One-way frontage roads do not have to be the end of the DDI discussion but instead can be the starting point for innovation to deliver the best value configuration for the users at that specific location.

Introduction

Diverging Diamond Interchange (DDI) projects have gained popularity over the last decade and are being utilized across the United States as a lower cost and more efficient alternative to traditional diamond interchanges. The interchange type has risen in acceptance to a point where it is almost always considered as a potential alternative during the project development alternative analysis. It is at the alternatives analysis stage that the DDI is often screened out because it is not seen as compatible with existing conditions such as frontage road systems or other features that don't fit into the traditional application of the DDI interchange configuration. A number of projects have taken a second look, diving deeper into the geometry and application of DDIs, and how they can remain viable and complement existing one-way frontage road systems.

Diverging Diamond Interchange Benefits

The DDI provides operational benefits compared to the standard diamond interchange by reducing the signal phasing from 3-phase to 2-phase at the intersection terminals and increasing capacity for turning movements to and

Figure 1 I-85 and Poplar Tent Road DDI, North Carolina
Source: HDR Inc.

from the cross street. There are safety benefits associated with the DDI due to the reduction in speed through the curvature and the reduced number of conflict points at the intersection terminals. DDIs frequently require a reduced number of lanes on the cross street due to the higher processing rate of turning movements because of the reallocation of green time with the 2-phase signal. This lane reduction is a common advantage over other interchange types because of the reduction in overall construction cost associated with the extra roadway width and the extra bridge width / length.

Frontage Road Benefits

Frontage roads are utilized along stretches of highway as a parallel access or service roadway at a lower speed. This allows the flexibility to separate the local access traffic which is entering / exiting driveways and connection streets from the high-speed traffic on the limited access mainline. Frontage roads provide alternate routes which reduce congestion on the mainline by encouraging users to not enter the highway for short duration routes. There are safety benefits associated with the frontage road because of reductions in entry / exit vehicles to the mainline. This in turn reduces the number of merging movements vehicles make, as well as general safety benefits from reduced congestion. In the event of a crash or other incident requiring closure of the mainline, frontage roads also provide a means to bypass or detour mainline traffic. Frontage roads exist in two configurations: one-way frontage roads and two-way frontage roads. For the purposes of this paper, only one-way frontage roads will be considered.

Figure 2 West Chase District Frontage Roads along Sam Houston Parkway, Texas
Source: Westchasedistrict.com

Why DDIs and Frontage Roads Conflict

A standard diamond interchange utilizes a 3-phase signal controlling movements at each intersection terminal. One phase is allocated to the off-ramp traffic which can go left, right, or straight at the intersection; the other two are for the cross street traffic and depending on the terminal consist of the through and either right- or left-turn movements to access the on-ramps and if applicable

Figure 3 DDI Intersection Terminal on I-85, North Carolina
Source: HDR Inc.

the frontage road. Frontage road systems utilize the through movement at the off-ramp to allow vehicles to continue to travel on a parallel route to the highway without entering the highway. Because the DDI only has 2 phases, there is no phase that allows vehicles to continue straight through the interchange from the off-ramp. This is the problem that is often brought up when trying to apply a DDI to an interchange location with frontage roads. The DDI does not allow for the through movement and adding the 3rd phase would negate the main operational benefit of the DDI. Applying the DDI without consideration of the frontage road network would create a dead end and result in wayfinding complications that would likely lead to reduced access for businesses that reside along the frontage road.

Case Studies

I-17 and Happy Valley Road (Arizona)

Existing Condition

The existing spread diamond interchange at I-17 and Happy Valley Road is located in the northern part of Phoenix, Arizona, which is experiencing significant growth. The northeast and southeast quadrants of the interchange have two large shopping centers with plans to build several new condominium complexes, a new office building complex, and a new 400-acre mixed-use development in the immediate vicinity of the interchange. The western quadrants of the interchange are occupied by a Park and Ride facility, a juvenile detention facility, and a closed city landfill that is planned to be converted into a park. There is also a large residential population further to the west that uses the Happy Valley Road interchange. A one-way frontage road system exists in the northwest, northeast, and southeast quadrants and ADOT's ultimate I-17 corridor plan shows the addition of a one-way frontage road in the southwest quadrant.

Figure 4 I-17 and Happy Valley Road Interchange Existing Configuration, Arizona
Source: Google Earth, 2017

Happy Valley Road has a seven-lane cross section; however, the bridge across I-17, which is over 50 years old, is only a two-lane bridge with one lane in each direction. Today, the interchange intersections are controlled by two-lane roundabouts at the ramp termini. Traffic analysis has shown that the interchange has a significant directional split with peak hour traffic. In the morning peak hour, the majority of traffic enters the highway on the southbound on-ramp, while in the evening peak hour the majority of traffic is exiting on the northbound off-ramp. The existing interchange regularly breaks down with the NB off-ramp frequently backing up onto the I-17 mainline.

Interchange Alternatives Considered

ADOT's primary reason for replacing the Happy Valley Road interchange is for safety and operational improvements; however, a secondary reason is to accommodate I-17's ultimate cross section. Existing I-17 has three general purpose lanes and one High Occupancy Vehicle (HOV) lane in each direction, and the ultimate I-17 cross section will have five general purpose lanes and one HOV lane in each direction.

In 2008, ADOT funded a preliminary engineering study to complete the environmental clearances and to determine the best replacement interchange configuration for Happy Valley Road. Six different interchange configurations were considered, which included replacing in kind with a spread diamond interchange and roundabouts; a traditional spread diamond interchange; a tight diamond interchange; several variations of a partial cloverleaf (ParClo) configuration; a Single Point Urban Interchange (SPUI); and a DDI. The study quickly discarded the DDI because of its non-compatibility with the existing frontage roads. Out of the remaining five interchange types, it was determined that while a traditional diamond interchange would work, a ParClo worked better because it removed the majority of the left-turning, on-ramp traffic from the interchange intersections, thus improving the intersection operations. Coincidentally there is enough right-of-way available in this area for a ParClo because it used to be a full cloverleaf interchange 20+ years ago.

DDI Application

Shortly before the preliminary engineering study was finalized, Maricopa Association of Governments (MAG), the local Metropolitan Planning Organization (MPO), funded a Cost Risk Assessment (CRA) workshop for the Happy Valley Road interchange to assist in identifying major cost and schedule risks to the project. Two major schedule risks were identified that had the potential to either delay the project or extend the construction duration. The first risk was the necessity to obtain an Interstate Modification Report (called a Change of Access Report in Arizona) because of the two new loop on-ramps required for the ParClo. The second risk was that rebuilding the interchange on the same alignment would force the contractor to do phased bridge construction, which would put the demolition of the existing bridge on the construction critical path. It was suggested in the CRA that a DDI could eliminate both of these risks. The preliminary engineering study team was asked to take another look at a DDI configuration, but the DDI was again deemed not viable because of frontage roads.

Not satisfied with the DDI dismissal, HDR began looking at various configurations of the DDI to accommodate the one-way frontage road through movement. Grade separation of the frontage road movement was considered, but because the frontage road through traffic was not a heavy movement (approximately 35 vehicles per hour at peak hour), a grade separation did not provide enough value to justify the additional cost. Cheaper options that were investigated included using roundabouts to facilitate the frontage road movement similar to today's configuration, or using Michigan Lefts to allow the frontage road through movement to weave its way across Happy Valley Road. Traffic simulations, however, showed that both the roundabout option and the Michigan Left option would not provide an acceptable LOS for the frontage road through movement.

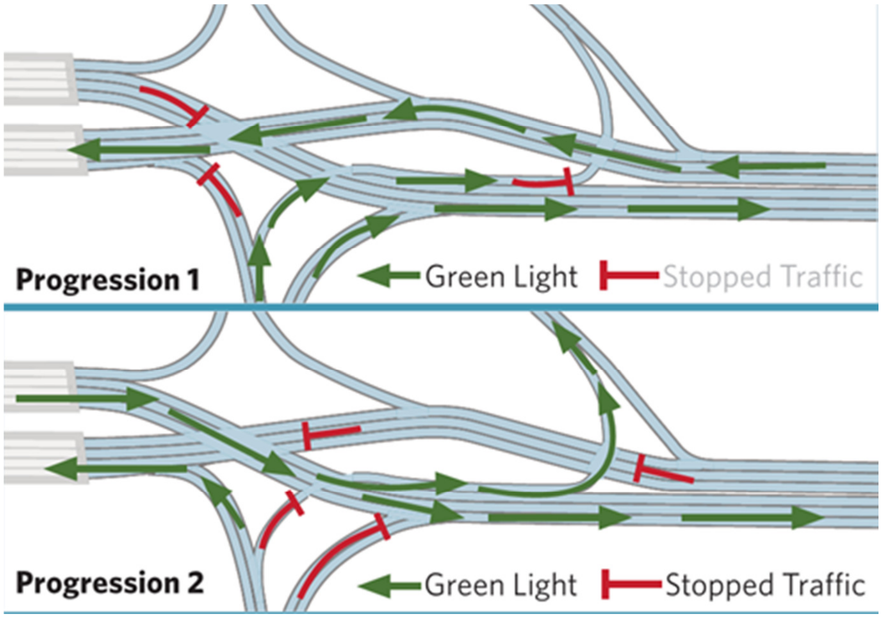

Figure 5 I-17 and Happy Valley Road DDI Intersection Signal Progression, Arizona
Source: HDR Inc.

Stemming from the exploration of the Michigan Left option, HDR started looking at merging the off-ramp and frontage road movement and then utilizing the available ROW by offsetting the frontage road termini. The offset allowed frontage road traffic to enter Happy Valley Road, weave across to the median during a protected signal phase and then make a left-turn from Happy Valley Road continuing on the frontage road system. After further refinement, HDR settled on a solution that embedded a two-phase intersection between the DDI crossover and the off-ramp right-turn movement. The embedded intersection, which is coordinated with the 2-phase DDI crossover, allows the frontage road traffic to cross the DDI while not impacting the DDIs operational performance.

By solving the DDI/one-way frontage road compatibility issue, HDR was able to realize many other benefits associated with the DDI. By eliminating the loop ramps, the need for a COAR was eliminated and the new pavement for the interchange was decreased. The bridge over I-17 was also shortened because it did not need to accommodate the two additional lanes from the loop ramps. A realignment of Happy Valley Road was easily accomplished with the curvature that is integral to a DDI, eliminating the need to construct the new bridge in phases, which shortened the duration of construction by 7-months and cut the required detours by 9-months. In all, by resolving how to accommodate one-way frontage roads in this DDI, HDR offered ADOT a cost savings of approximately $2 million and 7-month shorter construction duration without sacrificing operations or safety. In fact, safety may even be improved, especially for bike and pedestrian movements.

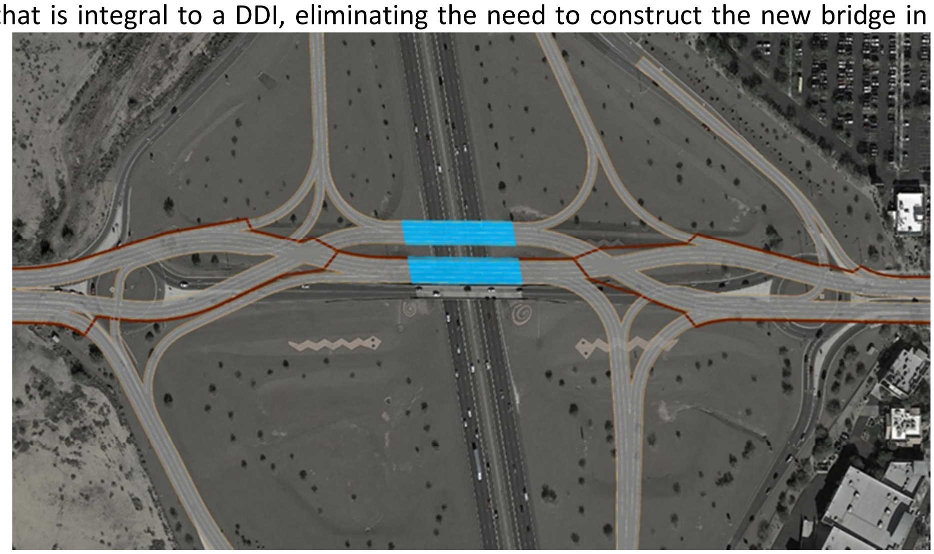
Figure 6 I-17 and Happy Valley Road Proposed DDI Configuration, Arizona
Source: HDR Inc.

The key to implementing this configuration was space. The ability to include a separated right-turn movement for only vehicles who wish to access the frontage road and then a follow-up left-turn pocket across the oncoming traffic lanes. Many interchange locations in urban environments do not have this type of space available, but when it is, there are creative ways to modify the DDI to still take advantage of the traditional DDI benefits without expensive grade separations.

South Colony Boulevard and Sam Rayburn Tollway / SH 121 (Texas)

Existing Condition

The existing South Colony Boulevard only connects to the one-way frontage road on the north side of the highway, and an interchange did not exist prior to the project. The area surrounding the interchange location was empty until recent development spurred the need for improvements, which included an interchange at this location. The existing highway consisted of eastbound and westbound direction travel on the highway itself and on one-way frontage roads connecting traffic to periodic side streets. There are adjacent interchanges ¾ of a mile in each direction from South Colony Boulevard further complicating the one-way frontage road access.

Figure 7 Existing Conditions at Proposed Interchange of South Colony Boulevard and Sam Rayburn Tollway, Texas
Source: Google Earth, 2013

Interchange Alternatives Considered

The adjacent interchanges follow a common Texas configuration using the one-way frontage roads to facilitate a "U-turn" movement under a grade separation of the highway and cross street with a modified diamond connection between the "U-turns" (see Figure 8 for adjacent interchange configuration). This interchange location was initially thought to follow the same configuration for consistency throughout the corridor. To create the grade separation, the highway is raised to cross over the cross street and placed on a lengthy bridge. All of the cross street movements are at-grade. To accommodate the heavy volume of left-turn movements to and from the one-way frontage roads, the cross section under the bridge is very wide. Because there is not an existing cross street at the South Colony Boulevard location, an opportunity presented itself to look at different interchange concepts. The topography of the land surrounding the interchange is higher than the highway than in other areas of the corridor, which lent itself to look at an overcrossing of the cross street instead of an undercrossing. An overcrossing would have resulted in a very large bridge that would act as a lid more than a

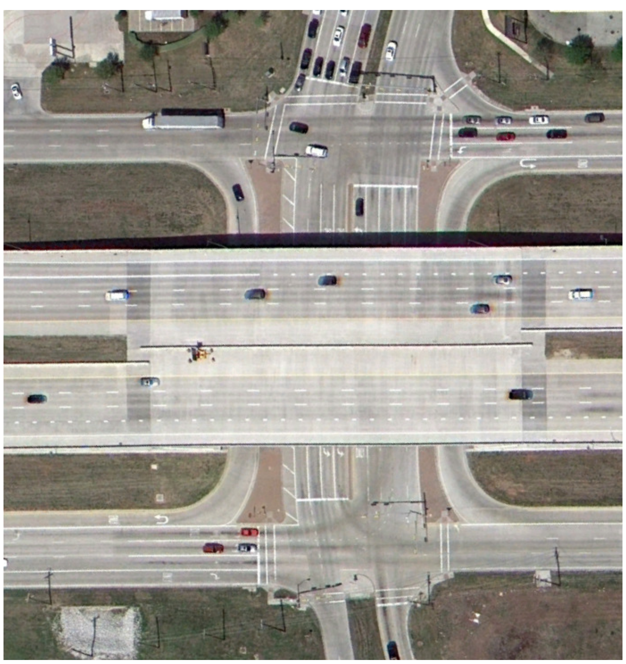

Figure 8 Common Interchange Type along Sam Rayburn Tollway, Texas
Source: Google Earth, 2013

traditional bridge structure. These factors led the design team to start considering a DDI configuration. The DDI traffic operations reduced the total number of lanes needed at the crossing and therefore reduced the total width of the overcrossing structure, which reduced project cost. However, the one-way frontage road connections still had to be modified to maintain connectivity around the new interchange.

<u>DDI Application</u>

Figure 10 Constructed DDI Configuration at South Colony Boulevard and Sam Rayburn Tollway, Texas
Source: Google Earth, 2016

The South Colony Boulevard DDI includes one-way frontage roads and access points to business complexes just north and south of the interchange. The frontage road is a fairly large facility as well consisting of a 3-lane section throughout most of its length, making it similar size to the east and west highway sections. With such a large frontage road needing to make the through movement at the interchange, the size influenced the potential solutions available. The frontage road width and the close proximity of the adjacent interchanges created a difficult weaving movement. If the frontage road is placed under the main bridge structure immediately adjacent to the highway, then any movement from South Colony Boulevard to the highway would require a vehicle to weave across three lanes of traffic. The distance required for this movement easily extends past the next interchange in each direction. The solution to this challenge was to locate the ramps in between the frontage road and the highway and elevate the intersections providing a multi-span cross street structure reducing the span lengths of the bridge and providing areas for the frontage road to go under the cross street. To accomplish this, the distance between the DDI intersection terminals had to be reduced. In addition, dedicated drop lanes through the core of the interchange were required to facilitate the "U-turn" movements that are present on the other frontage road systems in Texas. The interchange ramps merge with the highway and one-way frontage roads on both sides of the interchange to create a system

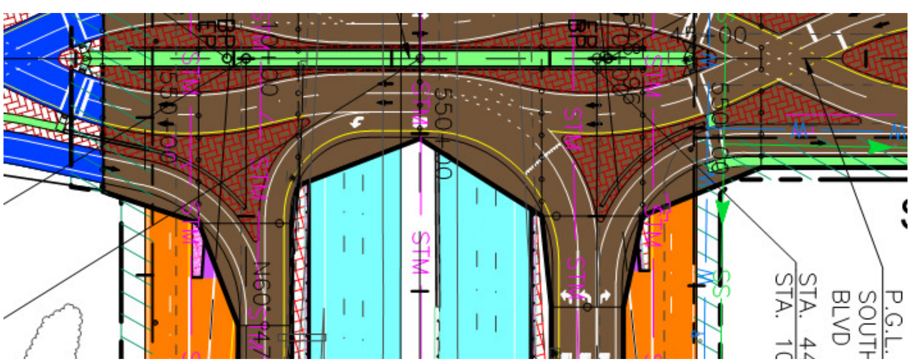

Figure 9 Proposed DDI design including off-ramp "U-turn" for frontage road connection, Texas
Source: HDR Inc.

that maintains connectivity for the frontage roads while optimizing operations at the interchange. The bridges in this design do take on an atypical shape, and the location of abutments and girder sequence are crucial to optimizing the layout to minimize the structural cost. The one-way frontage roads complicated the design of the structure and DDI but, in the end, did not result in the elimination of a DDI as an option.

FM 1431 and IH 35 (Texas)

Existing Condition

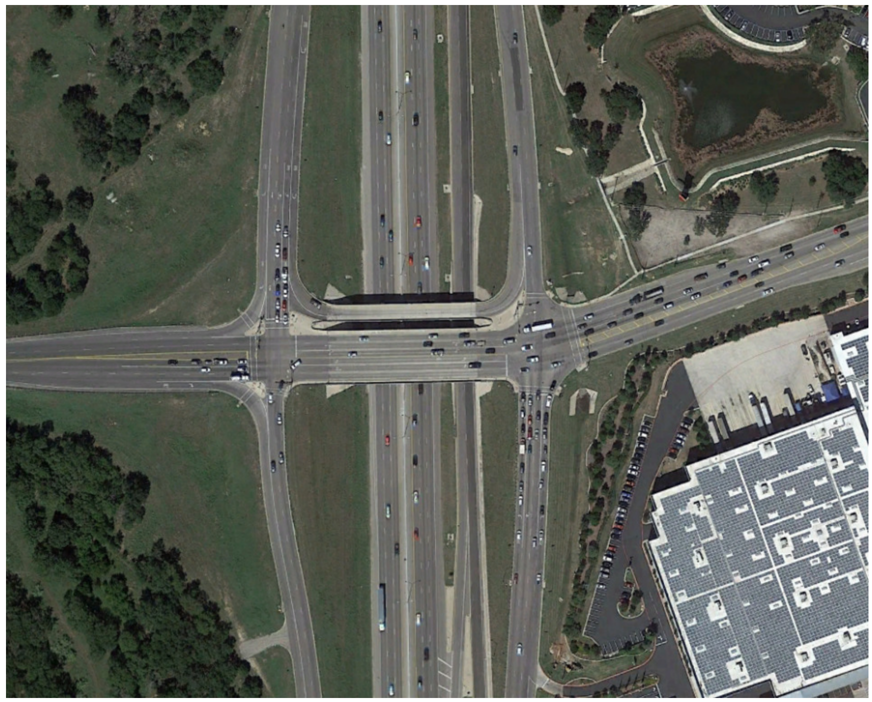

Figure 11 Existing Interchange Configuration at FM 1431 and IH 35, Texas
Source: Google Earth, 2013

The existing modified diamond at the interchange of IH-35 and FM 1431 is located in Round Rock Texas. The modified diamond includes a "U-turn" movement for traffic on the southbound highway or one-way frontage road to access the northbound direction on the same facilities. This "U-turn" movement is on a separate bridge structure from the existing 5-lane cross section for the arterial. The two eastern quadrants are occupied by major retail business centers including an IKEA, a movie theater, and HEB (major grocery store), and the western quadrants have a high potential for additional development. The volume of existing traffic and forecasts for increased growth in the area prompted the need to evaluate the interchange for potential solutions while maintaining access to all existing connection points. The existing roadway bridge spans have considerable life remaining. Saving and repurposing those structures was a key design component during the alternatives process.

Interchange Alternatives Considered

The existing diamond configuration required more capacity to reduce delay at the intersections. The most straightforward way to increase capacity was to evaluate the ability to add lanes by way of widening the existing bridge structures on the interchange. The separated bridge structure on the north side of the arterial for the "U-turn" frontage road connection complicated the widening by forcing it to occur asymmetrically to the south side of the structure. In conceptual design this introduced tapers and lane shifts that were not desirable with the diamond configuration. To widen the existing bridge was also very expensive. However, the addition of lanes to the same diamond configuration did maintain all frontage road connections. A DDI configuration was considered because of its perceived ability to reduce the total number of lanes required through the cross street, which would hopefully eliminate the need to widen. But the one-way frontage roads and separated "U-turn" movement required the DDI design to be atypical and would not follow a traditional DDI layout. It was also unknown during the initial concept design how the DDI would maintain the frontage road movements. The one-way frontage road on the northbound side of the highway connected to an existing slip ramp / collector – distributor (CD) road that was grade separated beneath the cross street through the bridge section. This configuration accommodated the northbound frontage road through movement connection; however, a traditional DDI design would not facilitate the existing one-way southbound frontage road connection or the eastbound to northbound arterial to frontage road connection.

DDI Application

DDIs have the advantage of flexibility built into its design. The curvature approaching and leaving the intersection terminals allows for the ability to move the approaches as needed provided the angle of the intersection and routing to prevent wrong way movements at the 2-phase signals. On this project the curvature is utilized to direct the left-turning traffic, the eastbound to northbound movement, to the separate northern "U-turn" bridge at the DDI's western intersection. This allows the DDI to maintain the connectivity of the southbound frontage road to the northbound frontage road by utilizing the existing "U-turn" movement on the northern bridge. The configuration also allows for additional storage on the through lanes and eliminates the possibility of queue's blocking the left turning traffic and degrading operations.

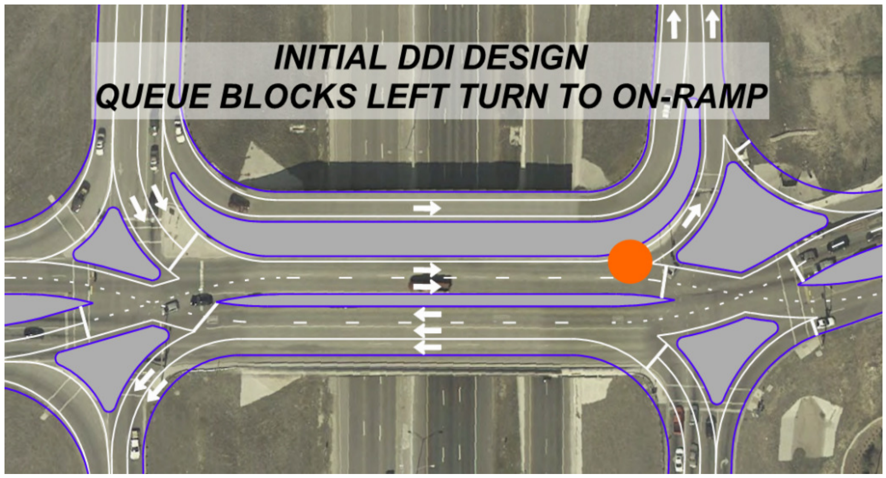

Figure 12 Initial DDI Alternative with inadequate queue distance at stop bars, Texas
Source: HDR Inc.

To connect the southbound frontage road through the interchange, analysis was completed to evaluate a slip ramp system similar to the system currently existing in the northbound direction. Because of the limited existing development on the western quadrants, immediate access was not required and the stakeholders agreed to the on-ramp/slip ramp connection further from the interchange to maintain frontage

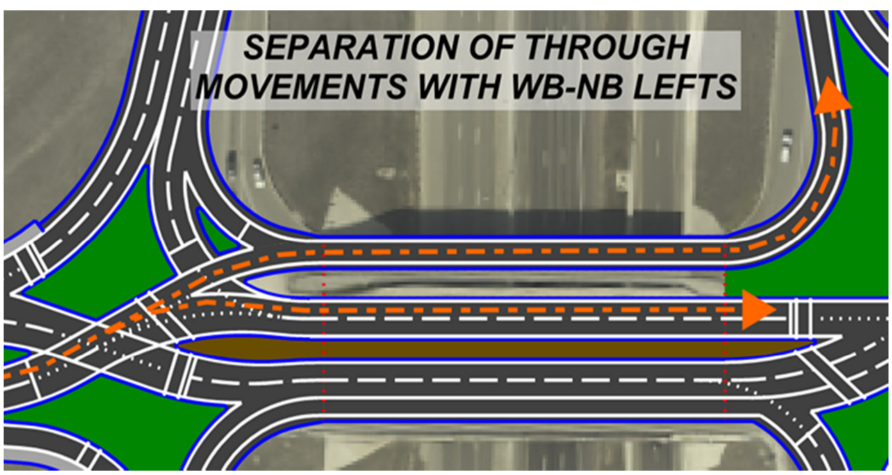

Figure 13 Final DDI conceptual design with separated left-turn and "U-turn" frontage road connection, Texas
Source: HDR Inc.

road connectivity and facilitate the westbound to southbound connection. The solution for the frontage road connection included maintaining the NB frontage road under the cross street bridge, adding a new SB frontage road connection under the cross street bridge, utilizing the separated bridge structure to maintain the frontage road "U-turn" on the north side of the cross street, and designing the DDI with a dedicated "U-turn" for the frontage road "U-turn" on the south side of the cross street.

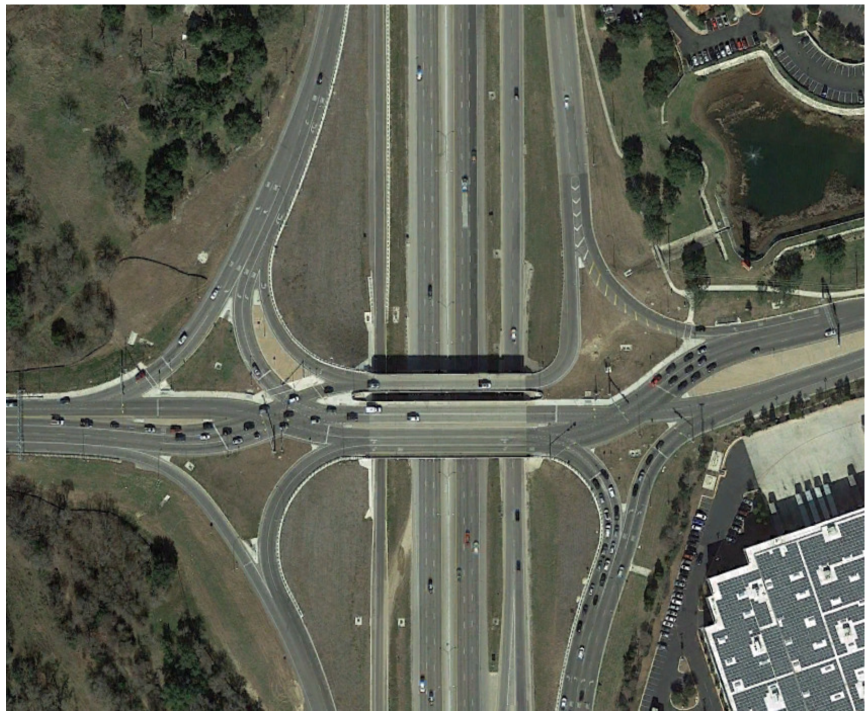

Figure 14 Final constructed Interchange at FM 1431 and IH 35, Texas
Source: Google Earth, 2017

This interchange design allows for re-purposing the existing structures and takes advantage of the 2-phase signals a DDI provides to reduce the total number of lanes required across the highway while keeping the one-way frontage road system intact. It does limit the ability to widen the highway while maintaining the existing structures if that ever becomes a need. DDIs with close spacing of intersections such as this one usually require atypical and costly bridge construction because the curves extend out onto the structure area. By utilizing the separated structure those atypical shapes were avoided and the frontage road connection was maintained. A byproduct of combining the southbound to northbound frontage road connection and the DDI left-turning traffic was that the configuration reduced weaving that occurred in the existing configuration by separating the left-turning movement from the through movement at the western intersection instead of carrying the movements together through the interchange. This design is now in operation and has received favorable reviews from local media outlets.

Findings

There are multiple ways to design a DDI that incorporates one-way frontage roads into the concept. Ideally, when there is enough space within the ROW, a frontage road connection that utilizes turn pockets and synchronized signals similar to the Happy Valley Road concept can be constructed to maintain the one-way frontage road system connectivity through the DDI configuration. However, even when the ROW does not exists, there are opportunities to move the one-way frontage roads to the inside or outside of the interchange ramps using grade separations similar to the South Colony DDI design to provide the connectivity through the interchange without conflicting with the interchange traffic. A variant between the Happy Valley Road concept and South Colony concept is to separate the left turning movements in order to facilitate turns onto the frontage roads such as was used at IH 35 and FM 1431. Each of the locations also could have utilized Michigan lefts at the adjacent intersections to facilitate the frontage road connections. There are many options available to maintain one-way frontage road system connectivity while also using a DDI interchange configuration. One-way frontage roads can no longer be used as the sole reason to dismiss a DDI interchange configuration from consideration, but they will require an atypical design to maintain access and connections for all users.

Recommendation

One-way Frontage roads no longer have to be a fatal flaw for a DDI configuration. By incorporating modifications to the DDI design, one-way frontage roads and DDIs can co-exist in the same space allowing for options that have the operational advantages of the DDI and the connectivity of a one-way frontage road system. To establish that connectivity, evaluate options that allow for the operational advantages of the DDI to be realized. The options presented in the case studies above work best when there is space around the intersection terminals to use for the modified DDI design features to allow for the incorporation of the one-way frontage road system continuity. While there may be added project costs for additional signal systems, ramp bridges, or additional bridge length, when used in the proper situations, the additional costs can be offset by the operational advantages of the DDI configuration and reduction in through lanes on the cross street. Take advantage of the inherent characteristics of DDI design and the flexibility the curvature allows to maintain one-way frontage road connectivity. The result will be the best value, operationally efficient, and cost effective projects.