

Breaking the Diamond: DDIs, CFIs, and SPUIs

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Abstract

With a recent push towards innovative solutions in interchange design, the diverging diamond interchange has been the next big thing. Two of its key weak points involve interchanges with heavy through movements along the crossroad and the split phasing of traffic along the crossroad creating issues with the coordination of traffic flow along the arterial corridor.

This presentation examines a case study in which all conventional interchange concepts as well as the DDI were incapable of handling the travel demand. A number of atypical concepts were then considered including a marriage between the concept of a single point urban interchange and a continuous flow intersection to create an interchange with a single signal and crossroad left turns that do not conflict with the opposing through movement. Also considered were variations on the DDI. This presentation will outline the concepts and provide initial operational results from VISSIM analysis to determine if and when benefits can be found from the implementation of these interchange forms.

Introduction

Advances in roadway and interchange design often come in fits and spurts. A new concept creates interest, apparently works on paper, and seems like the next big thing. Everyone waits for the first guinea pig. The first one gets built and gets some attention. If it is done well, the idea gains ground. If it is done poorly, the idea loses ground regardless of whether it was the idea or the execution that is to blame.

Roundabouts are a perfect example of this phenomenon. While the modern roundabout in the United States has gained widespread acceptance in many locations, in other regions it has not. In many of these cases, a local implementation is often to blame. In the case of roundabouts, many of these missteps have been nicknamed “suicide circle” or something to that effect.

Single Point Urban Interchanges have been around since 1974 though their acceptance and implementation did not reach a broader scale until the 1990s. Diverging Diamond Interchanges have also been around since the mid-1970sⁱ and are beginning their wide-scale deployment with 4 open as of the end of 2010. The Continuous Flow Intersection was developed and patented in 1987ⁱⁱ and saw its first US implementation in 1996.

This paper primarily covers the DDI and SPUI and attempts to find the breaking point of each. Concepts from the CFI were added to the SPUI to determine if the resulting hybrid interchange can handle more traffic than a conventional SPUI. The grade separation of the DDIs crossing intersections were also examined to see if braiding the DDIs crossroad movements would substantially increase its capacity as well.

The Diverging Diamond Interchange

This paper was born out of research into the newest fad in interchange design, the diverging diamond interchange. The DDI has been rapidly gaining acceptance across the US with the number of sites under consideration growing exponentially since 2006. The selling point of the DDI is its reputation as an interchange that can provide high capacity with fewer lanes than traditional signalized interchanges (including the SPUI) while doing so with minimal right-of-wayⁱⁱⁱ, particularly when compared to interchanges that include loop ramps.

The DDI is an interchange that uses an intriguing twist in that crossroad traffic is shifted to the left side of oncoming traffic (assuming right-side driving) in the core of the interchange. The benefit to this twist is that the turning movements do not occur at the signalized intersections. Instead, the signals control the opposing through movements.

Figure 1 - Rendering of the DDI at I-15 and Pioneer Crossing (opened in 2010)¹



This design excels where turning movement volumes to and from the ramps are high. Analysis has shown that high through volumes that conflict at the signals is its weak point. Depending on the traffic volumes and the spacing between the two ramp terminals, coordination with adjacent intersections and progression of both directions of travel are also potential hurdles. Progression in both directions is not always possible, but it can be done. No traffic analysis software currently on the market can optimize the signal timing of a DDI or of a corridor that has a DDI for progression in both directions. This must be done by hand using time/space diagrams. Both signals at a DDI are two-phase signals as no left turn phases are needed.

¹ Source: HDR

Single Point Urban Interchanges

Single Point Urban Interchanges offer the ability to handle large amounts of through and turning traffic by shifting all of the conflicting movements to a single signalized intersection that is typically controlled by a three-phase signal. The SPUI is much easier to coordinate with adjacent signals along an arterial corridor but is extremely expensive to construct either over (Figure 2) or under (Figure 3) the freeway due primarily to structure costs related to its width and odd shape.

Figure 2 – SPUI: Crossroad over Freeway²



Figure 3 – SPUI: Crossroad under freeway³



² Source: HDR

³ Source: HDR

Breaking the Diamond

For the analysis, a site was selected that was the first that HDR has analyzed where a DDI failed from a strictly operational aspect even without the influence of nearby intersections. The interchange in question is I-85 and Concord Mills/Burton Smith Boulevard, also known as Speedway Boulevard north of Charlotte, NC.

To complicate matters, there is extensive existing development in all four quadrants. The Concord Mills Mall is located in the southwest quadrant and the Lowe's Motor Speedway is east of the interchange. In order to accommodate long term improvements in the area, the number of through lanes on the approaches to the interchange must not exceed three in each direction. The width of the bridge was assumed to be unconstrained for the comparative analysis.

Figure 4 - Map of study location

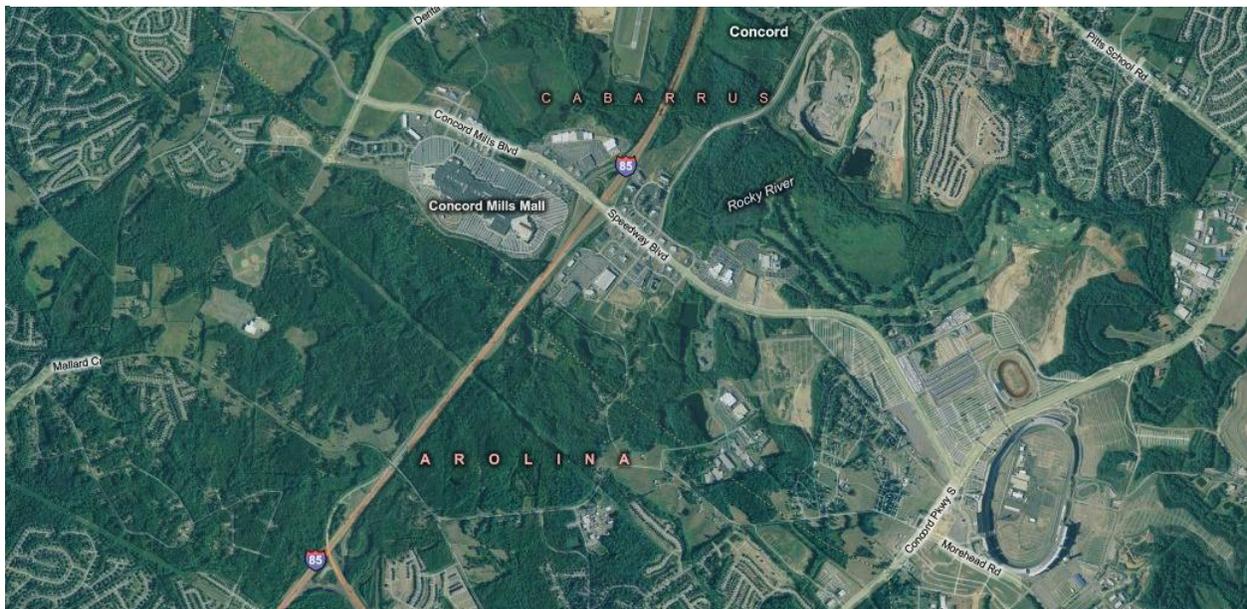


Figure 5 - Closer view of study corridor



Figure 4 - Turning movement percentages based on count data



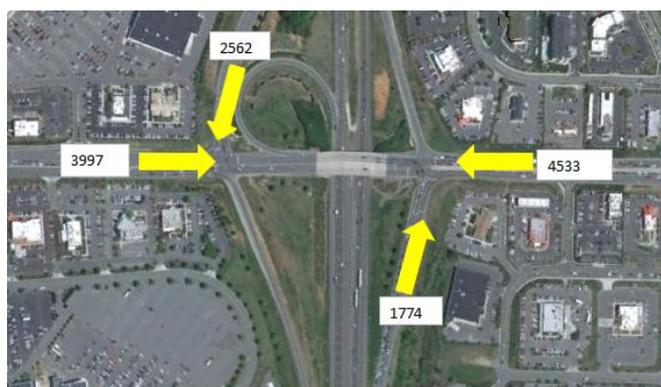
The volume scenarios used for this analysis ranged between the actual base volumes (2009 count data shown in Figure 5) to a maximum of 50% more traffic than the 2009 volumes (Figure 6). For simplicity, the increase in traffic volumes was applied universally to every movement.

Breakpoints

Table 1 shows the various volume scenarios in which the DDI and SPUI exceed their capacity.

The problems that arise in the DDI pertain to the volumes that conflict at the two signals. Additional lanes would be needed at the crossing intersections which would require additional lanes on the approaches to the interchange, which, for the purposes of this comparison, were limited to three lanes in each direction. In the DDI alternatives, a fourth lane is added on the left (north side) approaching the interchange (from the west) which acts as a de facto left turn lane. A right turn lane is also provided on the crossroad approaches.

Figure 6 - 150% volumes by approach



The base volume scenario for this analysis is based on the existing (2009) traffic data at this interchange. For each interchange alternative, the volumes were increased by 10% increments until the alternative fails. Failure, in the case of this analysis, involves the complete collapse of operations with more than 3% of traffic demand unserved (queuing off of the network). As the models are uncalibrated, they serve only as qualitative measures that can show the relative differences between models, but are not accurate for detailed level of service or delay estimates.

Figure 5 - Baseline volumes by approach

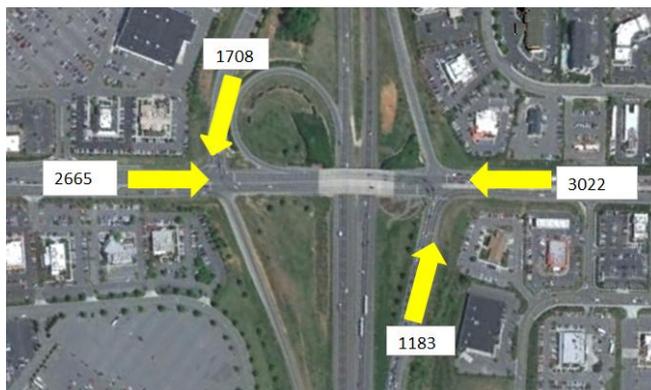


Figure 7 shows the DDI alternative's lane configurations at the interchange. The queuing from the two signals extends beyond the edges of the network on the crossroad.

The SPUI also uses three lanes in each direction and includes dual left turn lanes and dedicated right turn lanes on both approaches. (See Figure 8) The mode of failure for the SPUI was queue spillback from the left turns. Triple

lefts to and from the ramps would likely be required to make the SPUI function as the critical conflicts are the crossroad through movements and the crossroad lefts. The interchange is controlled by a three-phase signal with all three phases serving significant demand. The only potential solution is to provide more capacity (more lanes) for each phase or to eliminate a phase.

Table 1 – Comparison of the DDI and SPUI

Alternative	Volume Scenario	Delay (seconds)	Latent Delay ^{iv} (seconds)	Total Delay (seconds)	Latent Demand ^v (vehicles)	Total Demand (vehicles)	% Unserved ^{vi}
DDI	Base + 30%	97	284	381	726	19515	3.7%
SPUI	Base + 20%	143	728	871	1708	18013	9.5%

Figure 7 – VISSIM Screenshot of DDI alternative at 130% volume

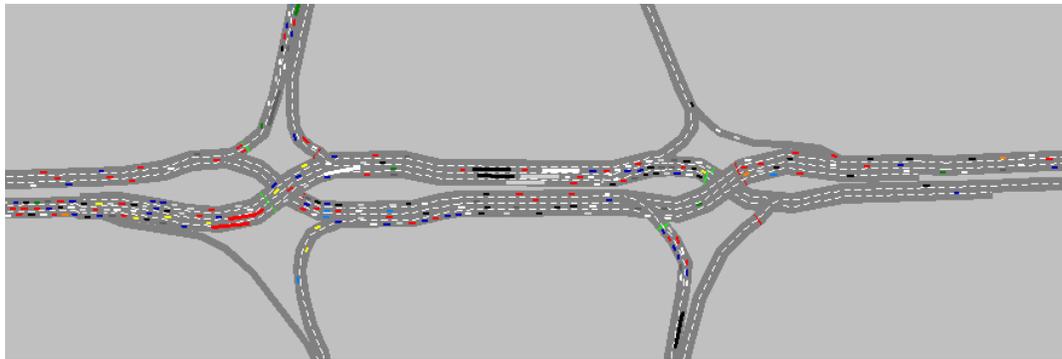
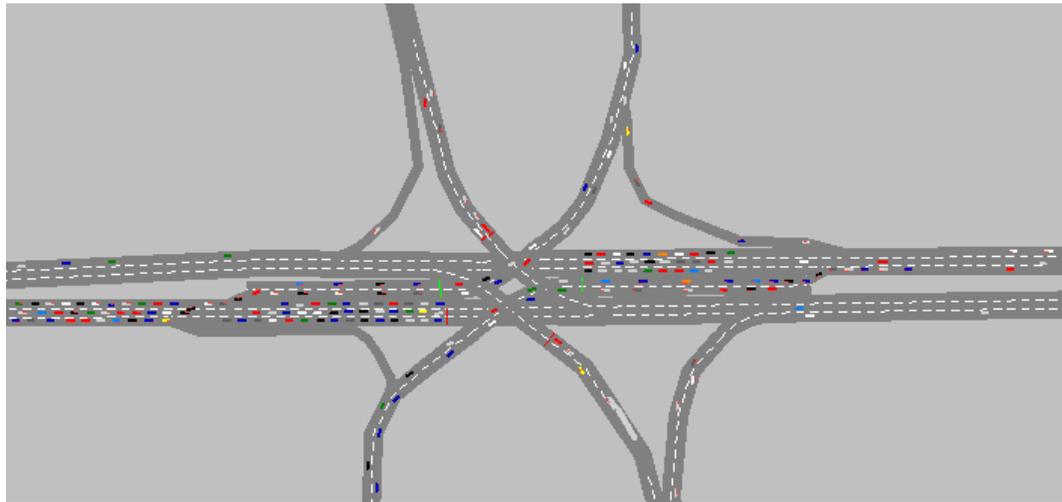


Figure 8 – VISSIM Screenshot of SPUI alternative at 120% volume



Displacing a Phase

The SPUI's mode of failure resulted from a lack of capacity for each of the three phases at the signalized intersection. Under this particular scenario, adding more through lanes and turn lanes would lead to

unacceptably wide cross sections on the crossroad approaches. If adding capacity for each of the three signal phases is not an option, then removing a phase is the only remaining option.

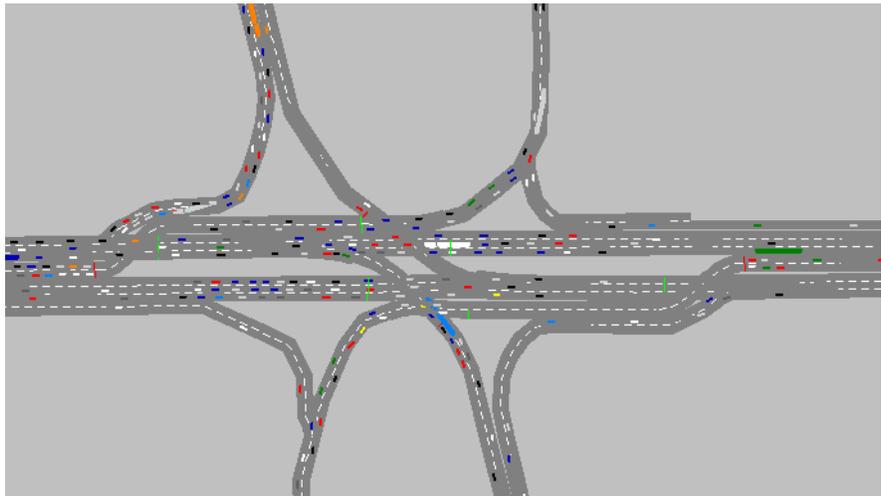
The Continuous Flow Intersection (Figure 9) is designed to handle significant amounts of left turning traffic while minimizing the effect left turning traffic would have on the opposing through movement. It does so by displacing the left turn movement. The left turns are moved to a signalized crossover prior to the cross-street. In this example, two of the four legs of the intersection have displaced left turns. In practice, one or all four legs could be designed with displaced left turns.

Figure 9 - Rendering of a Continuous Flow Intersection



The signals at the two crossover intersections in this example are coordinated with the main signal at the intersection of the two arterials to ensure that through traffic flow is optimized. While the displaced left turn concept increases the number of stops required for left turning traffic, it eliminates the left turn phase from the main intersection. Eliminating one

Figure 10 - VISSIM Screenshot of a SPUI with Displaced Left Turns



of the three phases from the main intersection allows more green time to be provided to the remaining phases and may shorten the cycle length of the signal, further reducing delay. Figure 10 shows what a SPUI would look like with the displaced left turn concept taken from the CFI and applied in a completely different concept which will be referred to in the rest of this paper as the CFSPUI.

While the CFSPUI fits the six-lane cross-section 750 feet from the centerline of the freeway, this design gets very wide at the interchange itself. The width of the crossroad is ten lanes plus a median wide enough to accommodate another two lanes for a total width of 12 lanes. That totals 144 feet without accounting for sidewalks, shy distances, drainage features, etc. shows the number of lanes needed at various cross-sections within the interchange.

Displacing the left turns and removing a phase from the main signal does add two additional signals to this interchange. The analysis results for the CFSPUI show a significant improvement resulting from the displaced left turn. The SPUI failed spectacularly at the *base plus 20%* volume scenario. The CFSPUI does not reach the level of congestion experienced by the SPUI at *base plus 20%* even when the volume is increased to *base plus 50%*. Table 2 shows the results for various CFSPUI scenarios. The mode of breakdown for the CFSPUI was queuing from the main signal back along the arterial and the ramps. It should be noted that no alternative was analyzed for volumes greater than *base plus 50%* as volumes beyond that would require additional capacity leading into the model as well. Even at the *base plus 50%* volumes, it is unlikely that upstream signals on the arterials would be able to deliver these volumes to the interchange.

Figure 11 - Cross-section widths for the CFSPUI

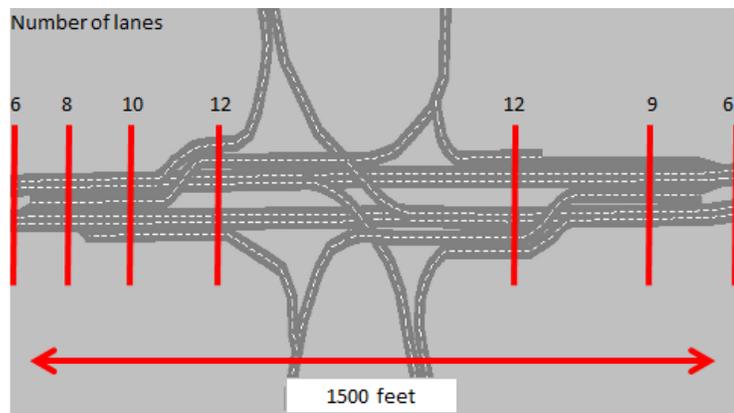


Table 2 - Comparison of SPUI-based Alternatives

Alternative	Volume Scenario	Delay (seconds)	Latent Delay (seconds)	Total Delay (seconds)	Latent Demand (vehicles)	Total Demand (vehicles)	% Unserviced
SPUI	Base + 20%	143	728	871	1708	18013	9.5%
CFSPUI	Base + 30%	50.8	151.3	202.1	370.1	19515	1.9%
CFSPUI	Base + 40%	63.2	269.2	332.4	628.6	21014	3.0%
CFSPUI	Base + 50%	89.6	519.4	609.1	1249.3	22517	5.6%

Diverging Diamonds and Braids

The DDI failed at the *base plus 30%* scenario due to the capacity at the intersections that cross the two directions of through traffic on the crossroad. What if those crossings were grade separated?

Geometric constraints, particularly those related to vertical geometry, are paramount to making a grade separation work at the crossing points of a DDI. Assuming a grade separation can be made to work, it is strongly recommended that the outbound crossroad go over the inbound crossroad as the inbound crossroad will likely need to be signalized to eliminate the weaving issue that would otherwise be created between the two ramp terminals.

Eliminating the need to signalize the crossing of the two directions of the crossroad does not result in a reduction in the number of signals needed. Instead, the signal removed by grade separation is instead used to control the crossroad through movement and its conflict with the exit ramp left turn. Grade separation can be done on one or both of the crossroad crossings. For this paper, the grade separation of only one crossing is referred to as the DDI – PB (DDI – partially braided, see Figure 12), and the grade separation of both crossings is referred to as the DDI – FB (DDI – fully braided, see Figure 13). In both figures, the darker color represents the bridge over the opposing roadway.

Figure 12 - DDI - Partially Braided

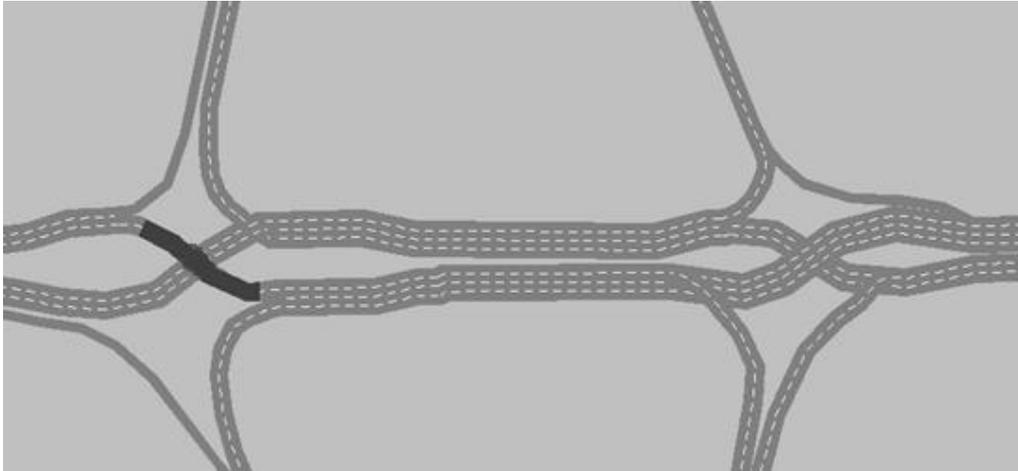
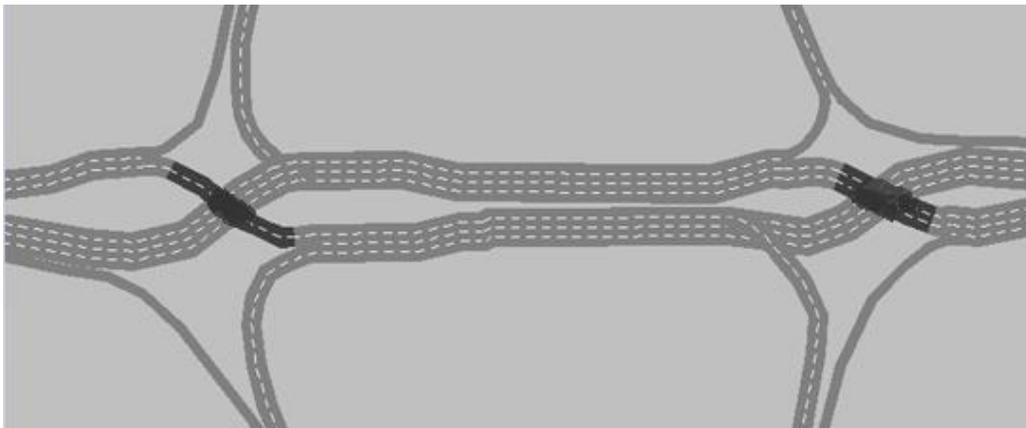


Figure 13 - DDI - Fully Braided



While braiding (grade separating) the crossing intersection does not eliminate the need for a signal, as previously discussed, it does increase the green time that can be allocated to the through movement and has a measurable impact on operations. This will not always be the case because as with all DDI operations, the efficiency of a DDI is heavily dependent on the manner in which traffic volumes are distributed around the interchange. In other scenarios, it is expected that the ramp may need more green time than the crossroad. Table 3 shows the results for the three DDI alternatives: typical, partially braided, and fully braided.

Table 3 - Comparison of DDI-based Alternatives

Alternative	Volume Scenario	Delay (seconds)	Latent Delay (seconds)	Total Delay (seconds)	Latent Demand (vehicles)	Total Demand (vehicles)	% Unserviced
DDI	Base + 20%	78.9	48.3	127.2	130.7	18013	0.73%
DDI	Base + 30%	97.4	283.9	381.3	725.7	19515	3.72%
DDI – PB	Base + 30%	76.1	126.5	202.6	411.8	19515	2.11%
DDI – PB	Base + 40%	86.7	424.4	511.2	1083.9	21014	5.16%
DDI – FB	Base + 30%	21.6	1.8	23.4	0.4	19515	0.00%
DDI – FB	Base + 40%	26.6	13.4	40.0	11.2	21014	0.05%
DDI – FB	Base + 50%	37.4	64.7	102.1	176.5	22517	0.78%

In the case of the DDI-FB, additional benefit to the crossroad traffic results from the fact that through traffic only has a single signal to pass through. While the traditional DDI failed with the *base plus 30%* volume, the partially braided DDI performed slightly better and failed with *base plus 40%* volumes. The fully braided DDI did not fail even at *base plus 50%* volumes, though the ramp begins to queue significantly. In this volume scenario, the southbound exit ramp is carrying almost 2600 vehicles per hour and would likely need a third lane. The delay in the 50% model largely results from backups on the ramp that arise from a lack of distance from the network entrance to the point in which vehicles need to decide whether to turn right or left. Looking solely at the delay experienced within the network, the interchange is still performing efficiently, even under the heavy volume loads in this scenario.

Summary

The DDI and SPUI are widely considered to be the best available options for handling interchanges with large turning volumes without loops or directional ramps such as flyovers. In general, DDIs are much cheaper to construct than SPUIs, particularly when it comes to structure costs.

Assuming a fixed width on the approaches, there are interesting twists that can be applied to modify both the DDI and the SPUI to get a bit more capacity from each of these concepts. Braiding the crossovers on a DDI can increase the capacity, but adds additional structures and may not be possible under some circumstances due to tricky vertical geometry required to provide adequate clearance at the crossovers.

Displacing the left turns on a SPUI can increase the capacity of the interchange, though it results in a very large structure. However, the CFSPUI structure is more rectangular than a traditional SPUI structure. It is doubtful that a CFSPUI can be constructed where the freeway goes over the crossroad as the span length required to clear the entire interchange may lead to very large structure depths and costs.

Author Information

Smith was involved in the selection of the DDI for Oregon's first deployment, the development of the Utah DOT's Diverging Diamond Interchange Guidelines, the Missouri DOT's post evaluation study for the MO 13 DDI, and the analysis and/or design of DDIs in North Carolina, South Dakota, Illinois, Wyoming, Colorado, Minnesota, Nevada, and Oregon. Smith has also been involved in the evaluation of CFIs in Oregon and Colorado. He has a background in both roadway design and traffic analysis and microsimulation.

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ⁱ The construction data of the first DDI in France is unknown, but thought to be in the mid-1970s. The first DDI in the United States opened to traffic in 2009 in Springfield, Missouri.

ⁱⁱ U.S. Patent # 5049000, expired in 2003 (U.S. Patent and Trademark Office)

ⁱⁱⁱ The fact is that while the number of lanes required to meet a certain capacity is typically less than other interchanges, this does not always translate into reduced right-of-way. However, the right-of-way footprint is substantially different than other interchanges in terms of *where* right-of-way is required.

^{iv} Latent delay refers to the delay encountered by vehicles waiting to enter the network

^v Latent demand refers to the number of vehicles that could not enter the network

^{vi} Percent unserved refers to the percentage of vehicles that were unable to enter the network due to queue spillback. Ideally, the network would be coded, particularly on the ramps, for a longer distance upstream to allow for vehicles to make the lane changes required.