New Interchange and Intersection Designs: The Synchronized Split-Phasing Intersection and the Diverging Diamond Interchange

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ABSTRACT

Existing intersections and interchange designs can be deficient due to the inability to accommodate common traffic patterns and due to road networks being originally engineered for a strong hierarchy of intersecting roads when currently many intersecting roads have similar characteristics.

The purpose of this paper is to introduce two new designs, developed by the author, which can accommodate the traffic patterns at major intersections and interchanges. The intersection design is called the "synchronized-split phasing intersection". The interchange design is called the "diverging diamond interchange". These designs take advantage of the benefits of split-phasing and signal synchronization to theoretically improve signal timing at heavy volume intersections or heavy turning movements. Simulations were conducted to compare the delay and total stops of these new designs to other conventional designs. The results showed that the synchronized split-phasing intersection and the diverging diamond interchange operated much more efficiently then the original designs. There seems to be great potential for these designs, although more research would be needed to look into alterations in traffic patterns and signal spacing, as well as a cost analysis.

INTRODUCTION

Purpose

Traffic patterns in the United States are increasingly decentralized. Suburb to suburb commute has been the most common type of commute since the 1970s (1). This commute includes work trips, shopping trips, and recreational trips. The road system is not well equipped to handle this type of commuting. Circulatory highways, like beltways, and a few local roads needs to carry a very large portion of the suburb-to-suburb commuting traffic.

Due, in part, to the changes in traffic behavior, many intersections do not accommodate some common traffic patterns very well. Heavy turning movements are often a problem at intersections. Many intersections now need three lanes for left or right turns, which can cause safety and operational problems. Some of these intersections need to be grade-separated, which can be costly. When there is heavy directional movement in more then one direction, most intersections have difficulties accommodating the traffic. If the heavy movements are both ways along the same road, there are often synchronization problems with other signals on the road.

The intersection designs are also engineered for a strong hierarchy of intersecting roads. For example, an arterial road normally intersects collector roads at signals. However, there are many cases where the two heavily utilized arterials or intersect, which makes designing intersections and interchanges even more difficult.

The purpose of this paper is to introduce two new designs, developed by the author, which can accommodate the traffic patterns at major intersections and interchanges. The intersection design is called the "synchronized-split phasing intersection". The interchange design is called the "diverging diamond interchange". These designs take advantage of the benefits of split-phasing and signal synchronization to theoretically improve signal timing at heavy volume intersections or heavy turning movements.

Synchronized Split-Phasing Intersection

The idea of a synchronized split-phasing intersection design came from an interchange north of Baltimore where I-95 intersects I-695 (see Figure 1). The idea of this interchange was to have short exit ramps while maintaining high speeds, in order to have smooth transitions for travelers who exit to the other interstate. There have been several criticisms for this interchange design in terms of safety due to high speed merging and driver's expectations (of left exits). However, the concepts of this design have been moved to an at-grade intersection, where left turns from left lanes are expected and speeds are slower. Some of the criticisms of the interchange would not be valid anymore and some of the advantages of this kind of design could become especially useful for an intersection design.

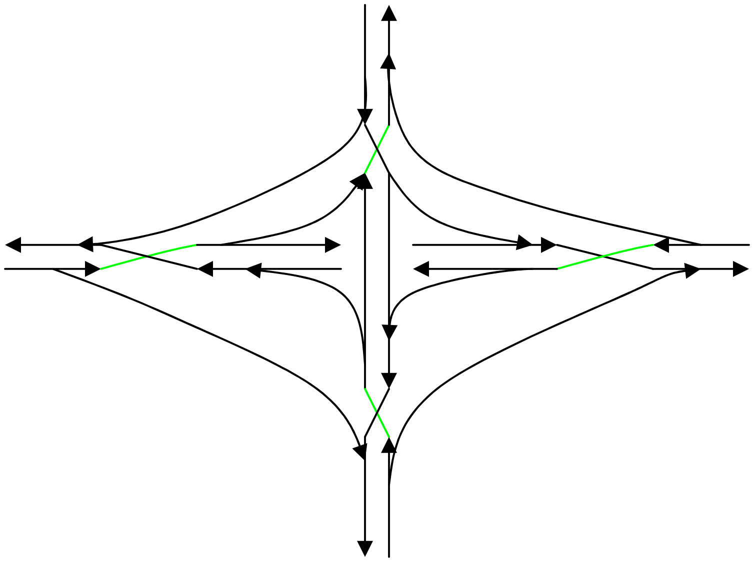

Figure 1. Approximate Geometry of I-95 / I-695 Interchange North of Baltimore City. All Crossings are Overpasses or Underpasses.

In order to simplify the design to make the operations potentially better, the crossover movements were eliminated for one of the roads. This makes the basic design of the synchronized split-phasing intersection appear like Figure 2.

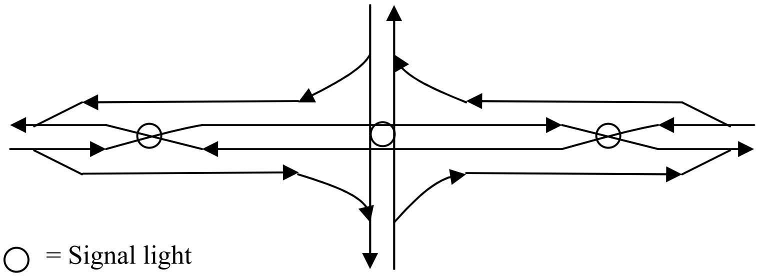

Figure 2. Synchronized Split-Phasing Design.

Some of the characteristics of the synchronized split-phasing design are similar to the continuous flow intersection (2). The flow of traffic is dispersed before the main intersection. However, the continuous flow allows left turning movements to cross over before the main intersection, whereas the synchronized split-phasing design allows both left and through movements to crossover. Different benefits in signal timing and phasing coordination are made with each design.

Diverging Diamond Interchange

The diverging diamond interchange developed from the concept of the synchronized split-phasing design. The idea was to use the crossing over movement on an interchange design. The conventional diamond interchange seemed to be the easiest design to create crossover movements for. The main goal was to better accommodate left turn movements and potentially eliminate a phase in the cycle for the signals.

Figure 3 shows the layout of the diverging diamond interchange. The highway portion does not change but the movements off the ramps change for left turns. Through and left turn traffic for the arterial road also maneuvers in a different manner from a conventional diamond interchange because the traffic crosses to the "wrong" side in between the ramps.

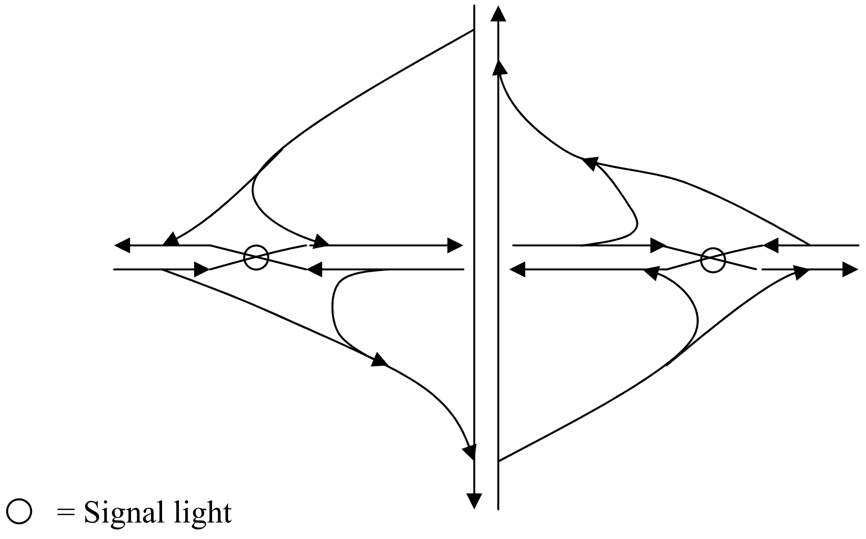

Figure 3. Diverging Diamond Interchange.

THEORETICAL DISCUSSION

Traffic Patterns

Synchronized Split-Phasing Intersection

Traffic patterns for the synchronized split-phasing intersection are shown in Figure 2. Starting from the west side of the figure, eastbound traffic will be allowed to use a slip ramp to make a right turn to go southbound. After the right turn is provided, the travel lanes will cross the westbound traffic so that the eastbound traffic would be able to travel on the left side of the road, as if it was a British divided highway. A signal light would control the crossing of the eastbound and westbound traffic. Following the crossing, the east-west road will intersect the north-south road with another signal light, which will be known here on as the “main intersection” or “main crossing”. After this main crossing, another signal light will be provided ahead to allow the eastbound traffic to cross over the westbound traffic again and return to the right side of the road. Once on the right side of the road the eastbound traffic will have a ramp merge for the right turning movement of previous northbound traffic who desire to go east.

The design is symmetrical about either road. All right turn movements are done with ramps and left turn movements are made at the main intersection, regardless of the initial direction. Through movements for northbound and southbound traffic progress to what drivers normally expect, but the eastbound and westbound traffic through movements will need to cross over twice, once before the main intersection and once after the main intersection.

The main intersection signal light will be a three-phased signal. The first phase will be protected left turns from the northbound and southbound movements. This phase can be any combination of lead lefts and lag lefts. The second phase will be the through movements for the northbound and southbound phases. The third phase will allow through and left tuning movements for the eastbound and westbound directions. Note that the left turning movements for eastbound and westbound traffic can move without conflict.

The other signal lights at the crossings need to be coordinated with the main intersection signal light. The goal of the coordination is to allow traffic to go uninterrupted from the first signal to the last signal in both the eastbound and westbound directions as well as having the same green time at the main intersection. The coordination should also allow left-turning vehicles from the north-south road to progress freely though the next signal light. This coordination will need to depend on the distance between the three signal lights, the phase length, and the speed of the traffic.

Diverging Diamond Interchange

For the diverging diamond interchange, which is illustrated in Figure 3, eastbound traffic allows a right turn movement to the ramp before the crossover. This right turn ramp will merge with the left turn movement from the westbound direction to provide one ramp to the southbound direction. After the crossover for the eastbound movement, traffic will come in from the southbound direction that wants to head eastward. This traffic will come from the left side of the eastbound traffic. An exit will then be provided on the left for left turn movements to the northbound movement after the highway passes over or under the other highway. The crossover will then occur again to get the eastbound traffic to the right side and finally receive the traffic from the northbound right turn movement. The design is symmetrical for the westbound traffic.

Two signal lights are needed for this design, one at each crossover. Each signal will be two-phased. The ramp phase will be combined with the non-conflicting flow of traffic for the east/west road. The length of the green time for the ramp may not need to be as long as the other green time in the same phase, due to possible queuing problems at the other signal. However, the green time for the second signal in a given direction can be longer then the other phase to prevent the left turn movements from the ramps from queuing a second time in the system. The longer the green time is for the second signal though, the more the signal timing resembles three phases.

Benefits and Drawbacks

Synchronized Split-Phasing Intersection

Other phases at the main signal can benefit if the required length of time is different for the eastbound compared to the westbound. For example, suppose that the eastbound traffic only needed 45 seconds of green time and the westbound traffic needed 60 seconds. The eastbound traffic could change to red 15 seconds earlier then the westbound traffic, which would allow the southbound traffic to start its left turn phase. If the left turning movement lasted for 15 seconds, it would turn red at the same time the westbound traffic turned red. This would allow the northbound traffic to start its left turn phase and through phase at the same time. This would be especially useful if the northbound traffic requires more green time then the southbound traffic and/or if the left turning traffic from the southbound direction is significantly larger then the left turning movement from the northbound direction.

Phase combinations that are not possible in conventional intersections are possible in the synchronized split-phasing intersection design. These combinations without conflicts include:

(1) Eastbound through and left movements with northbound left movements
(2) Westbound through and left movements with southbound left movements
(3) Eastbound through and left movements with westbound through and left movements

With any combination, there are no conflicts with right turn movements.

Green time can also be extended considerably to the phases compared to a conventional split-phase design. Since this design essentially combines both phases of a conventional split phase design, extra green time can be distributed among the phases for the lost time of the extra split phase. There is also a more direct left turn in all directions, when compared to conventional intersections, which reduces the clearance time for the left turn phases.

Another benefit of this design is allowing the use of lane sharing for turning movements. This is one of the similarities of this design compared to a conventional split-phasing design. For the eastbound/westbound traffic at the main intersection, it is possible to have a shared left/through lane. Many different lane combinations can be made due to the flexibility of the synchronized split-phasing intersection.

The other noticeable benefit to this type of intersection design is the cost reductions in construction and right-of-way costs, if the synchronized split-phasing intersection is chosen over an interchange design. Almost any at-grade intersection design will cost less to construct then a grade-separated structure. Less right-of-way is needed for the synchronized split-phasing intersection when the eastbound and westbound roads are as close to each other as possible, which is ideal. However, in most cases, the synchronized split-phasing intersection will be more expensive then other conventional intersections due to the additional signals, geometric needs, and more right-of-way costs.

The most noticeable pitfall to the synchronized split-phasing intersection is safety concerns due to driver confusion. Drivers have the potential to be confused when they need to be on the “wrong” side of the road. Driver confusion can be reduced with good geometric design, proper signing, and roadway markings and signals.

Conflicts with access to driveways for businesses and residents near the main intersection can cause problems in building the synchronized split-phasing intersection. There may also be problems with other intersections being too close to the main intersection. The synchronized split-phasing intersection can still work if movements are restricted for these driveways and intersections on to the east/west road. Service roads along the east/west road are another possible solution.

Both pedestrians and cyclists may experience safety problems due to the unconventional traffic pattern. Pedestrians will get the benefit of having a median for refuge in all directions. Also, with the potential for longer green times in all directions with the synchronized split-phasing intersection, the pedestrian signals can be longer without interfering with traffic behavior.

Diverging Diamond Interchange

The biggest potential benefit of the diverging diamond interchange is the ability to combine phases in ways that cannot be done in other interchange designs. Ramp phases can be combined with a mainline through movement, and mainline left movements can be combined with through movements throughout the whole phase without a major penalty to other phases. Coordination of the signals can be made between a ramp phase and a through phase without much difficulty due to the unique geometry. The reduction of a phase when compared to a conventional three-phased diamond interchange can also benefit the signal timing.

The diverging diamond interchange has less conflict points then a conventional diamond interchange. The ability to make left turns without crossing over the road to make the left produces less conflict points. Although driver confusion may cause safety problems in this design, the reduction in conflict points has the potential to lessen the hazards for the drivers.

Another advantage the diverging diamond has over the conventional diamond and urban diamond is the ability to combine lane assignments (i.e. a lane assignment that allows left and through movements) on the east/west road without changing the phasing of the signals. This is a common feature in the synchronized split-phasing intersection.

Theoretically, this design should perform very efficiently when the heaviest movements are left or right turning movements on to or off of the ramps. In other words, if a very popular trip attraction was towards the west, and very few trips were to the east, the signal at the west crossover would be highly used and the signal at the east signal would not. The phasing and coordination systems should perform better, which will be tested in one of the experiments. An example of the diverging diamond interchange already exists in France, outside of Paris, where highway A12 has an interchange with a road that has rural characteristics towards the east and Versailles, a major town and tourist attraction towards the west.

When the ramp movements approach the amount of vehicles as the mainline through movements, this design may become inferior to other diamond interchange designs. This is because the coordination between the two signals becomes more difficult when it doesn't fit with the geometric design of the diverging diamond interchange. This design may not be able to coordinate all movements effectively if they are all equally as heavy.

Right-of-way cost may become an issue for two reasons. First, the median on the road where traffic is on the "wrong" side may need to be wide in order to reduce driver confusion. This may result in a wider bridge as well. The other need for additional right-of-way could occur near the ramp terminals because of the need to bend the ramps into the road, which wouldn't necessarily be needed for a conventional diamond interchange. The right-of-way cost increases would not likely be as significant as the possible right-of-way costs for the synchronized split-phasing intersection.

Driver confusion is another concern for this design. Similarly to the synchronized split-phasing intersection, driver confusion can be reduced with good geometric design, proper signing, and roadway markings and signals.

The final concern deals with access to driveways for businesses and residents next to the interchange. This is not nearly as big of a concern as in the synchronized split-phasing intersection because access is generally not permitted between ramp terminals and the road converts back to conventional characteristics almost immediately after a driver passes the interchange. With some minor changes in access locations, most problems could be solved.

SIMULATION TESTS

Method

A sample intersection and interchange were chosen to test the operations of the synchronized split-phasing intersection and diverging diamond interchange, respectively. These new designs were compared to the original designs and another possible design. The locations chosen had high turning movement volumes in at least one direction. At the time of the traffic counts, the designs were causing multiple stops at the signals for many of the movements.

Synchro 5 was used as the simulation tool to compare the phasing and geometric strategies. The software optimized each strategy's signal timing automatically for a fair comparison. SimTraffic 5 was used for the analysis of the intersections. This software was chosen for its acceptability at the state agencies as well as its ability to create short links.

The lane configurations were initially kept the same for all the designs. Based on preliminary simulation runs, minor improvements were made on the comparison designs, such as lengthening the turn bays and adding additional turn lanes.

Each intersection was tested using fixed timed signals. Although this would make each strategy perform less efficiently than an actuated signal, it was used for a more fair comparison between strategies. Other variables were also kept as constant as possible, including travel speeds, turning speeds, and truck percentages.

The three measures of effectiveness (MOEs) chosen for the comparison were total delay, stop delay, and total stops. These MOEs would effectively demonstrate the actual time wasted for the signals, as well as the psychological frustrations of the drivers.

Intersection Comparisons

The synchronized split-phasing intersection was compared to a standard split-phased signal, which was the original design at the test intersection, and a four-phased signal, which was chosen because it was likely to be superior to the split-phased design.

The intersection of US 29 @ East Randolph Road/Cherry Hill Road in Montgomery County, Maryland was chosen as the test intersection. US 29 is a major north-south arterial that connects Baltimore, Maryland to Washington D.C. as well as other employment centers along the corridor. East Randolph Road and Cherry Hill Road are parts of a long stretch of road that changes names multiple times. These roads run radial to Washington and serve as a major connection between different suburbs as well as an alternate route for the congested Washington beltway (I-495). Due to the nature of these roadways, there are heavy movements in all directions. Table 1 shows the AM peak hour volumes that were used for the simulation tests.

The MOEs were tested at the main intersection. These results are in Table 2. An additional comparison was made for the whole network since the synchronized split-phasing intersection has multiple signals which could cause more delays. This analysis is shown in Table 3.
The total delay for the network was about twice as much for the four-phase design and over five times as much for the split-phasing design as it was for the synchronized split-phasing design. The stop delay was over two and a half times worse for the four-phase design and over seven times as worse for the split-phasing design when compared to the synchronized split-phasing design. The total stops was approximately 20% more for the four-phase design and over two and a half times worse for the split-phasing design, compared to the synchronized split-phasing design.

Several explanations can be deduced as to why the synchronized split-phasing design outperformed the other designs. The synchronized split-phasing accommodated the heavy left turn movement from Cherry Hill Road without the need for an additional phase for the movement. Also due to the decrease of phases compared to the comparison designs, more green time was permitted for all the movements. The synchronization of the crossover signals was simple and did not add a significant amount of delay. The left turns from SB US 29 were able to get a head start for its phase, since EB E. Randolph Road was allowed to go to a red phase before the WB Cherry Hill Road needed to go to a red phase. Finally, the shared left/through lane allowed more vehicles to get through the intersection without the need for another lane.

Interchange Comparisons

The diverging diamond interchange was compared to a standard diamond interchange, which was the original design at the test interchange. A diverging diamond interchange with a signal and one without a signal for left turning ramp traffic was also used in the comparison to see what differences this would make.

The interchange of I-695 (Baltimore Beltway) @ MD 140 (Reisterstown Road) in Baltimore County, Maryland was chosen as the test interchange to compare the diverging diamond interchange with a conventional diamond interchange. This interchange is a very busy interchange that serves traffic for the northwest suburbs of Baltimore. Movements are heavy in all directions as can be seen in Table 4, which represent the AM peak hour traffic movements. For the westbound traffic, 46% is through traffic, 26% is right turning traffic, and 28% is left turning traffic. For the eastbound traffic, 46% is through traffic, 28% is right turning traffic, and 26% is left turning traffic. This interchange was chosen because of its heavy turning movements and its fairly evenly distributed split of movements in all directions. The split of the traffic movements was expected to be a challenge for the diverging diamond interchange.

Table 5 summarizes the left and through movement characteristics for each signal. Table 6 calculates the network stops and delays. With the exception of the through movements for the second signal in each direction, the diverging diamond interchange designs operated more efficiently. When combining the delay for the through movements at both signal lights, both diverging diamond designs functioned more efficiently.

The signalized diverging diamond design, where the left turning ramp movements had a signal, compared similarly to the diverging diamond design, where the left turning ramp movements only needed to merge into traffic. This was a positive result, because the signalized diverging diamond is likely to be safer then the non-signalized design due to eliminating the merging hazards and controlling the traffic better. The probable reason why this occurred is due to the fact that the delay for the left turning ramp vehicles was being transferred from the ramp entrance to the other signal in the non-signalized design.

When viewing the comparisons between the conventional diamond and diverging diamond interchanges, the total delay for the conventional diamond was about three times as great as the diverging diamond. The stop delay was over four times worse for the conventional diamond. The total stops were approximately twice as many for the conventional diamond when compared to the diverging diamond designs.

CONCLUSIONS

This study explored new ways to accommodate common traffic patterns that current intersections and interchanges are not managing efficiently. The author developed the synchronized split-phasing intersection and diverging diamond interchange as new ways to provide more efficient operations.

Both the synchronized split-phasing intersection and diverging diamond interchange were compared against other conventional designs where the operations of the original design was already at very poor conditions. The new designs were given disadvantages compared to the comparison designs such as less turning lanes, non-ideal turning movement volumes based on the theoretical usage of the new designs, and no adjustments from the Synchro analysis. Still both new designs had significantly better operational capabilities then the comparison designs. The research shows great potential for these designs.

Further research could look into what happens when the length between signals for a synchronized split-phasing design is not ideal. Different volume ratios and turning movement ratios should also be explored in some greater detail. A closer look at the speeds and superelevations may also be needed to see how fast vehicles will be practically able to travel in the crossover movements. A cost analysis is another item to explore.

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Table 1. Turning Movement Volumes for Intersection.

EB E. Randolph Road			WB Cherry Hill Road			NB US 29			SB US 29		
Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
150	630	100	500	750	480	150	1070	195	550	2780	270
17%	72%	11%	29%	43%	28%	11%	75%	14%	15%	77%	8%

Table 2. Through and Left Turn Movement Moes for Synchronized Split-Phasing Comparisons.

1) Split phasing 2) SSP* 3) 4-Phase	EB E. Randolph Road			WB Cherry Hill Road			NB US 29			SB US 29		
	1	2	3	1	2	3	1	2	3	1	2	3
Through Total Delay (hr)	34.9	0.5	34.6	44.3	7.8	18.0	11.7	5.0	7.5	236.9	8.0	37.9
Left Total Delay (hr)	2.2	0.5	2.9	30.0	4.6	30.3	9.4	2.2	12.7	37.0	4.4	6.2
Through Stop Delay (hr)	31.9	0.3	31.9	39.1	5.1	15.7	9.7	4.3	6.0	189.4	6.0	23.8
Left Stop Delay (hr)	1.9	0.3	2.7	26.8	3.2	28.3	9.3	2.1	12.5	30.0	4.2	5.3
Through Total Stops	1363	69	1211	1772	547	802	816	538	603	8094	503	2322
Left Total Stops	134	69	156	1248	351	1061	182	153	196	1343	330	305

* = Synchronized Split-Phasing

Table 3. Network for Synchronized Split-Phasing Comparisons.

	Split-Phasing	SSP*	4-Phase
Total Delay (hr)	447.3	85.2	169.4
Delay / Vehicle (sec)	221.7	40.5	79.7
Stop Delay (sec)	362.4	50.4	132.6
Stop Delay / Vehicle (sec)	179.6	23.9	62.4
Total Stops	16642	6346	7706
Stop / Vehicle	2.29	0.84	1.01

* = Synchronized Split-Phasing

Table 4. Turning Movement Volumes for Interchange.

EB MD 140		WB MD 140		SB Ramp I-695	
Thru	Right	Left	Thru	Left	Right
1212	472	389	1119	328	665
EB MD 140		WB MD 140		NB Ramp I-695	
Left	Thru	Thru	Right	Left	Right
446	1094	1033	367	475	408

Table 5. Through and Left Turn Movement Moes for Diverging Diamond Interchange Comparisons.

1) Conventional 2) DDI* 3) Signalized DDI*	EB MD 140			WB MD 140		
	1	2	3	1	2	3
Through (SB Ramps) Total Delay (hr)	37.5	5.9	5.3	2.5	3.3	3.1
Through (NB Ramps) Total Delay (hr)	1.3	3.2	3.1	17.7	5.1	4.4
Through (SB Ramps) Stop Delay (sec)	30.5	4.3	3.9	0.7	2.9	2.6
Through (NB Ramps) Stop Delay (sec)	0.2	2.6	2.6	14.3	3.7	3.0
Through (SB Ramps) Total Stops	2582	804	738	349	405	421
Through (NB Ramps) Total Stops	157	400	429	1381	707	634
	WB MD 140			SB I-695		
	1	2	3	1	2	3
Left (SB Ramps) Total Delay (hr)	15.2	0.2	0.2	2.0	0.1	1.1
Left (SB Ramps) Stop Delay (sec)	14.0	0.0	0.0	1.8	0.0	0.9
Left (SB Ramps) Total Stops	963	1	13	220	3	204
	EB MD 140			NB I-695		
	1	2	3	1	2	3
Left (NB Ramps) Total Delay (hr)	7.7	0.3	0.3	5.7	0.2	1.6
Left (NB Ramps) Stop Delay (sec)	6.8	0.0	0.0	5.2	0.0	1.4
Left (NB Ramps) Total Stops	464	11	3	451	24	275

* = Diverging Diamond Interchange

Table 6. Network for Diverging Diamond Interchange Comparisons.

	Conventional	DDI*	Signalized DDI*
Total Delay (hr)	107.1	37.1	35.9
Delay / Vehicle (sec)	80.2	26.7	26.1
Stop Delay (sec)	83.4	19.7	19.4
Stop Delay / Vehicle (sec)	62.5	14.2	14.1
Total Stops	8336	4205	3960
Stop / Vehicle	1.73	0.84	0.80

* = Diverging Diamond Interchange