COMPARATIVE ANALISYS OF THE DIVERGING DIAMOND INTERCHANGE AND PARTIAL CLOVERLEAF INTERCHANGE USING MICRO-SIMULATION MODELING

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ABSTRACT
In the last decades, population growth has been outpacing transportation infrastructure growth, and today's transportation professionals are challenged to meet the mobility needs of an increasing population. The effectiveness of the transportation system is an essential constituent of people's daily lives as they commute between different points of interest. Studies show that at many highway junctions, congestion continues to worsen, and drivers are experiencing greater delays and higher risk exposures. Engineers have very little resources to handle this increase in population. One solution to alleviate congestion is in implementing alternative designs. This approach will help traffic engineers determine which design will be the most appropriate for a particular location. This study compares and evaluates the Diverging Diamond Interchange (DDI), which is an unconventional design, to Partial Cloverleaf (ParClo) interchange design by evaluating different Measure of Effectiveness (MOEs). Using micro-simulation platform AIMSUN, each interchange type was evaluated under various traffic flows. The analysis revealed that in terms of queue, the DDI design had a much better performance. The results from the analysis help in providing guidelines to the decision makers for selecting the best performance alternative.

Keywords: Diverging Diamond Interchange (DDI), Partial Cloverleaf (ParClo), Micro-Simulation Platform

INTRODUCTION

The need for innovation in the highway sector has never been greater. The highway system has had a major impact in the U.S. society and economy, and the mobility has become a necessity since people have grown accustomed to it. Whether driving or riding the bus, many Americans use the highway system every day in their personal, social or professional activities. The system of highways, bridges, public transportation, and railroads on which the nation depends upon have been the main cause of this achievement. The United States, in contrast to the Western world, relies more on its roads both for personal and commercial use. Car ownership is virtually universal except for few of the larger cities where mass transit systems have been built. The development of the Interstate System allowed the U.S. economy in the last half of the 20th century to nourish and grow in size and productivity. But currently, the capacity and performance of the existing Interstate Highway System are too congested which reduces the Interstate's ability to sustain the increased productivity this country will need to compete in the global economy. According to the Bureau of Transportation Statistics from 2006, Americans use personal vehicles for 87 percent of daily trips and 90 percent of long-distance trips (*1*).

In 2009, congestion caused urban Americans to travel 4.8 billion hours more and to purchase an extra 3.9 billion gallons of fuel, adding up to a total cost of $115 billion, and all this waste comes with a heavy price in terms of productivity and fuel. 2008 appeared to be the best year for congestion in recent times since congestion worsened in 2009. But this is no reason for celebration since prior to the economy slowing, just 5-6 years ago, congestion levels were much higher than a decade ago, and these conditions are expected to return with a strengthening economy (*2*).

Researchers have developed several innovative designs, in the past, to address these problems. One of these alternative interchange designs has been the Diverging Diamond Interchange (DDI). Chlewicki (*3*) suggested the DDI interchange design as a viable interchange type that could decrease congestion and increase capacity. The main goal of the DDI design is to better accommodate left-turn movements and hence eliminate a phase in the signal cycle. Figure 1(c) shows the layout of the diverging diamond interchange. In a DDI, through and left-turn traffic on the crossroad maneuver differently from a conventional diamond interchange as the traffic crosses to the opposite side in between the ramp terminals.

This paper analyses further the designs presented by Chlewicki (*4*). Various traffic scenarios are considered and a comparison is done with a Partial Cloverleaf (ParClo) interchange design. Additional analyses to the capacities of the designs are also performed and results reported.

The objective of this research was to provide better guidance on unconventional interchange designs by comparing the delay, stop time, number of stops and maximum queue length of the DDI and ParClo designs under a range of scenarios including balanced and un-balanced traffic flows.

In the first section, sample of a literature is presented and detailed designs of the inter-changes are presented. The second section presents the analysis methodology including the simulation tools used, signal setting criteria, performance measures and the scenarios modeled. The following sections discuss the results, conclusions and recommendations.

DESCRIPTION OF DESIGNS

Background

Bared (*5*) presented the results of a study on two new alternative designs, one of them being the Diverging Diamond Interchange (DDI). This design was studied for different traffic scenarios using traffic simulation and the results showed better performance of the measure of effectiveness when compared to similar corresponding conventional designs. Sharma *(6)* presented a paper of the results of a study comparing the DDI to the Conventional Diamond Interchange (CDI). Both alternatives were studied for a range of volume scenarios using traffic micro-simulation and a cost-effectiveness analysis was also conducted. The results suggested that for all traffic scenarios, the performance of the DDI was found to be better than the CDI with lower delays for critical movements, lower travel time and lower maximum queue lengths. Speth (*7)* discussed the operational benefits of the DDI in comparison to a diamond and a single point urban interchange. The traffic engineering computer program Synchro was used to develop an optimum timing plan for each scenario. The traffic signals were coded as pre-timed to reduce the variability in results that can occur when simulating semi or fully actuated signal control. Abbas (*8)* offered a traffic comparison between the single point interchange (SPI) and the Diverging Diamond Interchange (DDI) grade separated interchanges. The comparison was conducted using the VISSIM simulation platform and the MOEs considered were throughput, delay and number of stops.

Siromaskul (*9)* defines a DDI as a standard diamond interchange with the key difference being a shift in the crossroad traffic in the interchange. This research covers the basics of a DDI design starting at the beginning of the planning process and running through design. From the operational comparison, it was determined that the DDI's effectiveness at managing traffic increases as the turning volume increases. Chlewicki (*4)* introduced a paper with theories on how the DDI works by examining the signal progressions both within the interchange and outside of the interchange. Chlewicki examined the unique traffic pattern within the interchange to make the interchange more effective, and the subsequent signals to increase the overall efficiency of the traffic progression for the entire corridor. This research determined that several factors play into synchronizing any two signals in the DDI, which are the space between signals, the speed of the vehicles, the cycle lengths, and the phase distribution. Chlewicki states that determining the correct cycle length can significantly increase the amount of bandwidth in both direction of the progression and that taking the signal timing into consideration during design can make an effective design even better.

Partial Cloverleaf Interchange

A Partial Cloverleaf (ParClo) interchange is a modification of a cloverleaf interchange. A major characteristic of a ParClo Interchange is the ability to accommodate heavy left-turn traffic by means of a loop thereby improving capacity, operations and safety. A major disadvantage of a ParClo is that it suffers from many of the same disadvantages as the full cloverleaf's do with regards to loop ramps and weaving areas. According to a survey conducted by Graber and Fontaine, in which 36 state DOTs out of 50 took part, ParClo interchanges, which consist of 16% of all types of interchanges in the US, are accepted as one of the most popular freeway-to-arterial interchange in North America behind Diamond Interchanges (*10)*.

The Partial Cloverleaf (ParClo) designs that are compared with the DDI have the following design. The ParClo A4 consists of four on-ramps and two off-ramps. The on-ramp left turn movements to access the freeway are conducted via an exclusive loop ramp. This merging lane adds an extra lane to the bridge structure, which is an advantage compare to the DDI. The ParClo B4 consists of two on-ramps and four off-ramps. The merging lane and the left turn exclusive lane on the bridge structure also add an extra lane to the bridge structure. This extra lane will give advantage to this type of interchange compared to the DDI with a total of 4 through lanes since it will increase capacity. The traffic movements can be better understood by viewing Figure 1. To make a fair comparison, all the models had a total length on the arterial of 1,400 feet. Also the distance used between the signals for these models was the minimum allowed for the design. For the ParClo designs, the distance is usually between 600 and 900 ft. Therefore, the minimum distance of 600 feet was used in this research.

Diverging Diamond Interchange

Figure 1(c) shows the layout of a DDI.

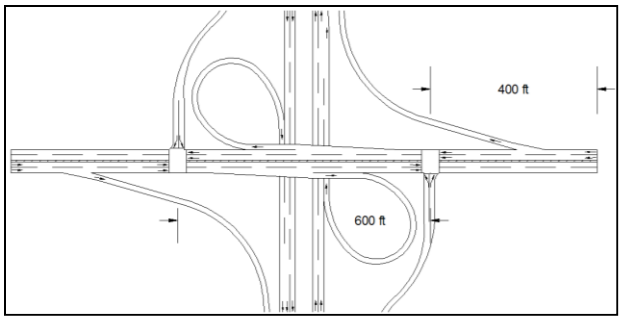


FIGURE 1(a) ParClo A4

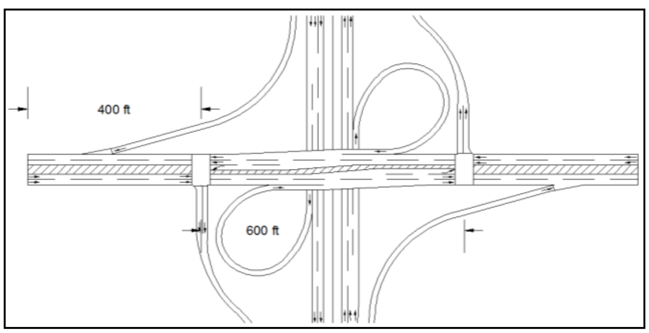


FIGURE 1(b) ParClo B4

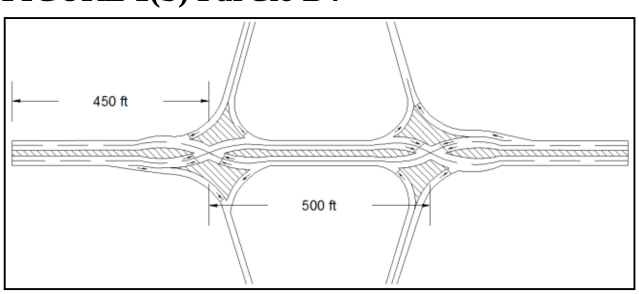


FIGURE 1(c) Diverging Diamond Interchange (DDI)

FIGURE 1 Different Types of Interchanges (a) ParClo A4, (b) ParClo B4 and (c) DDI

The crossroad in this model has two lanes in each direction. The left turn movement shares the second lane with the through movement before the first ramp terminal and then takes the exit ramp before the second ramp terminal. This eliminates the need for an exclusive left turn bay and a left turn signal phase, permitting the use of a two phase traffic signal. There are two on-ramps and two off-ramps that connect the crossroad and the freeway. The distance between the two terminals (i.e. between the crossings) is 500 ft. This distance was chosen from a previous paper where the DDI was compared to other interchanges *(5)*. The model was designed with a total length of 1,400 ft. In a DDI, ramp phases can be combined with crossroad through movements, and mainline left turn movement phases can be combined with through movements, which is an ability the DDI holds that cannot be done with other interchange designs without a major penalty to other phases.

ANALYSIS METHODOLOGY

The type of interchange configuration used at a specific location is based on a variety of factors such a highway classification, traffic volume and distribution, design speed, availability of right of way, degree of access control (*11)*. As mentioned before, in this study, the interchanges been compared are the DDI and the ParClos. The reason being that both of these designs have shown excellent results when high left turn volumes are present. In the previous section, the geometry of the DDI and ParClo were described. In this section, the traffic volume conditions present and the signal plan configuration will be explored in detail.

One tool that has effectively been used to compare and analyze interchanges has been Micro-simulation. Simulation software used for the analysis is AIMSUN NG 6.1. Also the animation output is very powerful because it enables the analyst to quickly see and qualitatively assess the overall performance of each interchange alternative.

In this study, all the scenarios were simulated in Synchro to determine the optimum cycle length pertaining to each traffic distribution. It's been noted in other studies that Synchro is not an ideal program to optimize a DDI. Synchro was used in this study to be consistent, but it is possible that with better optimization tools for the DDI, the DDI may perform even better than this study indicates.

Analysis of DDI

The computer aided drafting (CAD) designs in Figure 1 are transferred to AIMSUN simulation platform as background. Desired speeds, vehicle classes, and priority rules are defined and signal heads were placed on the links. The designs were analyzed for five different scenarios: various high volumes, medium volume, and low volume. Three high volume scenarios were tested to see how the interchanges behaved when approaching capacity. Two designs of DDI are analyzed: four-lane DDI, in which the total number of lanes in the east-west direction is four, and six-lane DDI, in which the total number of lanes is six in east-west direction. The main reason to have a 4-lane DDI and a 6-lane DDI in this study is that if the DDI with 4 thru lanes turns out to perform worse than the ParClo interchanges with the same amount of thru lanes, then one could make the assumption that constructing a DDI with one extra lane per direction compared to the ParClos with 4 lanes would not be more costly. This is because of the acceleration/deceleration lanes in the bridge structure in the ParClo designs operate as extra lanes.

The traffic volumes were expressed in number of vehicles per hour, where traffic was composed of only two vehicle types, cars and trucks, and corresponding percentage of 98% and 2% are assigned to them respectively. For this study, five different ranges of volume scenarios were considered.

Table 1 shows how each of the traffic volumes ranges is broken down for the different movements. The volume ranges used were taken from a previous study by Bared. in 2005 with reference to the DDI *(5)*.

TABLE 1 Traffic Movements

Traffic Scenario	Eastbound (veh/hr)			Westbound (veh/hr)			Southbound off-ramp (veh/hr)		Northbound off-ramp (veh/hr)		Total Flow (veh/hr)
	L	T	R	L	T	R	L	R	L	R	
High 3	450	850	550	450	850	550	750	450	750	450	6100
High 2	400	800	500	400	800	500	700	400	700	400	5600
High 1	350	750	450	350	750	450	650	350	650	350	5100
Medium	200	500	300	200	500	300	400	200	400	200	3200
Low	100	300	150	100	300	150	200	100	200	100	1700

The mentioned volumes provide some insight into the relative operations of the different types of interchanges, but Garber *(11)* in an earlier study recommended that the spectrum of volume scenarios should be extended from balanced to unbalanced conditions. Therefore, the volume scenarios were further divided into 10 different scenarios to test the impact of different varieties of traffic volumes and distributions and to gain a better picture on the operational performance of the interchange. Table 2 is an illustration of the 10 scenarios that each of the volumes mentioned before will be subjected to. Therefore, a total of 50 different scenarios will be tested to better understand and to better analyze the interchanges been compared.

The signal phasing scheme for the DDI is shown in Figure 2a. Whether or not all movements within the DDI are signal controlled, each signal should be timed as a two-phase signal. This two-phase operation permits for shorter cycle lengths and decreased lost time per phase. Figure 2b is an illustration of one of the signal timing plans for one of the scenarios for the DDI. The first phase of the interchange is controlled by phases Ø1, Ø3 and Ø6 and the second phase is controlled by phases Ø2, Ø5 and Ø4. This phase order was determined by Synchro to be the optimum order. The signal timing plan figure shows the optimum signal phasing scheme as well as the duration for each phase (Figure 2(b)).

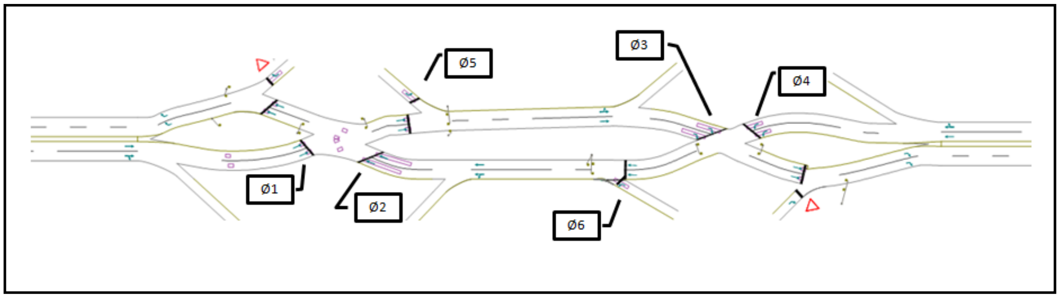
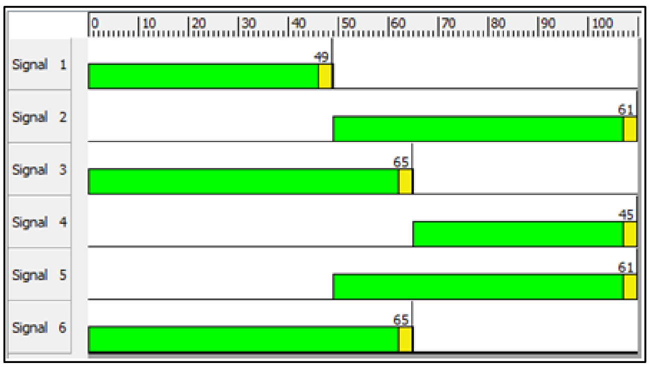


FIGURE 2(a) Movements and Phase Numbering Scheme for the DDI



Start Time	Duration
0	46
49	58
0	62
65	42
49	58
0	62

Figure 2b) Optimal Signal Timing Plan for DDI 4 High 3.1 Volume ScenariosFigure 2: Movements, Phase Numbering Scheme and Optimal Signal Timing Plan for DDI

Analysis of Partial Cloverleaf

For this study, ParClo interchanges with closely spaced intersections were studied. In a ParClo A4 interchange, the signals are controlled by a 2 phase operation. The signal phases for the ParClo A4 are illustrated in Figure 3a. Figure 3b illustrates one of the optimal signal timing plans obtained from Synchro for the ParClo A4 Interchange. The first phase of the interchange is controlled by phases Ø1, Ø2, Ø4 and Ø5 and the second phase is controlled by phases Ø3 and Ø6. This phase order was determine by Synchro to be the optimum order. Figure 3b illustrates the signal phase scheme for the High 3.1 traffic scenario for the ParClo A4 along with the duration of each phase.

The ParClo B4 is also controlled by a 2 phase operation, but the signal setting is much different. An illustration of the signal settings can be observed in Figure 3. Figure 3d illustrates one of the optimal signal timing plans obtained from Synchro for the ParClo B4 Interchange. The first phase of the interchange is controlled by phases Ø2, Ø3, Ø4 and Ø6 and the second phase is controlled by phases Ø1, Ø3, Ø5 and Ø6. This phase order was determine by Synchro to be the optimum order. For this type of interchange, phases Ø3 and Ø6 will have green for the entire cycle length since there are no conflicts with other movement. This characteristic makes it very hard to have pedestrian crossings.

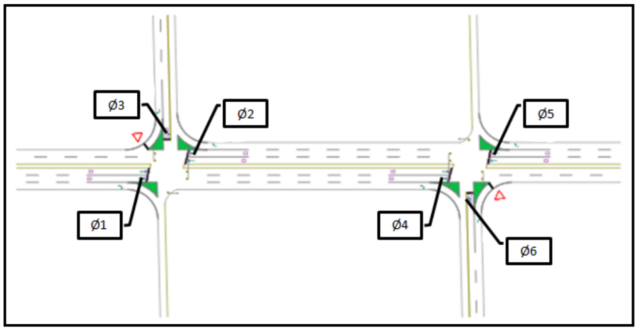


FIGURE 3(a) Movements and Phase Numbering Scheme for the ParClo A4

Start Time	Duration
0	49
0	49
52	45
0	49
0	49
52	45

FIGURE 3(b) ParClo A4 Optimal Signal Timing Plan for High 3.1 Volume Scenario

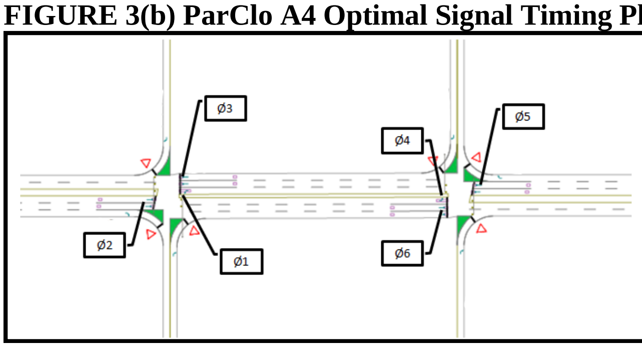
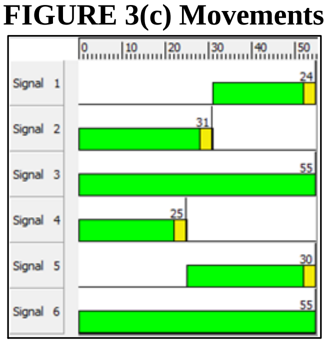


FIGURE 3(c) Movements and Phase Numbering Scheme for the ParClo B4



Start Time	Duration
31	21
0	28
0	55
0	22
25	27
0	55

FIGURE 3(d) ParClo B4 Optimal Signal Timing Plan for High 3.1 Volume Scenario

FIGURE 3 Movements, Phase Numbering Scheme and Optimal Signal Timing Plan for ParClo A4 and ParClo B4

In terms of the cycle length, compared to the ParClo B4, the ParClo A4 required a much longer cycle length to provide optimal results. The main reason for this is that in a ParClo B4, one through movement at each intersection does not have to stop. The optimum cycle lengths for low and medium volumes were very similar for both of these interchanges, but for the high volume scenarios, the optimum cycle length changed significantly.

As mentioned before, the key simulation MOEs that were considered in the analysis included delay time, number of stops, stop time and maximum queue length. The same input traffic volumes were applied to all designs. In this way, the performance measures from the designs that have been studied in this research are comparable. On the subsequent figures and tables, a comparison is done for all three types of interchanges (four if we consider the DDI with 4 thru lane and the DDI with 6 through lanes) which are shown in a graphical and tabular format. Results are divided into the five different traffic flows (high 3, high 2, high 1, medium and low) and different graphs and tables are created to represent the different MOEs.

RESULTS AND COMPARISON

Balanced Conditions

The performance of the interchanges for lower and medium volumes is very similar for all designs, but as seen in Table 3, results still indicate that the ParClo B4 outperforms the other interchanges. In this research, an all-balanced condition occurred in Scenario 1, where all the movements have the same amount of vehicles per hour. Both ParClo type interchanges showed much better results for scenario 1 conditions compared to the DDI with 4 lanes in terms of delay time and stop time.

Having a lower Delay time and Number of stops for the ParClo B4 was expected since one through movement at each intersection does not have to stop. As was mentioned before, the reason the DDI-6 was studied was that if the DDI-4 underperformed compared to the ParClo's, then one could make the assumption that constructing a DDI with one extra lane per direction would not be more costly than constructing the ParClo designs. This is because the ParClo's have acceleration/deceleration lanes in the bridge structure. But for balanced conditions, it was clear that the 4-lane DDI could compete with the ParClo A4 and the 6-lane DDI could compete with the ParClo B4.

Compared to the ParClo B4, the DDI-4 and ParClo A4 had at least double the delay for all the High flows. But comparing the DDI-6 with the ParClo B4, it can be observed that as the flows increased, the difference between their delay times decreased, to the point that by High-3 flow scenario, the delay times almost came to be equal. The ParClo B4 went from a Delay time of 8.45 sec/veh to a delay of 13.9 sec/veh (an increase of 64.5%), where the DDI-6 only changed from a delay of 12.9 sec/veh to a delay of 14.1 sec/veh (an increase of 9.3%).

It can be noted that the stop time for the vehicles in the DDI-6 interchange was not affected as much when the traffic flow was increased, since from High-1 to High-3 flows the stop time only increased by 6%, compared to an increase of 95% for the ParClo B4.

The lowest queues for all traffic flow scenarios corresponded to the DDI-6, which was expected, since having an extra lane per direction would help in decreasing the queue. If we take into consideration maximum queue for balanced conditions ranging from low traffic flow to high traffic flow, then the ParClo B4 experienced the highest change. It went from having a queue of five vehicles at low flows to having a maximum queue of 40 vehicles, which is an increase of 700% compared to an increase of 158% for the DDI-4, 116% for the DDI-6 and 575% for the ParClo A4 design. The reason why the ParClo B4 experienced the highest queue value was that, at high traffic volumes, the cars coming off the ramps had a hard time accessing the crossroad. The through movements in the ParClo B4 have green throughout the whole cycle length, which means that they never stop, consequently they do not allow enough space for the cars coming off the ramps to merge onto the crossroad.

TABLE 2 Results for All Balanced Conditions

Traffic Flow Scenario	*Delay Time (sec/veh)*				*Stop Time (sec/veh)*				*No. of Stops*				*Max. Queue (veh)*			
	DDI-4	DDI-6	ParClo A4	ParClo B4	DDI-4	DDI-6	ParClo A4	ParClo B4	DDI-4	DDI-6	ParClo A4	ParClo B4	DDI-4	DDI-6	ParClo A4	ParClo B4
High 3	32.6	14.1	30.1	13.9	25.5	8.81	20.9	9.5	0.837	0.595	0.939	0.496	15.5	13	27	40
High 2	21.9	13.4	20.06	10.1	15.9	8.52	12.9	6.24	0.696	0.554	0.606	0.399	12	12	23	27
High 1	18.9	12.9	16.6	8.45	13.4	8.27	10.3	4.87	0.635	0.532	0.518	0.365	11.5	10	18	15
Medium	11.4	11.3	8.75	6.09	7.18	7.18	4.12	3.29	0.515	0.501	0.358	0.285	7.5	7	8.5	6
Low	10.2	9.89	7.43	4.96	6.63	6.48	3.47	2.73	0.475	0.465	0.317	0.24	6	6	4	5

Unbalanced Conditions

Table 3 shows the results for the unbalanced flow conditions. The performance of the interchanges for low and medium volumes is very similar for all designs, but results still indicate that the ParClos perform better than the DDIs for these types of conditions. Overall, the ParClo B4 still had the lowest delay time, stop time, number of stops and maximum queue for low and medium volumes.

A considerable observation was that the DDI-4 performed better than the ParClo A4 at high volumes for the unbalanced conditions, which was not the case in the balanced scenarios. At High-3 traffic flows, the DDI-4 had a delay of 33.7 sec/veh compared to 43.2 sec/veh for the ParClo A4. The impact on the delay done from changing from balanced conditions to unbalanced traffic conditions at High-3 volume was much more substantial for the ParClos than it was for the DDIs. The DDI-4 and DDI-6 had a percent increase of 3.37% and 12.8% respectively, compared to the percent increase of 43.5% for the ParClo and 30.9% for the ParClo B4.

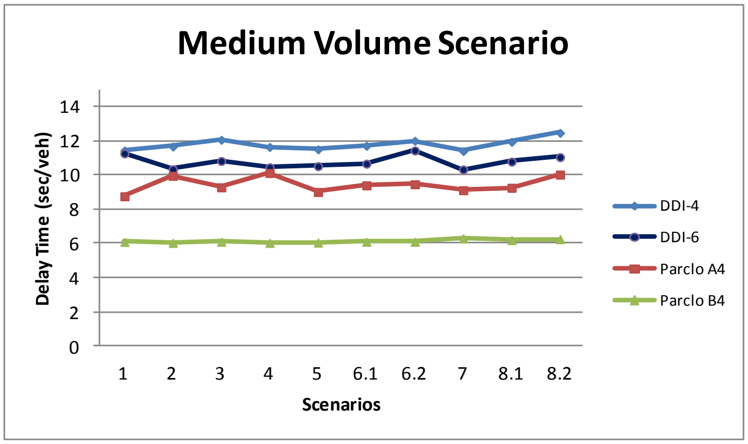
With respect to stop time at very high volumes, the DDI-6 had the lowest value followed by the ParClo B4 for the unbalanced conditions, which was the same case when balanced conditions were present. But for the DDI-4 and ParClo A4, the ParClo A4 had a lower stop time at balanced conditions compared to the DDI-4, but for the unbalanced conditions, the DDI-4 was observed to have a smaller stop time value.

Regarding number of stops, the DDI-6 had the lowest value, which was followed by the ParClo B4, DDI-4 and ParClo A4. For number of stops, one main observation was that the ParClo A4 had almost double the stops during the unbalanced conditions compared to the balanced condition, whereas the DDI's number of stops where almost constant. In terms of queue, the DDI-6 had the lowest values for High traffic volumes. But if we again compare the interchanges with 4 through lanes, then again the DDI-4 outperformed both ParClos.

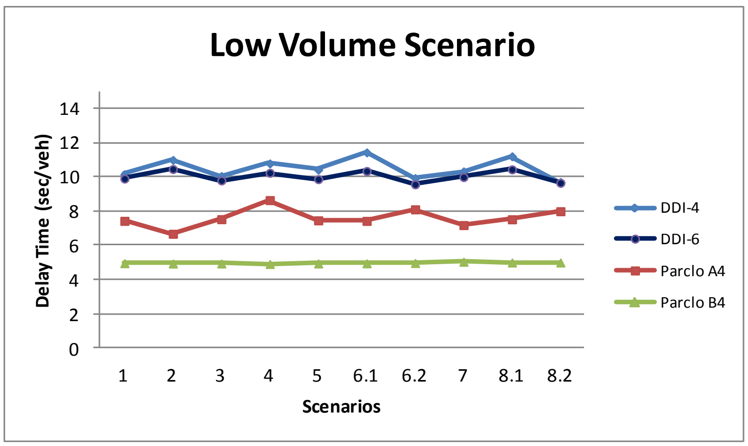
TABLE 3 Results for All Unbalanced Conditions

Traffic Flow Scenario	*Delay Time (sec/mile)*				*Stop Time (#/veh/mi)*				*No. of Stops*				*Max. Queue (ft)*			
	DDI-4	DDI-6	ParClo A4	ParClo B4	DDI-4	DDI-6	ParClo A4	ParClo B4	DDI-4	DDI-6	ParClo A4	ParClo B4	DDI-4	DDI-6	ParClo A4	ParClo B4
High 3	33.7	15.9	43.2	18.2	26.5	10.6	31.9	13.3	0.834	0.58	1.71	0.61	18.5	15	27	49
High 2	31.4	14.1	37.5	10.7	24.5	9.15	27.1	6.62	0.793	0.561	1.27	0.42	15	14.5	27	25
High 1	23.1	13.4	32.2	8.71	17.2	8.51	22.6	5.13	0.679	0.556	1.072	0.35	15	14	26	19
Medium	12.5	11.1	10.1	6.25	8.07	6.96	5.17	3.41	0.533	0.486	0.36	0.29	10	7	12.5	6.66
Low	9.70	9.65	7.99	5.01	6.20	6.10	3.76	2.77	0.456	0.448	0.33	0.24	6	6	5	4.33

In addition, Figure 4 and 5 are illustrations in graphical format of the delay time for all the traffic flows for each interchange. Refer to Table 2 for more information about each scenario. It was obvious from the graphs that the ParClo A4 and DDI-4 did not perform as well as the other two interchanges. It was no surprise that the DDI-6 had better results than the DDI-4 since one extra lane per direction added more capacity, and it was also expected that in terms of Delay time, Stop time and Number of stops that the ParClo B4 outperformed the ParClo A4 since as has been mentioned earlier one through movement on the crossroad for the ParClo B4 does not stop. Therefore, the analysis was mostly divided into comparing the DDI-4 with the ParClo A4 and the DDI-6 with the ParClo B4. For Low and Medium volume scenarios, it can be noted that the lowest delay occurred for the ParClo B4 followed by the ParClo A4. When the scenarios moved from all balanced to all unbalanced scenarios (i.e. from Scenario 1 to Scenario 8.2), there were no apparent changes in the graphs.



a)



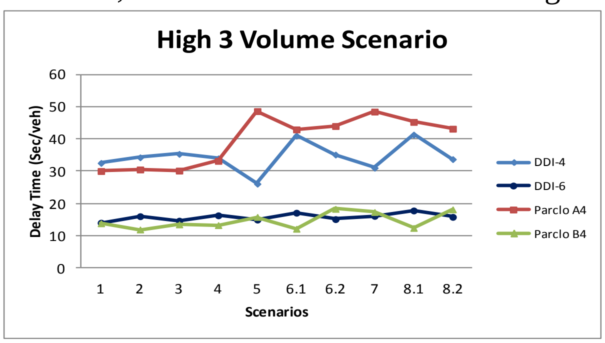
b)

FIGURE 4 (a) and (b) Results for Delay Time for Medium and Low Scenarios

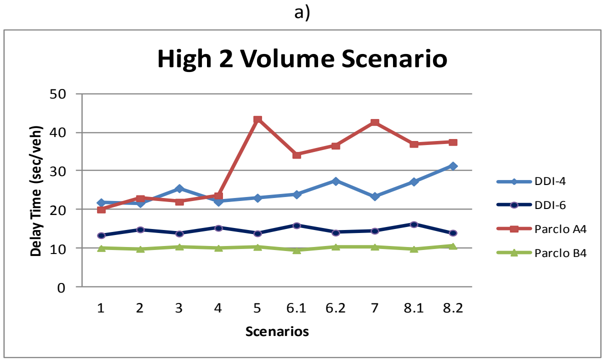
On the other hand, for High volumes the outcome is a little different. Firstly, the ParClo B4 outperforms the rest of the interchanges at all volumes, but as the volumes became larger, we see that the difference between the DDI-6 and the ParClo B4 starts getting closer, to the point that at High-3 volume scenario, the average delay for the ParClo B4 is 14.7 sec/veh for all 10 scenarios and the average delay for the DDI-6 is 15.84 sec/veh. Between the High-1 to High-3 scenarios, the average delay for the DDI-6 changed from a delay of 13.7 sec/veh to a delay of 15.8 sec/veh, a 15% increase, compared to the ParClo B4 which went from a delay of 8.62 sec/veh to a delay of 14.7 sec/veh, an increase of 70%. This tells us that for the High scenarios simulated in this study, the ParClo B4 outperformed the DDI-6, but if higher traffic flows (e.g. 6,600 veh/hr) would have been studied, it is likely that the DDI-6 would have outperformed the ParClo B4 based on the volume trends.

DDI-6 and the ParClo B4 performed comparable at High-3 scenarios, and we have stated before that the average delay for all 10 scenarios was lower for the ParClo B4. But the graph denotes that there are two instances in particular were the DDI-6 outperforms the ParClo B4, which are scenarios 6.2 and 8.2. This indicates that the DDI-6 would perform better when the heavier through movement on the crossroad opposes the lighter left turn movement from the ramp.

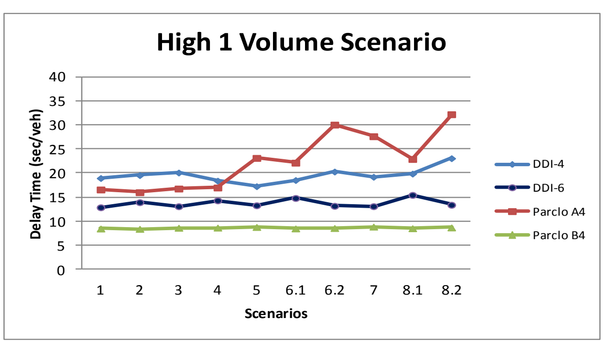
If the results are analyzed for the ParClo A4 and the DDI-4 for all High scenarios it is clearly seen that for the more balanced scenarios (Scenarios 1 through 4) the ParClo A4 had a smaller delay time compared to the DDI-4. This suggests that if balanced scenarios would occur in the field in a real scenario, then the ParClo A4 would be the more suitable choice. On the other hand, after scenario 4 the DDI-4's performance was better than the ParClo A4. So if the conditions in the field behave more unbalanced, which is the case during peak hour traffic, then the DDI-4 would be a more appropriate design to implement. The main reason for this occurrence was that a higher mean queue value was observed for the ParClo A4 than the DDI. Since the vehicles trying to make a left turn from the off-ramp had to cross the through traffic, then this increased the delay time since there were cars back up for the major part of the simulation. Also the unique geometry of the DDI allowed for a lower cycle length, therefore decreasing the overall delay time. Another observation about the DDI-4 at High-3 traffic flow was that it performed best for scenario 5, which was when all movements were balanced except the through movement on the cross road. The ParClo A4 showed best results for the first four scenarios, where all scenarios had one thing in common, through movements were balanced.



a)



b)



c)

Figure 5 (a) and (b) Results for Delay Time for High Scenarios

CONCLUSIONS

To conduct the comparison of the interchanges different steps were taken to gain insight into the relative performance of each interchange type. For the first part of this study, each interchange design was introduced and their geometrical features were described. Then different traffic flows and distributions were introduced so that a broader understanding of the operations of each interchange could be understood. From the traffic distribution, 50 different scenarios were generated for each type of interchange. Before simulating the models in a Micro-simulation software, the signals were optimized using Synchro so that the best possible results could be extracted for each different scenario. Finally, the AIMSUN Micro-simulation software tool was used to obtain results for the different magnitudes of traffic volumes and distributions tested in this study to conduct the comparison.

The performance of the interchanges for low and medium volumes was found to be very similar. For the High traffic flows, the ParClo B4 outperformed the rest of the Interchanges except in Maximum queue. In terms of delay time, stop time and number of stops for the high flow balanced conditions, the DDI with 4 through lanes was found to have the largest value followed by the ParClo A4, the DDI with 6 through lanes and the ParClo B4. For unbalanced conditions occurring at high flows, the ParClo A4 had the largest average delay time, average stop time and average number of stops followed by the DDI-4, the DDI-6 and ParClo B4. Therefore, the DDI-4 would be a more effective type of interchange when unbalanced conditions are present compared to the ParClo type A4, which is the more popular ParClo type. Unbalanced conditions are the most seen conditions in the majority of highway interchanges.

One observation was that as the flows increased, the difference between the delay times, stop time and number of stops of the DDI with 6 through lanes and the ParClo B4 decreased, to the point that at High-3 flow scenario (6,100 veh/hr), the above mentioned MOEs almost came to be equal. This suggests that for higher volumes not tested in this work, the DDI with 6 through lanes would be a more viable option. The results also showed that there were two scenarios were the DDI with 6 through lanes outperformed the ParClo B4 for High-3 volume flows, which was when the heavier through movement on the crossroad opposes the lighter left turn movement from the ramp. Therefore, if these conditions are found at a specific location, then the DDI with 6 through lanes should be considered. In terms of average maximum queue, both types of DDI interchanges outperformed the ParClo designs. For all the scenarios, queue did not spill back to the freeway segment. If queue is a major problem at a location where an interchange needs to be replaced, then the DDI would be a viable option.

To finalize, this study will aid engineers on the selection of the best traffic operations between the DDI and the ParClo. All of the types of interchanges studied in this research have their benefits and drawbacks, therefore a close look will need to be taken to understand the requirements of the location where the designs will be implemented. The next section describes the limitations and further research in more detail.

RECOMMENDATIONS FOR FUTURE RESEARCH

The limitations in the research study have indicated the following areas as recommendations for future work:

1. The design studied in this work should be expanded to accommodate higher volumes by adding double left-turn lanes.
2. Platooning occurred due to the signal timings can affect the traffic flow pattern onto the freeway at the merge points. Therefore a comparison should be

conducted to see the difference on the freeway merge operations with different interchange types.

3. The effect of pedestrians and bicycles should be examined to evaluate the operations of the interchange configurations.
4. A high traffic flow scenarios should be performed and analyzed to determine the capacity for each interchange configuration.
5. Evaluate some DDI analysis from the North Carolina Department of Transportation to evaluate this method as a study case.

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