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Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange

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Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange

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Abstract
Transportation planners and traffic engineers are facing the challenge of inventing ways to mitigate congestion during the peak hours. Alleviating delays and improving safety for passengers and pedestrians is the primary motive. One way of achieving this objective is to search for alternative intersection and interchange designs. This paper presents the results of a study on two new alternate designs – Double Crossover Intersection and Diverging Diamond Interchange. These designs are studied for different traffic scenarios using traffic simulation and the results showed better performance during peak hours when compared to similar corresponding conventional designs. Better performance includes better level of service, lesser delays, smaller queues, and higher throughput.

BACKGROUND
Transportation planners and traffic engineers are facing the challenge of mitigating congestion during the peak hours and at lower costs. Alleviating delays and improving safety for motor vehicles and pedestrians are primary motives. In urban areas the land available for constructing roads is less and hence should be used more judiciously by designing roads, intersections, and interchanges that occupy less right of way. One way of achieving all these objectives is to search for alternative intersection designs.

Researchers have developed several innovative intersection designs in the past to address these problems. These designs include the quadrant roadway intersection, median U-turn, superstreet median, jughandle, split intersection, and the continuous flow intersection (CFI). The most influential factor in the intersection performance for heavy flows is achieved by reducing the number of phases in the signal cycle. The CFI especially is finding increasing acceptance in the United States lately (1).

Chlewicki (2) suggested two new designs for intersection and interchange designs - the Synchronized Split-Phasing (SSP) Intersection and the Diverging Diamond Interchange (DDI). As in the CFI, SSP design also disperses the flow of traffic before reaching the main intersection. The synchronized split phasing design allows both the through and the left movements to cross over prior to the intersection. (see Figure 1(a))

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 (b) shows the layout of the diverging diamond interchange. The freeway portion does not change but the movements off the ramps change for left-turns. 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.

Chlewicki (2) discusses the simulation tests performed for a case study intersection and interchange using Synchro as the simulation tool. Results showed that the SSP and DDI designs outperform similar corresponding conventional designs. In his conclusion, Chlewicki (2) discusses the future scope of research including analysis of different volume ratios and turning movement ratios, and the speeds and superelevations to see how fast vehicles can travel practically in the crossover movements.

This paper analyses further the designs presented by Chlewicki (2). Four different traffic scenarios are considered and pedestrian performance is simulated for one case. A comparison is done with conventional intersection and interchange designs. Additional analyses related to the capacities of these innovative designs are also performed and results reported.

ORGANIZATION OF THE PAPER
In the first section, detailed designs of the intersection and interchange are presented. The second section presents the analysis methodology including the simulation tools used, signal setting criteria, performance measures, and the four different scenarios modeled. The following sections discuss the results, conclusions, and recommendations.
DESCRIPTION OF THE DESIGNS

Double Crossover Intersection (DXI)
In this paper, we will use DXI as a more descriptive name than synchronized split phasing. Figure 2 shows the layout of a Double Crossover Intersection. The Eastbound (EB) traffic (through and left-turners) crosses over to the left side at signalized intersection A, while the right-turners use the dedicated right lane before reaching A. The crossed traffic will crossover back to the right side at signalized intersection C. The Westbound (WB) traffic also crosses over in a similar way. At intersection B, there is one through lane and one through+left-turn lane. No dedicated left-turn lanes are provided. Right-turn lanes are required for EB and WB traffic. Merging lanes for the Northbound (NB) and Southbound (SB) for right-turn movements are required. Radii of crossover movements can range from 150 to 200 ft and that of the left-turn movement at B is 100 ft. Movements can be better understood by following the arrow markings in the figure. The NB and the SB traffic are exactly similar to the corresponding movements at a conventional intersection, with one left-turn lane, one through lane, and one through+right-turn lane. No dedicated right-turn lanes are provided for NB and SB traffic; also no merging lane for the EB and WB right-turn movements are necessary. The length of left-turn lane is 450 ft.

The conventional intersection that is compared with the DXI has the following design. There is only one signalized intersection in this case. For EB and WB traffic, there are two through lanes, one dedicated left-turn lane and one dedicated right-turn lane. However, there is no merge lane for the right-turn movements from the NB and SB traffic. For NB and SB traffic there are two through lanes, one dedicated left-turn lane, and there is no dedicated right-turn lane (right turn movements share the lane with through movements). Also there is no merging lane for the right-turn movements from EB and WB traffic. The right of way requirement is the same as the DXI design.

Diverging Diamond Interchange (DDI)
Figure 3 shows the layout of a Diverging Diamond Interchange. There are two on-ramps and two off-ramps that connect the crossroad and the freeway. The off-ramps have two left-turn lanes and one right-turn lane. One left-turn lane and one right-turn lane lead to the on-ramp. The distance between the two terminals (and crossovers) is 500 ft. The arterial has one through lane, one through+left-turn lane, and one dedicated right-turn lane. The movements can be better understood by following the arrow markings in the figure. Two signalized intersections (A and B) are situated at the two crossover locations. The radii of the curves are same as the radii for DXI.

In rural high-speed environments the nature of this directional crossing of through flows may be hazardous. A suggested forgiving design could provide curved approaches to motivate speed reduction by heightening drivers’ awareness. In addition, the directional crossings are made more perpendicular and occupy shorter crossing distances (see Figure 3(b)).

The conventional diamond interchange that is compared with the DDI has the following design (see Figure 4). On-ramps and off-ramps are exactly the same as DDI, but there is a change in the number of lanes on the arterial. It has two through lanes, one dedicated left-turn lane, and one dedicated right-turn lane. Clearly, the section between the ramps needs more right of way as compared to the DDI (two extra left-turn lanes). There are two signals at A and B, and the distance between ramps is also 500 ft. The traffic movements can be better understood by viewing the Figure 4.

ANALYSIS METHODOLOGY
Analysis of these innovative designs is done using traffic simulation. Simulation software used for the analysis is VISSIM, a microscopic time step based simulation model.

Analysis of DXI
The CAD design shown in Figure 2 is transferred to VISSIM as background and the links are drawn on top of it. Desired speeds, vehicle classes, and priority rules are defined and signal heads are placed on the links. The DXI design is tested for four different traffic scenarios – peak volume, high volume, medium, and low volume. In urban conditions, it is reasonable to assume the desired speed for through movements to lie within 36 mph to 42 mph for cars and 30 mph to 36 mph for trucks. For the turn movements it is assumed to lie within 15 mph to 18 mph for cars and 12 mph to 15 mph for trucks.
Traffic volumes in each direction are shown in Table 1. Signal phasing scheme is shown in Figure 5. Seven phases provide for all movements, three at the main intersection and two each at the two crossovers although they basically operate within three phases. North bound left-turners (phase 3) and south bound left-turners (phase 2) go and store in the link until the phase 7 and phase 5 turn green respectively. Cycle length of 79 seconds (s) and signal timing shown in Table 1, are the result of numerous trials. The amber time interval used is 3 s, and the all-red interval is 3 s at the end of every phase.

Performance criteria for the intersection design include: average delay time per vehicle, average stop time per vehicle, average number of stops per vehicle, average queue length, and maximum queue length. After analyzing these four traffic scenarios, the capacity is estimated based on two criteria – level of service and model throughput. When the input volumes are so high that they result in LOS F (and beyond) for the intersection, or the model throughput is less than the input volume (assumed 100 vph) then we conclude that the capacity is reached. (see Table 3). The simulation period is one hour and the traffic arrivals are Poisson with exponentially distributed headways.

After determining the capacity for the DXI design, the next step is to compare the results obtained with the conventional intersection. A conventional four-legged intersection is analyzed in VISSIM for the same four scenarios and the same performance measures. The optimal signal setting for each traffic scenario is obtained from a signal optimization software TRANSYT-7F.

Pedestrian movement is simulated in VISSIM, a pedestrian volume of 75 peds/hr is assumed on each approach (Eastbound, Southbound, Westbound, and Northbound) and as there are three possible directions in which each of these volumes can be assigned, the directional volumes are equal to 25 peds/hr. (e.g. pedestrian trips generated at South approach is 75 peds/hr, the volume of trips towards East, West, and North is 25 peds/hr each). The walking speed of pedestrians is assumed to be 4 ft/s. The LOS criterion for the pedestrians is average delay per pedestrian.

Analysis of DDI

Two different designs of DDI are analyzed - a) Four-lane DDI in which the total number of lanes in the east-west direction is four, and b) Six-lane DDI in which the total number of lanes is six in the east-west direction. For the first case, five different traffic flow scenarios are considered including one low, one medium, and three high flows. The performance of DDI is measured for high flows beyond the capacity of conventional diamond (see Table 4). For the second case, six traffic flow scenarios are considered (see Table 5). Finally, capacities of DDI are estimated for both designs.

The signal phasing scheme used for the DDI is shown in Figure 6. At the left-side ramp terminal in phase 1, the eastbound through movements and the southbound lefts are allowed to crossover, and in phase 2, westbound through movements are allowed to crossover. At the right-side ramp terminal in phase 3, east bound through movements are given green, and in phase 4, the westbound through movements, and northbound rights are given green. Phases 5 and 6 are for left-turn movements from the ramp onto the arterial. These left-turners go and store in the link until phase 2 and phase 3 are given green respectively. In this way we can make efficient use of the intersection design. Phase 5 and phase 2 overlap, as there is no conflict between these two movements. In the same way phase 6 overlaps with phase 3. The signal timing shown in Figure 6 is obtained as a result of several trials. For the given phasing sequence, the cycle length of 70 s is optimal for lower to medium flows, and a cycle length of 100 s gives best results for higher flows. The amber time used is 3 s, and the all-red period is 2 s at the end of every phase. Overall, the signal operates under two phases.

Capacity of the DDI design is estimated based on the same two criteria mentioned for DXI. The results obtained for DDI are compared with the results of conventional diamond interchange. The signal design and optimal signal setting for the conventional diamond interchange is obtained from PASSER-3 software.

RESULTS

The results of traffic simulation are shown in Tables 1, 2, 3, 4, 5, 6, and 7. Table 1 shows the comparison of traffic performance of DXI with that of Conventional intersection. At lower and medium volumes, the performance is almost identical for both designs. However, for higher volumes the performance of DXI is noticeably better than the conventional one. For the conventional design, the model throughput is about 1000 veh/hr lower than the input flow, while for the DXI the input flow and the model throughput are almost similar (difference of about 100 veh/hr). The most important observation is that of the average delay per vehicle. For peak volumes, the delay for conventional design is 220 s/veh, while it is 86 s/veh for the DXI. It is also noted that the number of stops, average stop time per
vehicle, average queue, and maximum queue length are lower for the DXI when compared with the conventional design.

The traffic performance in the presence of pedestrians is studied for DXI and the results are shown in Table 2. We can see that in spite of the inclusion of pedestrian phase into the signal setting, the performance of DXI is still better than the conventional intersection at high volumes. In Table 2, the performance of pedestrians is shown for two different types of crossings, one adjacent crossing and diagonal crossing. Adjacent crossing is crossing a single approach, whereas the diagonal crossing would be crossing two approaches at the intersection (e.g. NE-SW). Apart from the standard performance measures like average delay per person, average stop time per person, etc, we also consider ‘average delay per person per stop’ which is the ratio of average delay per person and the average number of stops for that crossing. This measure gives an indication if the pedestrians are getting frustrated waiting for the signal and possibly disobeying the signals.

Capacities are estimated for both designs, for all signalized movements and results are summarized in Table 3. Right-turn movements are not included as there are no right-turn signals and all of them are free right-turns. From the results, the main contrasting difference between the capacities of these designs is for left-turns (S-W, and N-E). Capacity of the left-turns in a DXI design is more than twice that of the conventional design. This finding suggests that DXI is very suitable at places where there are heavy left-turn movements.

The results for a four-lane DDI are shown in Table 4. Performances for lower and medium volumes are identical in both designs (DDI and the conventional diamond). However, results from higher volumes show that this conventional diamond has lower model throughput, higher average delay per vehicle, higher stop time, and longer queues as compared to the DDI.

The maximum off-ramp flows for a DDI (700 vphpl) are greater than the corresponding flows in the conventional diamond (390 vphpl). When off-ramp flows are set to 390 vphpl, for a DDI, the capacity of the cross-road increased by 100 vphpl.

The results of six-lane DDI design are shown in Table 5. Apart from the three traffic scenarios discussed earlier, three very high volume scenarios are analyzed. Capacities of each of the three designs are shown in Table 6. Capacities of the northbound left-turns, southbound left-turns, eastbound through, eastbound left, westbound through, and westbound left are shown. The DDI design does not have any exclusive left-turn lane unlike the conventional diamond design, and the left-turners share the lane with the through movements. Once again, the big difference between the results of DDI and the conventional diamond relates to the capacity of left-turn movements; capacity of the DDI being twice that of the conventional diamond. Capacity of eastbound and westbound left-turns and off-ramp left-turns for the DDI is almost twice that of the conventional diamond.

In our research we assumed ramp terminals offset of about 500 ft, however, the DDI design also works for shorter offsets. When the offset was reduced from 500 ft to 300 ft, for the same signal setting (cycle length of 100 s), the capacity of northbound and southbound left turns (off ramps) decreased by 200 vphpl for the 6-lane design case. Capacity of all other movements remained unchanged. When choosing a shorter cycle length of 80 s, capacity of the off-ramp left turns decreased by only 100 vphpl but the capacity of through traffic decreased by 75 vphpl approximately. In any case, the performance is still better than the corresponding conventional diamond design.

CONCLUSIONS

In this paper, two novel intersection/interchange designs were analyzed and compared with conventional designs. The following conclusions can be made from the analysis and results:

DXI

- For higher traffic volumes, the DXI has better performance and offers lower delays (less than 60%), lesser number of stops, lower stop time and shorter queue lengths as compared to the performance of the conventional design. For lower volumes, the performance of DXI and conventional intersection are similar.
- Capacity of the through movements is the same for both designs. However, the capacity of left-turn movements (Northbound and Southbound) for the DXI is twice that of the conventional design. This suggests that the DXI may be suitable to situations where there are heavy left-turn movements in two opposing directions.
- Pedestrian performance is measured in terms of average delay per person per stop. The DXI offers a LOS C in terms of this measure. However, the number of stops for crossing is likely higher than corresponding number of stops at a conventional intersection.
- This design has two additional signals where through vehicle crisscross making the intersection more complex and with questionable safety.
DDI

- For higher traffic volumes, the DDI has better performance and offers lower delays, lesser number of stops, lower stop time and shorter queue lengths as compared to the performance of the conventional design. For lower volumes, the performance of DDI and conventional intersection are similar.
- Capacity for all signalized movements is higher for the DDI as compared to the conventional diamond. Especially, capacity of the left-turn movements is twice that of the corresponding left-turn capacity of the conventional diamond. The DDI design is very superior to the conventional diamond because exclusive left-turn lanes are not necessary.
- Conventional diamond design that is comparable to the 4-lane DDI consists of 6-lanes on the bridge section (2 through and 1 left-turn in each direction, E-W and W-E). When higher capacity is needed, it would be a good application to convert to a 6-lane DDI instead of pursuing the costly option of widening bridges and approaches with dual left lanes in each direction.
- While the DDI does not allow through movements from off- to on-ramps, it allows u-turn movements with fewer conflicts than at a conventional diamond interchange.

RECOMMENDATION FOR FUTURE RESEARCH

The safety aspects of the suggested designs need to be studied in more detail. A Surrogate safety assessment model is currently under development at FHWA, and after its completion, we expect to use it to compare the safety aspects of DDI, DXI, and conventional diamond. The proposed safety model aims at extracting the safety features from traffic simulation models (VISSIM, AIMSUN, and TEXAS Model) by analyzing the trajectory of vehicles and estimating their proximity. Another recommendation would be to compare the proposed DDI performance with the performance of a single point diamond interchange. Finally, pedestrian movements on a DDI also need to be studied.

REFERENCES


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Figure 3 (a) Typical layout of a Diverging Diamond Interchange layout, (b) Proposed geometric improvements at the right side ramp terminal.
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Figure 6 Signal setting for DDI (Fixed time signal controller type).
### TABLE 1 Double Crossover Intersection (DXI) vs. Conventional Intersection – Traffic Scenarios and Performance Results (without pedestrians)

<table>
<thead>
<tr>
<th>Traffic Scenario (veh/hr)</th>
<th>Northbound (veh/hr)</th>
<th>Southbound (veh/hr)</th>
<th>Eastbound (veh/hr)</th>
<th>Westbound (veh/hr)</th>
<th>Total Flow (veh/hr)</th>
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<td>T</td>
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<th>Traffic Scenario (veh/hr)</th>
<th>Input Flow (veh/hr)</th>
<th>Model Throughput (veh/hr)</th>
<th>Delay Time (s/veh)</th>
<th>Stop Time (s/veh)</th>
<th>No. of Stops</th>
<th>Ave Queue (ft)</th>
<th>Max Queue (ft)</th>
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<td>DXI</td>
<td>Conv</td>
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Conv = Conventional  
L = Left, T = Through, R = Right
### TABLE 2 Double Crossover Intersection (DXI) – Traffic Scenarios and Performance Results (with pedestrians)

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<th>Traffic Scenario</th>
<th>Flows (veh/hr)</th>
<th>Input</th>
<th>Actual</th>
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<th>No. of Stops</th>
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<th>Average Delay per stop (s/person)</th>
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<td>Diagonal Crossing (e.g. S-W)</td>
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<td>Adjacent Crossing (e.g. S-N)</td>
<td>63</td>
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TABLE 3 Capacity of Conventional and DXI designs

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<td>575</td>
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### TABLE 4 Diverging Diamond Interchange (4-lane) vs. Conventional Diamond Interchange – Traffic Scenarios and Performance Results

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<th>Traffic Scenario</th>
<th>Northbound (veh/hr) off-ramp</th>
<th>Southbound (veh/hr) off-ramp</th>
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<th>Westbound (veh/hr)</th>
<th>Total Flow (veh/hr)</th>
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<td>3200</td>
<td>3074</td>
<td>3104</td>
<td>20</td>
<td>26</td>
<td>12</td>
</tr>
<tr>
<td>Low</td>
<td>1700</td>
<td>1631</td>
<td>1631</td>
<td>17</td>
<td>20</td>
<td>11</td>
</tr>
</tbody>
</table>

Conv = Conventional  L = Left, T = Through, R = Right
### TABLE 5 Diverging Diamond Interchange (6-lane) - Traffic Scenarios and Performance Results

<table>
<thead>
<tr>
<th>Traffic Scenario</th>
<th>Northbound (veh/hr) off-ramp</th>
<th>Southbound (veh/hr) off-ramp</th>
<th>Eastbound (veh/hr)</th>
<th>Westbound (veh/hr)</th>
<th>Total Flow (veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>T</td>
<td>R</td>
<td>L</td>
<td>T</td>
</tr>
<tr>
<td>V.High-3</td>
<td>1000</td>
<td>0</td>
<td>700</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>V.High-2</td>
<td>800</td>
<td>0</td>
<td>500</td>
<td>800</td>
<td>0</td>
</tr>
<tr>
<td>V.High-1</td>
<td>700</td>
<td>0</td>
<td>400</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>High</td>
<td>650</td>
<td>0</td>
<td>350</td>
<td>650</td>
<td>0</td>
</tr>
<tr>
<td>Medium</td>
<td>400</td>
<td>0</td>
<td>200</td>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>Low</td>
<td>200</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traffic Scenario</th>
<th>Input Flow (veh/hr)</th>
<th>Model Throughput (veh/hr)</th>
<th>Delay Time (s/veh)</th>
<th>Stop Time (s/veh)</th>
<th>No. of Stops (per veh)</th>
<th>Max Queue (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.High-3</td>
<td>8600</td>
<td>8200</td>
<td>58</td>
<td>28</td>
<td>1.1</td>
<td>785</td>
</tr>
<tr>
<td>V.High-2</td>
<td>6600</td>
<td>6500</td>
<td>32</td>
<td>19</td>
<td>0.8</td>
<td>450</td>
</tr>
<tr>
<td>V.High-1</td>
<td>5600</td>
<td>5500</td>
<td>28</td>
<td>18</td>
<td>0.7</td>
<td>421</td>
</tr>
<tr>
<td>High</td>
<td>5100</td>
<td>5040</td>
<td>27</td>
<td>18</td>
<td>0.7</td>
<td>305</td>
</tr>
<tr>
<td>Medium</td>
<td>3200</td>
<td>3170</td>
<td>18</td>
<td>11</td>
<td>0.6</td>
<td>186</td>
</tr>
<tr>
<td>Low</td>
<td>1700</td>
<td>1690</td>
<td>16</td>
<td>11</td>
<td>0.6</td>
<td>121</td>
</tr>
</tbody>
</table>

L = Left, T = Through, R = Right
TABLE 6 Capacity of Conventional and DDI designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Northbound (veh/hr/ln) off-ramp</th>
<th>Southbound (veh/hr/ln) off-ramp</th>
<th>Eastbound (veh/hr/ln)</th>
<th>Westbound (veh/hr/ln)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>L</td>
<td>L T</td>
<td>L T</td>
</tr>
<tr>
<td>Diverging Diamond (4-Lanes)</td>
<td>600 L</td>
<td>600 L</td>
<td>600(L/T) 600</td>
<td>600(L/T) 600</td>
</tr>
<tr>
<td>Diverging Diamond (6-Lanes)</td>
<td>700 L</td>
<td>700 L</td>
<td>600(L/T) 600</td>
<td>600(L/T) 600</td>
</tr>
<tr>
<td>Conventional Diamond</td>
<td>390 L</td>
<td>390 L</td>
<td>330 600</td>
<td>330 600</td>
</tr>
</tbody>
</table>

L = Left, T = Through, R = Right, L/T = Left and Through
FIGURE 1 (a) Synchronized Split-Phasing Intersection, and (b) Diverging Diamond Interchange (after Chlewicki (2)).
FIGURE 2 Double Crossover Intersection (DXI) layout.
FIGURE 3 (a) Typical layout of a Diverging Diamond Interchange layout; (b) Proposed geometric improvements at the right side ramp terminal.
FIGURE 4 Conventional Diamond Interchange layout.
FIGURE 5 Signal setting for DXI (Fixed time signal controller type).

G - Green Interval, A+AR - Amber and All-Red Interval, R - Red Interval
FIGURE 6 Signal setting for DDI (Fixed time signal controller type).

| φ1 | G | A+AR | R | A+AR |
| φ2 | R | G | A+AR | G |
| φ3 | G | A+AR | G | A+AR |
| φ4 | R | G | A+AR | R |
| φ5 | O | A+AR | O | A+AR |

<table>
<thead>
<tr>
<th>Signal Timing (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

G - Green Interval, A+AR - Amber and All-Red Interval, R - Red Interval