Impact of U-Turns as Alternatives to Direct Left-Turns on the Operation of Signalized Intersections

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Abstract—Many transportation agencies have started using unconventional intersections to reduce overall delay and improve signal efficiency. Common unconventional left-turn control types such as right-turn followed by U-turn (RTUT) and U-turn followed by right-turn (UTRT); basically eliminate direct left-turn movements at the intersection by rerouting left-turning vehicles away from the main junction. This study evaluates the impact of replacing direct left-turns with RTUT or UTRT. Traffic signal evaluation and simulation tools, such as Synchro and Vissim, were utilized to calculate the optimized signal timings and evaluate intersection performance for each left-turn control type. The results indicate that unconventional left-turn control types have less delay compared to the direct left-turn. Also, The U-turn followed by right-turn (UTRT) control type has the lowest travel time among all left-turn control types. Finally, unconventional left-turn control types have higher vehicle kilometers travelled (VKT) compared to the direct left-turn control type.

Index Terms—traffic signal, direct left-turns, indirect left-turns, microscopic simulation

I. INTRODUCTION

Traffic congestion at signalized intersections poses a challenge for all large and growing urban cities. Nowadays, drivers are experiencing more delay at intersections because of the rapid increase in number of vehicles. Changing the geometry of intersections by adding more lanes is not a feasible solution, in many cases, due to the limited right-of-way at most of the signalized intersections. Therefore, transportation agencies worldwide are considering different alternatives to improve the vehicle-processing capacity and the level of service at signalized intersections without major changes to the existing intersection geometry.

In response to high left-turn volumes at signalized intersections, a longer green time is allocated to the phases serving these movements. Such action may cause negative effects on other movements (such as shorter green time and higher delays). There are some approaches to eliminate direct left-turns at signalized intersections, as depicted in Fig. 1. The signalized intersection will be controlled by two-phase traffic signal, after eliminating all the direct left-turns [1], [2].

II. LITERATURE REVIEW

There are many advantages associated with the elimination of direct left-turns at signalized intersections. For instance, it may improve the capacity of the main junction and reduce the number of stops for through traffic. In addition, applying signal progression to a two-phase signal control is more flexible as the cycle length is usually shorter in such cases. Using U-turns as alternatives to direct left-turns reduces the number of conflict points, thereby improving the safety performance of the intersection. Furthermore, intersections without direct left-turn may reduce the total travel time of the intersection, under moderate and high traffic volume conditions, which will result in less consumption of fuel, therefore, less pollution [1].

Figure 1. Concept of five alternatives of indirect left-turn measures [2]
driveways. Zhou et al. [3] conducted a study in Florida in order to quantify the operational effects of using unconventional left-turn control types. After collecting the required data, delay and travel time models were developed to study the effects associated with replacing direct left-turns (DLTs) with right-turns followed U-turns (RTUTs). Fig. 2 compares the operational performance of DLT and RTUT under different traffic volumes, where (RUV) is the flow rate of RTUT, and (LT) is the flow of DLT from a driveway.

Figure 2. Comparison of average delay of two movements [3]

Liu et al. [4] evaluated the operational impact of applying different left-turn alternatives from a driveway, which included direct left-turn (DLT) and indirect left-turns. Two indirect left-turn alternatives were considered including right-turn followed by U-turn before an intersection (RTUR) and right-turn followed by a U-turn at a signalized intersection (RTUT). The results of this study indicated that vehicles making DLT at driveway experience more delay as compared to those making RTUR at a median opening before a signalized intersection. However, vehicles making RTUT at a signalized intersection experience much more delay than those making DLT at a driveway and RTUR at median opening. It was also concluded that the vehicles making RTUT have similar total travel time to those making DLT at a driveway as long as the separation distance between the driveway and the downstream U-turn location is reasonable, as shown in Fig. 3.

Figure 3. Travel time comparison for different driveway left-turn alternatives

Hummer and Reid [5] compared the right-turns followed by U-turns with the conventional direct left-turns. After conducting the analysis, it was recommended that transportation agencies should consider this alternative when high through volumes conflict with moderate or low left-turn volumes.

In addition, another study found that prohibiting direct left-turns at signalized intersections and providing two-phase signal controls improved the capacity by about 20 to 50 percent [6].

Furthermore, many studies investigated the operational effects of unconventional intersections using simulation packages such as Synchro, SimTraffic, and CORSIM. The primary goal of using simulation techniques is to help the researcher to recognize the impact of changing any parameter in the study. Also, using such analytical tools will help in simulating as many scenarios as needed to reach precise conclusions.

Yang and Zhou [7] evaluated the operational performances of DLT and RTUT using CORSIM as the analytical tool. The simulation results showed that DLT has better performance at low through-traffic volume on the main street. However, the RTUT control type has less delay and travel time under moderate to high volumes on the main street.

Similarly, Reid and Hummer [8] analyzed a 2.5 mile corridor in Detroit to investigate the operational performance of using RTUTs. The optimal signal timing for each case was obtained using Synchro, and the traffic performance was evaluated using CORSIM software. Based on the results, RTUTs showed a 25 percent increase in the average speed and 17 percent decrease in the total travel time as compared to the conventional direct left-turns. The RTUT showed a higher number of stops than that for DLT.

Another study used CORSIM to evaluate the impact of using signalized U-turns on typical two 4-lane roads intersecting with each other. The study considered a three-phase signal operation with a direct left-turn movement, from the cross-street. The analysis considered several entering volumes, and the results showed that a significant reduction in travel time, for high traffic volumes, can be achieved by using the U-turn design [9].

Dorothy et al. [10] used TRAF-NETSIM model to simulate the impact of using RTUT compared to two-way left-turn lanes (TWLTL). For left-turning percentages of 10 and 25 percent, RTUT control type resulted in lower network travel time compared to DLT. Moreover, the STOP-controlled and the signalized U-turns had the same left-turn total time under low left-turning volumes.

Another study investigated the unconventional intersection design, where a major road and a minor crossroad are intersecting with each other, and direct left-turns are prohibited at the intersection. The purpose of the study is to compare the traffic performances of the U-turns located on both roads. For most of the volume combinations, the U-turns located on the crossroad reduced the total travel time, delay, and the number of stops in comparison to the U-turns on the major road [11].

In addition, the microscopic simulation software CORSIM was used in a study to compare the performance of direct left-turns (DLTs) with two forms of unconventional intersections including right-turn
followed by U-turn (RTUT), and U-turn followed by right-turn (UTRT). Total travel time, speed average, and speed variance were used as the measures of effectiveness in evaluating the operational performance of the three left-turn control types. Based on the simulation results, it can be found that unconventional intersections are more effective than DLTs [12].

Furthermore, a study investigated the impacts of U-turns on level of service of signalized intersections using Synchro and SimTraffic. Two parameters were calibrated based on the field data including the saturation flow rate and turning speed of U-turning vehicles in the left-turn lane. The results of the regression model showed that the impact U-turns on the level of service of signalized intersections shall be evaluated on a case-by-case basis [13].

As it is noticed from the previous paragraphs, there are good evidences that redirecting the left-turning vehicles away from the main intersection provided significant benefits such as improving the capacity and the level of service of the whole intersection. Also, the travel time and the total delay were reduced when compared to the conventional intersections. In fact, the previous studies considered providing U-turns either on the major road or on the minor road only. However, the proposed study investigates the operational effects of using U-turn on both arterials. Finally, the previous studies did not consider the impact of left-turning percentage on the intersection performance. However, the left-turning flow will range from 15 percent to 45 percent in the proposed study.

Table I. Geometric Characteristics of the Three Left-Turn Control Types

<table>
<thead>
<tr>
<th></th>
<th>DLT</th>
<th>RTUT</th>
<th>UTRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane width (m)</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Median width (m)</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Through lanes (per approach)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Channelized left-turn lanes (per approach)</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage length of left-turn channelization (m)</td>
<td>120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Right-turn lanes (per approach)</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Channelized right-turn lanes (per approach)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Right-turn control type</td>
<td>Free</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>Storage length of right-turn channelization (m)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>U-turn lanes downstream of the intersection (per approach)</td>
<td>80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage length of U-turn channelization (m)</td>
<td>80</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

III. METHODOLOGY

Three models were developed using Vissim to investigate three left-turn control types including direct left-turn (DLT), right-turn followed by U-turn (RTUT), and U-turn followed by right-turn (UTRT). The geometric characteristics of each intersection are shown in Table I. In order to evaluate each left-turn control type, many scenarios were created by changing certain traffic parameters. For the analysis, Synchro software was used to determine the optimized signal timing and intersection evaluation, for each scenario. Following that, the optimized signal timings were applied in Vissim software to evaluate the overall performance of each intersection.

Synchro [14] is a very powerful tool for optimizing signal timing and performing capacity analysis. In fact, the software can be used to optimize offset and cycle length for a single intersection or a whole network. In this paper, Synchro is used to optimize signal timing and evaluate the intersection’s delay for each scenario.

For the DLT control type, the phasing diagram consists of four phases. While for the RTUT and UTRT control types, the number of phases is reduced to two phases at the main junction, and all the U-turn locations are controlled by traffic signals.

Vissim [15] is a microscopic, time step, and behavior based simulation software that helps to visualize the traffic and its impact on a given network. Vissim produces very accurate and realistic models, therefore, it plays a significant role in the decision making process. The software can be used to evaluate different alternatives based on a transportation engineering measures of effectiveness. In this paper, Vissim is used to evaluate the traffic performance under the prevailing traffic conditions for each scenario. The measures of effectiveness considered in this study are the average delay per vehicle at the intersection, the total travel time per vehicle, and the vehicle kilometers travelled (VKT).
distribution on each approach, and percentage of vehicles for each turning movement. The values for the total traffic volume on the intersection were selected to represent low, moderate, high, and very high traffic volumes. It should be noted that Fig. 4 illustrates the experimental design for one traffic volume only. The same parameters apply for the other traffic volumes as well. The analysis included 180 scenarios, which is a reasonable number to reach to a precise conclusion.

The traffic volume distribution on each approach represents three cases. For case 1, the total traffic volume is equally distributed on all approaches of the intersection, which represents a case where all the approaches have the same level of congestion.

As shown in Fig. 5, each of the approaches A, B, C, D is assigned 25% of the total traffic volume. For case 2, the traffic volume is more dominant on two opposite approaches (i.e. more traffic volume is assigned to approaches A and C), which is the case when there is a major road intersecting with a minor road. For case 3, the traffic volume is more dominant in two perpendicular approaches (i.e. more traffic volume is assigned to approaches A and B).

delay. As the traffic volume increases, the delay in DLT approach increases with much higher rate compared to the unconventional control types. Moreover, case 2 and case 3 have very similar trend as case 1, for all considered scenarios in the experimental design.

It should be noted that Synchro’s delay calculation for unconventional left-turn control types is not accurate as it does not include the additional travel distance, when applying RTUT or UTRT. Furthermore, there is an additional travel time that should be considered for the RTUT and UTRT control types. Therefore, Synchro is not recommended to compare the overall performance for the three left-turn control types.

Because calculating the delay for unconventional left-turn control types using Synchro is misrepresentative, more detailed analyses are performed using Vissim software. A model for each left-turn control type was created using Vissim to evaluate different traffic conditions. A subset of the scenarios, presented in the experimental design, was simulated using Vissim, and the network performance was determined for each scenario. Table II illustrates the considered parameters for each scenario.

In order to have robust results, 5 runs were performed and the trimmed mean was calculated by excluding the largest and the smallest values from the results and calculating the arithmetic mean of the remaining three values. The trimmed average was considered to reduce the effects of extreme values on the calculated mean.

Table II: Considered Parameters for the Three Cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Traffic Volume (vph)</th>
<th>Left-Turn Control Type</th>
<th>% of vehicles on each approach</th>
<th>% of vehicles for each turning movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>3500 5000 6000 7000</td>
<td>DLT RTUT UTRT</td>
<td>25 25 25</td>
<td>NB 10 EB 10 SB 10 WB 10</td>
</tr>
<tr>
<td>Case 2</td>
<td>3500 5000 6000 7000</td>
<td>DLT RTUT UTRT</td>
<td>35 15 15</td>
<td>NB 10 EB 10 SB 10 WB 10</td>
</tr>
<tr>
<td>Case 3</td>
<td>3500 5000 6000 7000</td>
<td>DLT RTUT UTRT</td>
<td>35 35 15</td>
<td>NB 10 EB 10 SB 10 WB 10</td>
</tr>
</tbody>
</table>

All scenarios presented in Table II were evaluated based on different aspects using Vissim. For case 1, DLT
control type has more delay compared to the unconventional control types, as shown in Fig. 7. At low traffic volumes, the intersection delay is very similar between DLT and RTUT control types; however, the gap between the two curves increases as the traffic volume increases. The UTRT control type has the least delay among all the left-turn control types.

For case 2, the DLT control type has the highest delay and the UTRT control type has the least delay. For total intersection traffic volumes greater than 5000 (vph), the gap between UTRT and RTUT control types starts to decrease, also the delay for the DLT control type increases dramatically, as shown in Fig. 8.

Moreover, the delay for case 3 is very similar to the other two cases, as illustrated in Fig. 9. When the total traffic volume on the intersection is more than 6000 (vph), the delay for the three left-turn control types increases with higher rate in case 3 compared to the other cases.

In addition, travel time comparison was made among the three left-turn control types for each case. For case 1, the UTRT control type has the least travel time among all the control types, because vehicles will stop only once at the signalized intersection; while, for the RTUT vehicle will stop at the signalized intersection and the U-turn location. When the total intersection traffic volume is less than 5000 (vph), the RTUT control type has more travel time compared to the DLT control type. This can be attributed to the fact that the average delay is comparable for the two control types, as shown in Fig. 7, and the RTUT requires more travel distance. When the traffic volume is more than 5000 (vph), the RTUT control type has less travel time compared to the DLT control type.

As shown in Fig. 10, unconventional left-turn control types have similar travel time pattern over the range of travel volumes, while travel time for the DLT control type is more sensitive to the change in the traffic volume.

For case 2, travel time for both DLT and RTUT control types is very similar when traffic volume is less than 5000 (vph), which can be attributed to same reason mentioned for case 1. The gap between RTUT and UTRT control types starts to decrease when traffic volume is higher than 5000 (vph), as illustrated in Fig. 11.

For case 3, UTRT has the least travel time among all the control types. The travel time for the DLT control type increases with higher rate when traffic volume is more than 6000 (vph) as shown in Fig. 12.

Finally, a comparison based on the vehicle kilometers travelled (VKT) was made among the three left-turn control types for each case. VKT is the total distance in kilometers travelled by vehicles during a given period of time on a particular road system. Fig. 13 illustrates the VKT comparison for case 1. DLT control type has the least VKT compared to unconventional control types.
There is no significant difference in distance travelled is very small between DTL and unconventional control types. Moreover, RTUT and UTRT control types have exactly the same vehicle kilometers travel (VKT). In addition, cases 2 and 3 have the same trend as case 1.

Figure 13. Comparison of VKT for case 1 using vissim

V. CONCLUSIONS

This study showed preliminary results for the evaluation of the operational effects of three left-turn control types including direct left-turn, right-turn followed by U-turn, and U-turn followed by right-turn. Synchro and Vissim software packages were used in this study to evaluate each alternative. The analysis results proved that unconventional left-turn control types could have better operational performance than direct left-turns, under most of the traffic conditions. This implies that RTUT and UTRT control types would provide less delay and travel time compared the DLT control type. Delay and travel time at signalized intersection increases with the increase of traffic volume; however, the sensitivity of delay and travel time to the changes in traffic volumes is higher for the DLT control type. Another part of this study has demonstrated that vehicles using any of the unconventional left-turn control types have comparable vehicle kilometers travelled (VKT) as compared to those making direct left-turn at signalized intersections.

The UTRT showed superior performance over the other left-turn control types under all congestion levels. On the other hand, the RTUT resulted in an improvement in the intersection control for high traffic volumes only.

It is recommended to continue the rest of the scenarios presented in the experimental results for this study to confirm the final results. The remaining scenarios include higher left-turn percentages that may affect the conclusions of this study.

ACKNOWLEDGMENT

The authors would like to thank PTV-VISION group for providing a full version of Vissim.

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