Guidelines for the Use of Some Unconventional Intersection Designs

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ABSTRACT

Several unconventional intersection schemes have been proposed to improve the performance of intersections with heavy left-turn movements. These unconventional schemes were shown to outperform conventional intersections under moderate- and high-volume conditions or in the existence of extremely heavy left-turn movements. However, guidelines for the implementation of these intersections have not been extensively discussed. Little research has been done comparing the performance of these intersections under different flow conditions. This study evaluates and compares the operational performance of four unconventional intersection schemes: the Crossover Displaced Left-Turn (XDL), the Upstream Signalized Crossover (USC), the Half USC, and the Median U-turn (MUT) design. The paper discusses signal optimization strategies for the intersections and identifies the important operation issues. The micro-simulation software VISSIM was used to model and analyze the four unconventional intersections as well as a conventional one. Intersection average control delay was used as a Measure of Effectiveness (MOE) to compare the performance of different designs. Based on the analysis, guidelines for the implementation of each design under various traffic volume scenarios are presented.

INTRODUCTION

In recent years, transportation engineers have been challenged by the continuous increase in traffic volumes and the corresponding congestion at signalized intersections. One of the most important factors that significantly impact the performance of signalized conventional intersections is the existence of heavy left-turn movements. Therefore, there has been considerable interest in alternative measures to improve the performance of intersections with heavy left-turn movements, some of which have been unconventional schemes. Conventional measures to improve the performance of intersections with heavy left-turn movements include signal timing optimization, implementation of exclusive left-turn lanes, and grade separation. Unconventional measures for treating heavy left-turns include the Median U-turn (also known as Michigan U-turn), the Super-street, the Jughandle, the Crossover Displaced Left-Turn (XDL), the Upstream Signalized Crossover (USC) schemes, and the half USC, among others. The configuration and geometry of these intersections are different from the conventional schemes. They share the concept of reducing the conflicts between left-turn movements and the opposing through traffic by re-routing one or more of these movements. In a previous research (*1*), the performance of two of these unconventional schemes; the Crossover Displaced Left-Turn (XDL) intersection and the Upstream Signalized Crossover (USC) intersection, was compared. This paper extends the comparison to include two more designs: the Half USC and the Median U-turn. The comparison is made in terms of average vehicle delay and capacity. Safety issues, potential driver confusion, pedestrian movements were not considered in the current analysis and are left to future research. The microsimulation software VISSIM was used to model and analyze the unconventional intersections as well as a counterpart conventional intersection for comparison.

MOVEMENTS AT THE ANALYZED UNCONVENTIONAL INTERSECTIONS

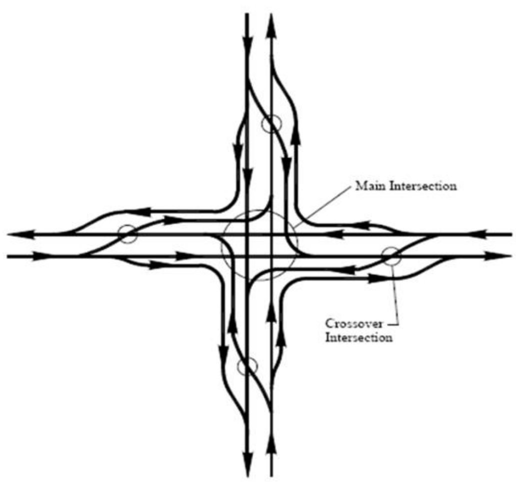
The XDL intersection eliminates left-turn conflicts with the opposing through traffic by displacing the left-turn lane to the opposing traffic direction and crossing the left-traffic to the left side of the road a few hundred feet upstream of the primary intersection (*2*). Right-turn movements are channeled to bypass the main intersection and are merged back into mainstream traffic downstream. Left-turn displacement at the four approaches creates four additional secondary intersections. Accordingly, the XDL can be described as a system of two-phase intersections that consists of one primary and four secondary intersections. The innovation of this scheme is the allowance of the operation of both through and left-turn movements simultaneously at the main intersection using a two phase signal (*3*).

The USC intersection is a four-leg intersection that eliminates left-turn conflicts with the opposing traffic by crossing both through and left movements to the left side of the road at the four approaches prior to the intersection (*4*,*5*). Similar to the XDL intersection, the through and left crossings create four additional secondary (crossover) intersections. By utilizing a simple two-phase signal timing scheme and coordinating all five signals, the USC intersection can minimize the overall average delay. Detailed description of the movements can be found in Tabernero et al. (*4*), Tabernero and Sayed (*5*), and Sayed et al. (*6*).

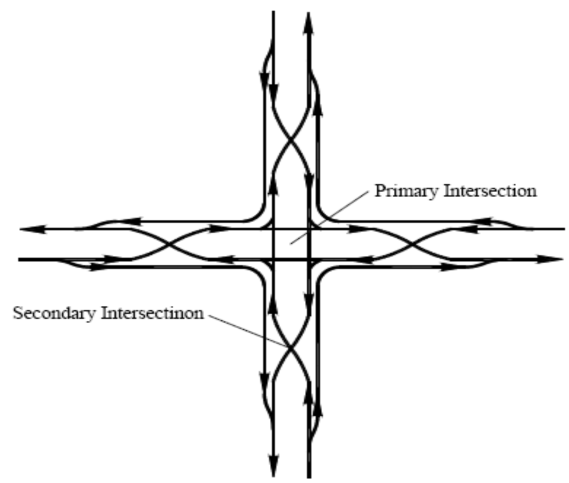
One unconventional intersection that is somewhat similar to the USC is the Double Crossover Intersection (DXI). The only difference between the two designs is that the USC crosses the through and left traffic prior to the main intersection for the four approaches while the DXI crosses the through and left traffic only for the approaches of the major road, hence it can be considered as a *Half* USC. The DXI was initially introduced by Chlewicki (*7*) and was referred as the

Synchronized Split-Phasing (SSP) Intersection. Bared et al. (*8*) suggested that the name "Double Crossover Intersection (DXI)" is more descriptive. Because of its similarity to the USC, this design will be referred to as the Half USC. A Half USC intersection may solve some of the problems associated with the USC design by reducing the number of required signals by two. It will probably be useful with only a relatively small volume of vehicles turning left from the minor road, since the left-turning vehicles will have to yield to opposing vehicles. The crossovers of the Half USC can be placed on the major street or on the minor street. In this paper both configurations will be tested and referred to as "Half USC Major" and "Half USC Minor".

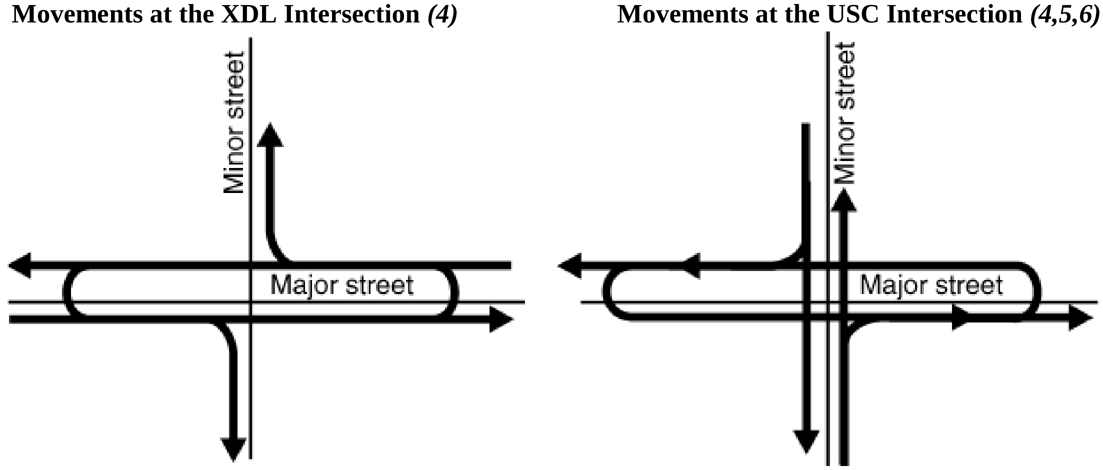
In the Median U-turn design, left-turn movements are prohibited at the intersection and moved to median crossovers beyond the intersection (*9*). The crossovers can be located either on the major street, the minor street, or both, depending on the available median width. Also, these crossovers can either be signalized by a two-phase signal or unsignalized. For major street U-turn crossovers, traffic turning left off the major road has to cross the primary intersection, make a U-turn, and turn right at the minor street. Minor street traffic wishing to turn left has to turn right at the primary intersection merging with the major street traffic, then make a U-turn at the crossover. Figure 1 illustrates the configurations of the XDL, USC, and the U-turn designs.



Movements at the XDL Intersection *(4)*



Movements at the USC Intersection *(4,5,6)*



Movements at the Median U-turn *(9)*

Figure 1 Movement at the Analyzed Unconventional Intersections

PREVIOUS WORK

The FHWA informational guide for signalized intersections (*9*) classifies alternative intersection treatments into three categories: intersection reconfiguration and realignment treatments, indirect left-turn treatments, and grade separation treatments. Indirect left-turn treatments include Jughandle, Median U-turn, Continuous Flow Intersection (CFI or XDL), Quadrant intersection, and Super-street. A large body of literature exists on the performance of different types of unconventional intersections. Jagannathan and Bared *(2)* used VISSIM to compare three different XDL configurations to their conventional counterparts. The results showed considerable savings in average control delays for all volume conditions. Furthermore, a significant increase of 15% to 30% in the overall capacity of the XDL intersection was found. The authors suggested that adjusting signal timing for pedestrian movement in the XDL played a dominant role in increasing the cycle length and hence the average delay. If pedestrian movement was not considered, the average delay would have been much lower. Reid and Hummer *(3)* used CORSIM to conduct travel time comparisons between seven isolated unconventional intersections and a similar conventional intersection. Their results showed that at least one unconventional scheme outperformed the conventional intersection in at least one volume scenario. In general, the analysis was in favor of the Quadrant and the Median U-turn intersections for most volume scenarios. Hummer (*10,11*) presented seven unconventional treatments for heavy left-turn movements. His discussion included qualitative guidelines for the implementation of these alternatives. He suggested that none of the solutions discussed can be considered as “a universal solution” and, for many particular problems, none of them will perform well. Both the FHWA informational guide (*9*) and Hummer (*11*) propose that the XDL intersection may be appropriate for locations with high through and left volumes. Because U-turns are prohibited in the XDL design, this configuration should not be implemented for sites with high demand for U-turns.

Tabernero and Sayed (*4,5*) introduced the USC intersection with a brief comparison to the conventional intersection. Their analysis showed that the USC has the potential for accommodating heavy left-turn movements while maintaining an acceptable performance level for through traffic. Sayed et al. (*6*) further investigated and compared the performance of the USC to a similar conventional scheme under different volume scenarios. They concluded that the USC intersection shows considerable potential for situations where one or more of the following conditions exists: 1) the intersection volumes are balanced and are near or over the capacity of a conventional intersection, 2) the traffic volumes are somewhat unbalanced, but the overall entering volumes are too high to be accommodated by a conventional intersection, and 3) the intersection has heavy left-turn volumes which cause excessive delays. Chlewicki (*7*) compared the performance of the SSP (i.e. Half USC) intersection to that of a similar conventional one using SimTraffic while optimizing signal phases and splits using Synchro. His results showed that the SSP intersection outperformed the conventional one. Bared et al. (*8*) used VISSIM to compare the DXI (i.e. Half USC) to a conventional four-leg intersection under four volume scenarios. The results showed that the performance of the two intersections is similar at low volume levels, while the DXI outperformed the conventional intersection at high volume levels and in heavy left turn scenarios.

Bared and Kaisar (*12*) used CORSIM to analyze a median U-turn intersection with signalized crossovers added to the major road. They reported a significant overall intersection delay reduction for the U-turn design compared to the conventional design under balanced volumes.

It should be noted that most of the previous work on unconventional intersections has dealt only with isolated unconventional intersections. Little research work has been directed to placing a series of unconventional intersections on a coordinated corridor. Reid and Hummer (*13*) used CORSIM to analyze traffic operations along an arterial with five signalized intersections. They compared the conventional two-way left turn lane (TWLTL) design and two alternative unconventional designs: the Median U-Turn Crossover design (MUT) and the Super-Street Median Crossover design (SSM). The results indicated that the MUT and SSM designs improved both system travel time and average speed compared to the TWLTL design during the peak hours. However, the MUT and SSM designs operated similar to the TWLTL during the off-peak hours. El Esawey and Sayed (*14*) studied the potential benefits of implementing a corridor of three USC intersections in comparison to existing conventional four-leg intersections. The analysis showed that the total system delay, for the USC configuration was less than that of the conventional configuration by 19.4%, 14.8% and 13.6% for the AM peak, Midday peak, and PM peak respectively. As well, the average control delay of each single USC intersection was lower than its conventional counterpart by between 7.6% and 22.9%.

ANALYSIS METHODOLOGY

Geometric Design

All of the intersections analyzed had the following geometric elements:

- All intersections were four-leg intersections,
- Each intersection had the same number of lanes per approach for each movement: two through-only lanes, one left-turn lane, and one right-turn lane,
- Each left-turn movement had an exclusive left-turn lane of 65 m in length.
- Separated exclusive right turn lanes were provided for all four approaches on all models. The lanes were created using the same length in all models to facilitate a fair intersection performance comparison. The lanes begin approximately 230 m upstream of the primary intersection, travel parallel to the through traffic lanes, then merge back with through traffic 230 m downstream of the primary intersection.

One of the key design elements of the analyzed unconventional intersections is the spacing between the primary and the secondary intersections. Sayed et al. (*6*) examined various distances from the USC crossover to the primary intersection to determine the optimal geometry for different levels of traffic volumes. El Esawey and Sayed (*1*) further tested different spacing distances between the primary and the secondary intersections for the XDL design. The results for both configurations showed that increasing the distance between the secondary intersection and the primary intersection will increase intersection capacity, but delays will be slightly higher for low volume conditions. This can be explained by the cycle length limit produced by the geometry. As the spacing between the primary and the secondary intersections becomes shorter, the amount of green band that can be provided for each phase has to be shortened to facilitate progression. Assuming a constant amount of lost time, the longer cycle length minimizes the overall lost time of the intersection. The reduced area for vehicles to queue between intersections may also contribute to the increased delay of shorter intersections at higher volumes. To be consistent with previous studies *(1)*, three different spacings were used in this study to test the Half USC design: 140 m, 175 m, and 210 m. According to the FHWA informational guide (*9*), the Michigan Department of Transportation suggests that the optimal distance for placing the U-turn crossover is 170 m to 230 m from the primary intersection. In this study, the distance between the primary intersection and the U-turn crossover was selected to be 200 m.

Traffic Volumes

To enable the comparison of the Half USC and the Median U-turn to the previously developed models of the XDL and the USC, the same hypothetical traffic volumes were used in the current study as in El Esawey and Sayed *(1)*. These volumes include both balanced and unbalanced volume conditions, where a balanced scenario represents a case of similar volumes on all four approaches and an unbalanced scenario represents a case of a major-minor intersection. Also, the impact of increasing left-turn volume on the intersection performance was considered by modeling the unbalanced volumes with 20% and 30% left-turn volume while maintaining the same approach volume. Table 1 presents a summary of all geometries and traffic volumes tested in this study.

Table 1 Volumes and Configurations Tested

	Approach Volume (veh. /hr.)		**Geometry Tested**	**Through/Left/Right (percentages)**
	Major Road	**Minor Road**		
Balanced Volumes	500	500	All*	70/20/10
	1000	1000		70/20/10
	1050	1050		70/20/10
	1125	1125	Conventional Only**	70/20/10
	1250	1250		70/20/10
	1500	1500		70/20/10
	1750	1750	All*	70/20/10
	2000	2000		70/20/10
	2500	2500		70/20/10
Minor/Major Road Volumes	1200	300		70/20/10
	1200	600		70/20/10
	1200	900		70/20/10
	1200	1200		70/20/10
	1500	600		70/20/10
	1500	900		70/20/10
	1500	1200		70/20/10
	1500	1500	175 m Half USC, 200 m Signalized and Unsignalized U-turn***	70/20/10
	1200	300		60/30/10
	1200	600		60/30/10
	1200	900		60/30/10
	1200	1200		60/30/10
	1500	600		60/30/10
	1500	900		60/30/10
	1500	1200		60/30/10
	1500	1500		60/30/10

*Including 140 m, 175 m, and 210 m spacing half USC (Major and Minor), 200 m spacing median U-turn (Major and Minor, Signalized and Unsignalized) and conventional intersection.
**volumes tested to determine point of intersection failure in terms of delay
*** In addition to the previously tested XDL, USC, and Conventional intersections

Signal Phasing and Timing

Signal timing for different geometries is based primarily on the time required for a vehicle to travel from the secondary intersection to the primary intersection. The cycle length of the Half USC can be determined by multiplying the travel time between a secondary intersection and the primary intersection by four. It is important to note that if the primary focus in signal timing is coordination and progression, the required cycle length is strictly dependent on the geometry. Therefore, there is only one optimal cycle length for a particular Half USC configuration for coordination and progression using this theoretical method. Under balanced volume conditions, the simple progression concept was used to calculate the cycle length for the Half USC intersections.

El Esawey and Sayed (*1*) used Synchro (*15*) to optimize the signal timing of the XDL and USC intersections under different balanced and unbalanced volume scenarios. Synchro processing is iterative as it calculates delays, queues, and vehicle stops of the network while adjusting the signal timing. It then assigns a score to each iteration based on these measures of effectiveness (MOE) to reach the optimal network signal timing *(15)*. A similar approach was used in this study by employing Synchro to optimize the signal timing and splits of Half USC and Median U-turn intersections for both the balanced and unbalanced cases. At high volumes, Synchro cycle length of the U-turn design was unrealistically long. Therefore, a shorter cycle length was imposed to improve intersection performance. This was done by forcing the cycle length to be between 40 and 150 seconds.

The Traffic Simulation Models

Modeling and simulation of the unconditional intersections was carried out using PTV's VISSIM 5.10, a behavior-based microsimulation software (*16*). VISSIM was selected because it allows road networks or junctions to be developed lane by lane. This facilitated the construction of the unconventional intersections exactly as they would appear in real life. Also, VISSIM has been extensively used before in analyzing unconventional intersections (*1,2,4,5,6,8,14*). The Wiedemann 74-car following model was selected in VISSIM for vehicle behavior, and, in general, default driving parameters were used. Generated traffic comprised 2% heavy vehicles (HV). A pre-timed signal controller was used with four seconds amber and one second all-red intervals for all signals in all intersections. Lane widths were 3.5 meters with no shoulders. All vehicles targeted a speed of 50 km/hr, except while turning, when cars reduced their speeds to 25 km/hr and heavy vehicles to 20 km/hr. Left-turn movements were assigned a protected-permissive phase in the conventional intersection.

Travel time detectors were placed relatively far upstream and downstream of the main intersection to better capture the delays produced by the intersection. The delay measured is the difference between the travel time between one detector and another detector unimpeded, and the time required to travel the same distance with the signal active (*16*). Each of the models was run five times with different seed numbers. Each run was a total of three model hours long. The first hour was a seed hour, or a warm-up stage. Delay data were extracted for the remaining two hours. When determining the delays for a model, the highest and lowest values were ignored so the results presented include the average of three intermediate runs. It should be noted that the exclusion of the highest and the lowest values generally did not have a significant effect on the results.

RESULTS

For each scenario, the primary method of evaluation was the average delay experienced by vehicles traveling along a given movement. VISSIM evaluates this by comparing the actual travel time between two selected points to an ideal travel time. As such, the delays cannot be directly compared to those used in the HCM methodology. However, they provide a good measure of intersection effectiveness.

Balanced Volume Scenarios

The first issue investigated is the effect of changing the spacing between the primary and the secondary intersections on the operational performance of the Half USC intersection. As shown in Table 1, different configurations for the Half USC were tested under balanced volume scenarios. The results showed very similar delay trends for both the 175m and 210m Half USCs, with the capacity of the 175m Half USC even being slightly higher (Figure 2). The Half USC with 175m spacing was therefore deemed the optimal configuration and was compared to other optimal configurations of the unconventional intersections.

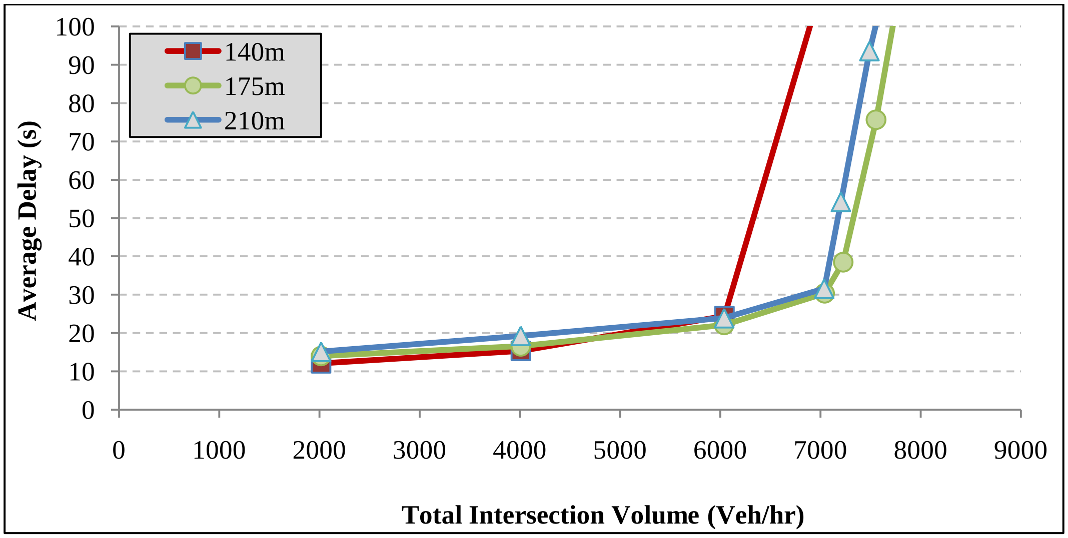


Figure 2 Delay Variation with Intersection Spacing Change for the Half USC Design

A comparison of signalized and unsignalized median U-turn designs showed that the unsignalized U-turn design always exhibited lower delays. However, neither of them could accommodate an approach volume of more than 1500 vehicles/hr with 20% left turn traffic (Figure 3).

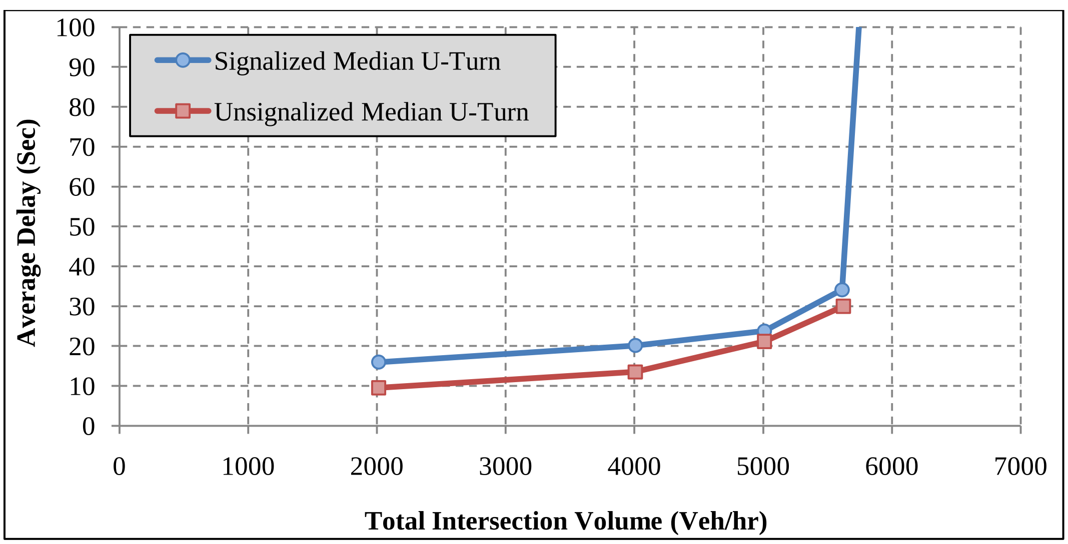


Figure 3 Delay Comparisons of Signalized and Unsignalized U-turn Designs

Figure 4 compares the Half USC and the unsignalized U-turn, in addition to the XDL, the USC, and the conventional intersections developed in the previous study (*1*).

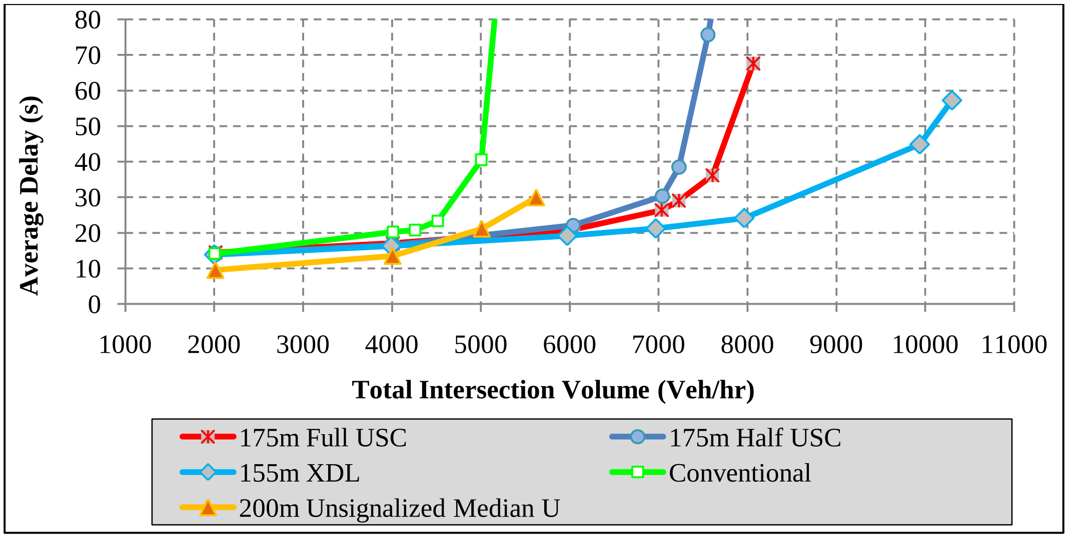


Figure 4 Average Delays for the Analyzed Intersections Under Balanced Volumes (20% LT)

The following can be inferred from Figure 4:

1. All of the analyzed unconventional designs outperform the conventional intersection, and the improvement becomes more significant at high traffic volumes.
2. Up to an approach volume of approximately 1100 veh/hr, the unsignalized Median U-turn design exhibits the lowest delays while the three other unconventional intersections exhibit similar delays.
3. Average control delays remain similar for the XDL, the USC and the Half USC up to an approach volume of 1500 veh/hr.
4. For an approach volume of more than 1500 veh/hr, the XDL intersection has lower delays than all other intersections followed by the USC and the Half USC.

The capacity of the XDL intersection, defined as the intersection failure point (i.e. LOS F), is about 90% higher than that of the conventional intersection, while the capacity of the USC and the Half USC intersection is about 50% higher and that of the median U-turn designs is less than 10% higher (Figure 5). Although the USC and the Half USC have almost the same capacity, 2000 veh/hr/approach, the USC reached this capacity with an average delay of 70 seconds compared to more than 120 seconds for the Half USC.

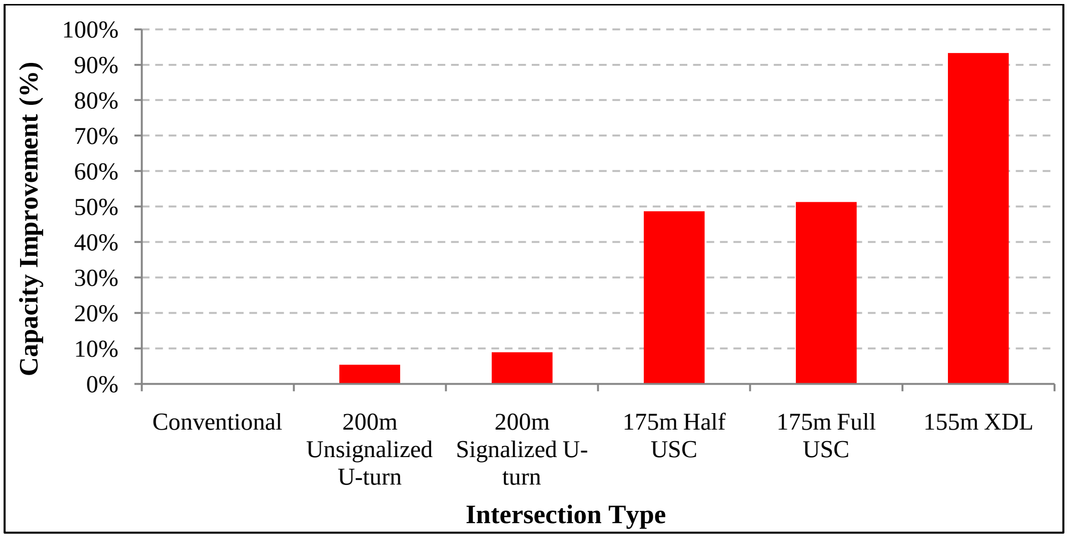


Figure 5 Capacity Improvements of the Unconventional Intersections in Comparison to the Conventional Intersection

Unbalanced Volume Scenarios

As mentioned earlier, Synchro was used to optimize the Half USC and the median U-turn intersections under unbalanced volume conditions. Synchro-optimized timing plans were used in VISSIM simulations for the two intersections under unbalanced volume conditions.

Two designs of the 175m Half USC intersection were further analyzed under unbalanced volumes. The crossovers were placed on the major street in the first design and on the minor street in the second. The aim was to study the potential benefits, if any, that might be gained by placing the crossovers of the Half USC on the minor streets. Similarly four different configurations of the median U-turn were tested including placing signalized and unsignalized crossovers on the major and on the minor streets. Major road volumes of 1200 vehicles/hour/approach and 1500 vehicles/hour/approach were tested with 20% and 30% levels of left turning movements.

The Half USC Design

The analysis revealed that a Half USC design with crossovers on the major street (Half USC Major) always performs better than a Half USC design with the crossovers placed on the minor street (Half USC Minor). The results are logical as the entire purpose of the USC/Half USC design is to facilitate through movements via a series of two-phase coordinated signals. It would be expected that placing the crossovers on the major street, which carries heavier traffic, will be more beneficial than placing them on the minor street where the benefits will be limited to the light through traffic. The results were consistent for the tested two major road volumes and for both levels of left turning movements. Figure 6 shows the average control delays of the two Half USC configurations at different demand levels of the minor street.

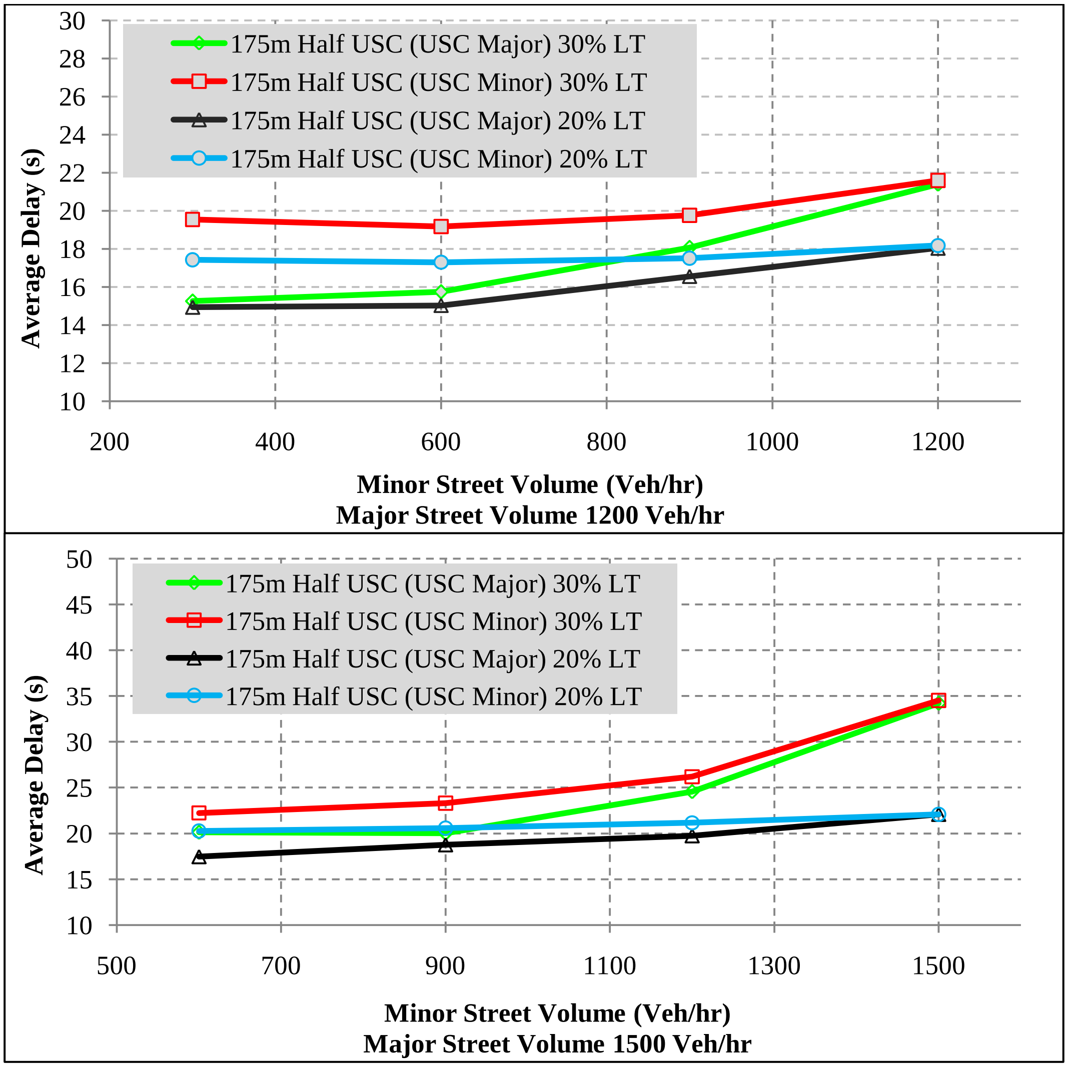


Figure 6 Average Delays for the Half USC Intersections under Unbalanced Volumes
Major Street Volume = 1200 veh/hr b) Major Street Volume = 1500 Veh/hr

The Median U-turn Design

A comparison of signalized and unsignalized median U-turn designs showed that the unsignalized U-turn always outperforms the signalized U-turn for the two left turn volume levels at a flow of 1200 veh/hr on the major street. The reductions in the average control delay ranged from 3 to 6 sec/veh for a left turning percentage of 20%, while the counterpart delay reductions for the 30% left turning traffic were between 5 and 8 sec/veh. The results (Figure 7) in general are consistent with the findings of the balanced volume scenarios. Hence it can be concluded that the median U-turn design with unsignalized crossovers will always perform better than or at least as well as the signalized median U-turn.

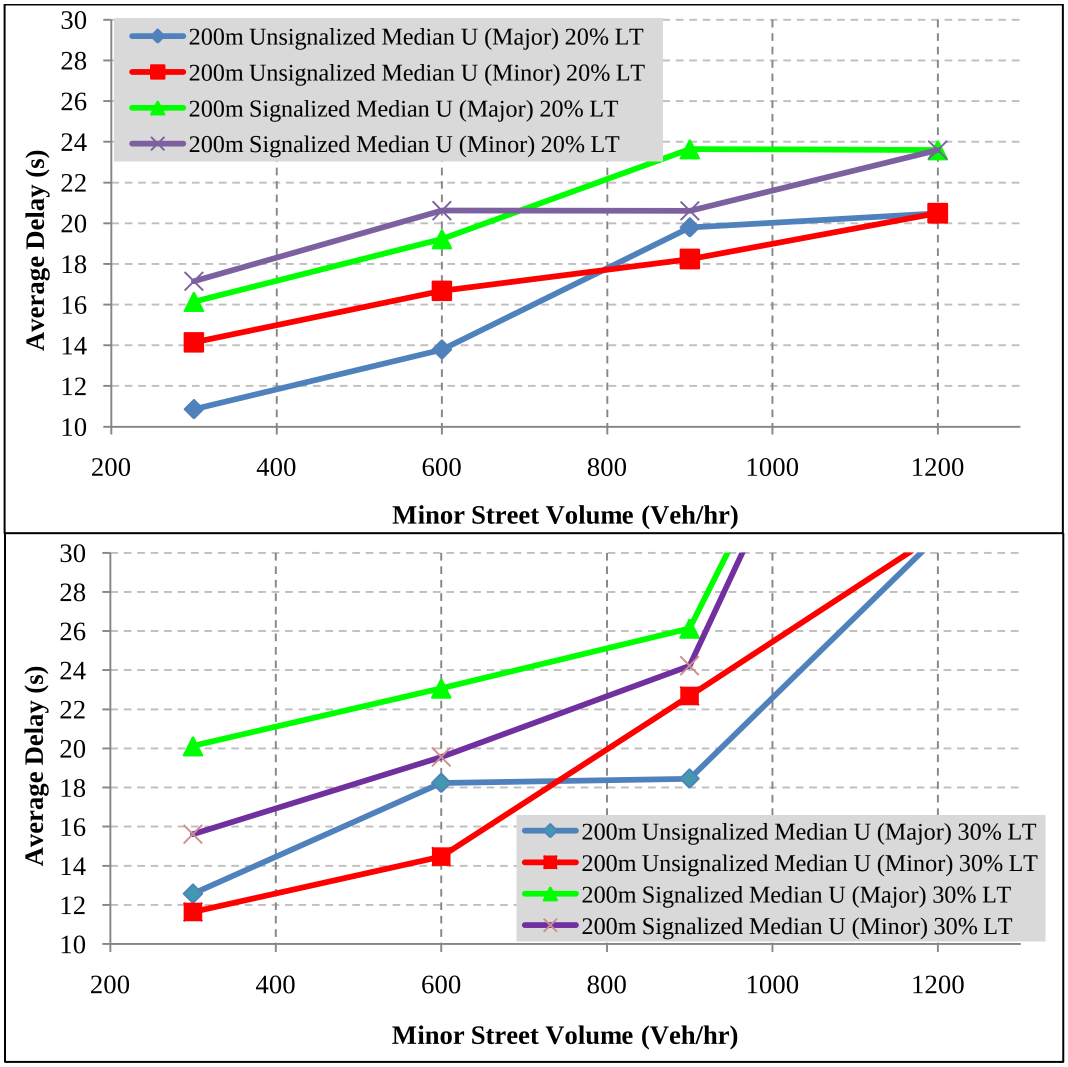


Figure 7 Average Delays for Median U-turn Intersections under an Unbalanced Volume Scenario, Major Street Volume = 1200 Veh/hr

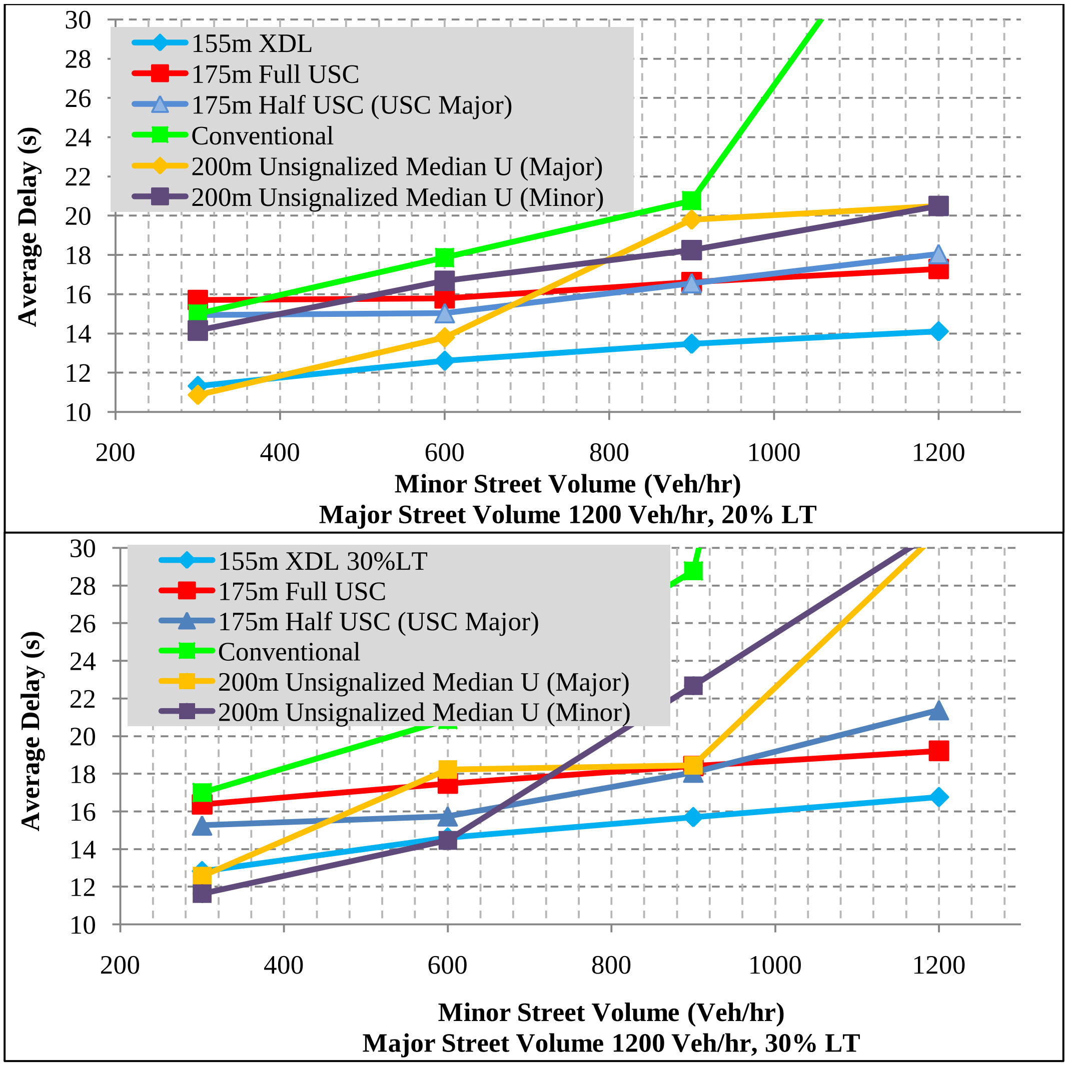
A comparison of the two U-turn designs for a demand level of 1500 veh/hr was not possible as both designs resulted in spillbacks locking the entire network at demand levels below 1500 veh/hr. This indicates the difficulty of using the Median U-turn design in high volume situations.

Comparing the U-turn configuration with the crossovers placed on the minor street to that with crossovers placed on the major street gave mixed results. Under the 20% left turn volume, the major street crossover configuration seems to perform better than the minor street crossover for both signalized and unsignalized designs in highly unbalanced scenarios, when the volume of the minor street is up to 0.6 of major street volume. When the intersection volumes are almost balanced, the minor street crossover design performs better. The differences diminish when both intersecting streets carry the same volume.

Changes in the percentage of left turn movements gave completely different results. Under the 30% left turn volume, the minor street crossover configuration performed better than the major street crossover for the signalized design. For the unsignalized Median U-turn, the minor street crossover resulted in lower delays for highly unbalanced scenarios and higher delays as the volumes became equal.

Overall Comparison of the Four Designs

As presented earlier, individual comparison were held for each type of unconventional intersections to determine the design configuration that performs the best. It was shown that the Half USC with the crossovers on the major street "Half USC Major" outperforms the Half USC with the crossovers placed on the minor street "Half USC Minor". Also, it was shown that Median U-turn intersections with unsignalized crossovers will always be more operationally better than those with signalized crossovers. Based on these findings and previous findings (*1*), a comparison was held between the best configuration of each unconventional design. The comparison results are presented in Figure 8.



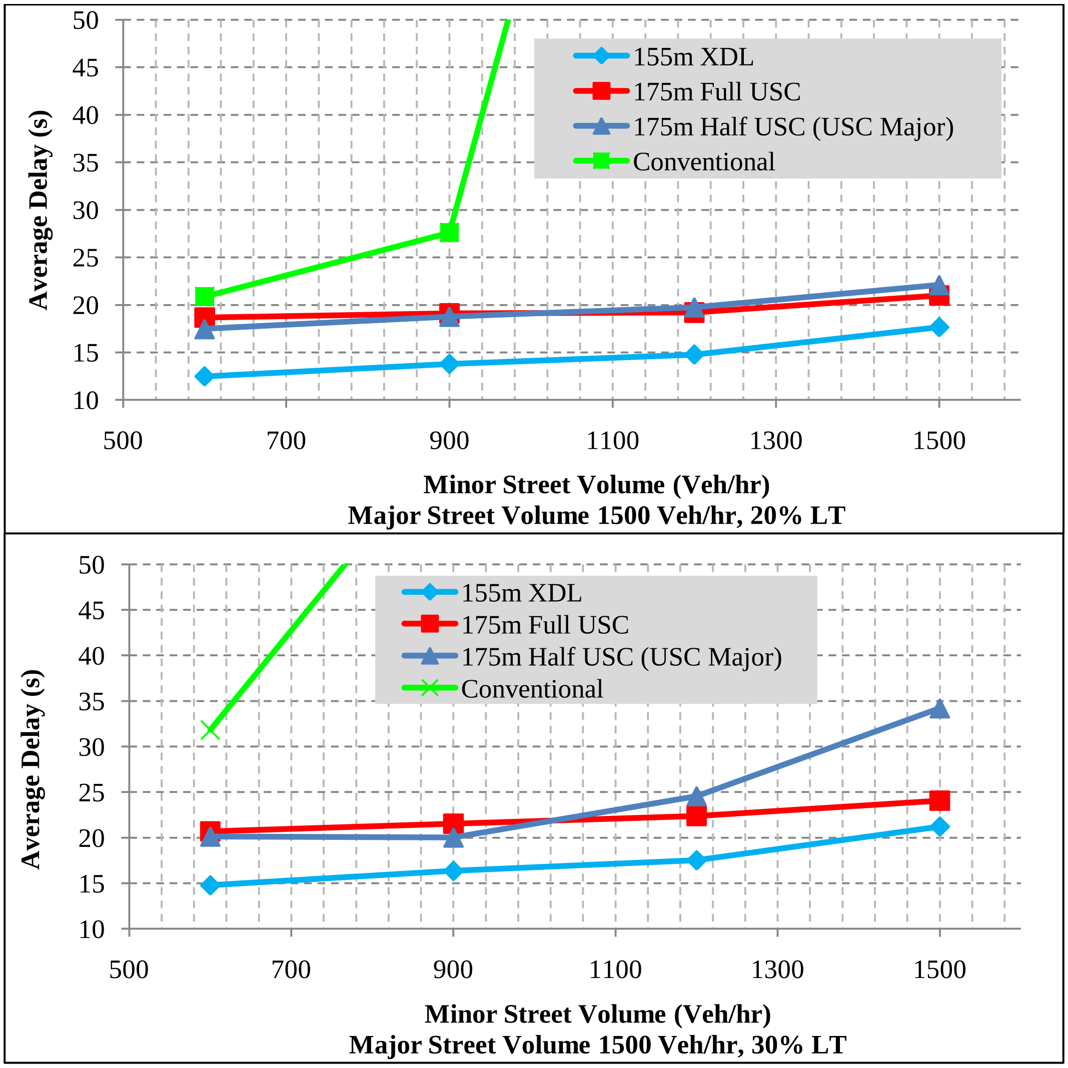


Figure 8 Average Delays of The Analyzed Unconventional Intersections under Unbalanced Volume Scenarios

a) Major Street Volume = 1200 Veh/hr, 20% LT b) Major Street Volume = 1200 Veh/hr, 30% LT

c) Major Street Volume = 1500 Veh/hr, 20% LT d) Major Street Volume = 1500 Veh/hr, 30% LT

The comparison shows that no single design that can consistently outperform all other design in all volume conditions. This conclusion is in agreement with the results of Hummer *(9,10)*. However, some useful conclusions can be drawn from Figure 8:

1. All of the analyzed unconventional designs outperform the conventional intersection, and the improvement becomes more significant as the demand increases.
2. The Half USC design always outperforms the USC design when the intersection volumes are highly unbalanced. As the volumes become relatively balanced, that is the ratio between the minor and the major streets volumes is 67% to 75%, the USC design performs better than the Half USC.
3. The XDL intersection always outperforms the USC and the Half USC designs in all volume scenarios. Moreover, the XDL intersection consistently outperforms the U-turn design except in few occasions where the traffic volume on the minor street is very low. The XDL has a left-turn bay that extends between the primary and the secondary

intersections which allows more storage length and is the main reason for the high capacity of the XDL.

4. Median U-turn designs, whether signalized or unsignalized, tend to fail rapidly as the as the percentage of left-turning traffic increases. Also, these designs are able to accommodate only light to moderate traffic volumes of not more than 1200 to 1500 veh/hr/approach (for the current number of lanes). When the ratio between the minor and the major streets volumes is higher than 60%, the USC and Half USC designs always perform better than the Median U-turn design.

IMPLEMENTATION GUIDELINES FOR THE ANALYZED UNCONVENTIONAL INTERSECTIONS

Based on the results of our analyses, some guidelines were developed to help traffic professionals select an appropriate unconventional intersection. These guidelines are based only on the operational performance of the intersection in terms of average intersection delay. Also, these guidelines are based on the tested geometries and volumes. However, it is expected that the results would be similar under different volume and geometry conditions. A set of guidelines is developed for intersections operating or expected to operate under balanced volume levels, while another set was developed for intersections carrying unbalanced volumes.

Balanced Traffic Volumes

1. Any of the unconventional intersections analyzed will outperform a conventional intersection.
2. For light volumes (i.e., approach volumes up to 1100 veh/hr for the same number of lanes), the unsignalized Median U-turn design is the best selection and all other intersection types would perform nearly equal.
3. For balanced approach traffic volumes of 1100 to 1500, the XDL, the USC, and the Half USC would perform equally well.
4. For an approach volume of more than 1500 veh/hr, the XDL intersection is the best choice followed by the USC and the Half USC, although the XDL has additional right of way requirements.

Unbalanced Traffic Volumes

1. Any of the analyzed unconventional designs will outperform the conventional intersection.
2. The XDL intersection is always superior to all other intersections in almost all volume scenarios.
3. The Half USC design is a better choice than the USC design when the ratio between the minor and the major streets volumes is less than 70%. The USC design becomes better in approximately balanced scenarios.
4. Median U-turn designs, whether signalized or unsignalized, are not recommended for situations with heavy left-turning traffic.
5. Median U-turn designs are able to accommodate only light to moderate traffic volumes of not more than 1200 to 1500 veh/hr/approach (for the current number of lanes).

DISCUSSION AND CONCLUSIONS

This paper compared the operational performance of four unconventional intersection schemes; the XDL, the USC, the Half USC, and the Median U-turn. The aim was to develop some guidelines on the implementation of these intersections. VISSIM was used to simulate different configurations of the unconventional schemes under balanced and unbalanced volume scenarios. The paper investigated the performance of these intersections under different levels of traffic flow as well as the impacts of the following design options:

a) using different primary to secondary intersection spacing on the operational performance of the Half USC design,
b) placing the Half USC crossovers on the major and the minor streets,
c) placing the Median U-turn crossovers on the major and the minor streets,
d) signalizing the Median U-Turn crossover, and
e) Increasing left-turn volumes on the average intersection delay.

It was shown the placing the crossovers of the Half USC on the major approach is more beneficial than placing them on the minor approach. U-turn designs with unsignalized crossovers tend to outperform those with signalized crossovers. The results were mixed with respect to placing the crossovers of the Median U-turn on the major or on the minor streets.

In terms of the average intersection delay, the analyses revealed that any of the tested unconventional intersections would perform better than a conventional intersection counterpart. The XDL intersection consistently outperformed all other intersections under most balanced and unbalanced volume levels. The USC and the Half USC perform similarly in most conditions, while the Median U-turn was unable to accommodate high approach volumes and heavy left turning traffic. The capacity of the XDL intersection is higher than that of the conventional intersection by about 90% while the capacity of the USC and the Half USC intersections is about 50% higher than that of the conventional intersection. The impact of increasing the left-turn volume was found to be much greater on the conventional intersection than on the XDL, the USC, and the Half USC. The XDL has a left-turn bay that extends between the primary and the secondary intersections. This bay is a basic design element and could not be eliminated. Note also that the implementation of a median U-turn design requires a wide median for the U-turn crossovers. This requirement restricts the implementation of the Median U-turn design. The USC design does not require any additional right of way. Therefore, it can offer a good alternative to conventional intersections where little changes can be made to existing conditions.

The analyzed unconventional schemes can be a good alternative to interchanges on rural highways. Rural highways have the perfect conditions for implementation: available right of way and low pedestrian movement. Good signing and marking is an essential practice for the implementation of these unconventional intersections.

A future extension of this work may include investigating potential pedestrian movements at the unconventional intersections, construction costs and cost-benefit analysis, and studying safety issues and driver confusion associated with these unconventional designs.

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