IMPACT OF USING INDIRECT LEFT-TURNS ON SIGNALIZED INTERSECTIONS' PERFORMANCE

by

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Dedication

This thesis is dedicated to my beloved parents and sisters for their endless love and encouragement. They provided me with great moral support throughout my graduate studies.

Abstract

Most developing areas are suffering from traffic congestion problems. The majority of traffic delays in urban areas occur at traffic signals. Over the past few decades, several transportation agencies have been applying geometric changes, through adding more lanes, to signalized intersections in an effort to reduce delays. Because of the limited availability of right-of-way, many transportation agencies have started using unconventional traffic control systems for intersections to improve signal efficiency and reduce overall delays. Common unconventional left-turn control types such as the right-turn followed by a U-turn (RTUT) and a U-turn followed by a right-turn (UTRT) basically eliminate direct left-turn (DLT) movements at the intersection by rerouting left-turning vehicles away from the main junction. Following any of these alternatives reduces the number of phases and the average delay per vehicle at the main junction. However, it adds some additional travel time for left-turning vehicles and some delays at the U-turn locations. This thesis presents a parametric study to evaluate the impact of replacing direct left-turns with U-turns (either RTUT or UTRT). The main goal of this study is to determine the traffic operational performance of each alternative under different traffic conditions. Traffic signal evaluation (Synchro) and simulation (Vissim) tools were utilized in this study to determine the optimized signal timings and evaluate intersection performance for each left-turn control type, respectively. Many parameters were considered, such as the total traffic volume on the intersection, the percentage of vehicles on each approach, the turning percentage for each movement, and the U-turn locations. It was concluded that unconventional left-turn control types have less delay and travel time compared to the DLT, when the U-turn locations are 200 meters away from the main intersection. Also, the right-turn followed by a U-turn showed superior performance over the other left-turn control types, when the U-turn locations are 100 meters away from the main intersection. Furthermore, it is not recommended to have the U-turns at a distance less than 100 meters when using unconventional left-turn control types because of the queue spillback effect. Finally, both conventional and unconventional control types have comparable vehicle kilometers travelled (VKT).

Search Terms: Traffic Signal optimization, Indirect left-turns, Microscopic simulation.

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List of Abbreviations

DLT	Direct left-turn
RTUT	Right-turn followed by a U-turn at the traffic signal
UTRT	U-turn followed by a right-turn
RTUR	Right-turn followed by a U-turn before the traffic signal
TWLTLs	Two-way left-turn lanes
AADT	Average annual daily traffic
vph	Vehicles per hour
LOS	Level of service
VKT	Vehicle kilometers travelled

Chapter 1: Introduction

1.1 General Introduction

Traffic congestion at signalized intersections poses a challenge for all large and growing urban cities. Due to the rapid increase in the number of vehicles, drivers are experiencing more delays at intersections. Changing the geometry of intersections by adding more lanes is not a feasible solution, in many cases, because of the limited right-of-way at many signalized intersections. Therefore, transportation agencies worldwide are considering different alternatives to improve operating conditions and level of service (LOS) at signalized intersections with minimal changes to the existing geometric design.

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 many alternatives to eliminate direct left-turns at signalized intersections, as depicted in Figure 1. The signalized intersection will be controlled by a two-phase traffic signal, after eliminating all of the direct left-turns [1, 2].

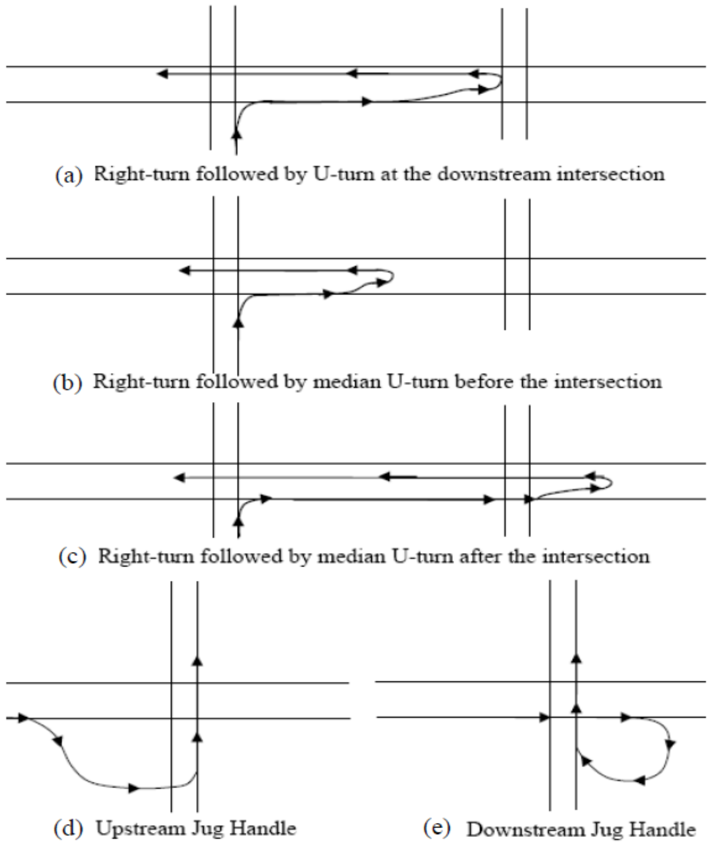


Figure 1: Concept of Five Alternatives of Indirect Left-turn Measures [2]

A right-turn followed by a U-turn (RTUT), and a U-turn followed by a right-turn (UTRT) are possible control types for eliminating direct left-turn. For the RTUT control type, vehicles desiring to turn left must first turn right at the main intersection through a signalized right-turn lane. After that, vehicles must make a U-turn at a signalized median opening downstream of the intersection, and then travel through the main intersection, as illustrated in Figure 2. For the UTRT control type, vehicles desiring the turn left must first travel through the signalized intersection. After that, vehicles must make a U-turn at a signalized median opening, and then make a right-turn at the main intersection, as illustrated in Figure 3.

Such control types aim to reduce conflicts and enhance safety along arterial roads; at the same time, they attempt to provide these benefits with minimum cost and have the least impact on the existing geometric design. Unconventional left-turn control types can be implemented with traffic signals at the U-turn locations.

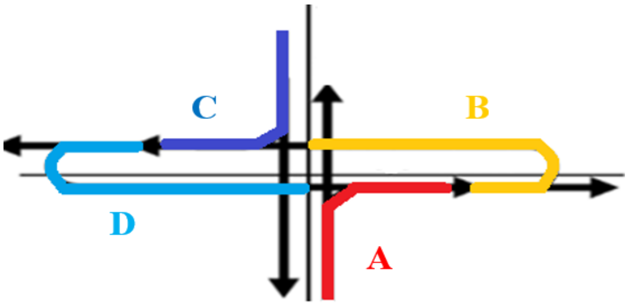


Figure 2: The Right-turn Followed by a U-turn Control Type

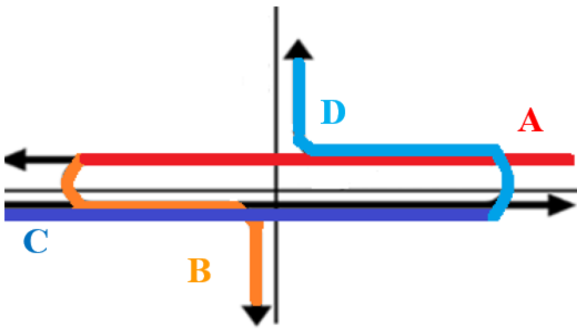


Figure 3: The U-turn Followed by a Right-turn Control Type

1.2 Problem Statement

In most urban areas, traffic growth means higher delays at signalized intersections. As a solution to reduce traffic delays, oftentimes agencies add more lanes to reduce the delay. However, such solutions are not always feasible for many intersections due to the limited right-of-way. Using unconventional left-turn control types is one of the possible solutions to reduce the overall delay and improve signal efficiency with minimal changes to the existing geometric design. The main purpose of unconventional left-turn control types is to reroute left-turning vehicles away from the main intersection. Left-turning vehicles are forced to make a U-turn at a median opening so that they can complete their movements through the intersection.

1.3 Significance of the Research

This study has evaluated the operational performance of three left-turn control types under different traffic conditions. Also, the study illustrates the impact of changing different traffic parameters on each left-turn control type. Therefore, the study provides recommendations about the left-turn control type to be used based on the prevailing traffic conditions.

There are many advantages associated with the elimination of direct left-turn movements at signalized intersections. For instance, unconventional left-turn control types 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 since 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. This results in less consumption of fuel, and therefore less pollution [2].

1.4 Research Objectives

The primary objective of this research is to improve traffic signal performance through providing a recommended left-turn control type, based on the prevailing traffic conditions. This was carried out by estimating the operational effects of using unconventional left-turn control types as compared to direct left-turn at signalized intersections. To achieve this objective, the research will:

- Evaluate vehicle delay, travel time, and level of service at a signalized intersection under three different left-turn control types: DLT, RTUR, and UTRT.
- Recommend the most suitable left-turn control type based on the prevailing traffic conditions.
- Determine suggested U-turn locations for indirect left-turn treatments under different traffic conditions.

1.5 Organization of Thesis

The manuscript consists of the following chapters:

- ***Chapter 1: Introduction***. Provides an overview of unconventional left-turn control types and sets out the primary objectives of the research.
- ***Chapter 2: Background***. Presents a comprehensive literature review on the operational and safety impacts of replacing direct left-turns with U-turns, and the optimal location of U-turns.
- ***Chapter 3: Methodology.*** Describes the procedures which will be followed to achieve the objectives of the research.
- ***Chapter 4: Experimental Design.*** Explains the traffic parameters considered within the research. Defines the experimental code which will be given to each scenario.
- ***Chapter 5: Results and Discussion.*** Illustrates the results obtained after running the microscopic simulation. Discusses the impacts of each of the considered parameters on different left-turn control types.
- ***Chapter 6: Conclusions and Recommendations.*** Summarizes the main key findings and provide suggestions for future research.

Chapter 2: Background

Several research efforts [1, 3, 4] have considered the operational impact of replacing direct left-turns with U-turns. There are many advantages associated with using unconventional left-turn control types such as reducing conflicts and improving safety along arterial roads. Nowadays, many cities have started using various alternatives to redirect left-turning vehicles away from the main intersection. Table 1 shows some of the indirect left-turn control types which were adopted by different states in an effort to reduce the number of conflicts along arterials.

Table 1: Various Alternatives for Reducing Conflicts in Different States

State	Left-turn control type
California	Providing dual left turns at intersections with collector streets, with the innermost lane accommodating U-turns.
Florida	Prohibiting left-turn exits onto major arterials, and providing midblock U-turn lanes.
New Jersey	Using jug handles along multi-lane divided highways.
Michigan	Using U-turn channels on highways with wide medians and prohibiting left turns at signalized intersections.

A detailed analysis is performed in this thesis about the operational impacts of using U-turns as alternatives to direct left-turns. Also, the optimal U-turn locations will be investigated.

Levinson at el. [5] provide an overview of the indirect left-turn control type that has been implemented in Oakland County, Michigan (Michigan “U”). Their study discussed the design features of this new concept, and also compared the capacity and level of service of the Michigan “U” with the conventional left-turn control type. Finally, the paper discussed operational and safety effects of the Michigan “U” control type.

In fact, many transportation agencies have started using unconventional left-turn control types as alternatives to direct left-turns from driveways. For instance, the Florida Department of Transportation (FDOT) prohibits direct left-turn (DLT) from driveways in many locations. As a result, drivers desiring to turn left have to make RTUT at a downstream U-turn location rather than making a direct left-turn onto a major-street from driveways. At un-signalized intersections, the main purpose of using a right-turn followed by a U-turn is to reduce conflict points associated with the direct left-turns. Table 2 summarizes the advantages and disadvantages of DLT and RTUT [6].

Table 2: Summary of Advantages and Disadvantages of Two Movements [6]

	DLT	**RTUT**
Advantages	The delay and travel time could be less as compared to the RTUT under low traffic volumes. Vehicles making DLT would travel less distance and may consume less gas as compared to the vehicles making RTUT.	Travel time and delay could be less as compared with DLT movements under moderate and high traffic volumes conditions. The capacity of the U-turn movement at the U-turn median opening is much higher than a DLT. RTUT movements create fewer conflict points. Drivers would often make a RTUT movement in preference to a DLT under moderate to high traffic volume conditions. A U-turn median opening can be used to accommodate traffic from several upstream driveways, especially when the driveway spacing is very close.
Disadvantages	Traffic delay and travel time may greatly increase under high traffic volume conditions. DLT movements involve obtaining gaps in two directions at a time when the median is too narrow to safely store more than one vehicle. DLT results in more conflict points, and vehicles making DLT have to yield to all other movements at a full median opening. Capacity of DLT movements is seriously limited by median storage. Large trucks may block the through traffic when they are making DLT.	Total travel time could be longer as compared with DLT option if major road traffic volume is low. It takes longer travel distance and may consume more fuel as compared with the DLT.

2.1 Traffic Operational Performance

A direct left-turn egress from a driveway must yield to all other movements since it has the lowest priority according to the Highway Capacity Manual [7]. Therefore, DLT is the most likely movement to be delayed, especially under heavy traffic volume conditions. On arterials with wide medians, DLT maneuvers from driveways require (a) stopping at the driveway, (b) waiting for a suitable gap in the traffic approaching from the left, (c) accelerating across the major roadway and coming to a stop in the median, (d) waiting for a suitable gap in the traffic approaching from the right, and (e) completing the left movement and accelerating on the major roadway. In case of narrow medians (i.e. <20 ft.), drivers must look for suitable gaps in both directions simultaneously [1].

Drivers may prefer to make a right-turn followed by a U-turn under high through-volume traffic conditions. RTUT maneuvers from driveways require (a) stopping at the driveway, (b) waiting for a suitable gap in the traffic approaching from the left, (c) accelerating, weaving to the U-turn bay, and decelerating to stop at the U-turn median opening, (d) waiting for a suitable gap in the traffic approaching from the right, and (e) completing the left movement and accelerating on the major roadway [1].

2.1.1 Capacity, delay, and travel time.

There are many studies that have investigated the operational performance of using unconventional left-turn control types as alternatives to a DLT from driveways. For instance, Zhou et al. [6] conducted a study in Florida to quantify the operational effects of using unconventional left-turn control types from driveways. In order to monitor traffic operations, video cameras were installed to obtain data including travel time, speed, and delay. Also, Automatic Traffic Counters were used to collect traffic volumes. After collecting the required data, delay and travel time models were developed to study the effects associated with replacing the direct left-turns with right-turns followed U-turns. Figure 4 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 rate of DLT from a driveway. Moreover, a model was developed to quantify driver selection of a RTUT or a DLT under different traffic conditions.

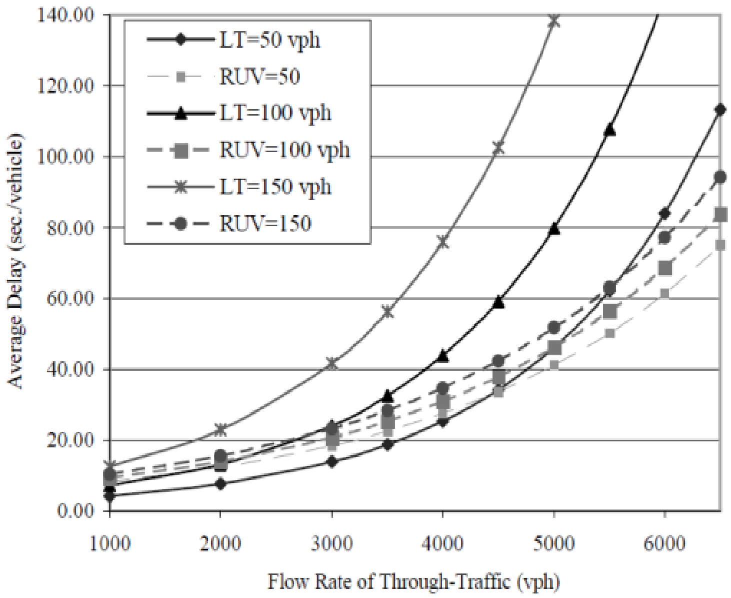


Figure 4: Comparison of Average Delay of Two Movements [6]

As shown in Figure 4, the average delay in the previous study [6] was estimated based on flow rates equal to 50, 100, and 150 vph from the driveway, and free flow of through-traffic ranges from 1000 vph to more than 6000 vph. The results of the previous study cannot be used to represent the operational performance of indirect left-turns at signalized intersections, because it considered the case of a driveway access to a main road. On the other hand, at signalized intersections, the delay and travel time for a left-turn movement depends on the flow rates of all of the approaches. In addition, this thesis will use microscopic simulation tools to calculate delay and travel time instead of developing delay and travel-time models.

Liu at el. [8] evaluated the operational impact of applying different left-turn alternatives from a driveway including both direct and indirect left-turns. Two indirect left-turn alternatives were taken into consideration including a right-turn followed by a U-turn before an intersection (RTUR), and a right-turn followed by a U-turn at a signalized intersection (RTUT) as shown in Figure 5.

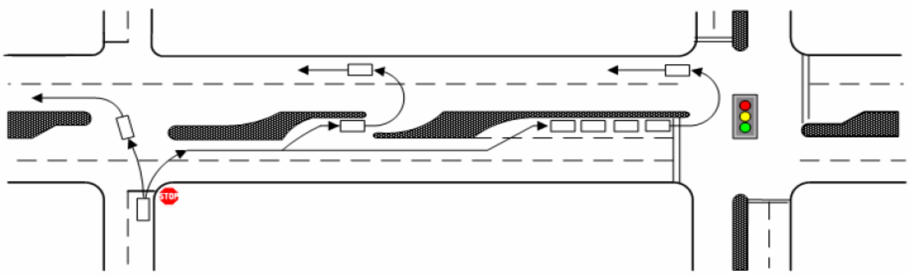


Figure 5: Three Different Driveway Left-turn Alternatives in Florida [8]

Moreover, data was collected at 34 selected roadway segments to estimate the delay and travel time for different driveway left-turn alternatives. In addition, a linear regression model was developed to estimate the running time that vehicles spend at weaving sections while making a RTUT at various separation distances between driveways and downstream U-turn locations. The results of the study indicated that vehicles making a DLT at a driveway experience more delay as compared to those making a RTUR at a median opening before a signalized intersection. However, vehicles making a RTUT at a signalized intersection experience much more delay than those making a DLT at a driveway and a RTUR at a median opening. It was also concluded that the vehicles making a RTUR have similar total travel time to those making direct left-turns at a driveway as long as the separation distance between the driveway and the downstream U-turn location is reasonable, as shown in Figure 6. Finally, a binary logit model was developed to estimate the percentage of drivers selecting indirect left-turns over direct left-turns under different conditions such as upstream traffic volume, left-turn traffic demand at a driveway, and left-turn volume from a major road into a driveway [8]. The researchers spent almost one year in the field collecting data for delay and travel time comparisons. For parametric studies, using simulation tools helps to compare many parameters in a very efficient and comprehensive manner.

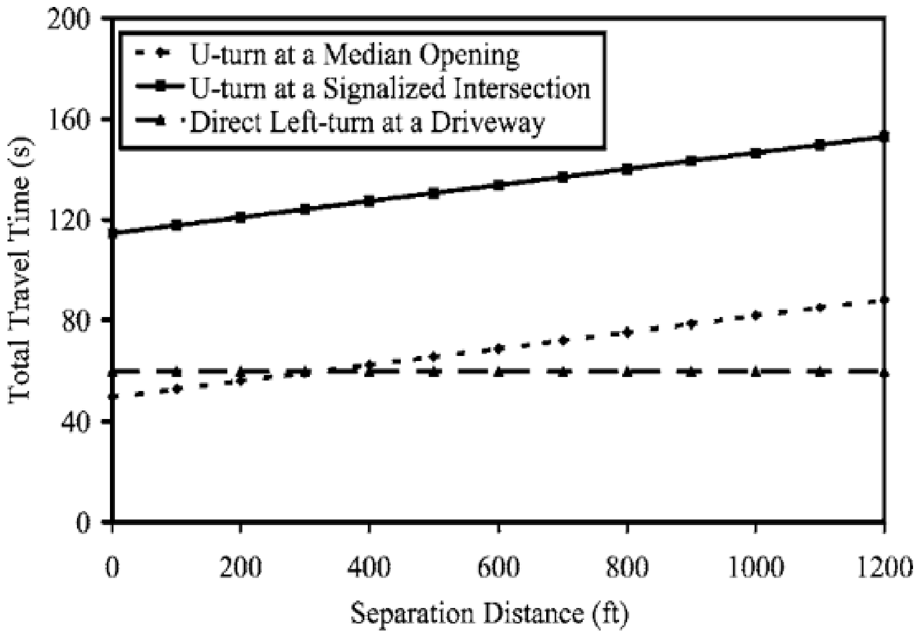


Figure 6: Travel Time Comparison for Different Driveway Left-turn Alternatives [8]

Hummer and Reid [9] compared a right-turn followed by a U-turn with the conventional direct left-turn for signalized intersections. In their study, they investigated the impact of utilizing U-turns on an arterial median only. As shown in Figure 7, drivers desiring to turn left from the arterial must first pass through the main intersection. After that, drivers must make a U-turn at the median opening downstream of the intersection, and then turn right at the main intersection. On the other hand, vehicles wishing to turn left to the arterial must first turn right at the main intersection, and then make a U-turn at the median opening. 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.

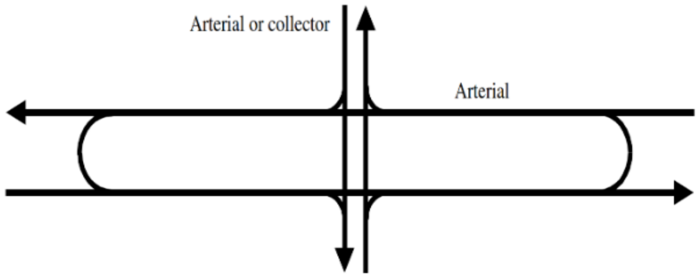


Figure 7: Median U-turn [9]

Another study found that prohibiting direct left-turns at signalized intersections and providing two-phase signal controls improved the intersection capacity by about 20 to 50 percent. Figure 8 shows the level of service compression for 4-lane and 6-lane boulevards, based on 20 percent capacity gain [10].

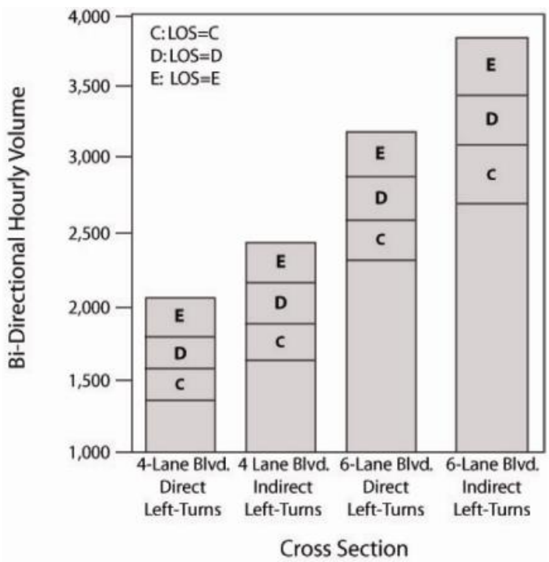


Figure 8: Divided Highway Level of Service Comparison [10]

2.1.2 Signal phasing.

Traffic signals will be operating with two phases only after prohibiting left-turns at signalized intersections. Reducing the number of phases has many advantages, such as increasing the capacity of the intersection and improving the level of service. Figure 9 illustrates a typical phasing diagram for an unconventional intersection with a right-turn followed by the U-turn control type. Pedestrians are moving in the direction of traffic, and the signalized pedestrian phases are represented by dashed arrows. In some cases, traffic signals at the U-turn locations are slightly delayed based on the separation distance between the intersection and the U-turn locations. Cycle length varies between 60 and 120 seconds in most cases studied [11].

In this thesis, the signal will have four-phases for the direct left-turn control type. However, for the unconventional left-turn control types, the signal will have two-phases. Also, traffic signals at the U-turns will be coordinated with the signals at the main intersection.

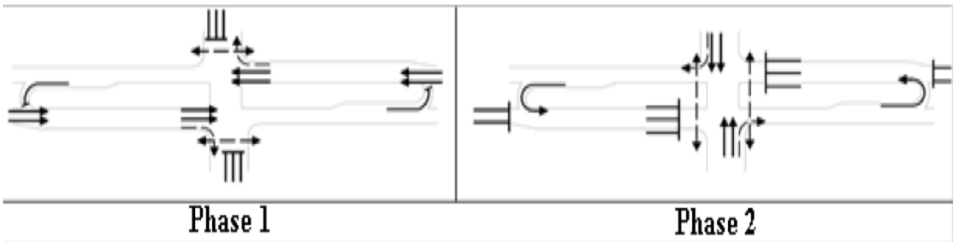


Figure 9: Example of the Typical Signal Phasing for the RTUT [11]

2.1.3 Microscopic simulation.

Many studies investigated the operational effects of unconventional left-turn control types using simulation packages such as Synchro, SimTraffic, and CORSIM. The primary goal of using simulation techniques is to help researchers recognize the impact of changing different parameters within the study. Also, using such analytical tools help in simulating as many scenarios as needed to reach precise conclusions. Using simulation packages are very useful and efficient for any parametric study.

A study evaluated the operational performances of DLTs and RTUTs from driveways, under different traffic conditions. Delay and travel time were used to evaluate each alternative, and CORSIM software was used as the analytical tool. A total of six sites were selected to collect field data, and then the data was used to calibrate each model. The simulation results showed that a DLT has better performance at low through-traffic volume on a main street. However, the RTUT control type shows less delay and travel time under moderate to high volumes on main streets. The study can be used as a guidance to determine which left-turn control type is more effective under the given traffic conditions. It should be noted that volume split at the driveway was assumed to be fixed during the simulations for all of the sites. Also, traffic volume on the main street was assumed to have a 50:50 split [12].

Reid and Hummer [13] analyzed a 2.5 mile corridor in Detroit to investigate the operational performance of using median U-turns as alternatives to two-way left-turn lanes (TWLTLs). The average annual daily traffic (AADT) ranges from 52,000 to 60,000 vehicles per day, and the corridor consists of 5 intersections. The U-turns were provided on the major arterial only, and all major driveways and unsignalized side streets intersecting with the corridor were considered in the study. The optimal signal timing for each case was obtained using Synchro, and the traffic performance was evaluated using CORSIM software. Based on the results, median U-turns showed a 25 percent increase in the average speed, and a 17 percent decrease in the total travel time as compared to conventional direct left-turns. Also, median U-turns showed a higher number of stops compared to TWLTLs.

Another study used CORSIM software to evaluate the impact of using signalized U-turns on typical 4-leg intersections formed by two 4-lane roads intersecting with each other. The U-turns were provided only on both sides of the major road, and left-turning vehicles from the minor road were allowed to turn at the main intersection. The study considered a three-phase signal operation with a direct left-turn movement from the cross-street. Several entering volumes were considered in the analysis. The results indicated that a significant reduction in travel time could be achieved for the signalized U-turn design at high traffic volumes [14].

Dorothy et al. [15] used the TRAF-NETSIM model to simulate the impact of using RTUTs compared to two-way left-turn lanes (TWLTL). The U-turn locations were modeled as STOP-controlled with low turning volumes, and signalized U-turns were assumed to have higher turning volumes. For left-turning volume of 10 and 25 percent, the RTUT control type had lower network travel times compared to conventional intersections. Moreover, the STOP-controlled and the signalized U-turns had the same left-turn total time under low left-turning volumes.

Another study considered unconventional left-turn control types at signalized intersections, where a major road and a minor crossroad intersected with each other, and direct left-turns were prohibited at the intersection. The main purpose of the study was to compare the traffic performances of the U-turns located on both roads. The through volumes on the major roads ranged from 1,000 vph to 2,000 vph, and the left-turning volumes ranged from 100 vph to 400 vph. However, through volumes on the minor roads ranged from 500 vph to 1,000 vph, and the left-turning volumes ranged from 50 vph to 200 vph. 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 [16].

In addition, CORSIM software was used in a study to compare the direct left-turn (DLT) with two forms of unconventional left-turn control types including a right-turn followed by a U-turn (RTUT), and a U-turn followed by a right-turn (UTRT). The three left-turn control types were investigated based on flow rates equal to 1800 vph on the main road, and 900 vph on the minor road. Total travel time, speed average, and speed variance were used as the measures of effectiveness (MOE) in evaluating the operational performance of the three left-turn control types. Based on the simulation results, unconventional left-turn control types were more effective than direct left-turns [17].

Furthermore, another study examined the impacts of using U-turns on level of service of signalized intersections, and Synchro and SimTraffic were used as the analytical tools. 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 of U-turns on the level of service of signalized intersections need to be evaluated on a case-by-case basis [18].

2.2 Impact of U-turn Location

To improve the performance of unconventional left-turn control types, the location of the U-turns has to be selected wisely. In fact, large separation distance may discourage drivers from making indirect left-turns because they will experience longer travel time due to the additional distance travelled. On the other hand, short separation distances will cause safety problems at the weaving sections of the road, and vehicles making RTUTs will not have sufficient distance to complete the lane change maneuver in a comfortable way [19].

2.2.1 Operational performance.

Based on a study done by Bared and Kaiser [14], increasing the offset distance between U-turn locations and intersections increased the travel time for the vehicles that were turning. On the other hand, it improved the performance of the intersection at higher traffic volumes by providing adequate storage to accommodate the queue for the turning vehicles, and prevented spillback into the intersection.

Junqiang et al. [20] investigated the impact of U-turn location on the operation performance of unconventional left-turn control types under different traffic conditions. Traffic volume on the main road varied from 1300 vph to 2000 vph, and the percentage of left-turning vehicles varied from 10 to 25 percent. Four different U-turn locations were investigated, as shown in Figure 10. For case 1, the U-turn movement is controlled by a traffic signal. For case 2, vehicles make a U-turn behind the stop line of the signalized intersection (the U-turn movement is not controlled by a traffic signal). For case 3, the location of the U-turn is dependent on the queue length, while the location of the U-turn is dependent on the weaving length for case 4. Vissim software was used to simulate all of the considered scenarios. After the analysis was complete, cases 3 and 4 showed superior performance compared to the other cases when a specific range of traffic volumes and left-turning vehicles was considered. Figure 11 shows the simulation results when the left-turning vehicles are at 10 percent.

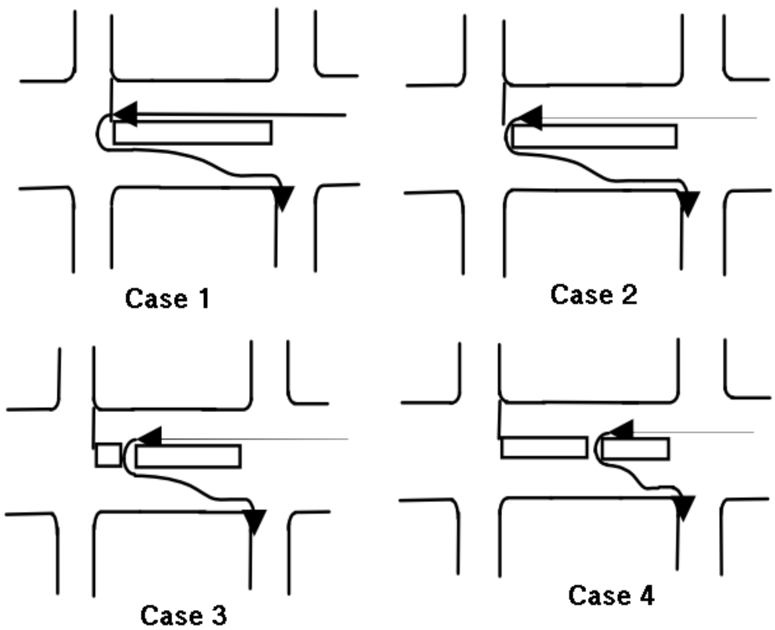


Figure 10: The Location of U-turn [20]

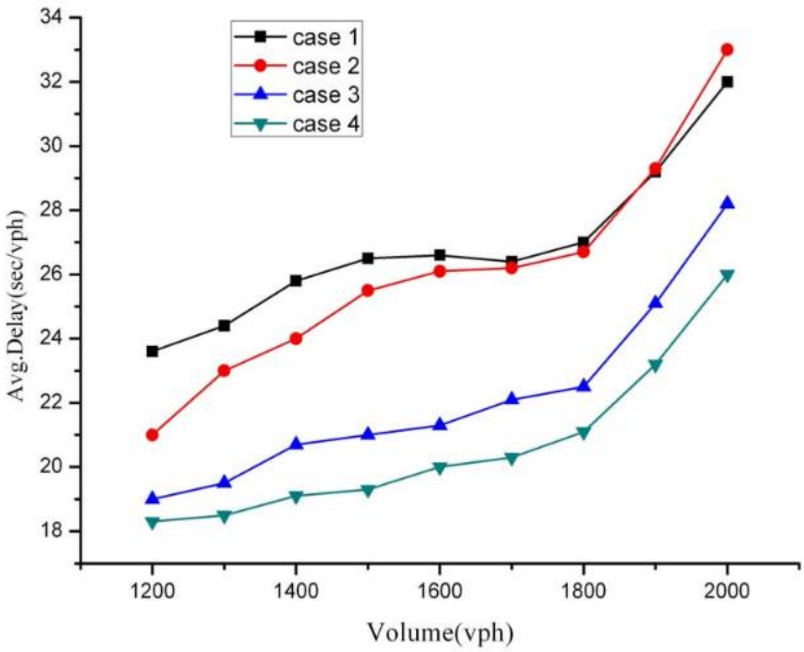


Figure 11: Comparison of Avg. Delay, 10% Left Turns [20]

In addition, another study investigated the optimal offset distance based on operational performance of vehicles making RTUTs. The study investigated the impact of the separation distance between driveways and U-turns at median openings and at signalized intersections. The separation distance includes transition length, length of the weaving section, and length of the storage bay. Based on the results, U-turns at signalized intersections require more offset distance compared to U-turns at median openings, as shown in Table 3 [21].

Table 3: Minimum Offset Distance [21]

U-turn Location	Number of Lanes	Offset Distance (ft.)
Median Opening	4	400
	6 or more	500
Signalized Intersection	4	550
	6 or more	750

Furthermore, a study evaluated the optimal separation distance between driveway exits and downstream U-turn locations. The separation distance includes the transition length and the exclusive left-turn bay. To collect travel time data, video cameras were installed at 29 different roadway segments. The average travel time that drivers spent at weaving sections while making right-turns followed by U-turns was calculated. Based on the travel time model, vehicles making RTUTs, on 6-lanes or more divided roadways, spend 4 seconds more than the vehicles performing the same maneuver on 4-lane roadways. Also, vehicles making RTUTs spend 3 seconds more at signalized intersections when compared to U-turns at median openings [19].

Long and Helms [22] investigated the impact of limiting access at unsignalized intersections in Fort Lauderdale, Florida. The results showed that limiting access at unsignalized intersections may increase operating speeds and improves safety for the arterial.

2.2.2 Effects of U-turns on capacity.

Liu et al. [23] investigated the impact of U-turning vehicles on capacity of signalized intersections. The research team recorded discharge times for 260 queues in the Tampa Bay area in Florida. The collected data included 571 U-turning vehicles and 1,441 left-turning vehicles. After conducting the analysis, a regression model was developed to estimate the adjustment factors. The adjustment factors were utilized to estimate the capacity reduction at a signalized intersection based on the presence of U-turning vehicles.

Another study estimated the capacity of U-turn movements at unsignalized intersections on four-lane divided roads. The study discussed several issues including conflicting traffic volume, impedance effects of minor movements, and left-lane capacity. After collecting the data, the capacity estimation method using the Highway Capacity Manual (HCM) was compared against the capacity measured in the field. It was found that using HCM method to estimate capacity for U-turn movements is very reasonable at unsignalized intersections. However, the HCM overestimated the capacity of the shared left-turn lane. Therefore, the effects of U-turning vehicles on the capacity of an exclusively left-turn lane were quantified using a regression model. The results showed that the capacity of the exclusively left-turn lane decreases with the increase of the percentage of U-turning vehicles, and the increase of major street traffic volume [24].

Carter et al. [25] investigated the operational effects of U-turns at signalized intersections. Vehicle headways in exclusive left-turn lanes were recorded at 14 signalized intersections. It was found that when the percentage of U-turning vehicles increases by 10 percent, the saturation flow rate decreases by 1.8 percent in the left-turn lane.

2.2.3 Safety performance.

Various research efforts [26-32] have evaluated the safety effects of using U-turns as alternatives to direct left turns. The results indicated that using U-turns reduced the number of conflict points and crashes compared to direct left-turns. As illustrated in Figure 12 and Table 4, median U-turns reduced the number of merge/diverge conflict points from 16 points to 12 points as compared to a four-leg signalized intersection. Moreover, all crossing (left-turn) conflict points were eliminated in the case of median U-turns.

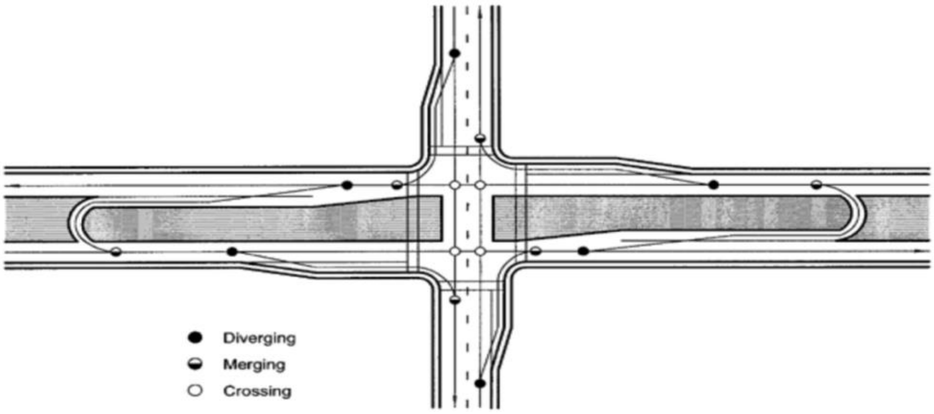


Figure 12: Conflict Diagram for a Four-leg Signalized Intersection with Median U-turns [33]

Table 4: Number of Conflict Points at a Four-leg Signalized Intersection Compared to a Four-leg Signalized intersection with a Median U-turn Crossover Configuration [33]

Conflict Type	Four-Leg Signalized Intersection	Median U-turn Crossover Configuration
Merging/diverging	16	12
Crossing (left-turn)	12	0
Crossing (angle)	4	4
Total	32	16

Liu et al. [34] compared the safety performance of different left-turn control types including a direct left-turn, a right-turn followed by a U-turn at a median opening, and a right-turn followed by a U-turn at a signalized intersection. A total of 2,873 conflicts were observed at sixteen driveway access sites. As shown in Figure 13, unconventional left-turn movements generate fewer conflicts compared to direct left-turn movements. Also, vehicles making RTUTs at a median opening generate fewer conflicts than those making RTUTs at a signalized intersection.

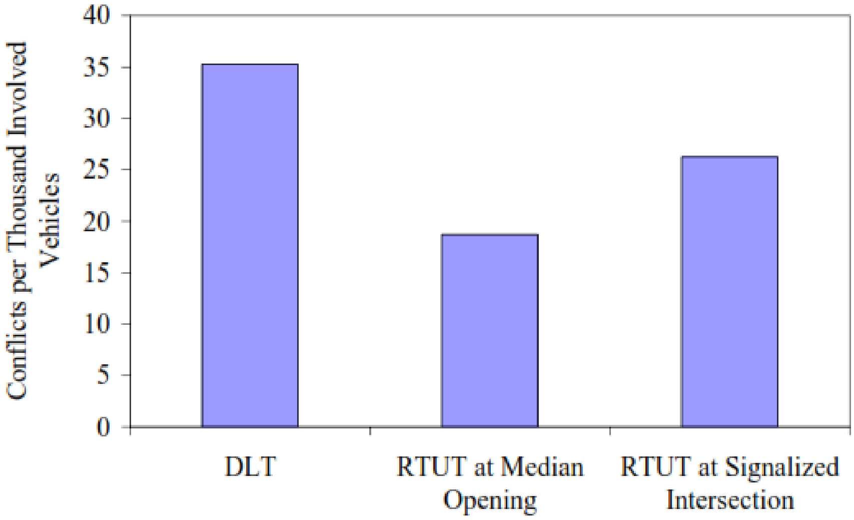


Figure 13: Conflict Rates for DLT and RTUT Movements [34]

A study conducted in Florida investigated safety performance of vehicles making right-turns followed by U-turns (RTUTs). Crash data was obtained from the Florida Department of Transportation (FDOT) at 179 different roadway segments. At the selected roadway segments, the separation distance between the driveway and the downstream U-turn location varies from 22.25m to 350.52m, with an average of 130.76m. Also, a total of 557 crashes were identified at the selected sites. Using the stepwise regression method, the separation distance and the traffic control at U-turn locations were found to be the most significant variables impacting the crash rate model. After developing the crash rate models, it was found that the crash rate at weaving sections decreased with the increase in the separation distance. The minimum separation distance was determined based on the 50th percentile value of the crash rate. If the U-turns are provided at median openings, the minimum separation distance from the driveway exit is found to be 104m on 4-lane divided roadways and 139m on 6- or more-lane divided roadways. In addition, if the U-turns are provided at signalized intersections, the minimum separation distance from the driveway exit is found to be 152m on 4-lane divided roadways and 229m on 6- or more-lane divided roadways [19].

In another study, seventy eight sites were selected to investigate the safety performance of U-turns at signalized intersections. During the 3-year study period, 65 of the 78 sites did not have any collisions involving U-turns. For the remaining sites, U-turn collisions ranged from 0.33 to 3.0 collisions per year [25].

2.2.4 Weaving analysis.

The safety of unconventional left-turn control types depends on the separation distance between driveway exits and downstream U-turn locations. Increasing the separation distance improves safety; however, travel time will increase for U-turning vehicles. Figure 14 illustrates different weaving patterns based on the volume approaching from the left and the separation distance [21].

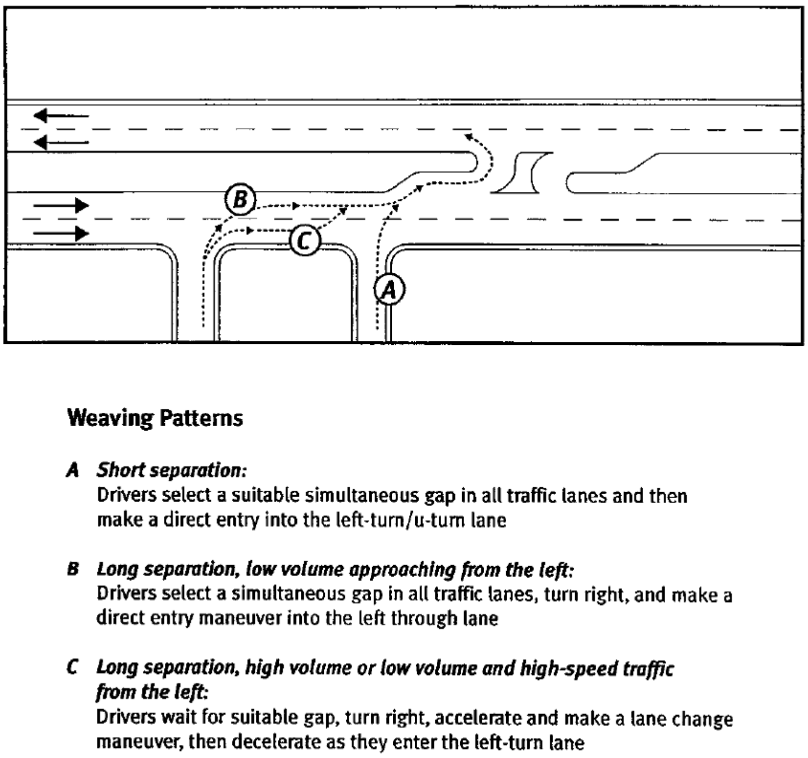


Figure 14: Right-turn/U-turn Maneuver from Access Drive to U-turn Median Opening [1]

Liu el al. [35] collected crash data at 140 road segments to investigate the impact of changing the separation distance between driveways and U-turn locations. The results indicated that the separation distances impact the safety of vehicles performing right-turns followed by U-turns. As the separation distance increases by 10 percent, the crashes related to RTUTs decreases by 4.5 percent. In addition, U-turns at signalized intersections result in more crashes compared to U-turns at median openings. Therefore, longer separation distances should be provided for U-turns at signalized intersections.

Zhou et al. [36] analyzed weaving and delay for right-turn followed by a U-turn control type on multi-lane roadways. A model was developed to determine the optimal weaving length for RTUTs by minimizing the average delay for U-turning movements.

2.3 Summary

Based on the literature review conducted, unconventional left-turn control types may reduce delays, travel time, and conflicts as compared to the direct left-turn control type at driveways and signalized intersections. Also, reducing the number of phases improves the capacity and the level of service of the intersection.

As it is noticed from the previous studies [1, 6, 8, 12], there is solid evidence that using U-turn treatments as alternatives to direct left-turns from driveways reduces the delay and the travel time under moderate and high traffic volume conditions. This thesis investigates if the same advantages are achieved by eliminating direct left-turns at signalized intersections instead of driveways. In addition, some studies [9, 13-17] considered providing U-turns at signalized intersections, where a major road is intersecting with a minor road either on the major road or on the minor road. The analyses showed that unconventional left-turn control types improved the capacity and the intersection's level of service. Also, the travel time and the total delay were reduced when compared to conventional intersections. However, this thesis investigates the operational effects of using U-turns on both arterials. Furthermore, the traffic volume was assumed to be dominant on the major road in the previous studies [9, 12-17]. However, in this thesis, the traffic volume will be distributed to cover more cases (i.e. equally distributed on all approaches, dominant on two opposite approaches, and dominant on two perpendicular approaches). Finally, very few of the previous studies considered the impact of left-turning percentages, ranging from 10 to 25 percent, on the intersection's performance. However, in this thesis the left-turning flow will range from 15 percent to 45 percent. Also, a previous study [20] considered an intersection between a minor road and a main road, while in this thesis the analyses will consider cases when both roads have equal traffic volumes.

Chapter 3: Methodology

In this thesis, certain procedures were followed to investigate the operational effects of using unconventional left-turn control types as alternatives to direct left-turns at signalized intersections. Three microsimulation models were developed, using Vissim, to investigate three left-turn control types including direct left-turns (DLT), right-turns followed by U-turns (RTUT), and U-turns followed by right-turns (UTRT). Many scenarios were considered through the variation of some traffic parameters to examine each left-turn control type. For the analysis, Synchro software was used to determine the optimized signal timing and the delay at the signalized intersection for each scenario. The optimized signal timings were then applied within Vissim software to evaluate the overall performance of each intersection.

3.1 Geometric Characteristics

The geometric details of the three control types (i.e. DLT, RTUT, and UTRT) are shown in Table 5. For each control type, two six-lane arterials are intersecting with each other. The dimensions are fixed at a constant value among the three left-turn control types so that an unbiased comparison can be made among the control types.

Table 5: Geometric Characteristics of Three Left-turn Control Types

	DLT	RTUT	UTRT
Lane width (m)	3.7	3.7	3.7
Median width (m)	3.7	3.7	3.7
Through lanes (per approach)	3	3	3
Channelized left-turn lanes (per approach)	1	-	-
Storage length of left-turn channelization (m)	120	-	-
Right-turn lanes (per approach)	1	2	1
Channelized right-turn lanes (per approach)	1	1	1
Right-turn control type	Free	Free/signalized	Free
Storage length of right-turn channelization (m)	100	100	100
U-turn lanes (per approach)	-	1	1
Storage length of U-turn channelization (m)	-	80	80

For the direct left-turn control type, all approaches have a free right-turn channelization, and each approach has a channelized left-lane. In contrast, for the right-turn followed by a U-turn control type, drivers desiring to turn left must first turn right at the main intersection through a signalized right-turn lane. After that, drivers must make a U-turn at a signalized median opening downstream of the intersection. For vehicles that are originally turning right on the intersection, the free right-turn canalizations are separated from the other lanes to allow right-turning vehicles to move without stopping at the signal. The separation is extended beyond the location of the U-turn to prevent right-turners from taking the U-turn at the median opening. Therefore, drivers desiring to turn left using the RTUT control type must first stop at the signal to turn right, and then execute a U-turn. Figure 15 illustrates the layout for the RTUT left-turn control type.

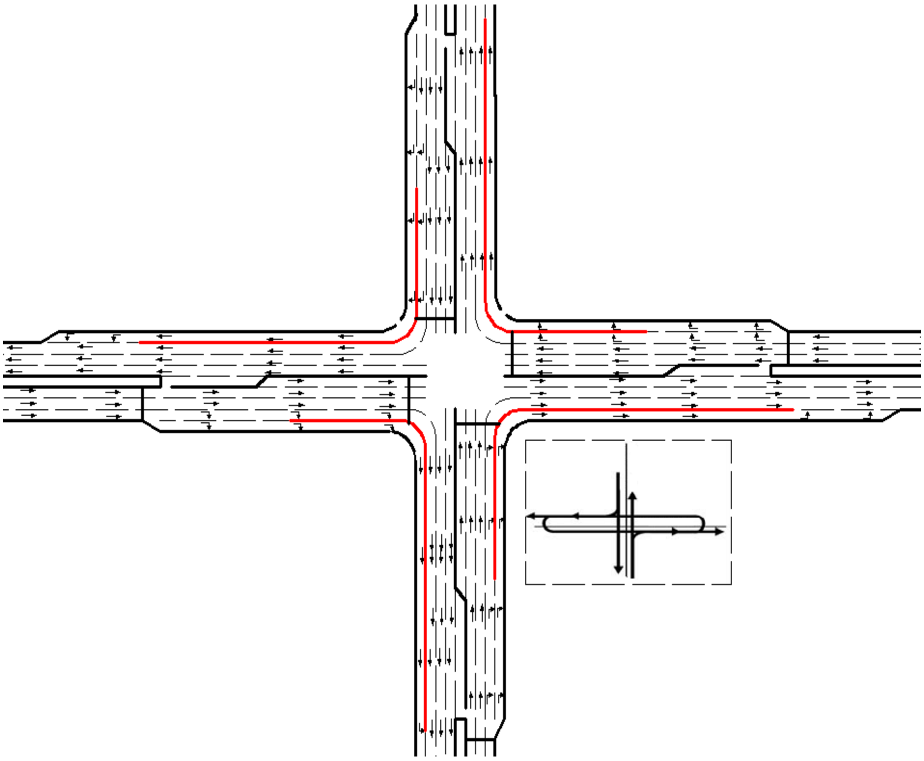


Figure 15: Layout for the Right-turn Followed by a U-turn Control Type

Moreover, for U-turns followed by right-turns control type, drivers desiring to turn left must first pass through the signalized intersection, make a U-turn at the signalized median opening, and then make a right-turn at the main intersection. In this control type, the right-turn channelization is shared between vehicles desiring to turn right and vehicles coming from the U-turn (desiring to perform indirect left-turns). Figure 16 illustrates the layout for the RTUT left-turn control type.

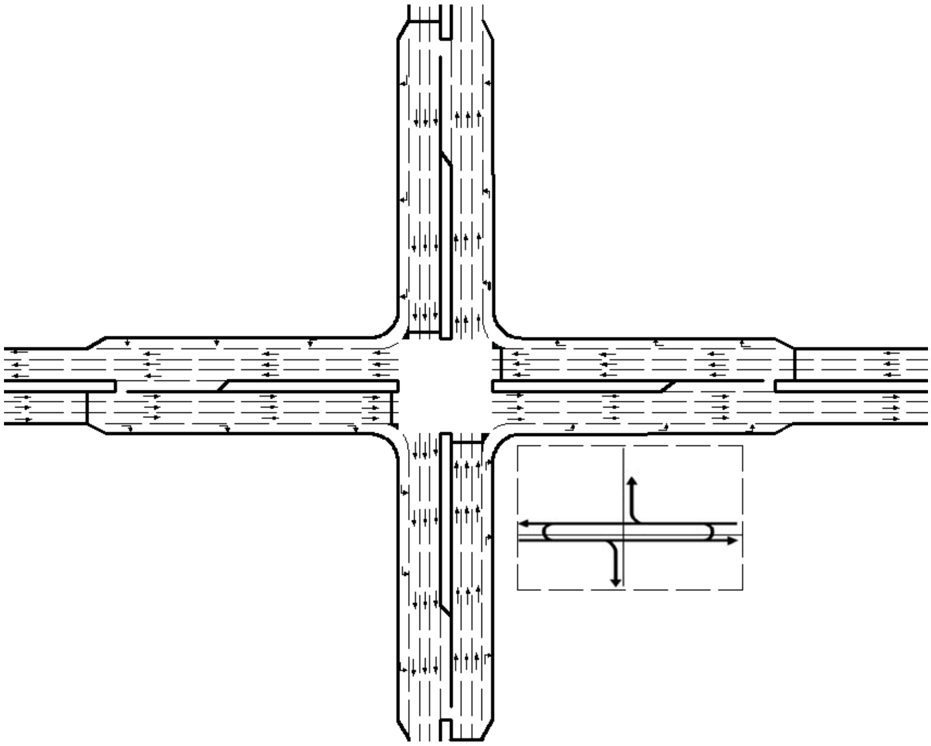


Figure 16: Layout for a U-turn Followed by a Right-turn Control Type

3.2 Analysis Tools

Different computer tools were used to achieve the objectives of this thesis. Synchro software was utilized to optimize traffic signal timing and to carry out an intersection capacity analysis. In addition, Vissim software was used to evaluate the overall operational performance of each left-turn control type.

3.2.1 Synchro software.

Synchro [37] is a very powerful tool for optimizing signal timing and performing a capacity analysis for signalized intersections. In fact, the software can be used to optimize intersection splits, offsets, and cycle lengths for individual intersections, arterials, or an entire network. In this study, Synchro was used to optimize signal timing and evaluate the intersection's delay for each scenario. Table 6 shows the network settings that were applied in Synchro throughout the various analyses.

For the direct left-turn control type, the phasing diagram consists of four phases as shown in Figure 17. Split signal phasing was used for this left-turn control type, which gives the green time for all vehicle movements of one direction followed by a phase for all vehicle movements of the opposite direction, as shown in Figure 17.

Table 6: Network Settings for Synchro Software

Peak Hour factor	0.92
Heavy Vehicles (%)	2
Flow Rate (vphpl)	1900
Travel Speed (Km/h)	60
Minimum Cycle Length (sec)	60
Maximum Cycle Length (sec)	120
Yellow Time (sec)	3
All Red Time (sec)	1

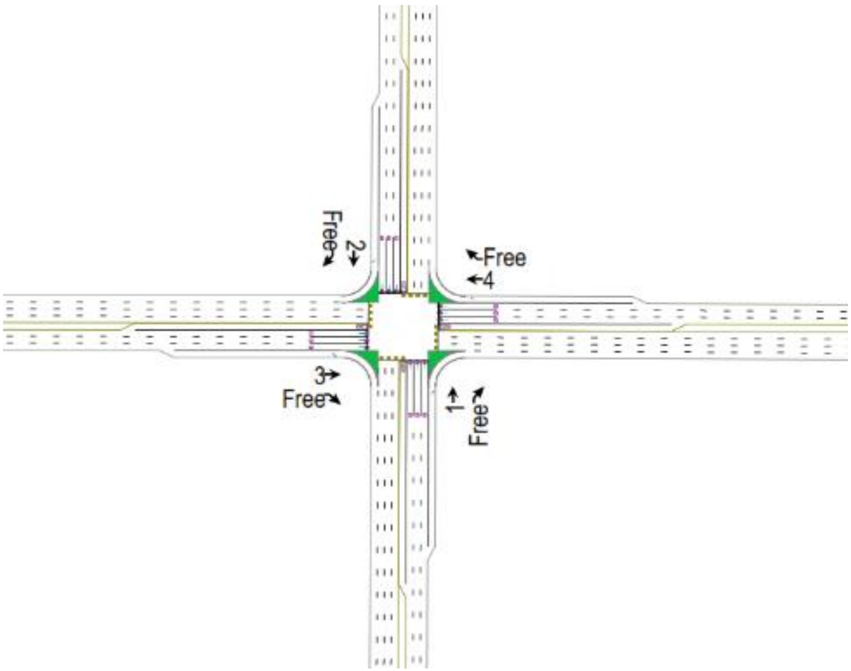


Figure 17: Number of Phases for DLT Control Type

For the right-turn followed by a U-turn control type, the number of phases at the main intersection was reduced to two phases instead of four phases, as shown in Figure 18. The first phase controls the northbound and the southbound through movements, and the U-turns in the eastbound and the westbound approaches. On the other hand, the second phase controls the eastbound and the westbound through movements, and the U-turns in the northbound and the southbound approaches. Moreover, phase 3 is an imaginary green phase that is constant because there are no conflicting movements to this phase. Therefore, phase 3 will not be applied on Vissim during the simulation process. In addition, right-tuning vehicles are going through a free right-turn channelization; however, the lane for the vehicles desiring to execute an indirect left-turn should be controlled by a traffic signal. Having two types of traffic control devices for each lane of the same movement cannot be done using this software. Therefore, the free right-turn volume will not be included in the analysis for this intersection because only one traffic control type can be used for the right-turn movement (i.e. a free right-turn and a traffic signal cannot be used at the same time). Excluding the right-turn volume from the analysis will not affect the signal timing since all right-turns are free right-turns.

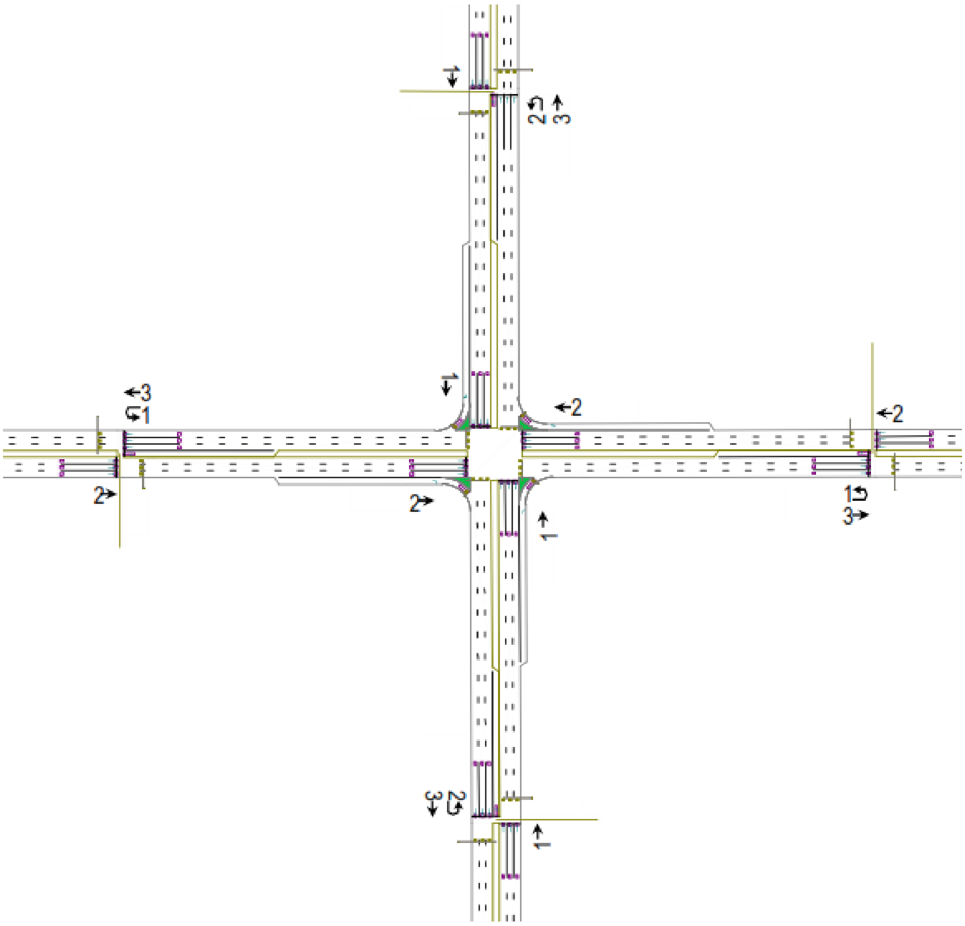


Figure 18: Number of Phases for RTUT Control Type

For the U-turn followed by a right-turn control type, the number of phases was also reduced to two phases instead of four phases at the main intersection, as shown in Figure 19. The two phases are the same as for the RTUT control type. In addition, the channelized right-turn lanes are shared between vehicles desiring to turn right and vehicles coming from the U-turn that also want to perform indirect left-turns.

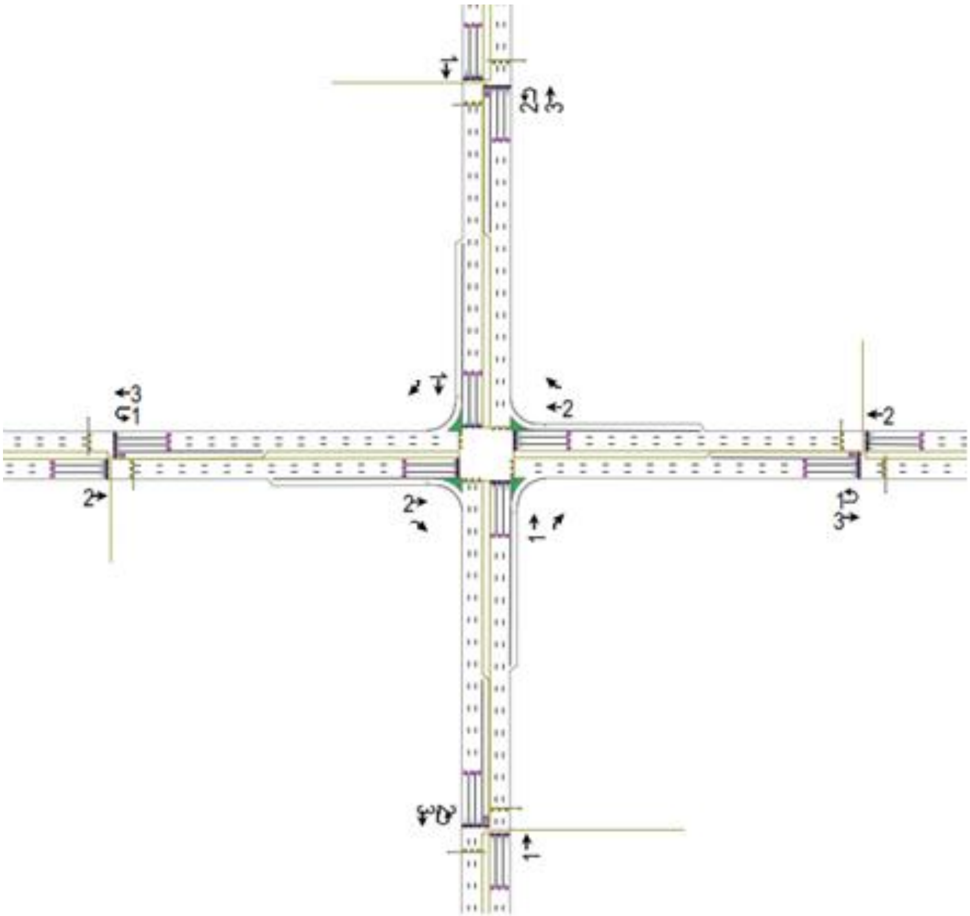


Figure 19: Number of Phases for UTRT Control Type

Figure 20 illustrates the phase diagrams for the three left-turn control types. As demonstrated, the phase diagram for the direct left-turn control type consists of four phases. However, the phase diagrams for unconventional left-turn control types consist of only two phases.

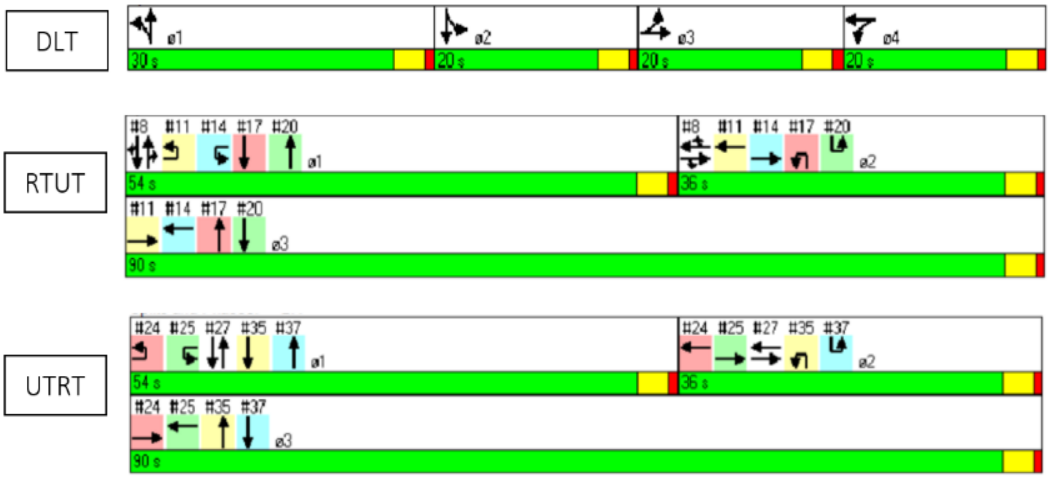


Figure 20: Phase Diagrams for the Three Left-turn Control Types

3.2.2 Vissim software.

Vissim [38] 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 transportation engineering's measures of effectiveness. In this study, Vissim was 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, the vehicle kilometers travelled (VKT), and level of service (LOS).

To develop and evaluate each model using Vissim, the following steps were followed:

- Draw background maps using AutoCAD for each left-turn control type (i.e. DLT, RTUT, UTRT), which will be recognized by Vissim.
- Import the maps into the software platform, and draw the links and the connectors as shown in Figure 21.
- Determine input locations and route for vehicles in each control type.
- Add a signal controller for each intersection, and determine the number of signal groups based on the number of phases.
- Put signal heads in all of the desired lanes, as shown in Figure 21.
- Define the conflict and reduced speed areas.
- For each scenario, input simulation data such as input, static routes, and signal timing for vehicles.
- Repeat the simulation five times for each scenario, exclude the largest and the smallest values from the results, and calculate the trimmed mean using the remaining three values.
- Compare and analyze simulation results for all of the scenarios, and draw conclusions.

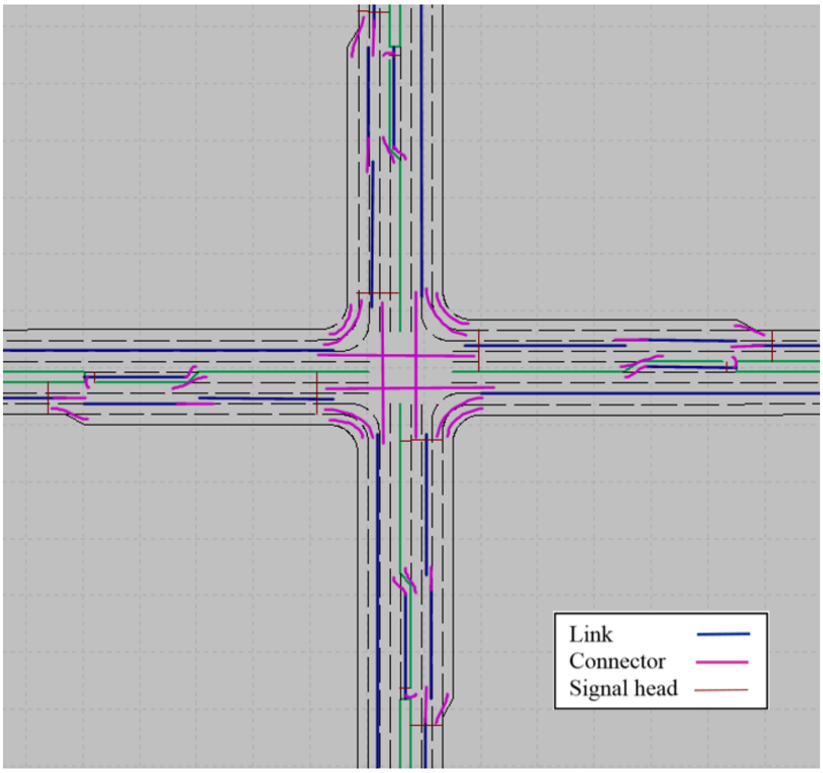


Figure 21: Vissim Model for Right-turn Followed by a U-turn Control Type

Chapter 4: Experimental Design

This chapter of the thesis explains the traffic parameters considered in the analysis, and defines the experimental code which is given to each scenario.

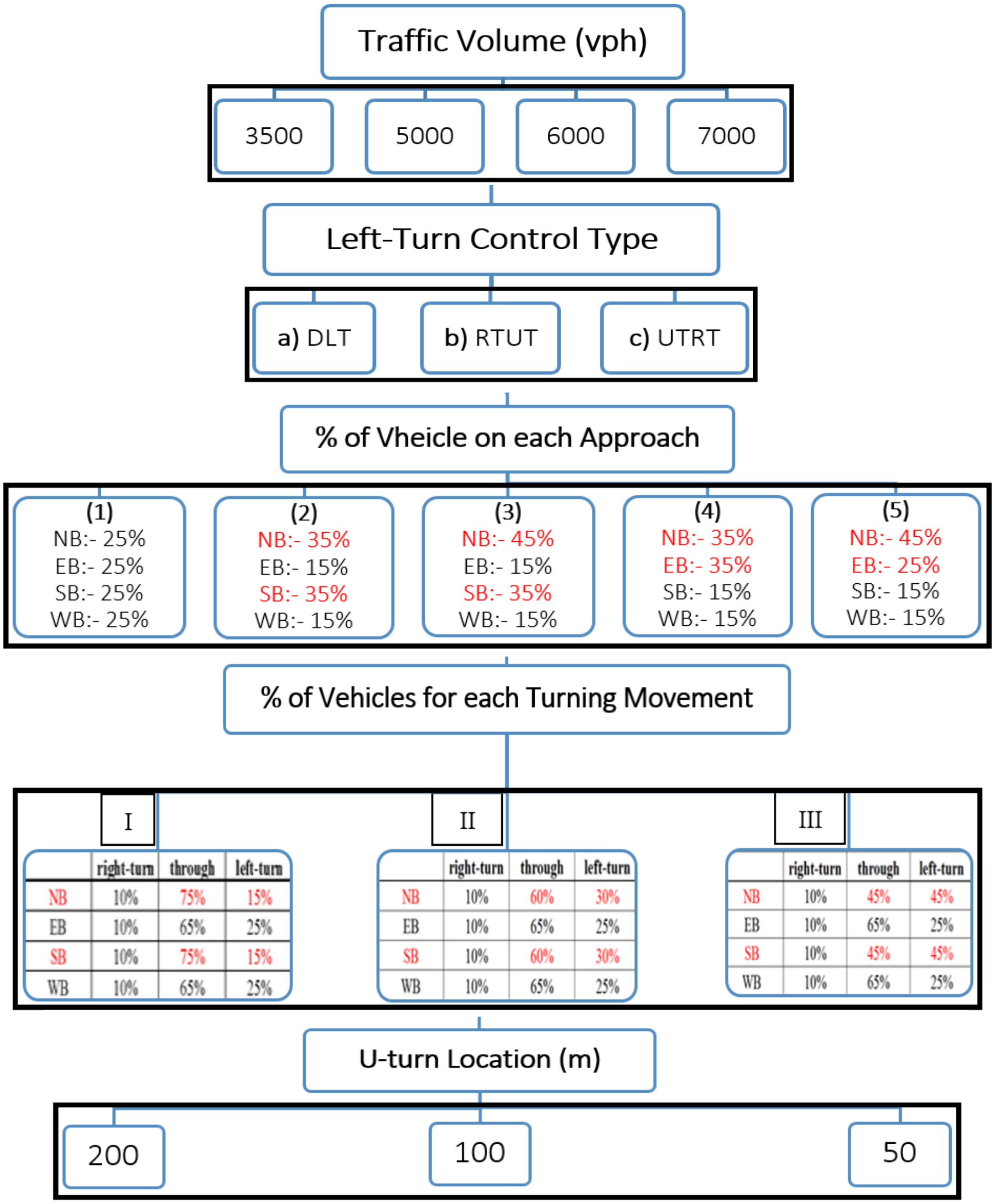
4.1 Considered Parameters

As shown in the experimental design, presented in Figure 22, different parameters were considered in the analysis including the total volume on the intersection, the left-turn control type, the traffic volume distribution on each approach, the percentage of vehicles for each turning movement, and the location of the U-turns. 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 Figure 22 illustrates the experimental design for one traffic volume only. The same parameters apply for the other traffic volumes as well. The analysis included 420 scenarios, which is a reasonable number to reach precise conclusions.

The percentage of vehicles for each turning movement represents three cases, and roman numerals were used to identify each case (i.e. I, II, and III). For all cases, right-turn movements represent 10 percent of the total volume assigned to each approach, and the turning percentages for the eastbound and the westbound approaches are constant. For case I, the left-turn movements for the northbound and the southbound approaches represent only 15 percent of the total volume assigned to these approaches. Moreover, the left-turn percentage represents 30 percent for case II and 45 percent for case III of the total volume assigned on the northbound and the southbound approaches.

The traffic volume distribution on each approach represents several cases, and Arabic numbers were used to identify each case. For case 1, the total traffic volume is equally distributed on all approaches of the intersection, which represents a case where all of the approaches have the same level of congestion. As shown in Figure 23, each of the approaches A, B, C, D is assigned 25 percent of the total traffic volume. For cases 2 and 3, traffic volume is dominant on two opposite approaches, which is the case when there is a major road intersecting with a minor road. For case 2, 35 percent of the total volume is assigned to approach A as well as to approach C. However, for case 3, 45 percent of the total volume is assigned to approach A, and 25 percent of the volume is assigned to approach C. Furthermore, for cases 4 and 5, traffic volume is dominant on two perpendicular approaches (i.e. more traffic volume is assigned to approaches A and B). For case 4, 35 percent of the total volume is assigned to approach A as well as to approach B. However, for case 5, 45 percent of the total volume is assigned to approach A, and 25 percent of the volume is assigned to approach B.

Three left-turn control types were considered in the analysis, and English alphabets were used to identify each case. Case (a) represents the direct left-turn control type, whereas cases (b) and (c) represent the right-turn followed by a U-turn and the U-turn followed by a right-turn, respectively.



I

	right-turn	through	left-turn
NB	10%	75%	15%
EB	10%	65%	25%
SB	10%	75%	15%
WB	10%	65%	25%

II

	right-turn	through	left-turn
NB	10%	60%	30%
EB	10%	65%	25%
SB	10%	60%	30%
WB	10%	65%	25%

III

	right-turn	through	left-turn
NB	10%	45%	45%
EB	10%	65%	25%
SB	10%	45%	45%
WB	10%	65%	25%

Figure 22: Experimental Design

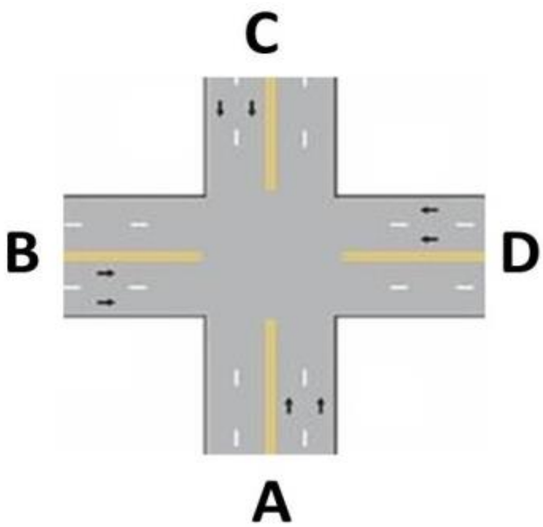


Figure 23: Typical Four-leg Intersection

4.2 Experimental Code

For ease of reference, each scenario will be given a unique code as shown in Table 7. The code includes the following:

- Location of the U-turn (i.e. 200, 100, and 50).
- Intersection's turning movements in Roman numerals (i.e. I, II, and III).
- Traffic volume distribution on each approach in Arabic numbers (i.e. 1, 2, 3, 4, and 5).
- Left-turn control type in English alphabets (i.e. a, b, c).
- Total volume at the intersection (i.e. 3,500; 5,000; 6,000; and 7,000)

Table 7: Experimental Code

U.I.P.L.T		
U	Location of the U-turn	200
		100
		50
I	Intersection Turning movements	I
		II
		III
P	Percentage of vehicles on each approach	1
		2
		3
		4
		5
L	Left-turn control type	a
		b
		c
T	Total traffic volume on the intersection	3,500
		5,000
		6,000
		7,000

For example, Figure 24 shows the experimental code for the scenario with the following characteristics:

- The U-turn locations are 200 meters away from the main intersection.
- The left-turn movements for the northbound and the southbound approaches are equal to 15 percent of the total volume assigned to these approaches.
- The total traffic volume is equally distributed among all approaches of the intersection.
- Direct left-turn control type.
- Total traffic volume on the intersection is equal to 3,500 vph.

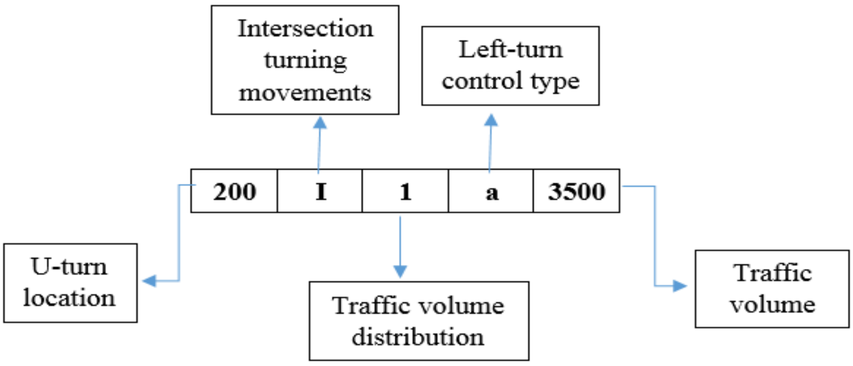


Figure 24: Experimental Code for Case 200.I.1.a.3500

Also, Figure 25 shows the experimental code to describe all of the scenarios that have the same U-turn location, intersection's turning movements, and traffic volume distribution. This could be used to describe a graph that shows all three left-turn control types and all of the considered traffic volumes.

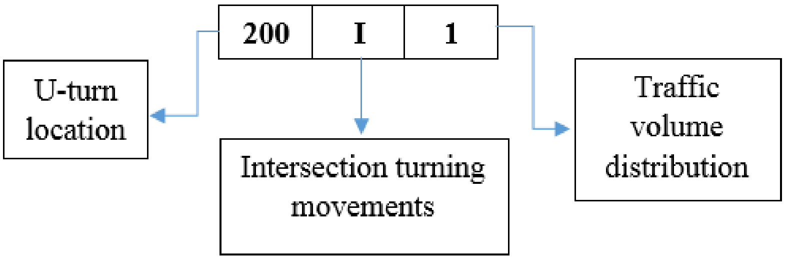


Figure 25: Experimental Code for Case 200.I.1

Figure 26 shows the experimental code to describe all of the scenarios that have the same U-turn location, traffic volume distribution, and total traffic volume.

This could be used to describe a graph that shows all three left-turn control types and all of the intersection's turning movements.

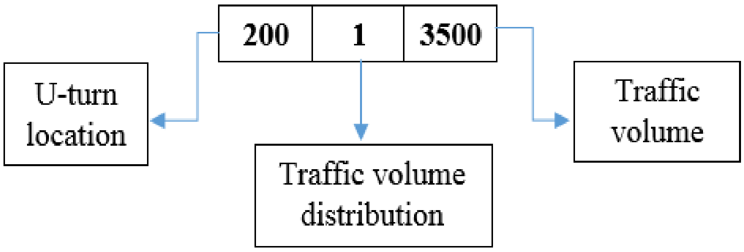


Figure 26: Experimental Code for Case 200.I.3500

Figure 27 shows the experimental code to describe all of the scenarios that have the same intersection's turning movements, traffic volume distribution, left-turn control type, and total traffic volume. This could be used to illustrate the impact of changing the U-turn locations for the unconventional left-turn control types.

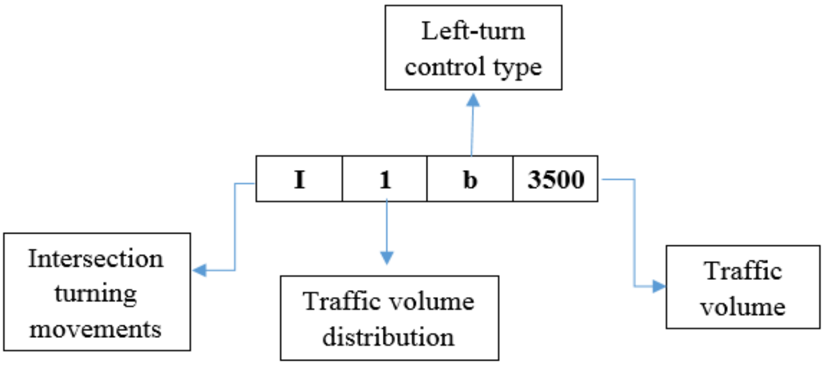


Figure 27: Experimental Code for Case I.1.b.3500

Finally, Figure 28 shows the experimental code to describe all of the scenarios that have the same intersection's turning movements, and left left-turn control type. This could be used to describe a graph that shows all of the considered U-turn locations, traffic volume distribution, and total traffic volume on the intersection.

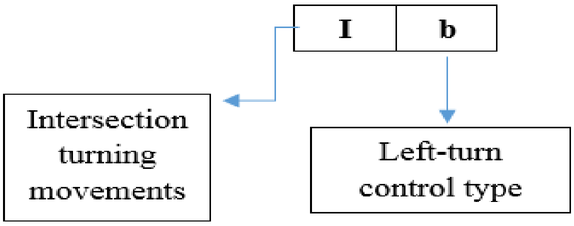


Figure 28: Experimental Code for Case I.b

Chapter 5: Results and Discussion

The analysis was performed to evaluate different left-turn control types including a direct left-turn, right-turn followed by a U-turn, and a U-turn followed by a right-turn. Synchro software was used to determine the optimized signal timing, and the Vissim software was used to evaluate the intersection's overall performance. In this study, the analysis was performed for many purposes. First, demonstrate the impact of using a combination of right-turns and U-turns, as alternatives to direct left-turns, on the intersection's performance. Also, if using indirect left-turns can improve the overall performance of intersections or not. Furthermore, determine the most efficient left-turn control type for each scenario based on the prevailing traffic conditions. Finally, recommend the optimal location of the U-turns for unconventional left-turn control types for all of the considered scenarios.

5.1 Signal Optimization and Intersection Delay

Synchro software was utilized in this study for two main purposes: First, to get the optimized signal timings for all of the considered scenarios; and second, to evaluate intersection delay for the three left-turn control types (i.e. DLT, RTUT, and UTRT). For unconventional control types, overall intersection delay was obtained by calculating the weighted average of delay at the main junction and all of the U-turn locations. Figure 29 presents delay comparison for case 200.I.1 using Synchro for all traffic volumes considered. As illustrated, unconventional control types (i.e. RTUT, and UTRT) have much less intersection delay compared to the DLT control type. Also, both unconventional control types have comparable delay over the considered range of traffic volumes. As shown in Figure 29, the delay for a DLT varies from about 30 to 130 seconds, while the delay for unconventional control types varies from nearly 7 to 12 seconds. As the traffic volume increases, delays for the DLT control type increases at a higher rate compared to the unconventional control types. Moreover, intersection delay has a similar trend as the one for case 200.I.1, and this is for all considered scenarios in the experimental design presented in Figure 22.

It should be noted that Synchro's delay calculation for unconventional left-turn control types is not accurate because it does not include the additional travel distance when applying RTUT or UTRT. Furthermore, there is an additional travel time that needs to be considered for the RTUT and UTRT control types. Therefore, Synchro will be used only to obtain the optimized signal timings for all scenarios, and it will not be used to compare the overall performance of the intersections.

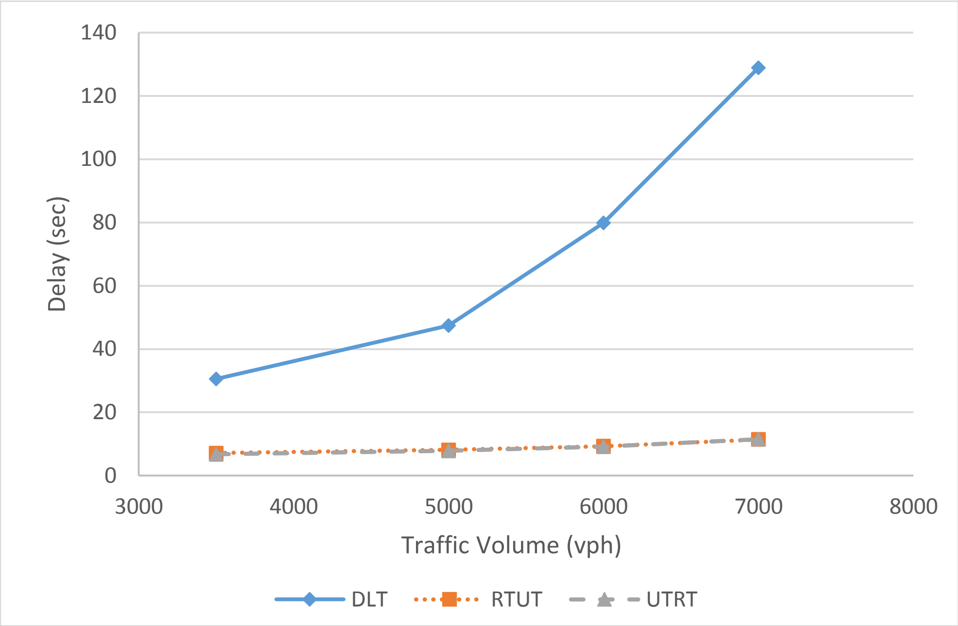


Figure 29: Comparison of Delay for Case 200.I.1 using Synchro

5.2 Microscopic Simulation

Because calculating delay for unconventional left-turn control types using Synchro is misrepresentative, more detailed analysis was performed using Vissim software. A model for each left-turn control type was created using Vissim to evaluate different scenarios. All scenarios presented in the experimental design were simulated using Vissim, and network performance was obtained for each scenario.

To achieve robust results, five 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 used in this study to reduce the effects of random variations on the calculated mean.

5.2.1 Delay comparison.

Table 8 presents delay comparisons for the three left-turn control types, where the U-turn locations are 200 meters away from the main intersection. Also, the left-turn movements are equal to 15 percent for northbound and southbound approaches. Each of the figures presents different distribution of the total volume on the intersection. In addition, Figures 30 to 34 present delay comparisons for each case.

Table 8: Comparison of Delay for Case 200.I

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
200.I.1	3,500	23.9	22.4	17.3
	5,000	28.8	24.5	19.1
	6,000	36.9	25.9	20.5
	7,000	42.6	28.9	22.9
200.I.2	3,500	25.0	20.3	15.7
	5,000	30.8	20.9	17.2
	6,000	36.5	23.2	19.2
	7,000	60.6	26.0	22.6
200.I.3	3,500	25.3	23.8	20.0
	5,000	29.5	21.8	18.1
	6,000	36.5	25.0	21.5
	7,000	74.7	28.5	25.1
200.I.4	3,500	25.2	23.3	17.5
	5,000	29.9	27.6	20.9
	6,000	35.5	30.1	24.5
	7,000	58.2	40.4	36.1
200.I.5	3,500	25.7	26.0	22.3
	5,000	29.2	24.5	20.4
	6,000	36.0	29.5	24.7
	7,000	72.8	39.6	36.8

For case 200.I.1, DLT control type shows more delay compared to the unconventional left-turn control types, as shown in Figure 30. At low traffic volumes, 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 of the left-turn control types, irrespective of different traffic volumes. In these simulations, the U-turn locations are 200 meters away from the main intersection; accordingly, vehicles making indirect left-turns take a considerable amount of time before reaching the U-turn locations. In the case of a RTUT, the traffic light at the U-turn changes from green to red before vehicles reach the U-turn locations. Therefore, vehicles making RTUTs stop at the signalized intersection and the U-turn location, whereas vehicles making UTRTs stop only once at the signalized intersection.

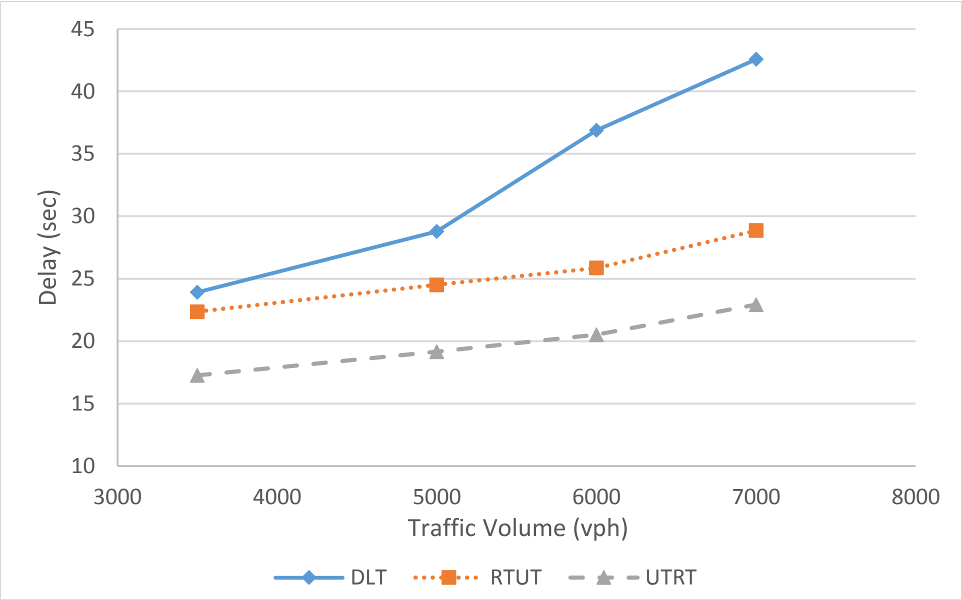


Figure 30: Comparison of Delay for Case 200.I.1

For case 200.I.2, the DLT control type has the highest delay and the UTRT control type has the least delay. At traffic volumes greater than 5,000 vph, the gap between UTRT and RTUT control types start to decrease. Also, intersection delay for the DLT control type increases dramatically, as presented in Figure 31. Unconventional left-turn control types have less delay compared to DLTs, especially at high traffic volumes because a longer green time is allocated to the phases serving the through movements. Vehicles performing indirect left-turns are equal to 15 percent only for northbound and southbound approaches; therefore, their impact on the other movements is insignificant.

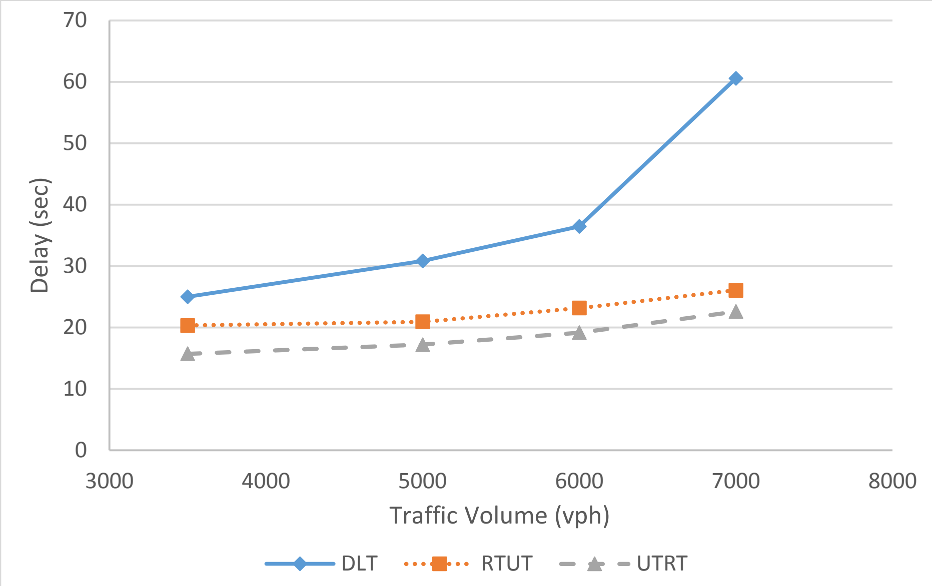


Figure 31: Comparison of Delay for Case 200.I.2

In addition, Figure 32 shows delay comparisons for case 200.1.3. As illustrated, DLT has the highest intersection delay, and both RTUT and UTRT have comparable delay over the considered range of traffic volumes because significant queues do not form at the main intersection even at high traffic volumes. At a traffic volume of 7,000 vph, the intersection delay for the DLT reaches about 74 seconds, while the intersection delay for RTUT and UTRT reaches approximately 28 seconds and 25 seconds, respectively. Intersection delay for the DLT increases at a rapid rate with high traffic volumes because queues begin to form and increase when the traffic volume exceeds 6,000 vph.

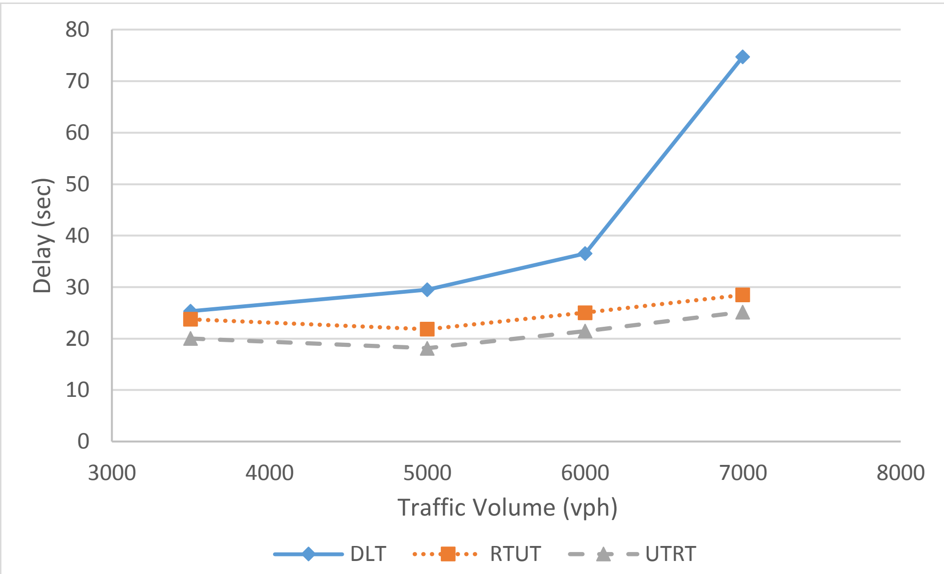


Figure 32: Comparison of Delay for Case 200.I.3

Moreover, intersection delay for case 200.I.4 is very similar to the other cases as illustrated in Figure 33. When the total traffic volume on the intersection exceeds 6,000 vph, the delay for unconventional left-turn control types increases at a higher rate compared to the other cases. Queues begin to form at the main intersection and the U-turn locations because traffic volume is dominant on two perpendicular approaches for case 200.I.4. Unconventional control types have less delay compared to a DLT because the left-turn movements are equal to 15 percent only for northbound and southbound approaches.

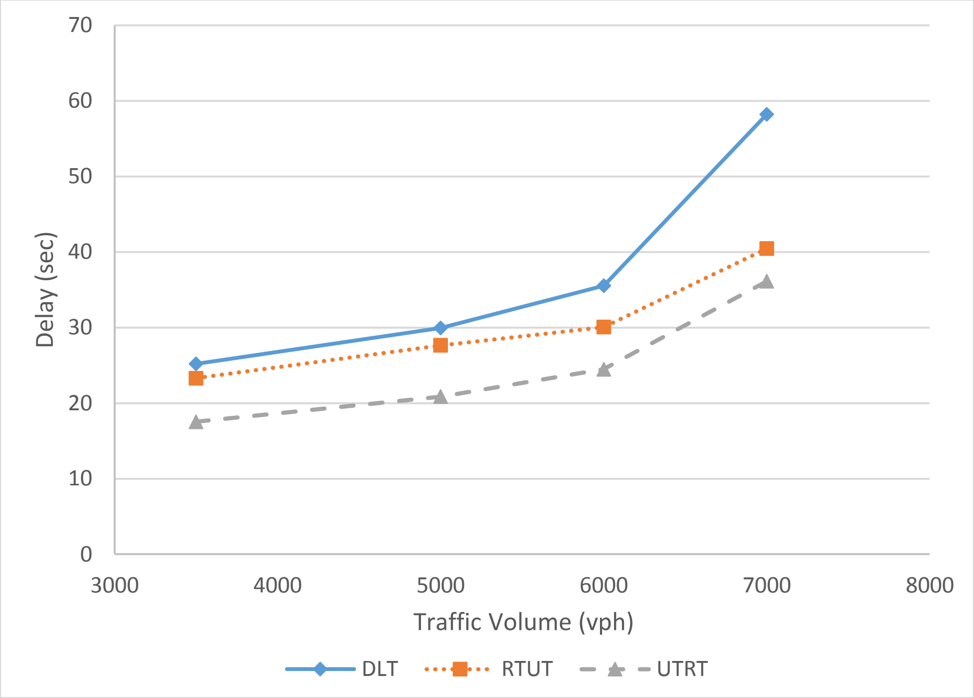


Figure 33: Comparison of Delay for Case 200.I.4

Furthermore, the DLT has the highest intersection delay for case 200.I.5, as shown in Figure 34. At a traffic volume of 3,500 vph, the delay for both a DLT and a RTUT is equal to about 20 seconds. Intersection delay for the DLT increases with the increase of traffic volume until it reaches nearly 73 seconds at a traffic volume of 7,000 vph. The UTRT has the least intersection delay and unconventional control types have a comparable delay over the considered range of traffic volumes. As mentioned earlier, the delay for a DLT increases significantly at high traffic volumes because of the queue formation at the main intersection. Also, the delay for unconventional left-turn control types increases at a higher rate at high traffic volumes because the traffic volume is dominant on two perpendicular approaches for case 200.I.5.

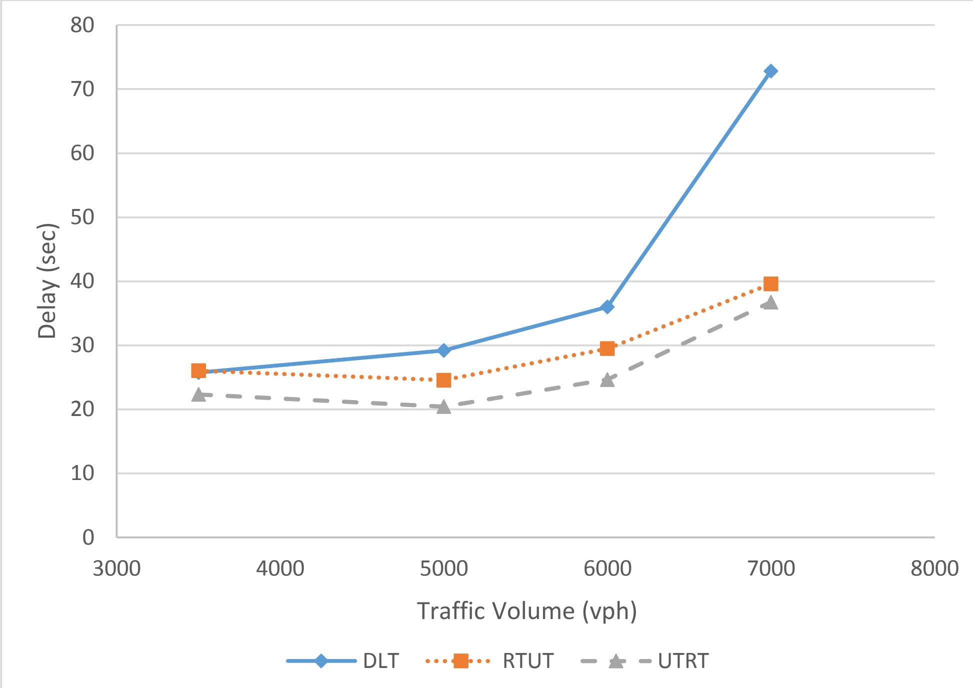


Figure 34: Comparison of Delay for Case 200.I.5

Table 9 presents delay comparisons for the three left-turn control types, where the U-turn locations are 200 meters away from the main intersection. Also, the left-turn movements are equal to 30 percent for northbound and southbound approaches. Each of the figures presents a different distribution of the total volume on the intersection. In addition, Figures 35 to 39 present delay comparisons for each case.

Figure 35 illustrates delay comparisons for case 200.II.1, for all traffic volumes. As shown, a DLT and a RTUT have similar delay at low traffic volumes. As the total volume on the intersection increases, the gap increases between the DLT and unconventional control types. The UTRT has the least intersection delay followed by a RTUT and then a DLT over the considered range of traffic volumes. A right-turn followed by a U-turn shows more delay compared to a U-turn followed by a right-turn for the same reason mentioned in case 200.I.1. Because traffic volume is equally distributed on all approaches, increasing left-turn movements to 30 percent for northbound and southbound approaches did not make a significant change to the intersection delay. As illustrated, the intersection delay for a DLT ranges from nearly 24 to about 50 seconds. Also, the intersection delay for a RTUT ranges from about 24 to approximately 32 seconds. Finally, the intersection delay for a UTRT ranges from nearly 17 to about 25 seconds.

Table 9: Comparison of Delay for Case 200.II

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
200.II.1	3,500	24.1	24.5	17.7
	5,000	29.0	26.5	20.1
	6,000	37.6	27.9	21.7
	7,000	49.8	31.4	24.4
200.II.2	3,500	25.3	23.3	19.6
	5,000	32.1	24.1	22.0
	6,000	40.4	27.0	21.8
	7,000	87.8	35.0	28.6
200.II.3	3,500	25.5	26.7	19.8
	5,000	31.4	24.6	21.2
	6,000	36.8	28.0	27.7
	7,000	75.9	34.5	50.9
200.II.4	3,500	20.6	25.8	18.4
	5,000	29.9	29.7	22.0
	6,000	37.7	32.5	26.0
	7,000	80.4	39.3	30.8
200.II.5	3,500	25.7	28.4	19.7
	5,000	29.5	28.9	23.8
	6,000	38.0	32.2	28.1
	7,000	81.5	44.6	51.8

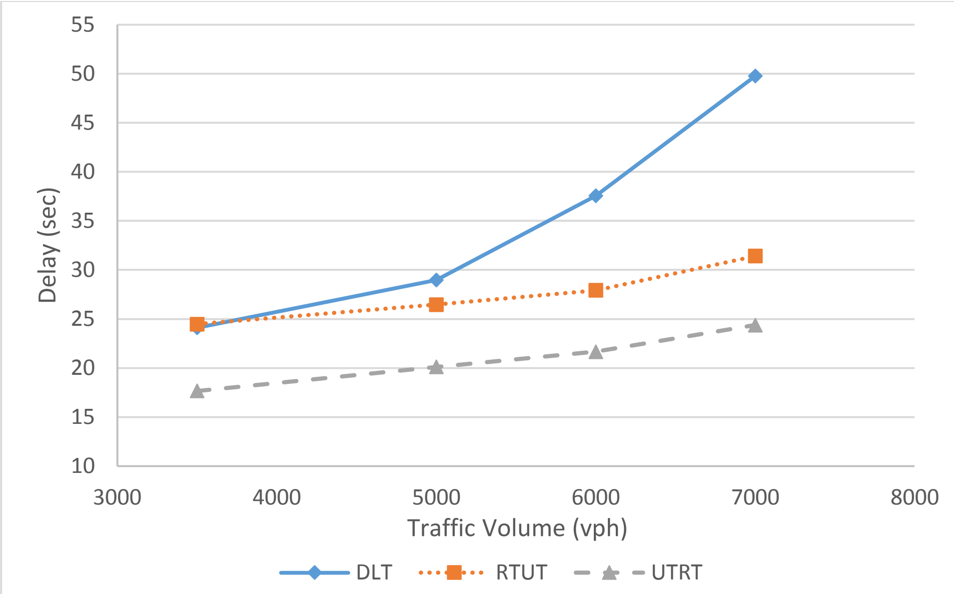


Figure 35: Comparison of Delay for Case 200.II.1

A comparison of intersection delay for case 200.II.2 is illustrated in Figure 36. As shown, the intersection delay is very similar for unconventional left-turn control types (i.e. RTUT and UTRT) over the considered range of traffic volumes because the traffic volume is dominant on the northbound and the southbound approaches. Having the majority of traffic volume on two opposite approaches results in less delay compared to the case when traffic volume is dominant on two perpendicular approaches. Also, the delay for the DLT increases at a higher rate when the traffic volume exceeds 6,000 vph, similar to the other cases.

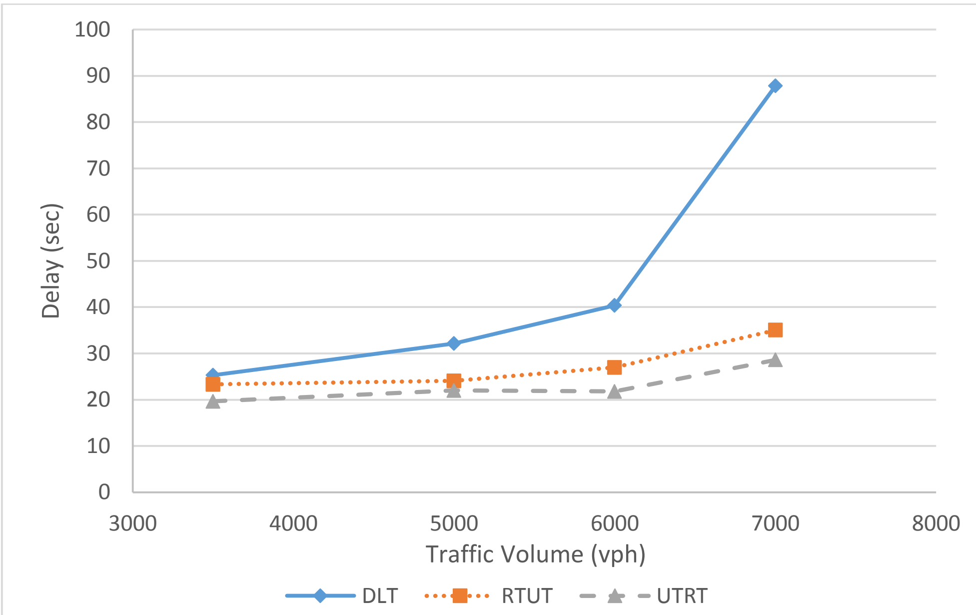


Figure 36: Comparison of Delay for Case 200.II.2

Figure 37 shows the delay comparisons for case 200.II.3. In this case, the UTRT has the least delay when the traffic volume is less than 6,000 vph. When the traffic volume exceeds 6,000 vph, RTUT has the least delay compared to the other left-turn control types. It appears that RTUT, for this case, has a reasonable delay over a fairly wide range of traffic volumes. In case 200.II.3, 45 percent of the total volume is assigned on the northbound approach; therefore, intersection delay for the U-turn followed by a right-turn increases at high traffic volumes because a queue starts to form at the U-turn bay for vehicles coming from the northbound road link. When 45 percent of the total volume is assigned on the northbound approach and left-turn movements are equal to 30 percent for this approach, intersection delay for the UTRT control type increases dramatically at high traffic volumes.

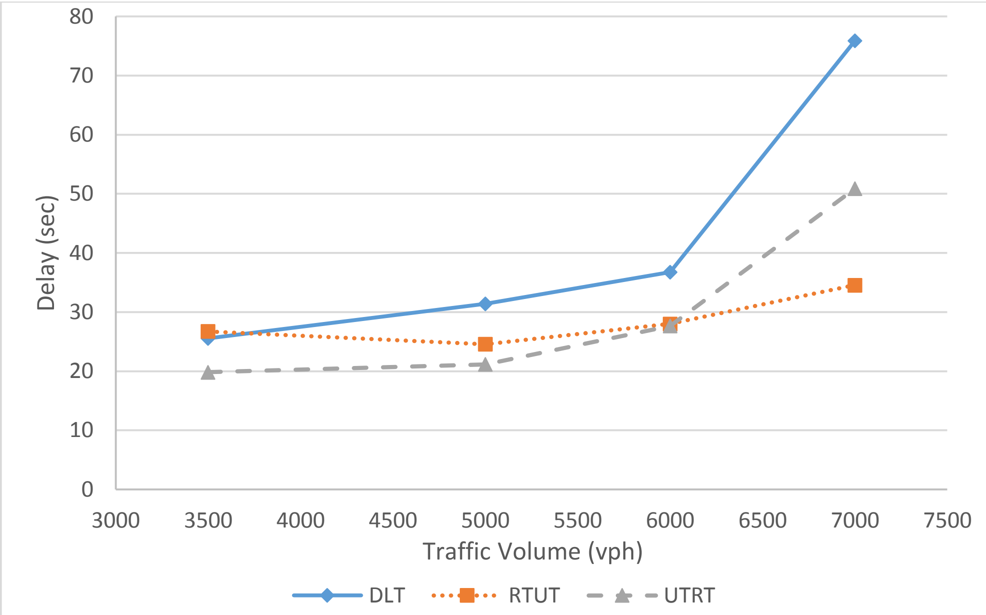


Figure 37: Comparison of Delay for Case 200.II.3

As shown in Figure 38, UTRT has the least delay for case 200.II.4. For traffic volumes less than 5,000 vph, the DLT shows less delay compared to the RTUT because queues did not form at the signalized intersection for vehicles making a DLT, and vehicles making a RTUT travel a longer distance. However, for traffic volumes higher than 5,000 vph, intersection delay for a DLT increases at a higher rate compared to unconventional control types until it reaches about 80 seconds. Delay curves for both unconventional left-turn control types have a slightly positive slope over the considered range of traffic volumes. Intersection delay for unconventional left-turn control types ranges from about 18 to nearly 40 seconds.

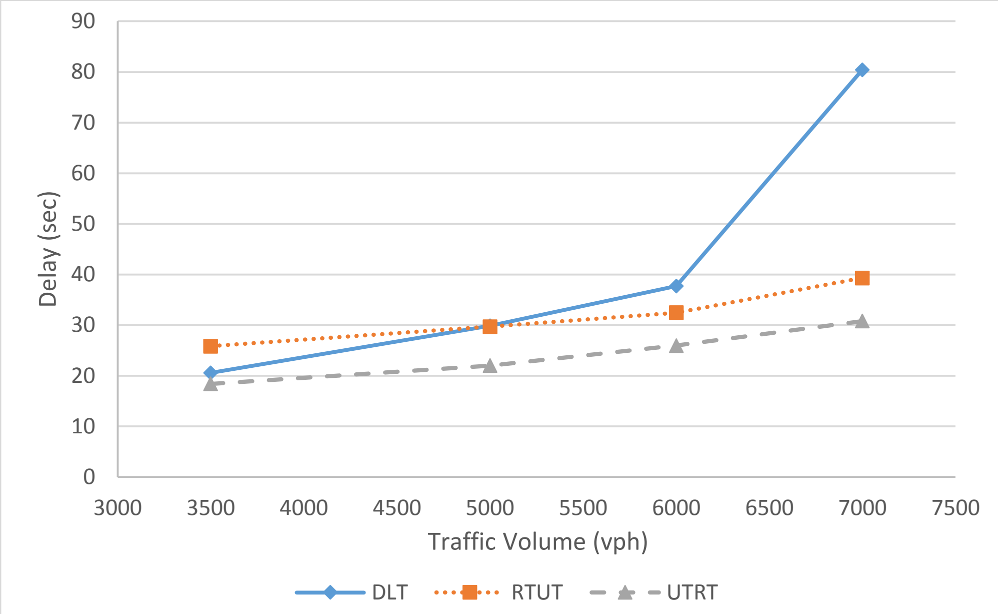


Figure 38: Comparison of Delay for Case 200.II.4

Figure 39 presents delay comparisons for a condition in which the traffic volume is dominant on two perpendicular approaches (i.e. case 200.II.5). At traffic volumes less than 5,000 vph, the DLT shows less delay in comparison to the RTUT due to the same reasons mentioned in the previous case. At traffic volumes less than 6,500 vph, the UTRT has the least delay compared to the other control types. When the total traffic volume on the intersection exceeds 6,500 vph, UTRT shows more delay compared to RTUT due to the queue formation at the U-turn bay for vehicles coming from the northbound approach, as mentioned in case 200.II.3.

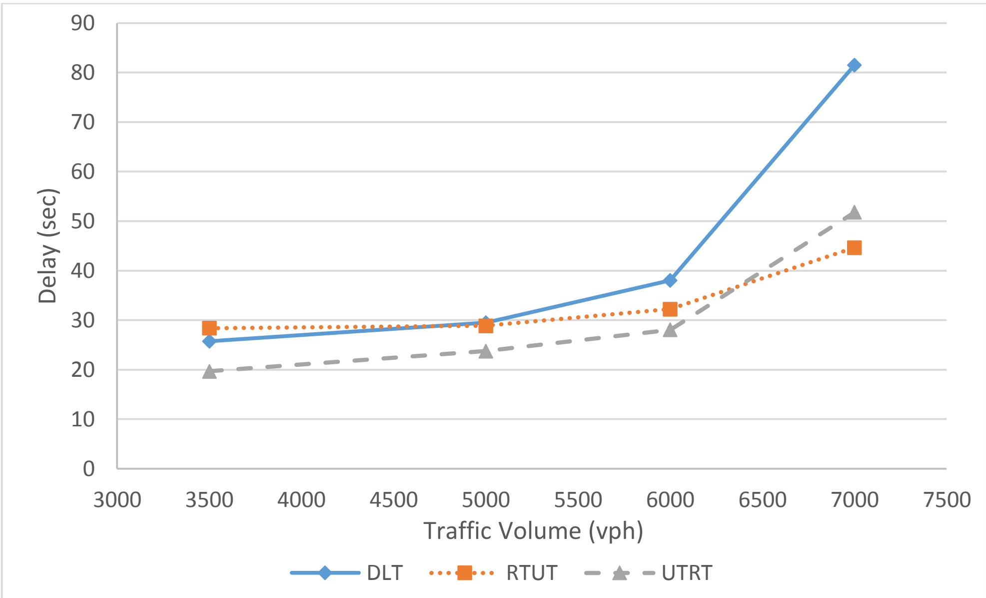


Figure 39: Comparison of Delay for Case 200.II.5

Table 10 presents delay comparisons for the three left-turn control types, where the U-turn locations are 200 meters away from the main intersection. In addition, left-turn movements are equal to 45 percent for northbound and southbound approaches. Each of the figures presents different distribution of the total volume on the intersection. In addition, Figures 40 to 44 present delay comparisons for each case.

Table 10: Comparison of Delay for Case 200.III

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
200.III.1	3,500	29.5	26.5	20.1
	5,000	56.1	30.1	24.2
	6,000	87.9	31.2	22.5
	7,000	168.4	36.7	29.2
200.III.2	3,500	51.8	24.2	25.8
	5,000	117.4	27.7	30.8
	6,000	181.0	31.9	41.0
	7,000	182.2	64.0	96.9
200.III.3	3,500	67.6	24.6	25.9
	5,000	111.9	28.6	35.3
	6,000	149.5	42.0	70.6
	7,000	158.2	79.4	69.4
200.III.4	3,500	27.4	28.5	21.2
	5,000	48.4	35.5	25.7
	6,000	117.8	39.9	31.0
	7,000	160.0	76.4	45.1
200.III.5	3,500	56.3	27.4	24.1
	5,000	98.0	33.1	34.8
	6,000	112.7	59.0	67.3
	7,000	142.8	68.4	70.8

As shown in Figure 40, the DLT shows more delay compared to unconventional left-turn control types over the considered range of traffic volumes. In addition, the variation of delay for unconventional left-turn control types is insignificant over a wide range of traffic volumes. At a traffic volume of 7,000 vph, the average delay for a DLT is about 170 seconds, while the average delay for a RTUT and a UTRT is approximately 37 and 29 seconds, respectively. Queue formation at the signalized intersection is the main reason behind the significant increase in intersection delay for the DLT control type at high traffic volumes.

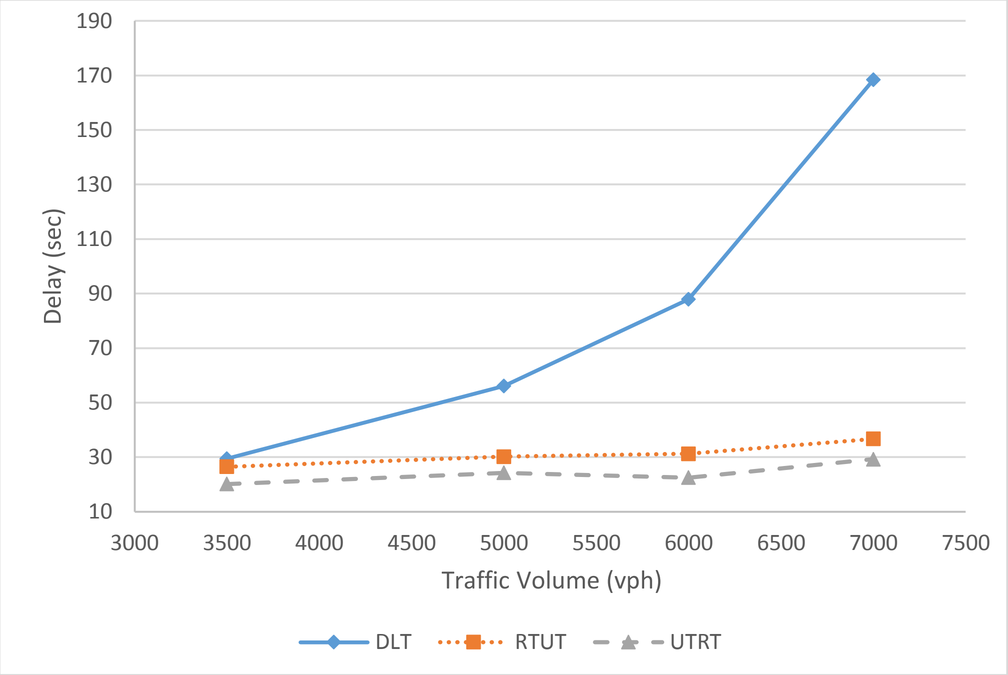


Figure 40: Comparison of Delay for Case 200.III.1

Figure 41 presents delay comparisons for case 200.III.2 using Vissim software. As illustrated, unconventional left-turn control types have less delay compared to the DLT; also, the delay for a DLT increases linearly until the traffic volume reaches 6,000 vph. The delay remains constant for the DLT at high traffic volumes because northbound and southbound approaches have reached their maximum capacity; moreover, the additional vehicles cannot enter the network before the end of the simulation. For case 200.III.2, the RTUT has the least delay among the other left-turn control types. When the traffic volume exceeds 6,000 vph, intersection delay for unconventional left-turn control types noticeably increase because of the queue formed at the U-turn locations.

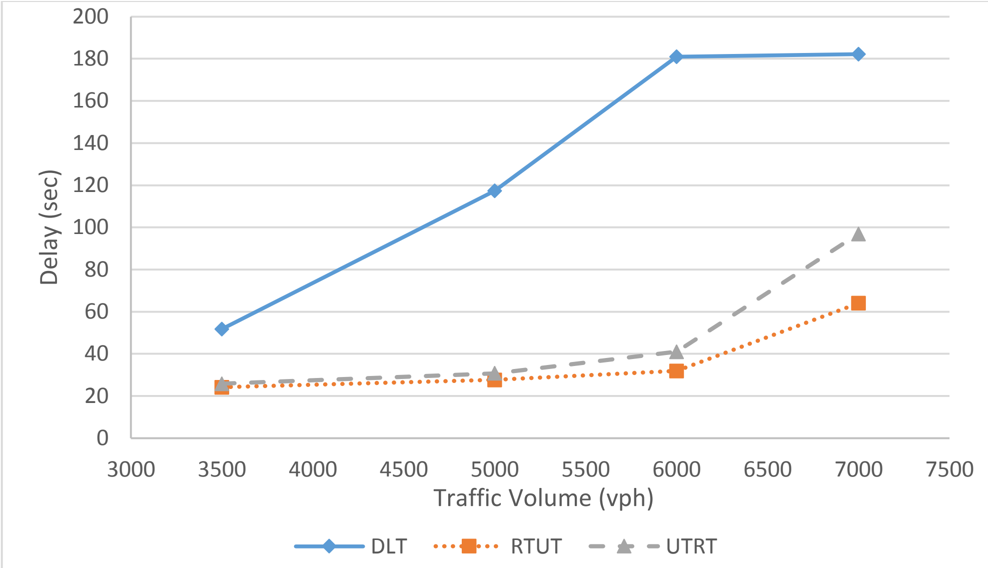


Figure 41: Comparison of Delay for Case 200.III.2

Figure 42 illustrates delay comparisons for case 200.III.3 among three left-turn control types. As shown, intersection delay remains constant for DLTs and UTRTs when the traffic volume exceeds 6,000 vph because the network has reached its maximum capacity and also because some vehicles were not loaded into the network. At high traffic volumes, intersection delay for the UTRT control type increases at a higher rate, and queue spillback blocks the main intersection for the RTUT control type. For case 200.III.3, traffic congestion occurs at high traffic volumes because 45 percent of the total volume is assigned on the northbound approach and 45 percent of that volume is assigned for the left-turn movement.

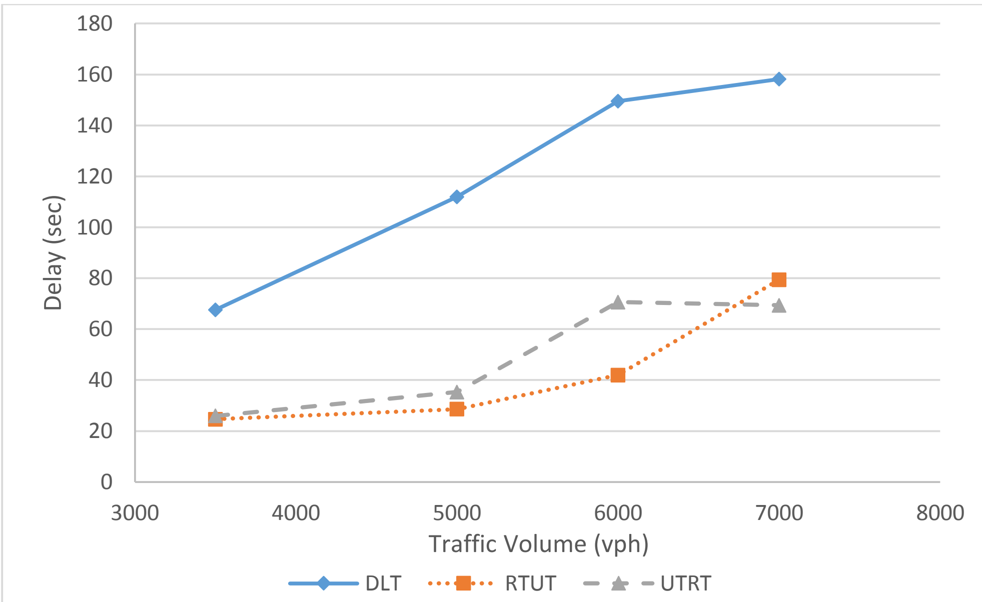


Figure 42: Comparison of Delay for Case 200.III.3

As shown in Figure 43, the UTRT has the least delay compared to the other left-turn control types. Also, intersection delay for the UTRT increases linearly with the increase in the traffic volume until it reaches a maximum value of about 45 seconds. Both a DLT and a RTUT have similar delay at low traffic volumes because vehicles making a RTUT stop twice at the signalized intersection and the U-turn locations; therefore, the reduction in delay is insignificant in the case of a RTUT. For the direct left-turn control type, intersection delay increases at a higher rate when the traffic volume exceeds 5,000 vph.

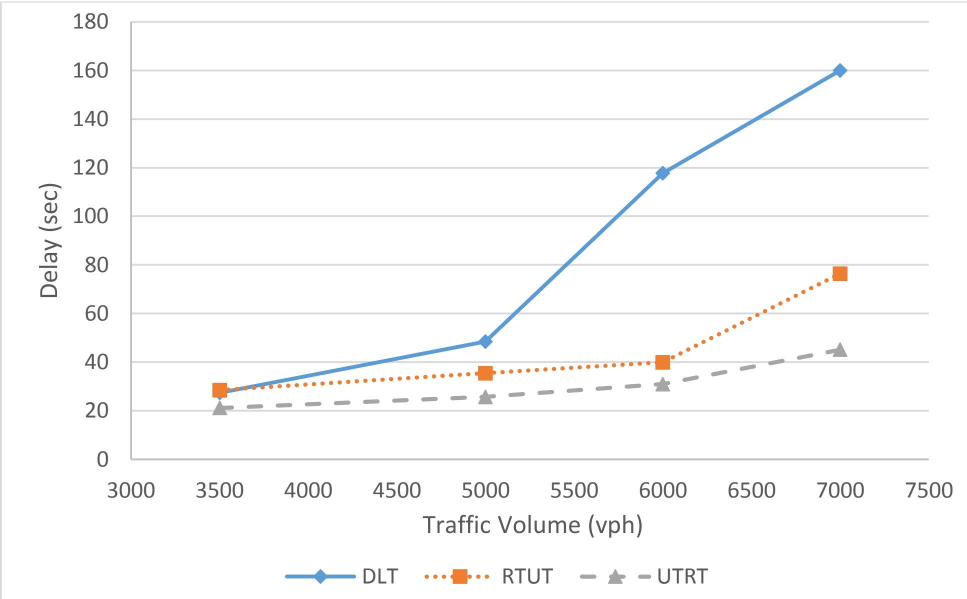


Figure 43: Comparison of Delay for Case 200.III.4

Figure 44 illustrates delay comparisons for a condition in which 45 percent of the total volume is assigned for the northbound approach, and 25 percent of the volume is assigned for the eastbound approach. As shown, the DLT has the highest delay and unconventional left-turn control types have very similar delays over the considered range of traffic volumes. At low traffic volumes, both unconventional control types have a similar trend because there is no queue formation at the U-turn locations due to the efficient signal timings. At high traffic volumes, the RTUT and the UTRT have a similar trend because queues at the U-turn locations block the intersection for both cases. At a traffic volume of 7,000 vph, the delay reaches nearly 142 seconds for the DLT and about 70 seconds for unconventional left-turn control types.

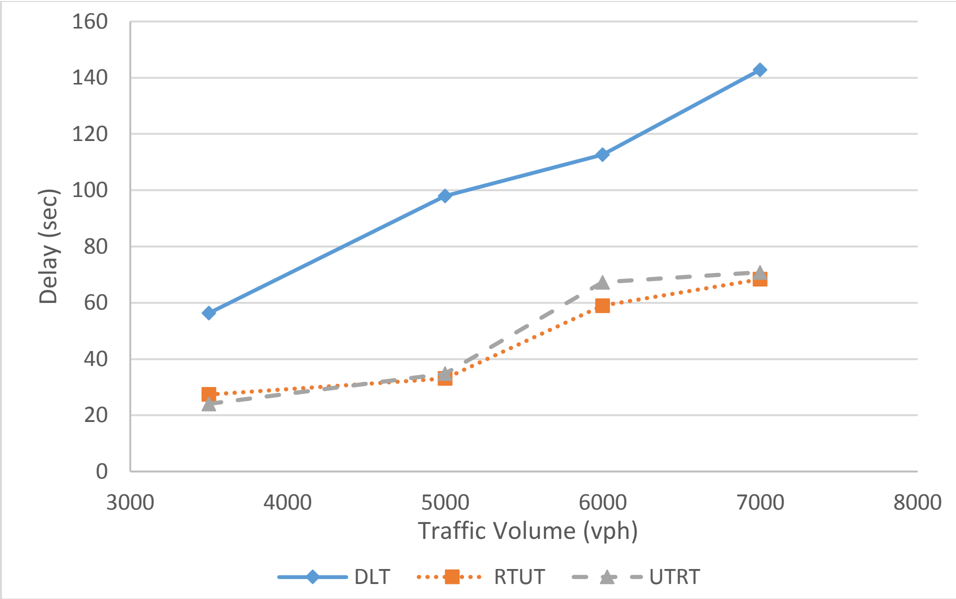


Figure 44: Comparison of Delay for Case 200.III.5

Furthermore, the performance of the three left-turn control types was investigated after moving the U-turn locations closer to the intersection. Tables 11 to 13 demonstrate delay comparisons for the three left-turn control types, where the U-turn locations are 100 meters away from the main intersection.

Table 11 presents delay comparisons for case 100.I, where left-turn movements for the northbound and the southbound approaches represent only 15 percent of the total volume assigned for these approaches. Also, Table 11 compares delay for different distributions of the traffic volume on the approaches. As illustrated, the delay for unconventional left-turn control types is less compared to a DLT when traffic volume is equally distributed on all approaches or dominant on two opposite approaches (i.e. cases 100.I.1, 100.I.2, and 100.I.3) over the considered range of traffic volumes. When the traffic volume is dominant on two perpendicular approaches (i.e. cases 100.I.4 and 100.I.5), the delay for the UTRT increases significantly as the traffic volume exceeds 6,000 vph. This can be attributed to the queue spillback effect when moving the U-turn locations closer to the intersection. Furthermore, the delay for the unconventional left-turn control types is comparable at low traffic volumes since there are no long queues at the signalized U-turn locations. For case 100.I, it seems that a right-turn followed by a U-turn has superior performance compared to the other left-turn control type over the considered range of traffic volumes.

Table 11: Comparison of Delay for Case 100.I

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
100.I.1	3,500	23.9	17.4	16.5
	5,000	28.8	19.1	17.6
	6,000	36.9	20.4	18.5
	7,000	42.6	23.1	23.0
100.I.2	3,500	25.0	16.1	14.9
	5,000	30.8	17.4	15.8
	6,000	36.5	19.3	18.1
	7,000	60.6	21.0	21.5
100.I.3	3,500	25.3	19.7	20.0
	5,000	29.5	18.5	15.8
	6,000	36.5	21.5	21.1
	7,000	74.7	24.9	23.3
100.I.4	3,500	25.2	18.2	16.5
	5,000	29.9	20.9	18.5
	6,000	35.5	25.1	27.4
	7,000	58.2	45.3	107.6
100.I.5	3,500	25.7	22.6	22.3
	5,000	29.2	20.3	17.6
	6,000	36.0	24.7	24.5
	7,000	72.8	37.6	94.3

Table 12 presents delay comparisons for case 100.II, where left-turn movements for the northbound and the southbound approaches represent 30 percent of the total volume assigned for these approaches. Also, Table 12 compares delay for different distributions of the traffic volume on the approaches. As illustrated, a right-turn followed by a U-turn has superior performance compared to the other left-turn control types over the considered range of traffic volumes. Also, the RTUT and the UTRT have comparable intersection delay at traffic volumes less than 5,000 vph. For all of the considered distributions of the traffic volume on the approaches, the delay for a UTRT increases at a higher rate when traffic volumes exceed 5,000 vph. Similarly, the delay for a RTUT increases significantly at high traffic volumes when 45 percent of the total volume is assigned to the northbound approach (i.e. cases 100.II.3 and 100.II.5). This can be attributed to the queue spillback from the U-turn locations to the signalized intersection.

Table 13 presents delay comparisons for case 100.III, where left-turn movements for the northbound and the southbound approaches represent 45 percent of the total volume assigned for these approaches. Also, Table 13 compares delay for different distributions of the traffic volume on the approaches. As illustrated, the delay for the unconventional left-turn control types increases significantly when the traffic volume exceeds 5,000 vph. For case 100.III, many vehicles are performing indirect left-turns since the left-turn movements represent 45 percent of the total volume assigned to the northbound and the southbound approaches. Therefore, using unconventional control types at high traffic volumes for case 100.III will result in the signalized intersection being blocked because of the queue that forms at the U-turn locations.

Table 12: Comparison of Delay for Case 100.II

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
100.II.1	3,500	24.1	18.9	17.4
	5,000	28.9	21.4	19.0
	6,000	37.5	23.0	22.7
	7,000	49.7	26.4	31.4
100.II.2	3,500	25.3	20.0	18.1
	5,000	32.1	20.5	19.8
	6,000	40.4	24.2	27.2
	7,000	87.8	28.2	61.4
100.II.3	3,500	25.5	22.9	18.7
	5,000	31.3	21.4	19.7
	6,000	36.7	26.4	34.0
	7,000	75.9	40.6	63.4
100.II.4	3,500	20.6	19.8	17.7
	5,000	29.9	23.0	19.7
	6,000	37.7	28.7	32.2
	7,000	80.4	36.3	70.1
100.II.5	3,500	25.7	25.2	18.5
	5,000	29.5	24.9	26.2
	6,000	38.0	28.8	50.4
	7,000	81.5	63.4	66.2

Table 13: Comparison of Delay for Case 100.III

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
100.III.1	3,500	29.5	21.9	21.3
	5,000	56.1	26.0	26.5
	6,000	87.9	33.3	28.6
	7,000	168.4	81.1	202.4
100.III.2	3,500	51.8	22.7	25.0
	5,000	117.4	28.6	44.1
	6,000	181.0	72.5	117.6
	7,000	182.2	134.6	233.1
100.III.3	3,500	67.6	23.0	27.6
	5,000	111.9	40.6	83.4
	6,000	149.5	85.3	90.9
	7,000	158.2	92.2	103.6
100.III.4	3,500	27.4	24.2	24.3
	5,000	48.4	31.1	43.2
	6,000	117.8	89.7	79.7
	7,000	160.0	128.3	125.5
100.III.5	3,500	56.3	24.6	28.4
	5,000	98.0	48.4	89.6
	6,000	112.7	88.8	84.5
	7,000	142.8	82.2	83.5

Furthermore, Tables 14 to 16 present delay comparisons for the three left-turn control types, where the U-turn locations are 50 meters away from the main intersection.

Table 14 presents delay comparisons for case 50.I, where left-turn movements for the northbound and the southbound approaches represent 15 percent of the total volume assigned for these approaches. Also, Table 14 compares delay for different distributions of the traffic volume on the approaches. As illustrated, unconventional left-turn control types have comparable delay at traffic volumes less than 5,000 vph. At high traffic volumes, the delay for UTRTs reach to extremely high values compared to the other control types. Also, intersection delay for the RTUT control type increases at a higher rate when traffic volumes exceed 6,000 vph. In fact, moving the U-turns closer to the intersection causes safety problems at the weaving sections of the road for unconventional left-turn control types. Also, vehicles making RTUTs will not have sufficient distance to complete the lane change maneuver in a comfortable way; therefore, the intersection will be blocked as a result of the spillback effect. For case 50.I, the direct left-turn has superior performance compared to the unconventional left-turn control types at high traffic volumes.

Table 15 provides a summary of the delay values for case 50.II. In this case, the left-turn movements for the northbound and the southbound approaches represent 30 percent of the total volume assigned for these approaches. Also, Table 15 compares delay for different distributions of the traffic volume on the approaches. As shown, a U-turn followed by a right-turn has a high delay over the considered range of traffic volumes when compared to the other control types. There is a noticeable increase in the delay for the UTRT at moderate and high traffic volumes. A right-turn followed by a U-turn has reasonable delay when the traffic volume is less than 5,000 vph. Moving the U-turns closer to the main intersection creates safety issues for the indirect left-turn control types. Also, the intersection delay increases dramatically for the unconventional left-turn control types because 30 percent of the traffic volume assigned on the northbound and the southbound approaches desire to make an indirect left-turn. The delay for DLTs ranges from approximately 20 seconds to about 90 seconds over the considered range of traffic volumes. For case 50.II, the direct left-turn has a superior performance compared to unconventional left-turn control types at moderate and high traffic volumes because of the U-turn locations.

Table 14: Comparison of Delay for Case 50.I

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
50.I.1	3,500	23.9	15.4	15.9
	5,000	28.8	16.8	17.7
	6,000	36.9	18.1	18.5
	7,000	42.6	99.7	332.8
50.I.2	3,500	24.9	13.9	14.4
	5,000	30.8	15.1	15.3
	6,000	36.5	16.5	17.8
	7,000	60.6	18.2	267.1
50.I.3	3,500	25.3	18.5	19.5
	5,000	29.5	15.2	15.7
	6,000	36.5	18.7	26.9
	7,000	74.7	24.1	224.8
50.I.4	3,500	25.2	15.5	16.1
	5,000	29.9	18.2	18.6
	6,000	35.5	32.5	226.6
	7,000	58.2	79.9	530.3
50.I.5	3,500	25.7	21.4	22.2
	5,000	29.2	17.0	17.4
	6,000	36.0	21.9	105.6
	7,000	72.8	96.3	484.9

Table 15: Comparison of Delay for Case 50.II

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
50.II.1	3,500	24.1	17.1	18.8
	5,000	28.9	18.8	21.3
	6,000	37.6	20.4	401.2
	7,000	49.8	152.0	549.4
50.II.2	3,500	25.3	18.7	19.6
	5,000	32.1	18.4	94.8
	6,000	40.4	183.5	715.9
	7,000	87.8	338.4	627.7
50.II.3	3,500	25.5	23.8	21.0
	5,000	31.4	24.1	346.0
	6,000	36.8	418.9	534.3
	7,000	75.9	403.4	571.0
50.II.4	3,500	20.6	17.5	47.5
	5,000	29.9	20.5	78.9
	6,000	37.7	113.2	555.9
	7,000	80.4	246.7	548.1
50.II.5	3,500	25.7	25.6	19.5
	5,000	29.5	95.2	326.3
	6,000	38.0	230.1	568.4
	7,000	81.5	488.8	627.7

Table 16 presents delay comparisons for case 50.III, where left-turn movements for the northbound and the southbound approaches represent 45 percent of the total volume assigned for these approaches. Also, Table 16 compares the delay for different distributions of the traffic volume on the approaches. As illustrated, unconventional left-turn control types have higher delay compared to a DLT over the considered range of traffic volumes. The delay for unconventional left-turn control types increases significantly at moderate and high traffic volumes due to the spillback effect that blocks the intersection. For the three left-turn control types, intersection delay increases at a higher rate since accumulated queues cannot fully dissipate in one cycle. The reality is that the direct left-turn control type has reasonable delays compared to the other control types over a wide range of traffic volumes.

Table 16: Comparison of Delay for Case 50.III

Case No.	Traffic Volume (vph)	Delay (sec)		
		DLT	RTUT	UTRT
50.III.1	3,500	29.5	19.7	21.4
	5,000	56.1	28.1	491.8
	6,000	87.9	316.2	614.4
	7,000	168.4	585.7	842.2
50.III.2	3,500	51.8	21.1	29.4
	5,000	117.4	338.1	799.6
	6,000	181.0	311.5	741.8
	7,000	182.2	378.3	885.7
50.III.3	3,500	67.6	29.9	100.0
	5,000	111.9	468.1	595.8
	6,000	149.5	503.2	706.8
	7,000	158.2	498.4	888.9
50.III.4	3,500	27.4	21.5	23.9
	5,000	48.4	249.9	274.5
	6,000	117.8	313.7	691.4
	7,000	160.0	359.1	663.9
50.III.5	3,500	56.3	40.5	36.9
	5,000	98.0	392.8	544.9
	6,000	112.7	311.6	594.3
	7,000	142.8	575.8	620.7

5.2.2 Travel time comparison.

The values for the average travel time were compared among the three left-turn control types for all of the considered scenarios. It should be noted that the travel time curves follow the same trend as the delay curves for the same reasons mentioned earlier in the delay comparison.

Table 17 presents travel time comparisons for different left-turn control types, where the U-turn locations are 200 meters away from the main intersection. In addition, left-turn movements are equal to 15 percent for northbound and southbound approaches. Each of the following figures presents a different distribution of the total volume on the intersection. In addition, Figures 45 to 49 present travel time comparisons for each case.

Table 17: Comparison of Travel Time for Case 200.I

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
200.I.1	3,500	87.9	90.5	86.7
	5,000	92.8	92.7	88.8
	6,000	100.3	93.6	89.3
	7,000	105.6	96.7	91.7
200.I.2	3,500	88.8	88.2	84.7
	5,000	94.1	88.5	85.8
	6,000	99.9	90.5	87.7
	7,000	121.9	93.2	90.8
200.I.3	3,500	89.4	91.4	88.9
	5,000	93.7	89.6	86.9
	6,000	99.7	92.7	90.1
	7,000	134.9	95.6	93.2
200.I.4	3,500	89.0	91.2	86.6
	5,000	93.9	96.7	89.9
	6,000	98.9	97.8	93.3
	7,000	120.1	107.5	104.7
200.I.5	3,500	89.2	93.4	91.0
	5,000	92.9	92.4	89.3
	6,000	99.5	96.9	93.1
	7,000	133.6	106.4	104.2

For case 200.I.1, the UTRT control type has the least travel time among all of the other control types. When the total traffic volume is less than 5,000 vph, the RTUT control type shows more travel time compared to the DLT control type. This is attributed to the fact that the average delay is comparable for the two control types, as shown in Figure 30, and the RTUT requires more travel distance. When the traffic volume exceeds 5,000 vph, the RTUT control type shows less travel time compared to the DLT control type. As shown in Figure 45, unconventional left-turn control types have similar travel time patterns over the considered range of traffic volumes, while travel time for the DLT control type is more sensitive to the change in traffic volumes.

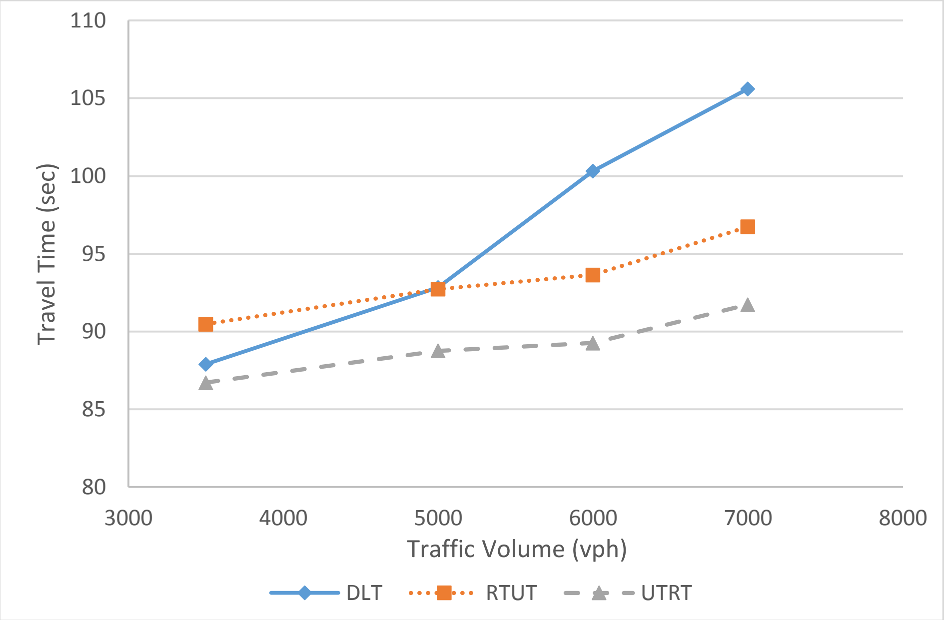


Figure 45: Comparison of Travel Time for Case 200.I.1

For Case 200.I.2, the direct left-turn and the right-turn followed by a U-turn control types have comparable travel time at low traffic volumes, which is attributed to same reason mentioned in the previous scenario. The gap between RTUT and UTRT control types starts to decrease when the traffic volume exceeds 5,000 vph, as illustrated in Figure 46. Also, a U-turn followed by a right-turn has the least delay compared to the other control types over the considered range of traffic volumes. The justifications provided for the delay variation, for this case, are also valid for the travel time.

Figure 47 illustrates travel time comparisons for case 200.I.3. As shown, the three left-turn control types have comparable travel time at low traffic volumes. As the traffic volume increases, the gap between the DLT and the unconventional left-turn control types increases as well. At traffic volumes more than 6,000 vph, travel time for the DLT increases rapidly because of the accumulated queues at the signalized intersection.

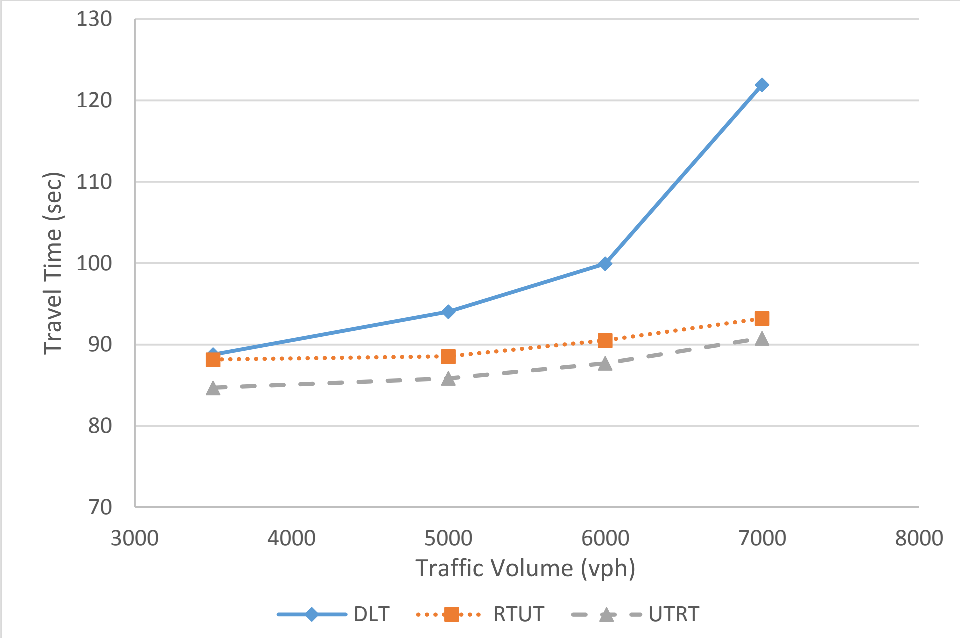


Figure 46: Comparison of Travel Time for Case 200.I.2

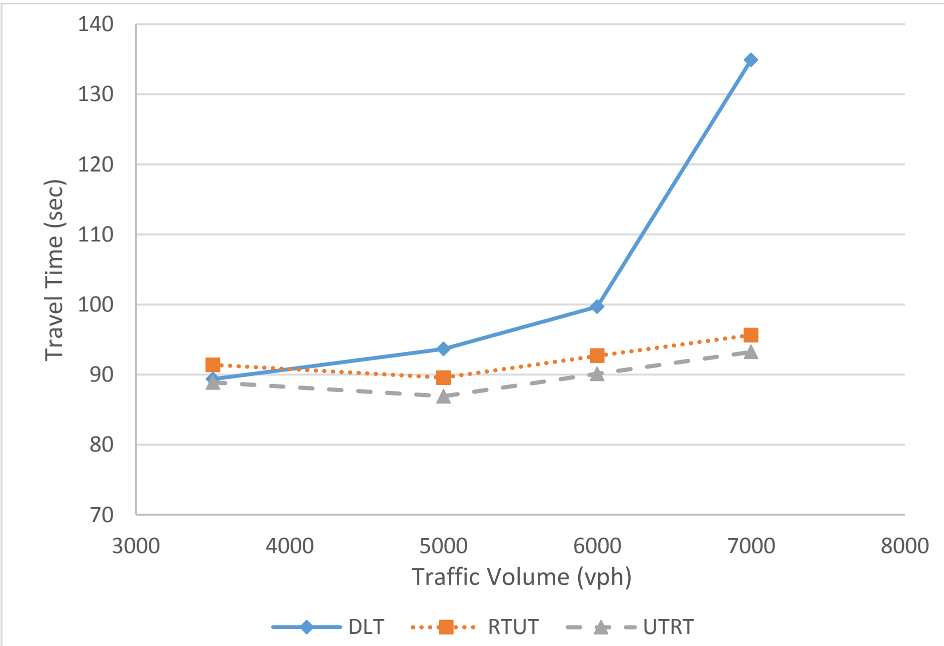


Figure 47: Comparison of Travel Time for Case 200.I.3

For case 200.I.4, a U-turn followed by a right-turn has the least travel time compared to the other control types. As shown in Figure 48, the RTUT shows more travel time compared to the DLT at traffic volumes less than 6,000 vph. Travel time for the three left-turn control types increases at a higher rate when the traffic volume exceeds 6,000 vph, as shown in Figure 48.

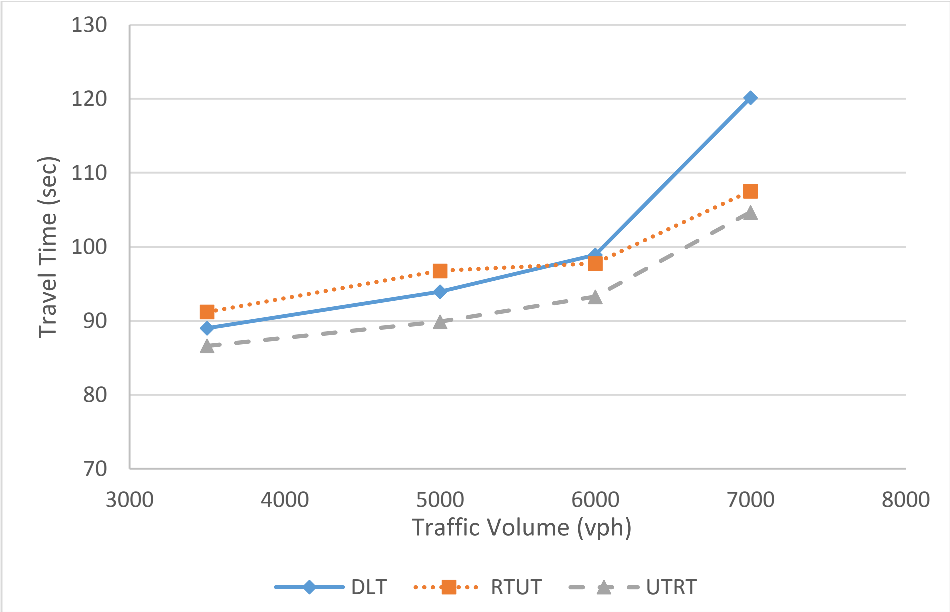


Figure 48: Comparison of Travel Time for Case 200.I.4

For case 200.I.5, the three control types have comparable travel time when the traffic volume is less than 6,000 vph. As shown in Figure 49, travel time for the DLT increases rapidly at high traffic volumes until it reaches about 134 seconds. Travel time for unconventional control types ranges from about 90 seconds to nearly 105 seconds.

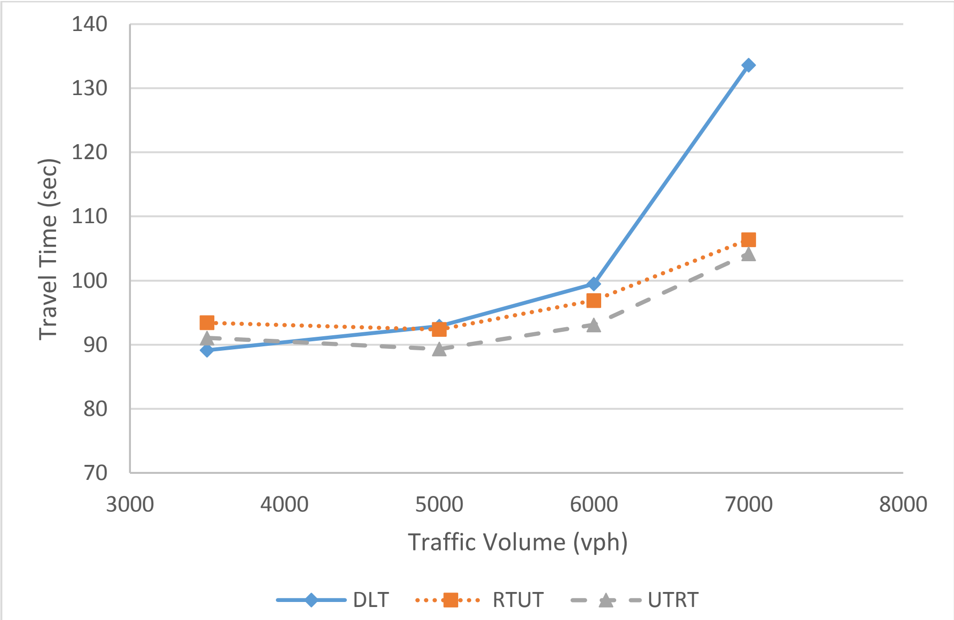


Figure 49: Comparison of Travel Time for Case 200.I.5

Table 18 presents delay comparisons for the three left-turn control types, where the U-turn locations are 200 meters away from the main intersection. Also, left-turn movements are equal to 30 percent for northbound and southbound approaches. Each of the following figures presents a different distribution of the total volume on the intersection. In addition, Figures 50 to 54 present the travel time comparisons for each case.

Table 18: Comparison of Travel Time for Case 200.II

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
200.II.1	3,500	88.0	94.0	88.6
	5,000	92.8	96.3	91.5
	6,000	100.9	97.2	92.0
	7,000	112.1	100.7	94.8
200.II.2	3,500	89.2	93.7	90.8
	5,000	95.6	93.7	92.5
	6,000	103.4	96.6	92.9
	7,000	146.8	104.1	98.7
200.II.3	3,500	89.4	97.3	90.6
	5,000	95.3	94.4	92.2
	6,000	99.6	97.5	97.9
	7,000	135.7	103.5	119.6
200.II.4	3,500	84.5	95.2	89.2
	5,000	93.8	100.5	93.0
	6,000	101.4	101.4	96.4
	7,000	140.6	108.0	101.0
200.II.5	3,500	89.1	97.3	90.7
	5,000	93.0	98.3	94.2
	6,000	101.1	101.6	98.2
	7,000	141.2	113.4	120.8

Figure 50 presents travel time comparisons for case 200.II.1. As shown, a direct left-turn has the least travel time when the traffic volume is less than 4,500 vph. On the other hand, a U-turn followed by a right-turn has the least travel time among the other control types when the traffic volume exceeds 4,500 vph. As illustrated, travel time for the DLT increases at a higher rate when the traffic volume exceeds 5,000 vph, because of the queues that accumulate at the signalized intersection.

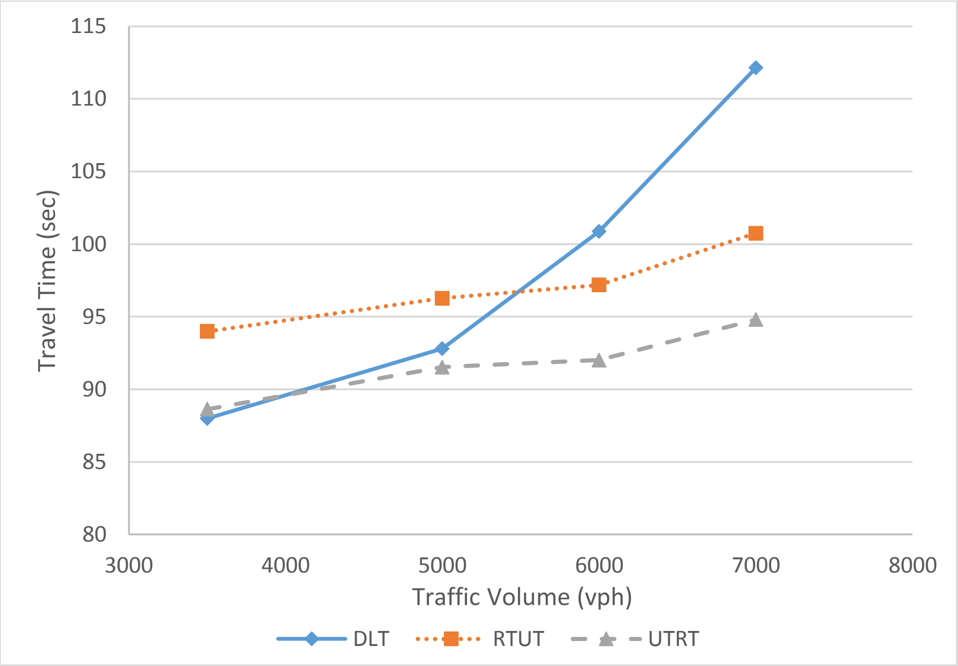


Figure 50: Comparison of Travel Time for Case 200.II.1

For case 200.II.2, unconventional control types have comparable travel times over the considered rang of traffic volumes. Travel time for unconventional control types ranges from approximately 90 seconds to about 105 seconds. As shown in Figure 51, travel time for the DLT increases rapidly at high traffic volumes until it reaches about 145 seconds.

Figure 52 shows travel time comparisons for case 200.II.3. The travel time for a DLT has a slightly positive slope until the traffic volume reaches 5,500 vph. Afterwards, the travel time increases rapidly until it reaches about 135 seconds. The RTUT has a reasonable travel time compared to the other control types over the considered range of traffic volumes.

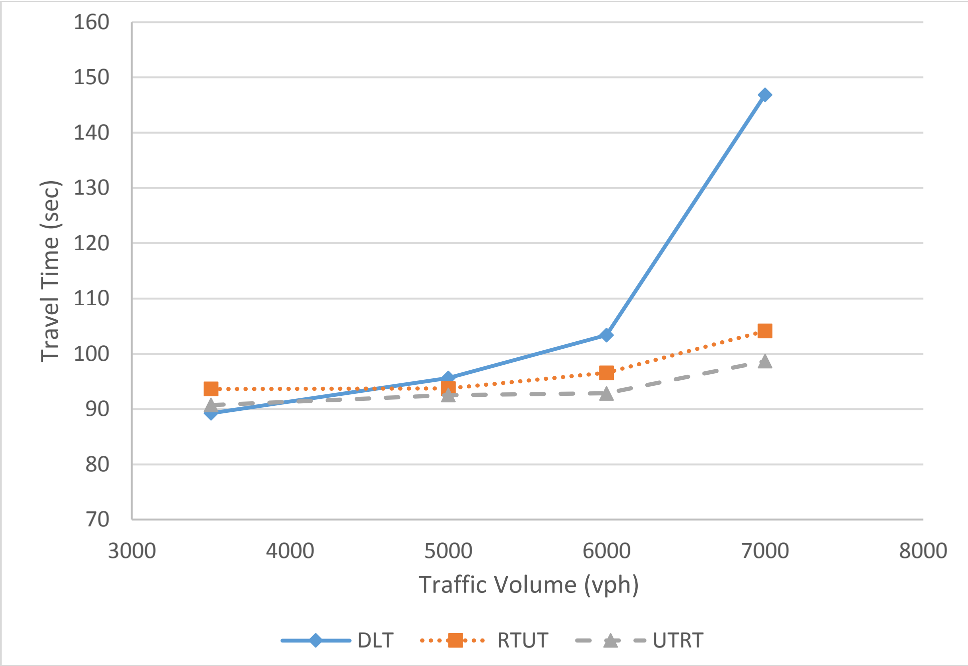


Figure 51: Comparison of Travel Time for Case 200.II.2

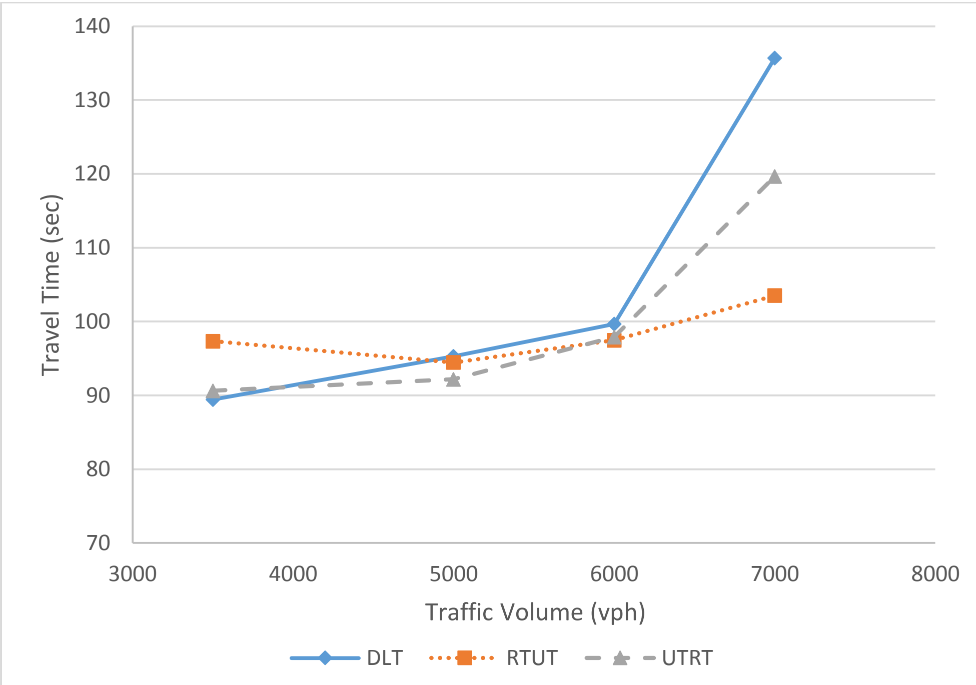


Figure 52: Comparison of Travel Time for Case 200.II.3

For case 200.II.4, the travel time comparisons are illustrated in Figure 53. As shown, the DLT has the least travel time among the other control types at a low traffic volume because all of the three control types have comparable delays and because vehicles performing an indirect left-turn travel a longer distance. When the traffic volume exceeds 5,000 vph, the UTRT has the least travel time compared to the other control types.

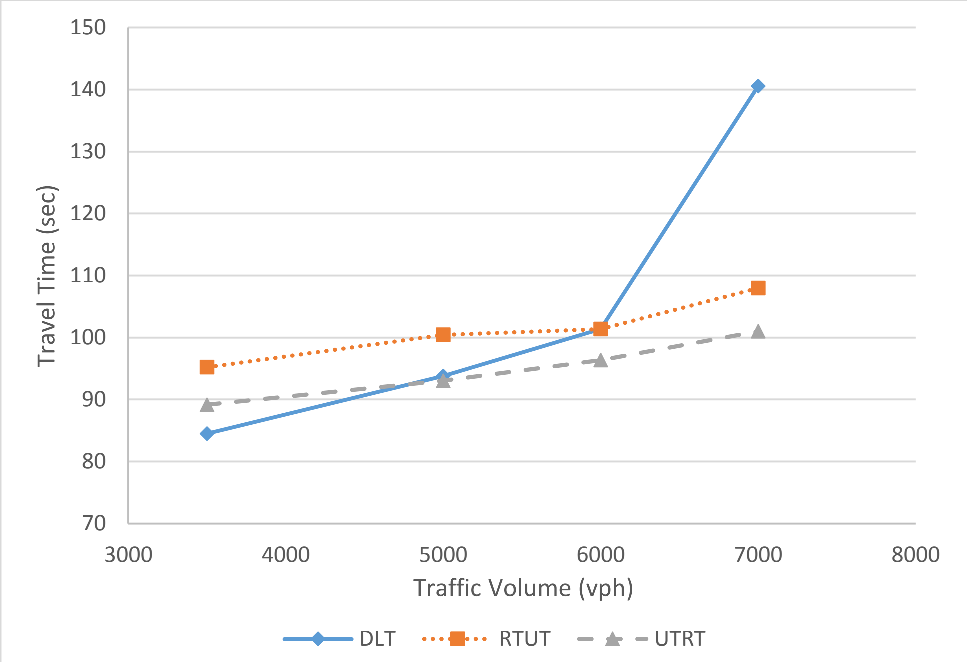


Figure 53: Comparison of Travel Time for Case 200.II.4

As shown in Figure 54, the direct left-turn has the least travel time at low traffic volumes. At traffic volumes less than 6,000 vph, the change in travel time is insignificant for unconventional left-turn control types. At traffic volumes more than 6,000 vph, the travel time for all control types increases at a higher rate because queues begin to form and accumulate at the signalized intersection and the U-turn locations, as shown in Figure 54.

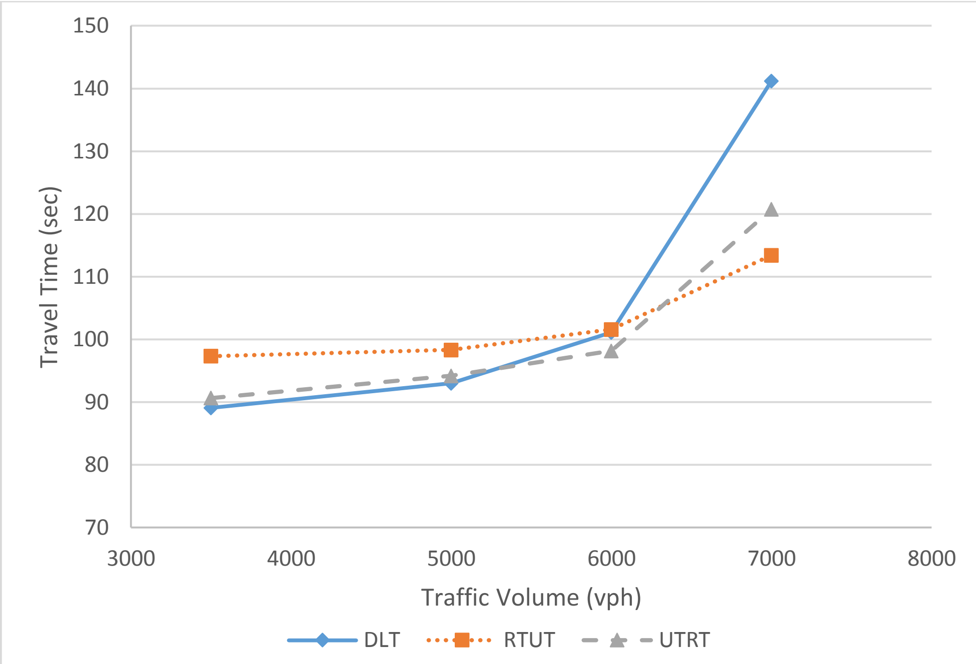


Figure 54: Comparison of Travel Time for Case 200.II.5

Table 19 presents delay comparisons for the three left-turn control types, where the U-turn locations are 200 meters away from the main intersection. Also, left-turn movements for northbound and southbound approaches are equal to 45 percent. Each of the following figures presents different distributions of the total volume on the intersection. In addition, Figures 55 to 59 present the travel time comparisons for each case.

Table 19: Comparison of Travel Time for Case 200.III

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
200.III.1	3,500	92.6	97.6	92.6
	5,000	117.2	101.5	96.8
	6,000	145.9	102.0	92.8
	7,000	220.6	107.3	101.1
200.III.2	3,500	113.5	96.8	98.7
	5,000	172.6	99.5	103.3
	6,000	232.7	103.8	112.8
	7,000	234.1	133.0	164.0
200.III.3	3,500	127.3	97.0	98.8
	5,000	167.8	100.5	107.1
	6,000	203.2	112.6	140.3
	7,000	211.6	146.9	138.8
200.III.4	3,500	90.1	99.4	93.5
	5,000	111.4	107.5	98.1
	6,000	174.1	110.1	102.6
	7,000	214.0	143.3	115.8
200.III.5	3,500	117.2	99.3	96.8
	5,000	156.3	104.4	106.6
	6,000	170.4	127.6	136.9
	7,000	197.9	136.9	139.8

As shown, Figure 55 depicts travel time comparisons for case 200.III.1. In this case, the total traffic volume on the intersection is equally distributed between all of the approaches. As illustrated, unconventional left-turn control types (i.e. RTUR and UTRT) have comparable travel times, and their travel time is insignificant compared to the travel time for a DLT, especially at high traffic volumes. Also, travel time for DLTs is very sensitive to changes in the traffic volume. This can be attributed to the phenomenon of growing queues, since accumulated queues cannot dissipate fully in one cycle.

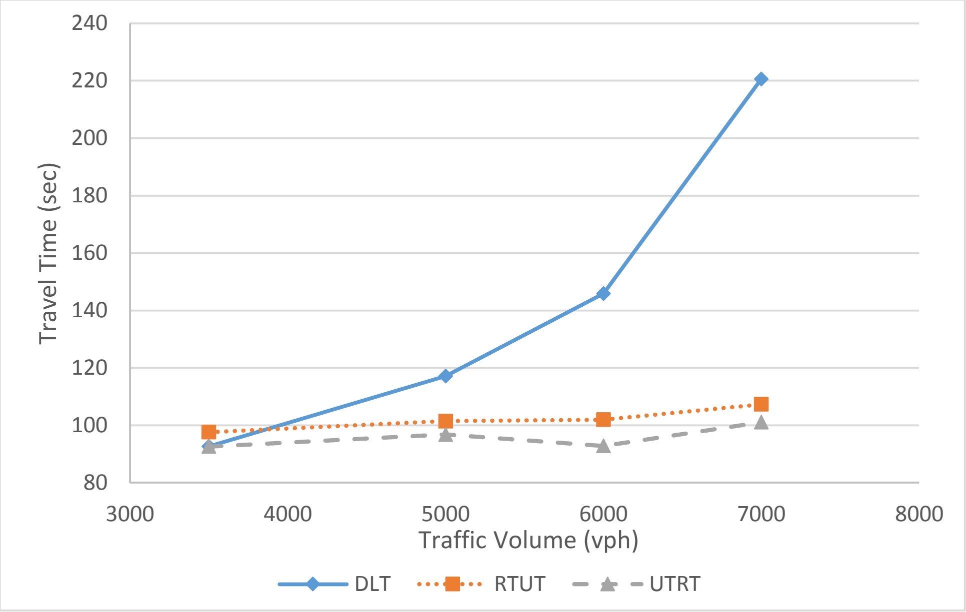


Figure 55: Comparison of Travel Time for Case 200.III.1

Figure 56 presents travel time comparisons for case 200.III.2. As illustrated, the DLT has the highest travel time, and the RTUT has the least travel time compared to the other control types. The travel time curve for the DLT is exhibiting a plateau effect when the traffic volume exceeds 6,000 vph because the network reached its maximum capacity and the additional vehicles could not enter the network before the end of the simulation. In similar traffic conditions, the right-turn followed by a U-turn has the least delay and travel time over the considered range of traffic volumes.

For case 200.III.3, Figure 57 presents travel time comparisons for the three left-turn control types. A shown, travel time for the DLT increases linearly until traffic volume reach 6,000 vph, and then the travel time continues to increase but at a slower rate. In addition, the UTRT exhibits a plateau effect at high traffic volumes because the additional vehicles fail to enter the network before the end of the simulation.

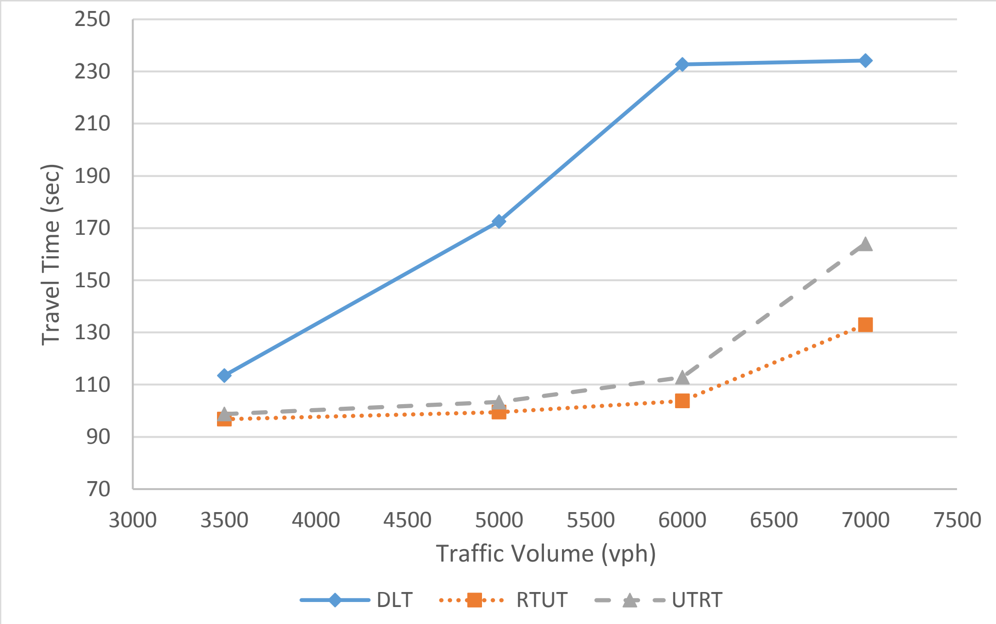


Figure 56: Comparison of Travel Time for Case 200.III.2

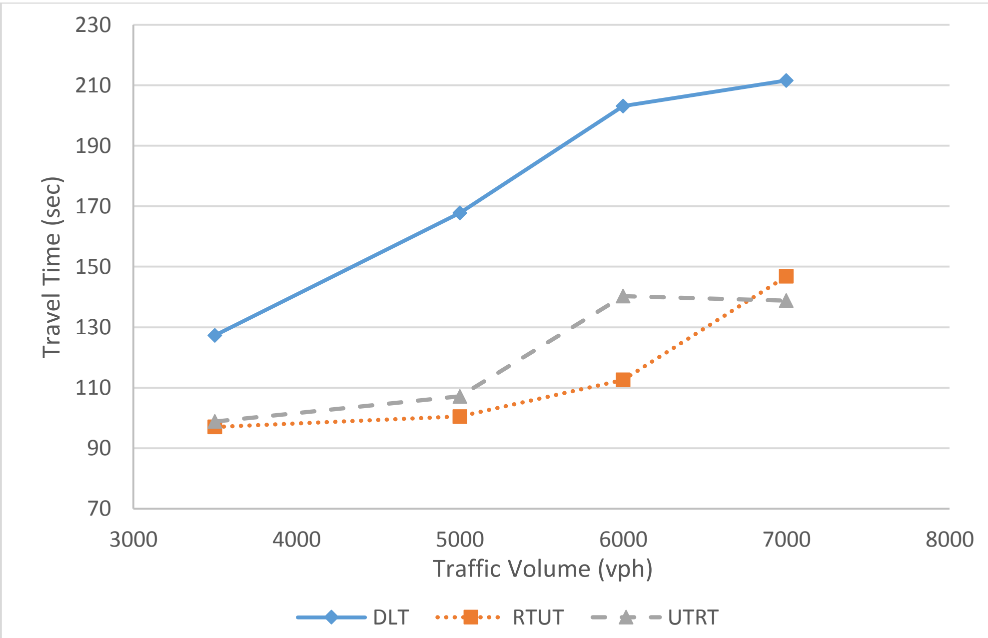


Figure 57: Comparison of Travel Time for Case 200.III.3

As shown in Figure 58, the UTRT has the least travel time compared to the other left-turn control types. Also, the travel time for the UTRT has a linear increase with a restorable rate over the considered range of traffic volumes. At traffic volumes less than 5,000 vph, the DLT shows less travel time compared to the RTUT. As the traffic volume increases, the travel time for the DLT increases rapidly until it reaches about 215 seconds.

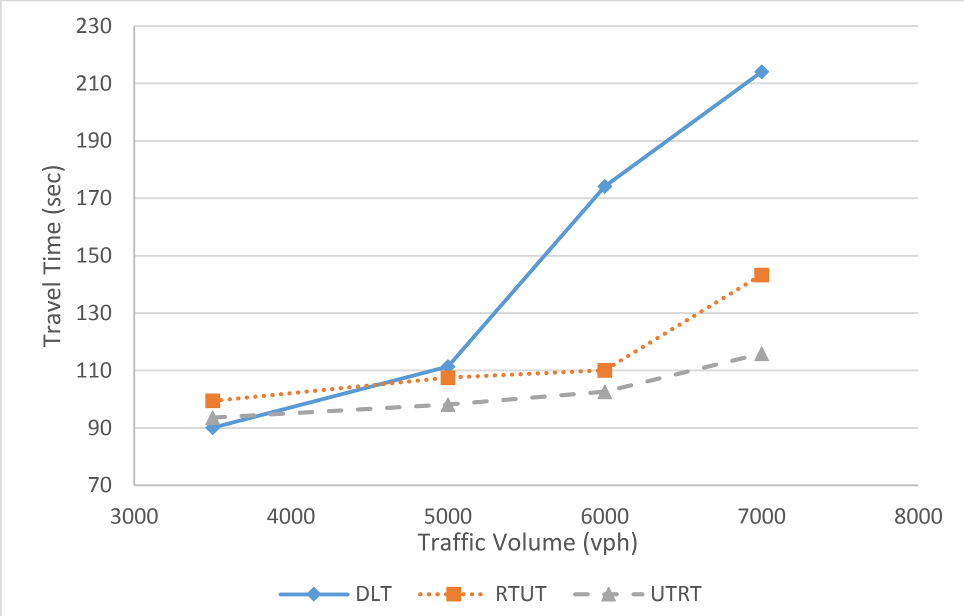


Figure 58: Comparison of Travel Time for Case 200.III.4

Figure 59 presents travel time comparisons between different left-turn control types for case 200.III.5. As illustrated, unconventional control types have comparable travel times, and the DLT has the highest travel time for this scenario. At 7,000 vph, the travel time for a DLT reaches approximately 200 seconds, while it only reaches about 140 seconds for unconventional control types.

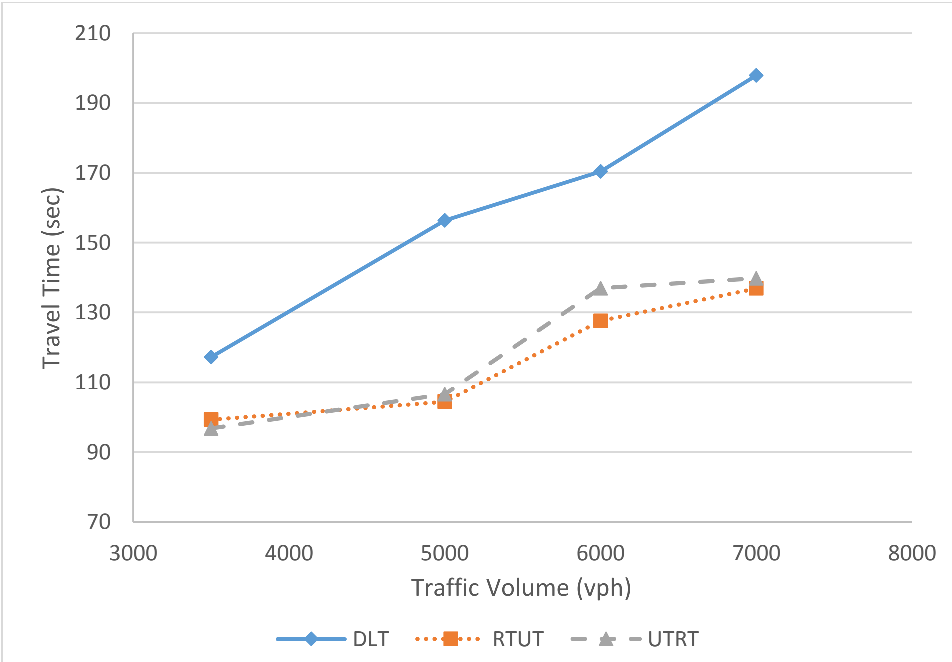


Figure 59: Comparison of Travel Time for Case 200.III.5

Furthermore, the performance of the three left-turn control types was investigated when moving the location of the U-turns closer to the intersection. It should be noted that the travel time tables follow the same trend as the delay tables for the same reasons mentioned earlier discussing delay comparisons. Tables 20 to 22 demonstrate travel time comparisons for the three left-turn control types, where the U-turn locations are 100 meters away from the main intersection.

Table 20 presents travel time comparisons for case 100.I, where left-turn movements for the northbound and the southbound approaches represent only 15 percent of the total volume assigned for these approaches. Also, Table 20 compares travel time for different distributions of the traffic volume on the approaches. As illustrated, unconventional left-turn control types have less travel time compared to the DLT when either the traffic volume is equally distributed on the approaches, or is dominant on two opposite approaches (i.e. cases 100.I.1, 100.I.2, and 100.I.3). Also, the gap between the DLT and the unconventional control types increases as the traffic volume intensifies. As the traffic volume exceeds 6,000 vph, the travel time for a UTRT increases dramatically when traffic volume is dominant on two opposite approaches (i.e. cases 100.I.4 and 100.I.5).

Table 21 presents travel time comparisons for case 100.II, where left-turn movements for the northbound and the southbound approaches represent 30 percent of the total volume assigned for these approaches. Also, Table 21 compares the travel time for different distributions of the traffic volume on the approaches. As illustrated, the three left-turn control types have comparable travel times at traffic volumes less than 5,500 vph. The travel time for the DLT and the UTRT increases when the traffic volume exceeds 5,500 vph. Both DLTs and UTRTs have similar travel times for cases 100.II.3 and 100.II.4. A right-turn followed by a U-turn has reasonable travel time compared to the other control types over the considered range of traffic volumes.

Table 22 presents travel time comparisons for case 100.III, where left-turn movements for the northbound and the southbound approaches represent 45 percent of the total volume assigned for these approaches. Also, Table 22 compares travel time for different distributions of the traffic volume on the approaches. As illustrated, travel time for the three left-turn control types increases dramatically with the increase of traffic volumes due to the accumulated queues at the U-turn locations and the signalized intersection.

Table 20: Comparison of Travel Time for Case 100.I

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
100.I.1	3,500	87.9	84.3	83.8
	5,000	92.8	86.1	85.4
	6,000	100.3	86.7	85.4
	7,000	105.6	89.5	89.5
100.I.2	3,500	88.8	82.8	82.3
	5,000	94.1	83.8	82.9
	6,000	99.9	85.5	84.9
	7,000	121.9	87.3	87.6
100.I.3	3,500	89.4	85.5	86.4
	5,000	93.7	85.2	83.2
	6,000	99.7	87.9	87.9
	7,000	134.9	90.7	89.7
100.I.4	3,500	88.9	84.6	83.6
	5,000	93.9	87.6	85.9
	6,000	98.9	91.3	93.9
	7,000	120.1	109.9	167.1
100.I.5	3,500	89.2	88.2	88.5
	5,000	92.9	86.9	84.8
	6,000	99.5	90.8	91.0
	7,000	133.6	102.7	154.0

Table 21: Comparison of Travel Time for Case 100.II

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
100.II.1	3,500	87.9	85.9	85.4
	5,000	92.8	88.9	87.5
	6,000	100.9	89.9	89.8
	7,000	112.1	93.5	98.1
100.II.2	3,500	89.2	87.8	86.3
	5,000	95.6	87.7	87.6
	6,000	103.4	91.6	94.7
	7,000	146.8	94.9	125.9
100.II.3	3,500	89.4	89.3	86.5
	5,000	95.3	88.9	88.1
	6,000	99.6	93.4	99.9
	7,000	135.7	106.7	127.7
100.II.4	3,500	84.5	86.9	85.5
	5,000	93.8	90.5	87.8
	6,000	101.4	95.5	98.9
	7,000	140.6	102.4	133.4
100.II.5	3,500	89.1	91.3	86.4
	5,000	93.0	91.9	93.7
	6,000	101.1	95.6	115.4
	7,000	141.2	127.6	130.3

Table 22: Comparison of Travel Time for Case 100.III

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
100.III.1	3,500	92.6	89.8	89.5
	5,000	117.2	94.1	95.1
	6,000	145.9	100.2	96.3
	7,000	220.6	144.3	249.3
100.III.2	3,500	113.5	90.9	94.1
	5,000	172.6	96.4	111.4
	6,000	232.7	136.5	178.5
	7,000	234.1	194.7	281.0
100.III.3	3,500	127.3	91.3	96.0
	5,000	167.8	107.9	146.1
	6,000	203.2	149.1	154.4
	7,000	211.6	154.9	165.9
100.III.4	3,500	90.1	91.8	92.4
	5,000	111.4	99.1	110.6
	6,000	174.1	152.2	143.7
	7,000	214.0	188.4	185.8
100.III.5	3,500	117.2	92.6	96.3
	5,000	156.3	114.4	153.2
	6,000	170.4	151.6	147.7
	7,000	197.9	146.1	147.8

Furthermore, a travel time comparison for the three left-turn control types was made when the U-turn locations were 50 meters away from the main intersection. As illustrated, Table 23 presents travel time comparisons for case 50.I, where left-turn movements for the northbound and the southbound approaches represent 15 percent of the total volume assigned for these approaches. Also, Table 23 compares the travel time for different distributions of the traffic volume on the approaches. As illustrated, unconventional left-turn control types have comparable travel time at traffic volumes that are less than 6,000 vph. At high traffic volumes, the travel time for a UTRT reaches exceedingly high values compared to the other control types.

Table 24 presents travel time comparisons for case 50.II, where left-turn movements for the northbound and the southbound approaches represent 30 percent of the total volume assigned for these approaches. Also, Table 24 compares travel times for different distributions of the traffic volume on the approaches. As shown, a U-turn followed by a right-turn has the highest travel time over the considered range of traffic volumes compared to the other control types. Also, the travel time for the U-turn followed by a right-turn increases significantly at moderate and high traffic volumes. In addition, the RTUT has a reasonable travel time when the traffic volume is less than 5,000 vph.

Table 25 presents travel time comparisons for case III, where left-turn movements for the northbound and the southbound approaches represent 45 percent of the total volume assigned for these approaches. Also, Table 25 compares the travel time for different distributions of the traffic volume on the approaches. As illustrated, unconventional left-turn control types have a very high travel time compared to a DLT over the considered range of traffic volumes. Also, intersection delay for unconventional left-turn control types increases dramatically at moderate and high traffic volumes because of the spillback effect that eventually blocks the intersection. The direct left-turn has a relatively reasonable travel time over a wide range of traffic volumes compared to the other control types.

Table 23: Comparison of Travel Time for Case 50.I

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
50.I.1	3,500	87.9	81.2	82.2
	5,000	92.8	82.9	84.1
	6,000	100.3	83.7	84.3
	7,000	105.6	156.3	370.3
50.I.2	3,500	88.8	79.8	80.7
	5,000	94.1	80.8	81.6
	6,000	99.9	82.1	83.6
	7,000	121.9	83.6	310.9
50.I.3	3,500	89.4	83.5	84.8
	5,000	93.7	81.1	81.9
	6,000	99.7	84.4	92.3
	7,000	134.9	89.1	271.2
50.I.4	3,500	88.9	80.9	82.0
	5,000	93.9	84.1	84.6
	6,000	98.9	96.1	269.7
	7,000	120.1	140.3	554.5
50.I.5	3,500	89.2	86.1	87.2
	5,000	92.9	82.9	83.6
	6,000	99.5	87.4	162.3
	7,000	133.6	155.1	513.2

Table 24: Comparison of Travel Time for Case 50.II

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
50.II.1	3,500	87.9	82.9	84.3
	5,000	92.8	85.3	87.8
	6,000	100.9	86.3	433.6
	7,000	112.1	202.3	572.7
50.II.2	3,500	89.2	84.9	85.9
	5,000	95.6	84.5	151.7
	6,000	103.4	236.2	727.2
	7,000	146.8	378.2	645.2
50.II.3	3,500	89.4	88.5	87.5
	5,000	95.3	89.6	381.9
	6,000	99.6	452.5	557.7
	7,000	135.7	437.5	592.2
50.II.4	3,500	84.5	83.2	112.1
	5,000	93.8	86.6	139.3
	6,000	101.4	170.8	578.6
	7,000	140.6	293.1	571.0
50.II.5	3,500	89.1	90.4	85.9
	5,000	93.0	155.0	363.9
	6,000	101.1	279.6	590.4
	7,000	141.2	516.9	645.4

Table 25: Comparison of Travel Time for Case 50.III

Case No.	Traffic Volume (vph)	Travel Time (sec)		
		DLT	RTUT	UTRT
50.III.1	3,500	92.6	85.8	87.6
	5,000	117.2	93.9	516.4
	6,000	145.9	357.5	632.2
	7,000	220.6	608.7	846.1
50.III.2	3,500	113.5	87.6	95.9
	5,000	172.6	379.9	804.1
	6,000	232.7	354.9	751.8
	7,000	234.1	415.3	886.4
50.III.3	3,500	127.3	95.9	157.1
	5,000	167.8	499.5	614.9
	6,000	203.2	530.3	719.5
	7,000	211.6	526.6	889.5
50.III.4	3,500	90.1	87.5	90.0
	5,000	111.4	295.7	317.2
	6,000	174.1	356.7	702.9
	7,000	214.0	398.2	679.4
50.III.5	3,500	117.2	103.7	102.3
	5,000	156.3	424.2	565.8
	6,000	170.4	354.1	611.7
	7,000	197.9	597.6	639.4

5.2.3 Vehicle kilometers travelled comparison.

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 all vehicles during a given period of time on a particular road system. Figure 60 illustrates the VKT comparisons for case 200.I.1. The direct left-turn control type has the least VKT compared to unconventional control types. There is no significant difference (less than 8%) in distance travelled between direct left-turn and unconventional left-turn control types. Moreover, the RTUT and the UTRT control types have approximately the same vehicle kilometers travel (VKT). In addition, all the other cases have a similar trend as case 200.I.1.

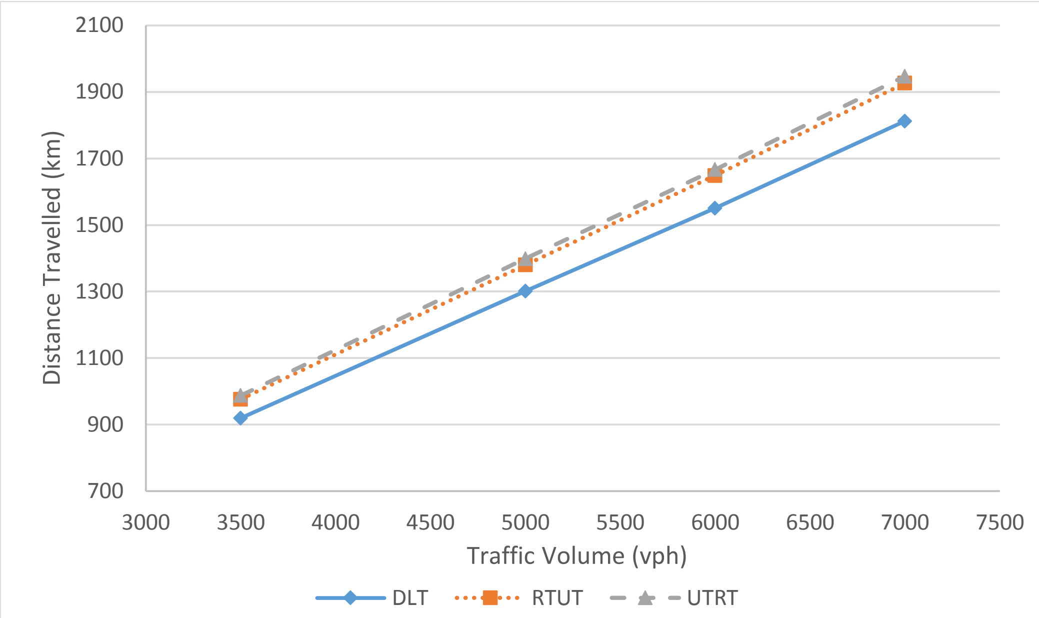


Figure 60: Comparison of VKT for Case 200.I.1

5.2.4 Level of service comparison.

Furthermore, a level of service (LOS) comparison was made to evaluate capacity and operating conditions for the three left-turn control types. Level of service is a function of the average control delay. There are many factors affecting the average control delay such as signal phasing, signal cycle length, and volume to capacity ratio at the signalized intersection. The level of service criteria for signalized intersections is shown in Table 26. As illustrated, the LOS is given a letter distinction (A) through (F), with (A) having the least delay and (F) having the highest delay. LOS (E) is the limit of acceptable delay for signalized intersections.

Table 26: Level of Service Criteria for Signalized Intersections [7]

Level-of-Service (LOS)	Average Control Delay (seconds/vehicle)	Description
A	≤ 10.0	Very low vehicle delays, free flow, signal progression extremely favorable, most vehicles arrive during given signal phase.
B	10.1 to 20.0	Good signal progression, more vehicles stop and experience higher delays than for LOS A.
C	20.1 to 35.0	Stable flow, fair signal progression, significant number of vehicles stop at signals.
D	35.1 to 55.0	Congestion noticeable, longer delays and unfavorable signal progression, many vehicles stop at signals.
E	55.1 to 80.0	Limit of acceptable delay, unstable flow, poor signal progression, traffic near roadway capacity, frequent cycle failures.
F	> 80.0	Unacceptable delays, extremely unstable flow and congestion, traffic exceeds roadway capacity, stop-and-go conditions.

Table 27 presents the level of service (LOS) comparisons for the three left-turn control types, where the U-turn locations are 200 meters away from the main intersection. It should be noted that the LOS was estimated for each range of traffic volume by calculating the arithmetic mean of the delay for the upper and the lower limits of each range. For case I, the traffic volume distribution on each approach does not have a great impact on the level of service, and the five cases have comparable LOS. Also, the three left-turn control types have comparable LOS at low and moderate traffic volumes. At a high traffic volume, the DLT has the worst LOS compared to unconventional left-turn control types. Similarly, all of the traffic volume distributions have comparable LOS for case II. The percentage of vehicles on each approach has an insignificant impact on the level of service. As illustrated, unconventional left-turn control types have similar LOS over the considered range of traffic volumes. At high traffic volumes, the direct left-turn control type has the worst LOS compared to unconventional left-turn control types. Furthermore, the DLT has the worst LOS compared to the other control types when the left-turn percentage reaches 45 percent (i.e. case III). Also, unconventional left-turn control types have exactly the same LOS over the considered range of traffic volumes for all of the considered distributions of traffic volume. For unconventional left-turn control types, the level of service gets worse with the increase of traffic volume. The traffic volume distribution on the approaches has an impact on the level of service. For instance, LOS is very similar when traffic volume is dominant on two opposite approaches (i.e.

cases 2 and 3). Also, LOS is very similar when traffic volume is dominant on two perpendicular approaches (i.e. cases 4 and 5).

Table 27: LOS Comparison for the Three Left-turn Control Types, U-turn Locations at 200m

Left-Turn (%)	% of Vehicles on each Approach	Traffic volume	Left-Turn Control Type		
			DLT	RTUT	UTRT
Case I (15%)	Case 1	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	B
		High (6,000-7,000 vph)	D	C	C
	Case 2	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	B
		High (6,000-7,000 vph)	D	C	C
	Case 3	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	B
		High (6,000-7,000 vph)	E	C	C
	Case 4	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	D	D	C
	Case 5	Low (3,500-5,000 vph)	C	C	C
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	D	C	C
Case II (30%)	Case 1	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	D	C	C
	Case 2	Low (3,500-5,000 vph)	C	C	C
		Moderate (5,000-6,000 vph)	D	C	C
		High (6,000-7,000 vph)	E	C	C
	Case 3	Low (3,500-5,000 vph)	C	C	C
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	E	C	D
	Case 4	Low (3,500-5,000 vph)	C	C	C
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	E	D	C
	Case 5	Low (3,500-5,000 vph)	C	C	C
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	E	D	D
Case III (45%)	Case 1	Low (3,500-5,000 vph)	D	C	C
		Moderate (5,000-6,000 vph)	E	C	C
		High (6,000-7,000 vph)	F	C	C
	Case 2	Low (3,500-5,000 vph)	F	C	C
		Moderate (5,000-6,000 vph)	F	C	D
		High (6,000-7,000 vph)	F	D	E
	Case 3	Low (3,500-5,000 vph)	F	C	C
		Moderate (5,000-6,000 vph)	F	D	D
		High (6,000-7,000 vph)	F	E	E
	Case 4	Low (3,500-5,000 vph)	D	C	C
		Moderate (5,000-6,000 vph)	F	D	C
		High (6,000-7,000 vph)	F	E	D
	Case 5	Low (3,500-5,000 vph)	E	C	C
		Moderate (5,000-6,000 vph)	F	D	D
		High (6,000-7,000 vph)	F	E	E

Table 28 presents a level of service (LOS) comparisons for the three left-turn control types, where the U-turn locations are 100 meters away from the main intersection. As illustrated, when the left-turn percentage is equal to 15 percent, unconventional left-turn control types have a better level of service compared to a direct left-turn. Also, the three left-turn control types have comparable LOS over the considered range of traffic volumes for cases 1, 2, and 3. When the traffic volume is dominant on two perpendicular approaches, a right-turn followed by a U-turn has the best level of service compared to the other control types over the considered range of traffic volumes. Furthermore, the percentage of vehicles on each approach has an insignificant impact on the level of service for case II. As shown, the three control types have almost the same LOS for case II under moderate traffic volume conditions. Also, a right-turn followed by a U-turn has the best level of service compared to the other control types under low and moderate traffic volume conditions. In addition, the direct left-turn has a better level of service compared to a U-turn followed by a right-turn control type under low and high traffic volume conditions. Moreover, a direct left-turn has the worst level of service for case III when the traffic volume is equally distributed between the approaches (i.e. case III.1). Also, the RTUT has the best LOS for case III.1 at a high traffic volume compared to the other control types. The level of service is very similar when the traffic volume is not equally distributed between approaches. As illustrated in cases 2, 3, 4, and 5, the three control types have similar LOS at high traffic volumes. Also, a right-turn followed by a U-turn has the best level of service under low and moderate traffic volume conditions.

Table 28: LOS Comparison for the Three Left-turn Control Types, U-turn Locations at 100m

Left-Turn (%)	% of Vehicles on each Approach	Traffic volume	Left-Turn Control Type		
			DLT	RTUT	UTRT
Case I (15%)	Case 1	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	B
		High (6,000-7,000 vph)	D	C	C
	Case 2	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	B
		High (6,000-7,000 vph)	D	C	B
	Case 3	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	C	B
		High (6,000-7,000 vph)	E	C	C
	Case 4	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	D	D	E
	Case 5	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	D	C	E
Case II (30%)	Case 1	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	D	C	C
	Case 2	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	D	C	C
		High (6,000-7,000 vph)	E	C	D
	Case 3	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	E	C	D
	Case 4	Low (3,500-5,000 vph)	C	C	B
		Moderate (5,000-6,000 vph)	C	C	C
		High (6,000-7,000 vph)	E	C	D
	Case 5	Low (3,500-5,000 vph)	C	C	C
		Moderate (5,000-6,000 vph)	C	C	D
		High (6,000-7,000 vph)	E	D	E
Case III (45%)	Case 1	Low (3,500-5,000 vph)	D	C	C
		Moderate (5,000-6,000 vph)	E	C	C
		High (6,000-7,000 vph)	F	E	F
	Case 2	Low (3,500-5,000 vph)	F	C	C
		Moderate (5,000-6,000 vph)	F	D	F
		High (6,000-7,000 vph)	F	F	F
	Case 3	Low (3,500-5,000 vph)	F	C	E
		Moderate (5,000-6,000 vph)	F	E	F
		High (6,000-7,000 vph)	F	F	F
	Case 4	Low (3,500-5,000 vph)	D	C	C
		Moderate (5,000-6,000 vph)	F	E	E
		High (6,000-7,000 vph)	F	F	F
	Case 5	Low (3,500-5,000 vph)	E	D	E
		Moderate (5,000-6,000 vph)	F	E	F
		High (6,000-7,000 vph)	F	F	F

Table 29 presents the level of service (LOS) comparisons for the three left-turn control types, where the U-turn locations are 50 meters away from the main intersection. For case I, the level of service is very similar when the traffic volume is equally distributed between the approaches or dominant on two opposite approaches. As illustrated, unconventional left-turn control types have comparable LOS under low and moderate traffic volume conditions. Also, a right-turn followed by a U-turn has the best LOS under high traffic volume conditions. When traffic volume is dominant on two perpendicular approaches (cases 4 and 5), the direct left-turn has a better level of service compared to unconventional control types, at high traffic volume conditions. Furthermore, a right-turn followed by a U-turn has the best LOS for case II.1 under low and moderate traffic volume conditions. In addition, a direct left-turn control type has better level of service compared to the other control types for cases 2, 3, 4, and 5. Finally, the DLT has the best level of service under low traffic volumes when the left-turn reaches 45 percent (i.e. case III). As illustrated, unconventional left turn control types are worse for case III compared to the direct left-turn control type.

Table 30 summarizes the level of service for the three left-turn control types for all of the considered U-turn locations. As illustrated, similar cases were combined together when there was no significant difference on the level of service (i.e. only one letter difference). Combining similar cases helps to visualize the impact of each parameter on the left-turn control types. Table 30 is used to summarize the results and draw the conclusions for this thesis.

Table 29: LOS Comparison for the Three Left-turn Control Types, U-turn Locations at 50m

Left-Turn (%)	% of Vehicles on each Approach	Traffic volume	Left-Turn Control Type DLT	RTUT	UTRT
Case I (15%)	Case 1	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	B
		High (6,000-7,000 vph)	D	E	F
	Case 2	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	B
		High (6,000-7,000 vph)	D	B	F
	Case 3	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	C
		High (6,000-7,000 vph)	E	C	F
	Case 4	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	C	F
		High (6,000-7,000 vph)	D	E	F
	Case 5	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	E
		High (6,000-7,000 vph)	D	E	F
Case II (30%)	Case 1	Low (3,500-5,000 vph)	C	B	B
		Moderate (5,000-6,000 vph)	C	B	F
		High (6,000-7,000 vph)	D	F	F
	Case 2	Low (3,500-5,000 vph)	C	B	E
		Moderate (5,000-6,000 vph)	D	F	F
		High (6,000-7,000 vph)	E	F	F
	Case 3	Low (3,500-5,000 vph)	C	C	F
		Moderate (5,000-6,000 vph)	C	F	F
		High (6,000-7,000 vph)	E	F	F
	Case 4	Low (3,500-5,000 vph)	C	B	E
		Moderate (5,000-6,000 vph)	C	E	F
		High (6,000-7,000 vph)	E	F	F
	Case 5	Low (3,500-5,000 vph)	C	E	F
		Moderate (5,000-6,000 vph)	C	F	F
		High (6,000-7,000 vph)	E	F	F
Case III (45%)	Case 1	Low (3,500-5,000 vph)	D	C	F
		Moderate (5,000-6,000 vph)	E	F	F
		High (6,000-7,000 vph)	F	F	F
	Case 2	Low (3,500-5,000 vph)	F	F	F
		Moderate (5,000-6,000 vph)	F	F	F
		High (6,000-7,000 vph)	F	F	F
	Case 3	Low (3,500-5,000 vph)	F	F	F
		Moderate (5,000-6,000 vph)	F	F	F
		High (6,000-7,000 vph)	F	F	F
	Case 4	Low (3,500-5,000 vph)	D	F	F
		Moderate (5,000-6,000 vph)	F	F	F
		High (6,000-7,000 vph)	F	F	F
	Case 5	Low (3,500-5,000 vph)	E	F	F
		Moderate (5,000-6,000 vph)	F	F	F
		High (6,000-7,000 vph)	F	F	F

Table 30: Summary of the LOS for the Three Left-turn Control Types

U-Turn Locations	Left-Turn (%)	% of Vehicles on each Approach	Traffic volume	Left-Turn Control Type		
				DLT	RTUT	UTRT
200 meters	Case I (15%)	Cases 1,2,3,4,5	Low (3,500-5,000 vph)	C	C	B
			Moderate (5,000-6,000 vph)	C	C	B
			High (6,000-7,000 vph)	D	C	C
	Case II (30%)	Cases 1,2,3,4,5	Low (3,500-5,000 vph)	C	C	C
			Moderate (5,000-6,000 vph)	C	C	C
			High (6,000-7,000 vph)	E	C	C
	Case III (45%)	Case 1	Low (3,500-5,000 vph)	D	C	C
			Moderate (5,000-6,000 vph)	E	C	C
			High (6,000-7,000 vph)	F	C	C
		Cases 2,3	Low (3,500-5,000 vph)	F	C	C
			Moderate (5,000-6,000 vph)	F	D	D
			High (6,000-7,000 vph)	F	E	E
		Cases 4,5	Low (3,500-5,000 vph)	D	C	C
			Moderate (5,000-6,000 vph)	F	D	D
			High (6,000-7,000 vph)	F	E	E
100 meters	Case I (15%)	Cases 1,2,3	Low (3,500-5,000 vph)	C	B	B
			Moderate (5,000-6,000 vph)	C	B	B
			High (6,000-7,000 vph)	D	C	C
		Cases 4,5	Low (3,500-5,000 vph)	C	B	B
			Moderate (5,000-6,000 vph)	C	C	C
			High (6,000-7,000 vph)	D	D	E
	Case II (30%)	Cases 1,2,3,4,5	Low (3,500-5,000 vph)	C	C	D
			Moderate (5,000-6,000 vph)	C	C	C
			High (6,000-7,000 vph)	E	C	D
	Case III (45%)	Case 1	Low (3,500-5,000 vph)	D	C	C
			Moderate (5,000-6,000 vph)	E	C	C
			High (6,000-7,000 vph)	F	E	F
		Cases 2,3,4,5	Low (3,500-5,000 vph)	E	C	D
			Moderate (5,000-6,000 vph)	F	E	F
			High (6,000-7,000 vph)	F	F	F
50 meters	Case I (15%)	Cases 1,2,3	Low (3,500-5,000 vph)	C	B	B
			Moderate (5,000-6,000 vph)	C	B	B
			High (6,000-7,000 vph)	D	D	F
		Cases 4,5	Low (3,500-5,000 vph)	C	B	B
			Moderate (5,000-6,000 vph)	C	C	E
			High (6,000-7,000 vph)	D	E	F
	Case II (30%)	Case 1	Low (3,500-5,000 vph)	C	B	B
			Moderate (5,000-6,000 vph)	C	B	F
			High (6,000-7,000 vph)	D	F	F
		Cases 2,3,4,5	Low (3,500-5,000 vph)	C	C	F
			Moderate (5,000-6,000 vph)	C	F	F
			High (6,000-7,000 vph)	E	F	F
	Case III (45%)	Cases 1,2,3,4,5	Low (3,500-5,000 vph)	E	F	F
			Moderate (5,000-6,000 vph)	F	F	F
			High (6,000-7,000 vph)	F	F	F

5.2.5 Impact of left-turn percentage.

Furthermore, the impact of changing the left-turn percentage was evaluated for all of the considered scenarios. For each U-turn location, the left-turn movements for the northbound and the southbound approaches represent three cases (i.e. 15%, 30%, and 45%).

Figure 61 shows the impact of changing the left-turn percentage for case 200.1.6000. As illustrated, the average delay is almost constant for the three control types at left-turns less than 30 percent. Also, the delay for the DLT increases at a higher rate when the left-turn exceeds 30 percent. However, the delay for unconventional control types increases at a trivial rate when the left-turn exceeds 30 percent. In addition, the UTRT has the least delay followed by the RTUT and then the DLT over the considered left-turn percentages.

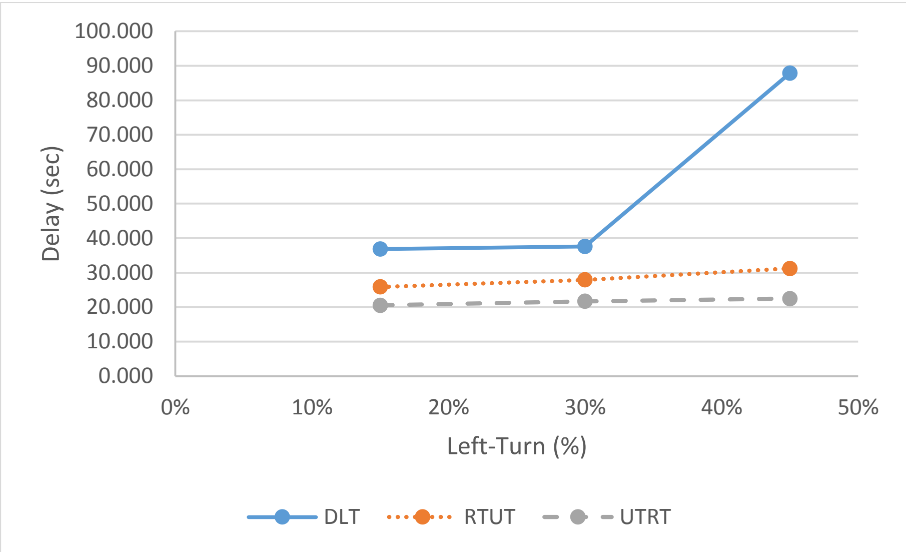


Figure 61: Impact of the Left-turn Percentage for Case 200.1.6000

Moreover, the impact of changing the left-turn percentages is very similar when the traffic volume is dominant on two opposite approaches. Figure 62 presents the impact of changing the left-turn percentage for case 200.2.6000. As illustrated, the delay for the UTRT increases at a higher rate when traffic volumes exceed 30 percent. Also, a right-turn followed by a U-turn control type has reasonable delay over the considered range of left-turn percentages.

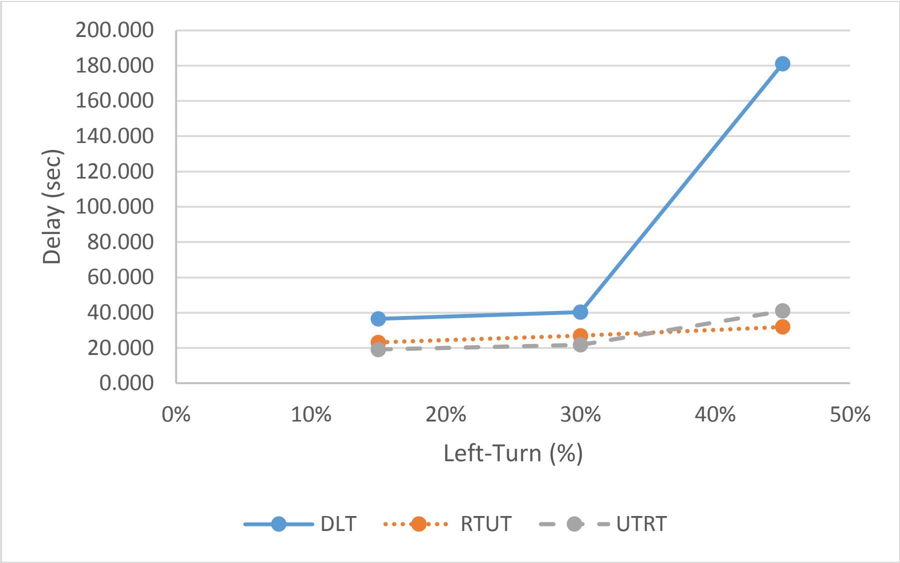


Figure 62: Impact of the Left-turn Percentage for Case 200.2.6000

Similarly, the impact of changing the left-turn percentages has a similar trend when traffic volume is dominant on two perpendicular approaches. Figure 63 compares the three left-turn control types for case 200.4.6000. As illustrated, the delay for the DLT increases at a higher rate when the left-turn percentage exceeds 30 percent. Also, the UTRT has the least delay for this case followed by the RTUT and then the DLT. It should be noted that the delay starts to increase at a higher rate for all of the considered scenarios when the left-turn percentage exceeds 30 percent. The curves will have a similar trend when the total volume on the intersection is varied and the location of the U-turns is moved closer to the intersection.

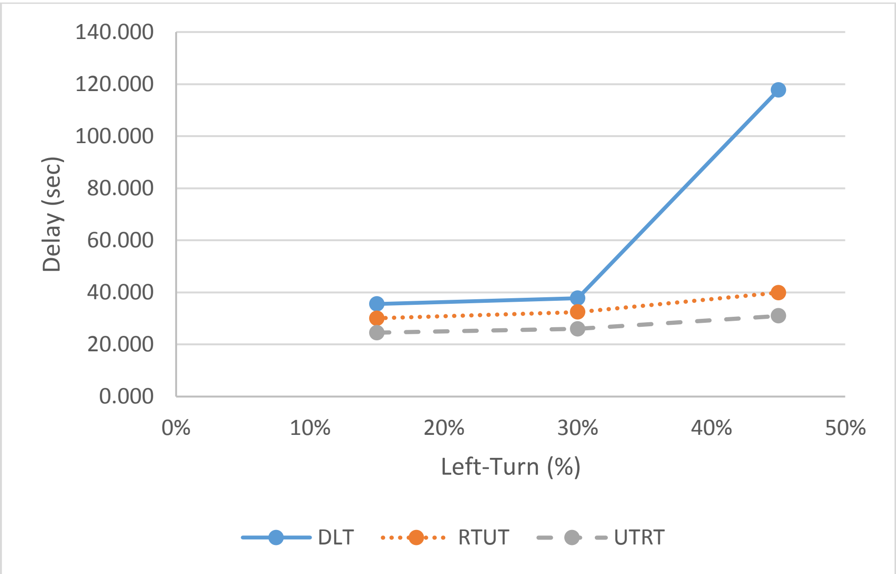


Figure 63: Impact of the Left-turn Percentage for Case 200.4.6000

5.2.6 Impact of U-turn location.

Moreover, the impact of a U-turn location on the operational performance of unconventional left-turn control types was investigated under different traffic conditions. Three different U-turn locations were investigated at 200 meters, 100 meters, and 50 meters.

Figure 64 illustrates the impact of changing the location of the U-turns for the right-turn followed by a U-turn control type. As illustrated, Figure 64 presents case I, where left-turn movements for the northbound and the southbound approaches represent 15 percent of the total volume assigned on these approaches. As shown, each column presents the average delay for one of the scenarios presented in the experimental design. The dashed line presents LOS E, where the overall delay of the intersection is equal to 55 seconds. The majority of the scenarios have a comparable delay at all of the considered U-turn locations. However, the average delay increases dramatically for three scenarios (I.1.b.7000, I.4.b.7000, and I.5.b.7000) when the U-turn locations are 50 meters away from the main intersection. When the total volume on the intersection reaches 7,000 vph, the average delay increases significantly for the RTUT control type when moving the U-turns very close to the main intersection (i.e. at 50 meters).

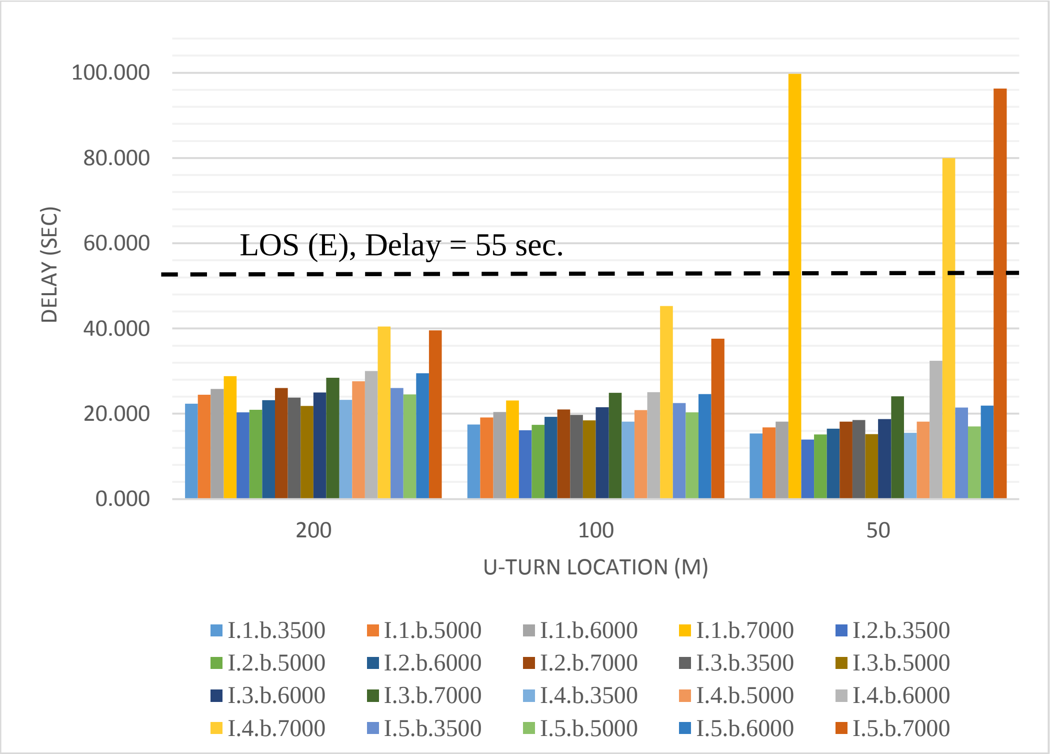


Figure 64: Impact of U-turn Locations for Case I.b

Figure 65 illustrates the impact of changing the location of the U-turns for the UTRT control type. As illustrated, Figure 65 presents case I, where left-turn movements for the northbound and the southbound approaches represent 15 percent of the total volume assigned on these approaches. As shown, all scenarios have a comparable delay when the U-turn locations are at 100 and 200 meters, except for two scenarios (I.4.c.7000 and I.5.c.7000). This is attributed to the queue formation at the U-turn location when the traffic volume reaches 7,000 vph, and the volume is dominant on two perpendicular approaches. On the other hand, the average delay increases significantly for some scenarios (I.1.c.7000, I.2.c.7000, I.3.c.7000, I.4.c.6000, I.4.c.7000, and I.5.c.7000), when the U-turn locations are 50 meters away from the main intersection. For case I.c, the average delay increases significantly when the traffic volume reaches 7,000 and the U-turn locations are 50 meters away from the main intersection.

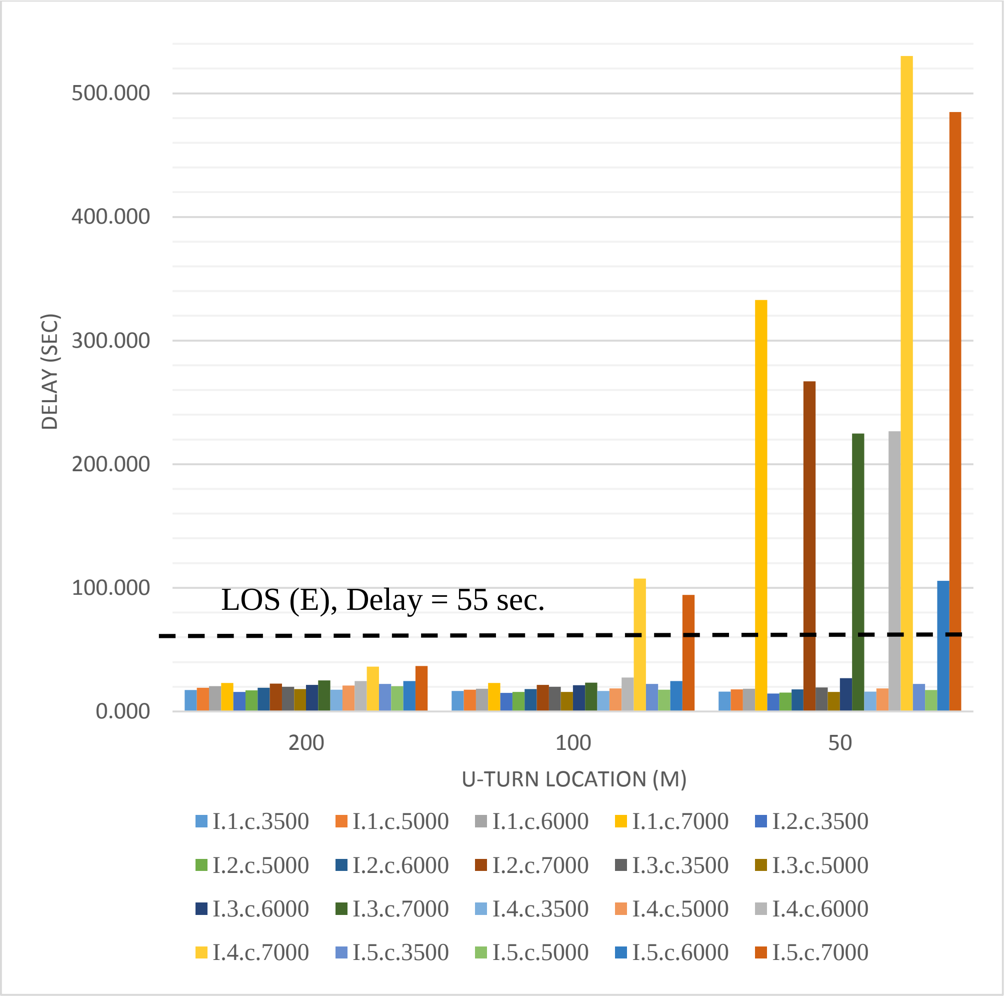


Figure 65: Impact of U-turn Locations for Case I.c

Furthermore, Figure 66 illustrates the impact of changing the location of the U-turns for the right-turn followed by a U-turn control type. As illustrated, Figure 66 presents case II, where left-turn movements for the northbound and the southbound approaches represent 30 percent of the total volume assigned on these approaches. As illustrated, all of the scenarios have a comparable delay when U-turn locations are at 100 and 200 meters. However, when the U-turn locations are 50 meters away from the main intersection, the average delay increases dramatically for many scenarios (II.1.b.7000, II.2.b.6000, II.2.b.7000, II.3.b.6000, II.3.b.7000, II.4.b.6000, II.4.b.7000, II.5.b.5000, II.5.b.6000, and II.5.b.7000). When the total traffic volume exceeds 6,000 vph, the intersection delay increases significantly for case II.b when moving the U-turns very close to the main intersection (at 50 meters).

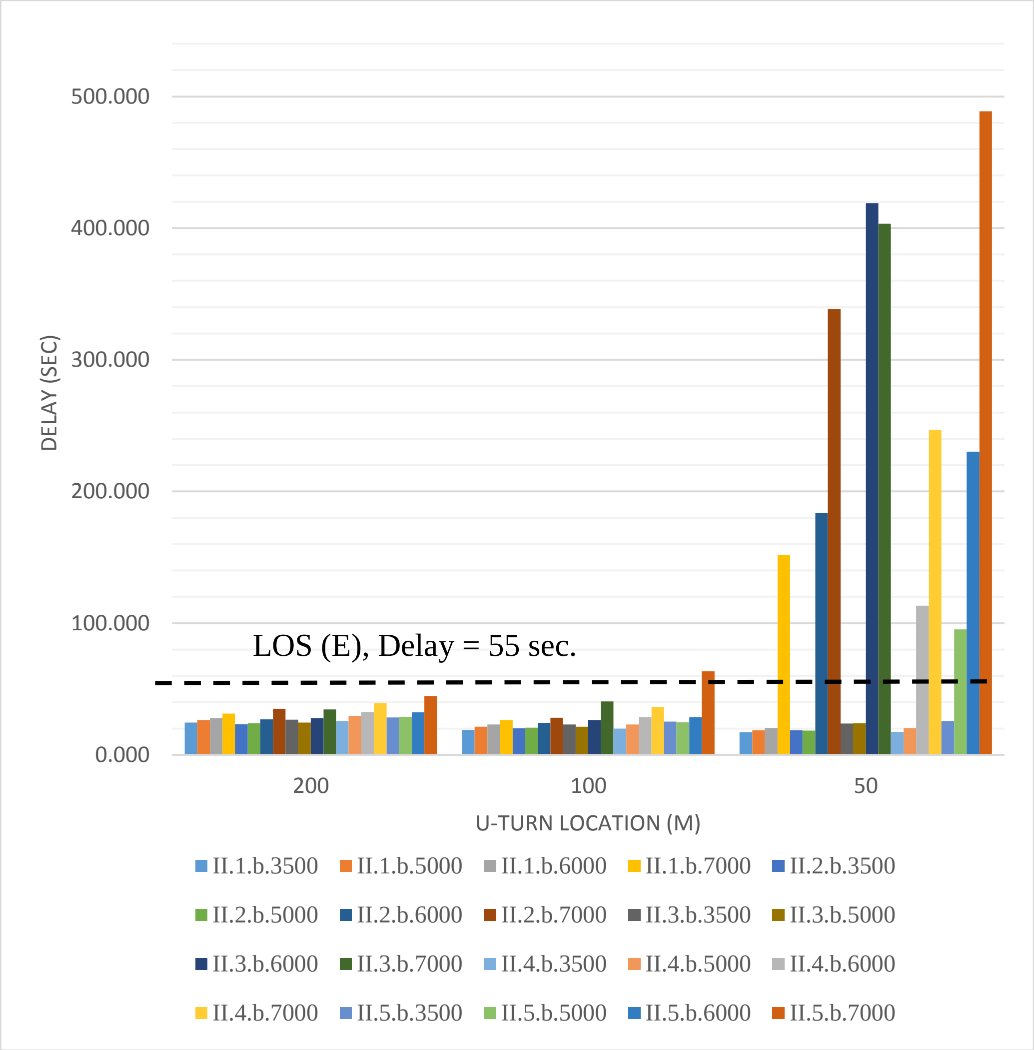


Figure 66: Impact of U-turn Locations for Case II.b

Figure 67 illustrates the impact of changing the location of the U-turns for a U-turn followed by a right-turn control type. As illustrated, Figure 67 presents case II, where left-turn movements for the northbound and the southbound approaches represent 30 percent of the total volume assigned on these approaches. As shown, all scenarios have a comparable delay when U-turn locations are at 100 and 200 meters. However, when the U-turn locations are 50 meters away from the main intersection, the average delay increases dramatically for most scenarios (II.1.c.6000, II.1.c.7000, II.2.c.5000, II.2.c.6000, II.2.c.7000, II.3.c.5000, II.3.c.6000, II.3.c.7000, II.4.c.5000, II.4.c.6000, II.4.c.7000, II.5.c.5000, II.5.c.6000, and II.5.c.7000). Based on Figure 67, the offset distance between the main intersection and the U-turn location has to be at least 100 meters for case II.c.

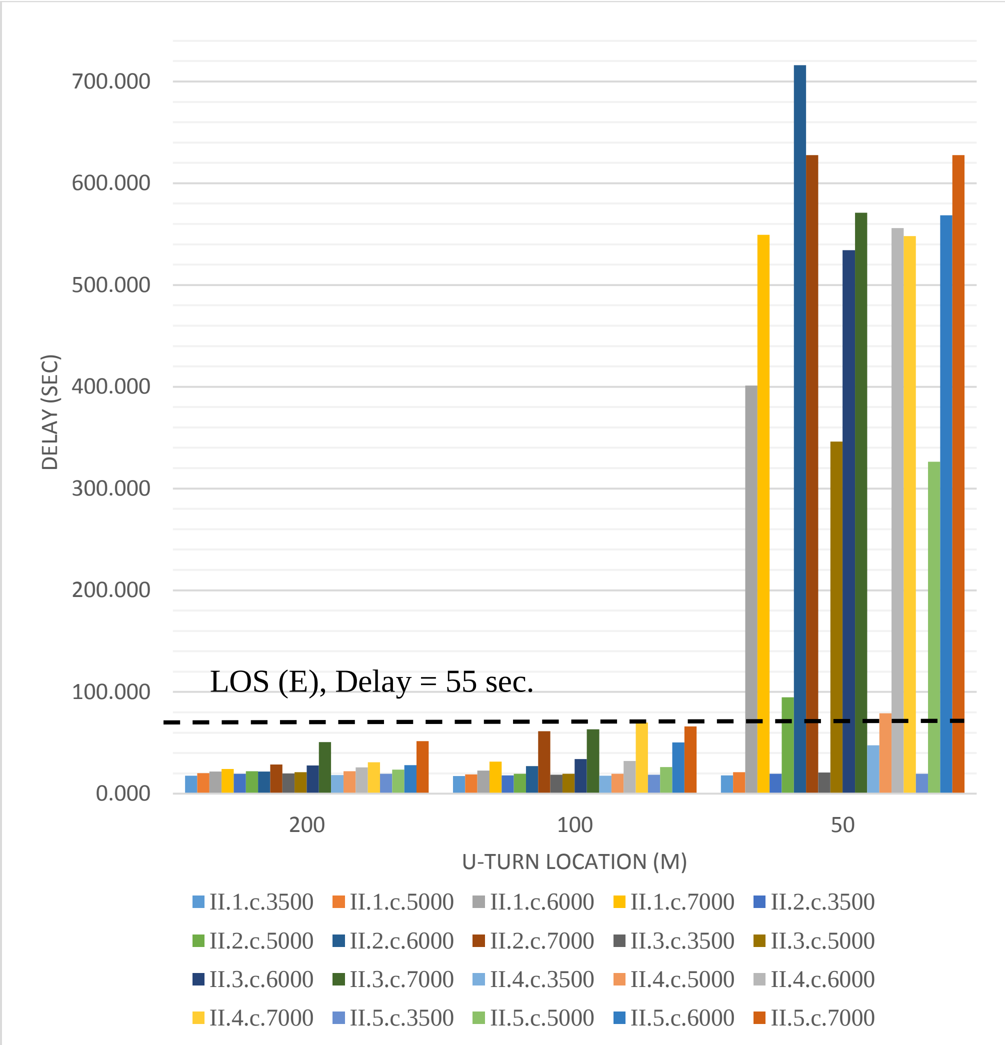


Figure 67: Impact of U-turn Locations for Case II.c

Moreover, Figure 68 illustrates the impact of changing the location of the U-turns for the right-turn followed by a U-turn control type. As illustrated, Figure 68 presents case III, where left-turn movements for the northbound and the southbound approaches represent 45 percent of the total volume assigned on these approaches. As illustrated, when the U-turn locations are 100 meters away from the main junction, the intersection delay increases for many scenarios (III.1.b.7000, III.2.b.6000, III.2.b.7000, III.3.b.6000, III.3.b.7000, III.4.b.6000, III.4.b.7000, III.5.b.6000, and III.5.b.7000). The intersection delay increases significantly when the traffic volume reaches 6,000 vph, regardless of the traffic volume distribution between the approaches. In addition, the average delay increased dramatically for most scenarios when the U-turn locations were 50 meters away from the main intersection. In fact, many scenarios require more offset distance for case III.b, as shown in Figure 68.

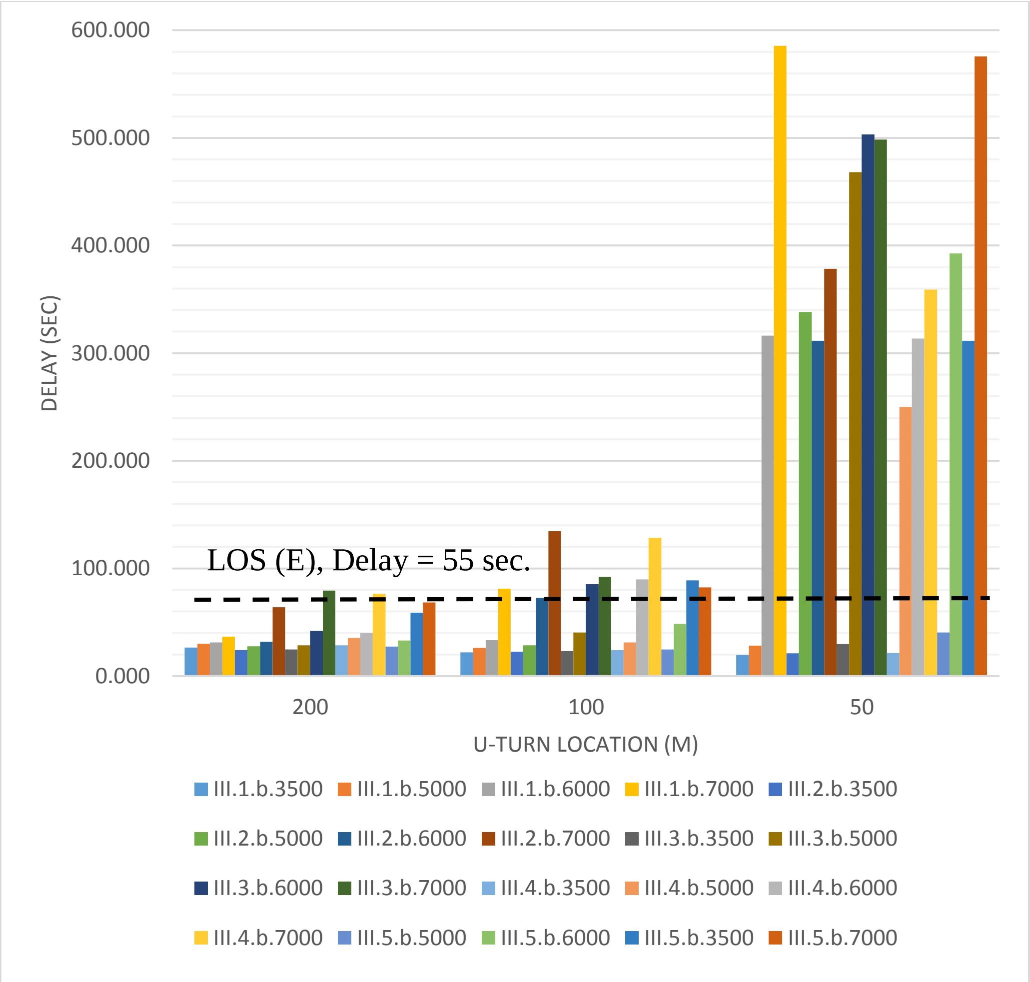


Figure 68: Impact of U-turn Locations for Case III.b

Figure 69 illustrates the impact of changing the location of the U-turns for a U-turn followed by a right-turn control type. As illustrated, Figure 69 presents case III, where left-turn movements for the northbound and the southbound approaches represent 45 percent of the total volume assigned on these approaches. As illustrated, when the U-turn locations are 100 meters away from the main junction, intersection delay increases for many scenarios (III.1.c.7000, III.2.c.6000, III.2.c.7000, III.3.c.5000, III.3.c.6000, III.3.c.7000, III.4.c.6000, III.4.c.7000, III.5.c.5000, III.c.6000, and III.5.c.7000). Intersection delay increases dramatically at moderate and high traffic volume conditions. Furthermore, the average delay increases significantly for most scenarios when the U-turn locations are 50 meters away from the main intersection. For the U-turn followed by a right-turn control type, Figure 69 is used to determine the optimal U-turn locations for case III.c.

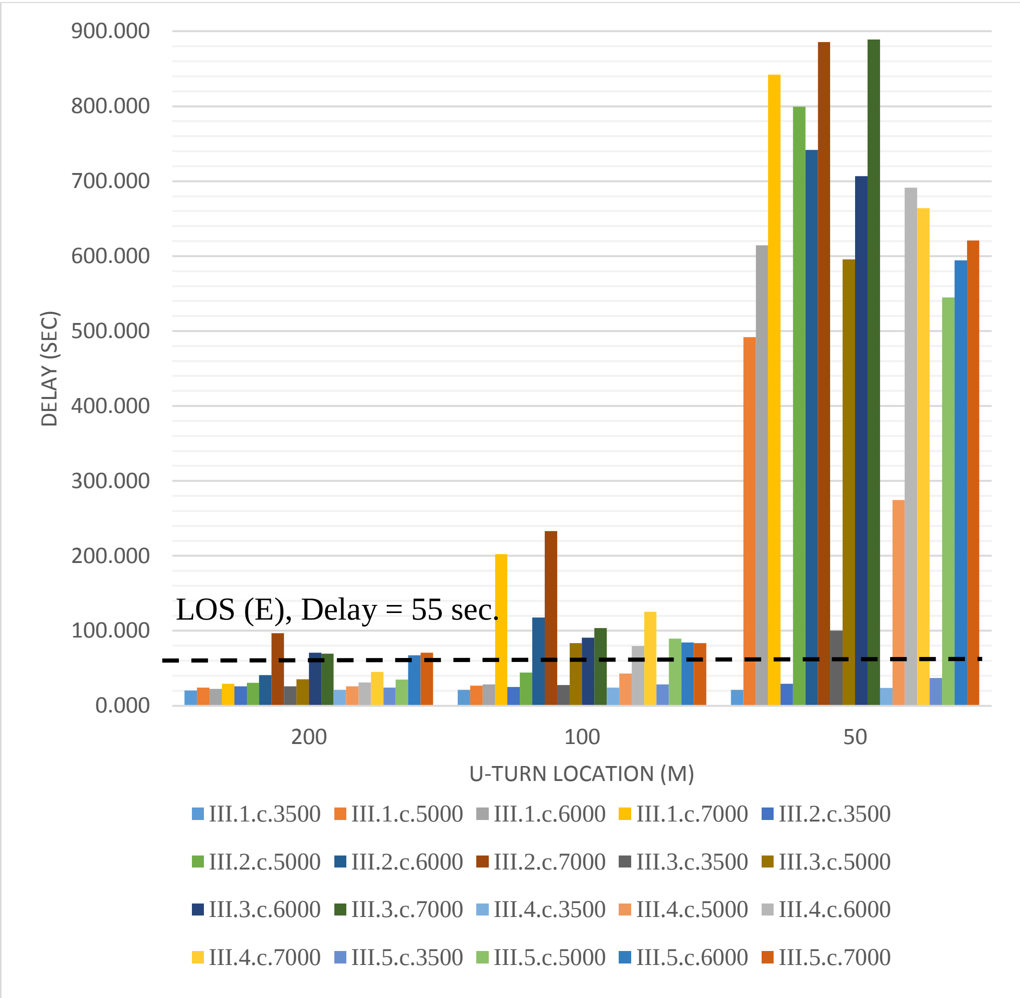


Figure 69: Impact of U-turn Locations for Case III.c

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

This thesis investigated the operational effects of three left-turn control types including a direct left-turn, right-turn followed by a U-turn, and a U-turn followed by a right-turn. Different traffic parameters were considered in the analysis including the total traffic volume on the intersection, the left-turn control type at the intersection, the distribution of traffic volume on each approach, the percentage of vehicles for each turning movement, and the location of the U-turns. The distribution of traffic volume on each approach represented several cases, and the left-turn percentages varied from 15 to 45 percent of the total volume on each approach. In addition, the study evaluated the impacts of the U-turn locations relative to the signalized intersection for each unconventional left-turn control type. The software packages Synchro and Vissim were utilized to evaluate each alternative. The conclusions of the study are summarized as follows:

1) When the U-turn locations are 200 meters away from the main intersection, unconventional left-turn control types show superior performance compared to the direct left-turn control type. This implies that the RTUT and the UTRT control types provide less delay and travel time compared the direct left-turn control type. Also, unconventional left-turn control types have comparable delay and travel time over the considered range of traffic volumes.
2) When the U-turn locations are 100 meters away from the main intersection, unconventional left-turn control types show superior performance compared to the direct left-turn control type for all of the considered cases. When the left-turn percentage is less than 30 percent, the RTUT and the UTRT show similar traffic performance over the considered range of traffic volumes. However, when the left-turn percentage is equal to 45 percent, the right-turn followed by a U-turn control type shows superior performance compared to the other left-turn control types.
3) When the U-turn locations are 50 meters away from the main intersection, unconventional left-turn control types show superior performance when the left-turn percentage is equal to 15 percent under low and moderate traffic volume conditions. However, the direct left-turn control type shows better performance under high traffic volume conditions. When the left-turn percentage exceeds 15 percent, the direct left-turn shows superior performance

compared to the other left-turn control types over the considered range of traffic volume.

4) For the direct left-turn control type, the intersection delay increases at a rapid rate during high traffic volume conditions because of the growing queue at the signalized intersection that cannot fully dissipate in one cycle.
5) When moving the U-turn locations closer to the intersection, the average delay increases dramatically for unconventional left-turn control types because of the queue formation at the U-turn locations and the spillback effect, which blocks the signalized intersection.
6) Unconventional left-turn control types have comparable vehicle kilometers travelled (VKT) when compared to the direct left-turn control type (i.e. the difference is less than 8%).
7) The average delay for all of the considered left-turn control types (i.e. DLT, RTUT, UTRT) increases at a higher rate when the left-turn percentage exceeds 30 percent.
8) At low traffic volumes (i.e. less than 5000 vph), the impact of changing the traffic volume distribution on each approach is insignificant.
9) Having equally distributed traffic volume on all approaches shows better performance than having dominant traffic volume in only two approaches.

6.2 Recommendations

Before implementing unconventional left-turn control types, transportation agencies and municipalities should consider the following issues:

1) In many cases, U-turns need to accommodate large vehicles. This is achieved by building a wider median.
2) Driver confusion and the impact of implementing unconventional left-turn control types on a driver's behavior. The signage on the approaches to the intersections should be very clear and noticeable to drivers. Also, public announcements should be made to indicate the change in traffic control system within the given city/area.
3) Traffic violation to the left-turn prohibition at the main intersection.
4) Enforcement and education to prevent illegal turns at the signalized intersection.

Future research related to the impact of U-turns as alternatives to direct left-turns may include the following cases:

1) Different layouts of intersections (i.e. a different number of lanes for each movement).
2) Different signal phasing.
3) Determining the maximum/minimum traffic volume requirements at which the unconventional left-turn types are inefficient.
4) Determining the minimum length of the U-turn storage lane.
5) Network level impact (i.e. simulate a network with more than one intersection).

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