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Пут и саобраћај
Journal of Road and Traffic Engineering

Journal homepage: www.putisaobracaj.rs

Introducing and Evaluating the Operational Performance of a New Interchange Design: The Continuous Green-T Median U-Turn Interchange

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ARTICLE INFO

DOI: 10.31075/PIS.69.03.02
Professional paper
Received: 22.08.2023.
Accepted: 20.09.2023.
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*Keywords***:**

CGT-MUT
Continuous Green-T
Median U-Turn
Single Point Diamond Interchange
VISSIM
ASC/3 Signal Controllers
Traffic Operations

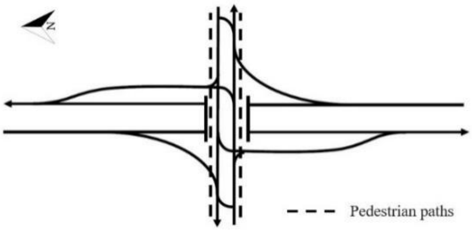
ABSTRACT

This study proposes a new design called the continuous green-T median U-turn (CGT-MUT) interchange and evaluates its operational performance compared to three interchanges. The selected interchanges for comparison are the Superstreet, Single Point Diamond Interchange (SPDI), and the Synchronized interchange. The evaluation is based on a microsimulation environment created in VISSIM combined with ASC/3 Software-in-the-Loop signal controllers. The findings show that the CGT-MUT enhanced the network-wide and intersection-level operations regarding various measures of effectiveness. Additionally, while the CGT-MUT did not always outperform all the other designs in terms of the on-ramp turning traffic travel times, it outperformed the Superstreet and Synchronized in terms of the off-ramp turning traffic travel times and resulted in the least through traffic travel times for all the tested scenarios. Particularly, the CGT-MUT's through travel times were 9% – 30%, 26% – 42%, and 13% – 38% less than those for the Superstreet, SPDI, and Synchronized interchanges, respectively.

1. Introduction

Population growth, the unprecedented increase in vehicle-miles traveled (VMT) combined with the increase in the number of privately-owned vehicles have led to congestions and delays in major urban centers in the United States, among other countries. Transportation professionals, as a consequence, have been investigating alternative, also known as unconventional, design treatments as one strategy to meet the mobility needs considering the limited availability of resources. Alternative designs attempt to increase intersections' capacities and improve their safety by reducing turning movements impact. This is done by favoring arterials heavy-volume through traffic, re-routing of the left-turning traffic, reducing the number of signal phases, and lastly, reducing the number of conflict points. Once followed, these principles would allow for an improved signal progression, reduced travel times, delays, crash frequencies and severities (Reid, 2004). The Superstreet and the Median U-turn (MUT) interchanges, shown in Figure 1, are two examples of previously created U-turn based interchange designs. The MUT interchange, however, requires two additional crossover bridges to handle left-turning traffic, making it more costly than many other alternatives including the CDI (Hummer, 2014). Previous studies have shown that the Superstreet interchange has provided the best operational performance among the CDI, Displaced Left Turn (DLT), Contraflow Left, and the MUT interchanges (Click et al., 2010; Hummer, 2014). According to Bared & Kaisar (2002), the average travel time for traffic making a U-turn is higher than that for direct left turns, however, the overall reduction in the network-wide travel time for the U-turn intersection treatment is significant. Median U-turn treatments have resulted in approximately 10% – 50% increases in capacities and in as high as 50% reductions in crashes (Esawey & Sayed, 2011; U.S. Department of Transportation, 2007). Due to these benefits, the MUT treatment has been gaining attention. Molan & Hummer (2018), for instance, have proposed the Synchronized interchange design, which combines the Superstreet with the Contraflow Left interchange as shown in Figure 2. Molan and Hummer mentioned that the Synchronized interchange could operate better than the CDI when the through traffic volumes are the highest.

The goal of this paper is to introduce a new interchange design called the Continuous Green-T Median U-Turn (CGT-MUT) interchange, and to evaluate its operational performance to that of three service interchange designs. The CGT-MUT combines the continuous green T intersection design, and the MUT intersection design with the CDI as shown in Figure 3. The three designs selected in the comparison are the Single Point Diamond Interchange (SPDI), Superstreet interchange, and the Synchronized interchange. The SPDI was chosen in the comparison because the current implemented interchange design in the study location is the SPDI, while the Superstreet and Synchronized interchanges were selected because they represent the most possible alternatives to the CGT-MUT in terms of concept and required footprint. For the operational evaluation, a replica of a real-world interchange was built in VISSIM microsimulation software in combination with Econolite's external ASC/3 Software-in-the-Loop (SIL) signal controllers. Additionally, various traffic conditions were modelled to ensure rigorous operational performance evaluation.



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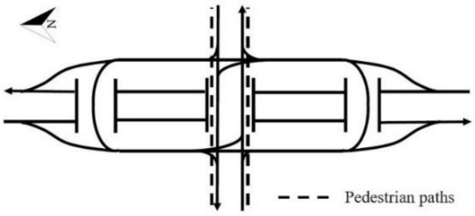

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Figure 1. Schematics of the Superstreet and MUT Interchanges.
a – Superstreet Interchange;
b – MUT Interchange;

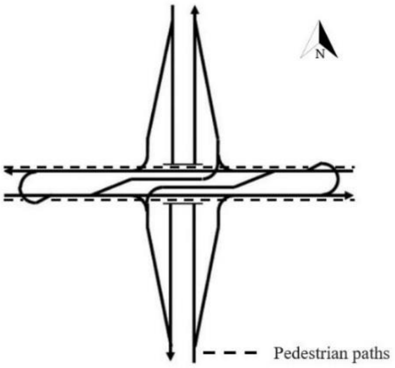

Figure 2. Schematic of the Synchronized Interchange.

This paper is organized as follows. The following section introduces the CGT-MUT interchange in detail. A review of the literature on the performance of conventional and unconventional designs is presented in the section that follows. The research methodology is presented in a subsequent section. Then, the results analyses, and discussion are provided. Lastly, the conclusions and recommendations are discussed in the final section.

2. The CGT-MUT Interchange

The CGT-MUT interchange shown in Figure 3 was developed by the first author of this study, and to the best of our knowledge, it has never appeared in the peer-reviewed literature. The CGT-MUT is a combination of a CDI, two continuous green T (CGT) intersections, and a MUT intersection.

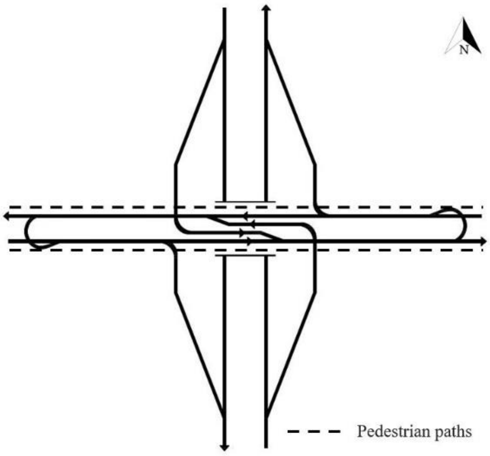

Figure 3. Schematic of the CGT-MUT Interchange.

The CGT intersection, shown in Figure 4, improves safety and operational efficiency of three-legged intersections (Virginia Department of Transportation, 2020). At the CGT, left-turning vehicles from the side street use an added channelized receiving lane on the major street to merge onto the major street. Consequently, reducing the number of signal phases and allowing the through moving traffic on the major street and the left turning traffic from the side street to move at the same time. Thereby, reducing delays and travel times. This also leads to improved safety since the number of crossing conflict points is reduced.

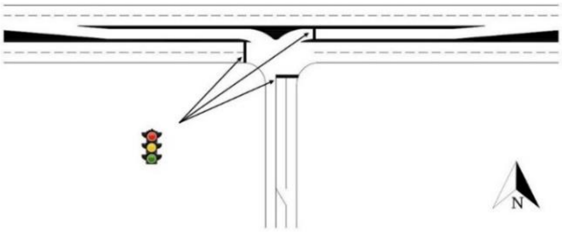

Figure 4. Schematic of the CGT Intersection.

Similarly, the MUT intersection, shown in Figure 5, improves intersection operations and safety by reducing the number of traffic signal phases and conflict points at the main intersection (Reid et al., 2014).

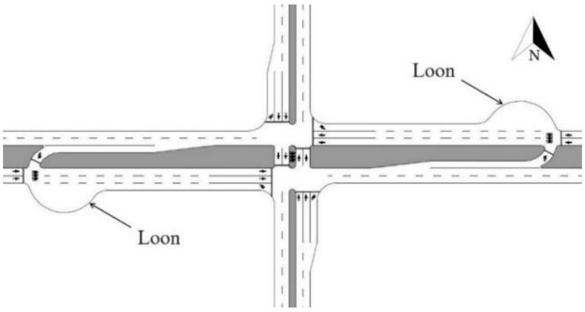

Figure 5. Schematic of the MUT Intersection.

The MUT replaces direct left turns at the main intersection with indirect left-turns completed by directing drivers through a downstream U-turn movement, which requires drivers to proceed back to the main intersection and then make a right turn onto the minor street. The CGT-MUT interchange design combines the CDI with the MUT and CGT to benefit from the operational and safety improvements that each of the CGT and MUT provides. In a CGT-MUT, the through moving traffic is separated from the off-ramp left-turning traffic and, therefore, they are no longer conflicting at the ramp terminal. This allows for the removal of the signal head for the through moving traffic at one of the interchange ramp terminals as shown in Figure 6.

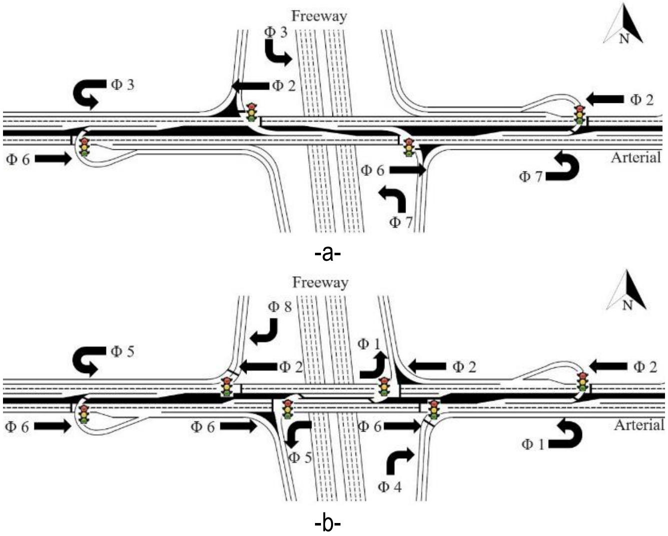

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Figure 6. Schematics of the CGT-MUT and Superstreet Interchanges and Signal Phasing.
a – CGT-MUT Interchange and Recommended Signal Phasing;
b – Superstreet Interchange and Signal Phasing;

The CGT-MUT, therefore, allows for a reduced number of signal phases. This is especially true since the on-ramp left-turning traffic is directed through the interchange terminals to a downstream U-turn, which eventually separates the off-ramp and on-ramp left-turning movements and allows them to move at the same time. The latter is possible by giving the green indication to the off-ramp left-turning traffic and the downstream U-turning traffic at the same time (i.e., assigning them the same signal phase), as shown in Figure 6. This practice reduces the required number of signal heads from 12 at a typical Superstreet interchange to eight at the CGT-MUT. Additionally, this allows for the CGT-MUT interchange to operate in a two-phase signal scheme, while a typical Superstreet interchange would require a 3-phase signal scheme for safe operations. A reduced number of signal phases results in more time available to be allocated to other phases, therefore, should improve the operational performance. The reduction of four signal heads, their signal controllers, detectors, and other associated equipment would result in the CGT-MUT requiring less costs for construction, operation and maintenance compared to Superstreet interchange. However, costs are beyond the scope of this study. Figure 7 shows the optimal signal progression for a CGT-MUT terminal and an adjacent intersection.

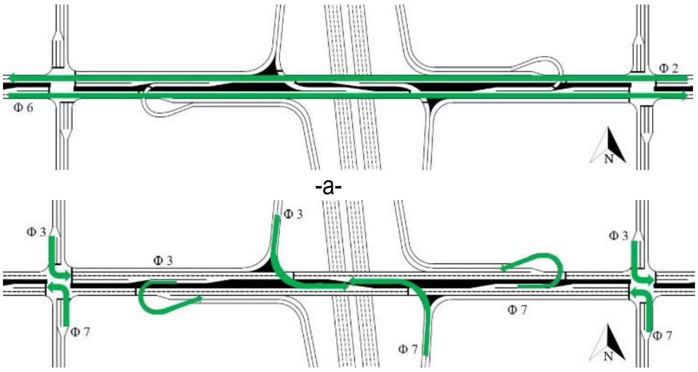

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Figure 7. Optimal Signal Progression through CGT-MUT and Adjacent Intersections.
a – Arterial Through Movements;
b – Off-Ramp Left Turns, U-Turn and Arterial Left Turns;

As previously mentioned, the CGT-MUT separates the through moving traffic of the arterial from the off-ramp left-turning traffic and, therefore, they are no longer conflicting at the ramp terminal. In fact, the CGT-MUT eliminates one crossing conflict point at each ramp terminal and substitutes it with a downstream merging conflict point. This change in the nature of conflict points, along with the recommended progression ensures minimal interaction between arterial's through traffic and off-ramp left-turning traffic. As a consequence, the number of vehicle-to-vehicle conflicts produced by a CGT-MUT would be reduced.

Regarding the footprint of the CGT-MUT, it would be identical to that of the Superstreet interchange for a specific location, as shown in Figure 6. In terms of the interchange geometrics, it is crucial to note that the only difference between a Superstreet interchange and a CGT-MUT is the configuration of the left-turn lanes between the interchange ramp terminals. In that, in a CGT-MUT, the left-turn lanes are designed to allow for the off-ramp left turning traffic to move at the same time with the arterial's through traffic, as depicted in Figure 6-a-.

The number of lanes for the CGT-MUT is also identical to that of the Superstreet interchange, or a CDI for the same location, roadway, and traffic conditions. Practitioners, researchers, and designers of the CGT-MUT, should note that the concept of the CGT intersection which constitutes the heart of the CGT-MUT requires the addition of a number of channelized receiving lanes on the arterial for the off-ramp left-turning traffic. These lanes will then merge onto the arterial as demonstrated in Figure 6-a-. The length and number of these channelized left-turn lanes is expected to be different from one location to another and is suggested to be determined based on the roadway and traffic conditions, and the guidelines of the American Association of State Highway and Transportation Officials' (AASHTO's) *A Policy on Geometric Design of Highways and Streets, 2018* (American Association of State Highway and Transportation Officials, 2018). An important feature of the CGT-MUT is the loon, shown in Figure 5.

A loon is the added pavement on the far side edge of the travel lanes that would make it possible for large vehicles and trucks to make U-turns (Hummer et al., 2014; Reid et al., 2014). Loons are included in each of the MUT intersection, Superstreet interchange, and Superstreet intersection. Therefore, incorporating them within any design is not a totally new practice. In fact, there are many locations around the United States that have MUT or Superstreet intersections with loons. It should be noted that loons make U-turns possible while imposing a minimal impact on right-of-way (ROW). The latter is true since loons require some acquisition of ROW at the U-turn locations only (Hummer et al., 2014; Reid et al., 2014). Loons are incorporated within the MUT or Superstreet designs to reduce the required median widths, or when the available median width along the major arterial is not enough to allow for cars and trucks to make U-turns. Thereby, the loons minimize the ROW impact along the major arterial (Hummer et al., 2014; Reid et al., 2014).

Additionally, the design guidelines of MUT and Superstreet intersections provide flexibility in U-turn loon locations, which provides more room for agencies to minimize ROW costs of loons (Hummer et al., 2014; Reid et al., 2014). It should be noted that loons could be designed to accommodate the WB-67, which is the recommended minimum size of a design vehicle for service interchanges (American Association of State Highway and Transportation Officials, 2018; Reid et al., 2014). In cases where medians are wide enough to allow U-turns by large trucks, loons won't be required, and no additional ROW will be needed. The latter applies to each of the new CGT-MUT, MUT, or Superstreet designs. The footprint of the CGT-MUT, is as mentioned, identical to that of the Superstreet interchange and is similar to that of a CDI interchange for a specific location.

Regarding the number and radii of U-turn lanes, practitioners, researchers, and designers of the CGT-MUT should follow AASHTO's *A Policy on Geometric Design of Highways and Streets, 2018* guidelines (American Association of State Highway and Transportation Officials, 2018). The proposed pedestrian paths for a CGT-MUT are shown in Figure 3 and are similar to those of the Superstreet interchange in the way pedestrians interact with vehicles.

3. Literature Review

Reid & Hummer (2001) used CORSIM to compare seven unconventional intersection designs. These designs included the Superstreet, and the MUT intersections, among other intersection configurations. The research team used multiple locations for the comparison. According to the results, the MUT and quadrant roadway intersections seemed to consistently reduce the travel times as opposed to implementing other designs. Hummer & Jagannathan (2008) found in their study that the rural applications of the Superstreet intersection in Maryland and North Carolina have resulted in remarkable safety improvements. Similar safety findings were reported by Hughes et al. (2010). Additionally, Hughes et al. (2010) compared the Superstreet to other conventional designs using VISSIM. The authors found that the Superstreet increased vehicular throughput by 30% and reduced network travel times by 40%. Haley et al. (2011) employed VISSIM to perform an operational performance comparison between the Superstreet and the conventional intersection. The results of their study provided evidence that the Superstreet increases capacity at higher traffic volumes, thereby buys transportation agencies extra years of acceptable traffic operations before improvements are required. Click et al. (2010) used VISSIM to compare the operational performance of 10 interchange configurations at two locations among which was the SPDI and Superstreet interchanges. They found that the SPDI has provided the best overall operational performance. Inman & Haas (2012) compared the Superstreet intersection to a conventional intersection and found that the weaving movements were similar for the two types of intersection.

Additionally, they found that the Superstreet design is capable of reducing crashes by up to 44%. Hummer (2014) compared the Superstreet to the Conventional Diamond, Diverging Diamond, Single Point Diamond, and MUT interchanges. Hummer reported that no design was superior in all examined measures. The Superstreet, as found by Hummer, exhibited the best signal progression, and generally provided good capacity. Esawey & Sayed (2011) found the MUT intersection to provide nearly 10% more in capacity than the conventional intersection. Fan & Liu (2021) studied the impact of Connected Vehicles (CVs) on Superstreets.

Results of their study indicated that delays and fuel consumption at Superstreets would be reduced by 8% to 10%, and 5% to 8%, respectively, depending on the market penetration rate of CVs. The CGT intersection design has demonstrated efficiency in improving the operational and safety performance substantially in seven U.S. states in which it was implemented as found in a study by CTC & Associates (CTC & Associates LLC, 2018). Previous studies have proven that combining the CGT intersection with interchanges results in substantial safety and operational improvements. Alzoubaidi and Zlatkovic (Alzoubaidi & Zlatkovic, 2022b), for instance, evaluated the safety of the Continuous Green-T Partial Cloverleaf A (CGT-parclo A) interchange against that of the Partial Cloverleaf (parclo A), Parclo ProgressA, Parclo B, Folded Interchange and the Displaced Parclo interchange. Alzoubaidi and Zlatkovic found the CGT-parclo A to have a superior safety performance when compared to the other parclo A alternatives. The CGT-parclo A was found to reduce the crossing conflicts, lane change conflicts, rear-end conflicts, and total number of conflicts by as high as 43.7%, 30.0%, 19.7%, and 28.1%, respectively.

As seen in the literature review part, the Superstreet, MUT and CGT designs, among other alternative intersection and interchange designs could bring major operational, and safety benefits. Therefore, there has been an increasing interest in assessing their performance. Similarly, many efforts have been made to develop new designs. However, to the best of our knowledge, there are no peer-reviewed studies, or technical reports that present or evaluate the performance of the CGT-MUT interchange. Therefore, this study is intended to introduce the CGT-MUT interchange and to compare its operational performance to the Superstreet interchange, SPDI, and Synchronized interchange. As previously mentioned, the SPDI was chosen in the comparison because the current implemented interchange design in the study location is the SPDI, while the Superstreet and Synchronized interchanges were selected because they represent the possible alternatives to the CGT-MUT in terms of concept and required footprint.

4. Research Methodology

4.1. Simulation Testcase and Data Collection

With more than 36% of Utah's total population, Salt Lake County has the highest population in Utah (U.S. Census Bureau, 2019), rendering it Utah's highest traffic-volume county. Therefore, the interchange of Interstate-15 (I-15) and 10600 S, a high volume major urban arterial in Salt Lake County was chosen for this study to assess the operational performance of the CGT-MUT design. The nearby intersections shown in Figure 8 were included in the modeled simulation network since they are likely to impact the arrival patterns and lane choices. The needed data to build the simulation models were obtained from the Utah Department of Transportation (UDOT) Traffic Operations Center, as well as UDOT's Automated Traffic Signal Performance Measures (ATSPMs) system. The used data consist of the traffic signal timing, traffic composition, the annual growth rate of traffic, and most importantly, the traffic volumes and turning movement counts for the study's base year of 2019. The annual growth rate of traffic was used along with the 2019 traffic volumes to predict the 2029 traffic volumes and turning movement counts. Data analysis showed three peak hours as follows: (7:45 – 8:45 AM), (12:15 – 1:15 PM), and (4:30 – 5:30 P.M.) during a typical work week.

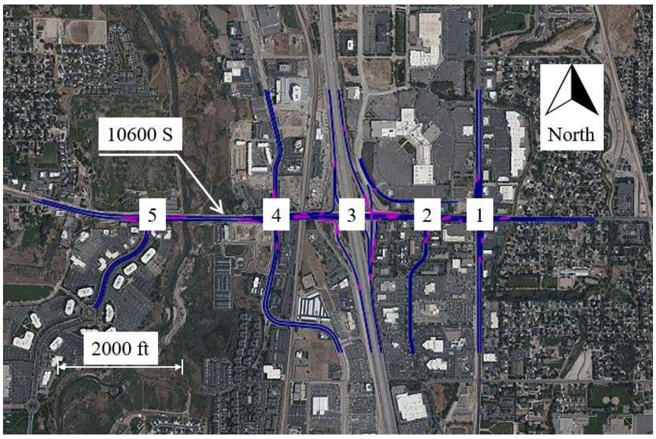

Figure 8. Testcase Network of I-15 and 12300 S, Salt Lake County, Utah.
1 – State St. (conventional intersection);
2 – Auto Mall Dr (conventional intersection);
3 – I-15 (SPDI);
4 – Jordan Gateway (conventional intersection);
5 – S River Front Pkwy (conventional intersection).

4.2. Microsimulation Modeling Methodology

To ensure a comprehensive operational evaluation of the CGT-MUT, two modeling years (2019, and 2029), three peak hours (morning, mid-day, and evening), and four interchange designs (CGT-MUT, Superstreet, SPDI, and Synchronized) were considered. This combination resulted in a total of 24 scenarios that would ensure the CGT-MUT is robustly evaluated under various traffic volumes and conditions. The Superstreet, Synchronized and CGT-MUT were all designed in Autodesk Civil 3D to conform with the guidelines of AASHTO's *A Policy on Geometric Design of Highways and Streets, 2018* (American Association of State Highway and Transportation Officials, 2018), the FHWA's Restricted Crossing U-turn Intersection Informational Guide (Hummer et al., 2014) and the FHWA's Median U-Turn Intersection Informational Guide (Reid et al., 2014).

Each of the Superstreet, Synchronized and CGT-MUT were designed to accommodate the WB-67, which is the recommended minimum size of a design vehicle for service interchanges (American Association of State Highway and Transportation Officials, 2018; Reid et al., 2014). In addition, the number of lanes for each design was kept the same as the number of lanes for the SPDI, which is the currently implemented design at the study location. For instance, all of the compared designs have two off-ramp and two on-ramp left turn lanes. Similarly, the number of through lanes, on-ramp right turning lanes, and off-ramp right turning lanes, were three lanes, one lane, and one lane, respectively, for all the compared designs. The latter ensured a fair operational performance comparison. This resulted in two U-turn lanes at the loon locations, as well as two off-ramp left-turn lanes at the CGT-MUT. The practice of providing two U-turn loon lanes and two left-turn lanes for the CGT intersection is not new and was followed in multiple CGT and Superstreet implementations around the United States. As for the traffic control and signal timing for each of the CGT-MUT, Superstreet, Synchronized and future SPDI scenarios, they were optimized using Synchro 10. According to UDOT's Traffic Analysis Guideline, it is considered acceptable to use Synchro for the analysis of conventional intersections, however, the analysis of unconventional designs is more complex and requires the use of VISSIM since it has proven to provide more detailed results (Utah Department of Transportation, 2018).

Similarly, as per the Transportation Research Boards' Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis (Transportation Research Board, 2016), since there is no available method to analyze weaving on urban streets, practitioners should use the available traffic simulation software tools for this purpose.

Additionally, multiple previous studies (Alzoubaidi, 2022; Alzoubaidi, Al-Balbissi, et al., 2021; Alzoubaidi et al., 2022; Alzoubaidi, Molan, et al., 2021; Alzoubaidi & Zlatkovic, 2022b, 2022d, 2022a, 2022c; Click et al., 2010; Hughes et al., 2010; Hunter et al., 2019) have used VISSIM for similar analyses.

Therefore, the microsimulation software VISSIM 21 was employed to build the simulation models for the 24 identified scenarios using the obtained data from UDOT, Synchro 10 and Autodesk Civil 3D. In order to mimic the real-world signal operations of each design, Econolite's external ASC/3 Software-in-the-Loop signal controllers were embedded in the simulation models.

4.3. Calibration and Validation

The results of calibration and validation are depicted in Figure 9. It should be noted that that the calibration and validation methodology recommended by multiple transportation agencies across the United States, among which is UDOT, was followed to ensure the developed microsimulation models mimic the real-world traffic conditions (Oregon Department of Transportation, 2011; Utah Department of Transportation, 2018; Washington State Department of Transportation, 2014). This methodology recommends that the traffic analysis results extracted from VISSIM should be based on a minimum of 10 simulation runs. Additionally, in this methodology, the use of the Geoffrey E. Heavers (GEH) statistic to compare the field-collected and simulation-generated turning movement counts is recommended. In a GEH analysis, if the GEH value is less than 5, then the developed simulation models are well calibrated. Therefore, the GEH value of 0.12 and R^2 value of more than 0.99 for calibration indicate a strong correlation between the collected and the simulated datasets, as shown in Figure 9. The phase green times acquired from UDOT's ATSPMs were compared to the phase green times recorded in the simulation to validate the base model. The R^2 value of 0.90 for validation shows a good match between datasets of green times. Each of the calibration and validation results show a good fidelity of the base simulation models developed for the study.

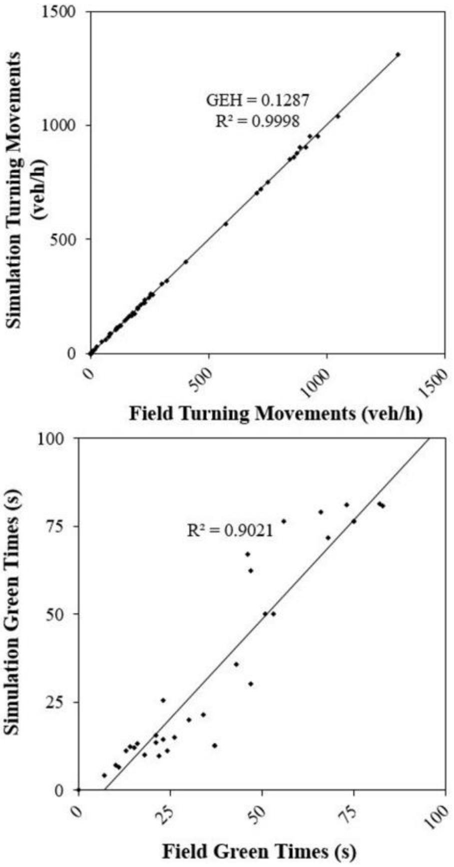

Figure 9. VISSIM model calibration and validation scatterplots.

5. Results and Discussion

To comprehensively evaluate the operational performance of the new CGT-MUT interchange design to that of each of the Superstreet, SPDI, and Synchronized interchanges, multiple performance metrics were considered. These were delays, section travel times, queue lengths, number of stops, and speeds. It has been previously proven that the average travel time for traffic making a U-turn is higher than that for direct left turns, however, the overall reduction in the network-wide travel time for the U-turn intersection treatment is significant (Bared & Kaisar, 2002). Therefore, some of the performance metrics for this study were recorded at the intersection level, while some other were recorded at the network-wide level. The results of these metrics were acquired and averaged from 10 randomly seeded simulation runs, as recommended by UDOT's Traffic Analysis Guideline, among other state guidelines. The statistical significance of the obtained results was evaluated using two-tailed t-tests that were conducted at the 95.0% confidence level. Table 1 shows the network-wide performance results, while Tables 2 and 3 show the intersection level performance results.

In Table 1, By looking at the network-wide delays results, it can be seen that the implementation of the new CGT-MUT is likely to result in 0.4% – 11.7% reductions in the total network delays compared to implementing either of the Superstreet, Synchronized, or the SPDI. All of the network delay reductions resulting from implementing the CGT-MUT are statistically significant except for the 2029 morning peak. The study's results show that for the 2029 morning peak, implementing the CGT-MUT would result in statistically significant delay reductions when compared to the Superstreet and SPDI but not the Synchronized. Particularly, for the same morning peak, while the CGT-MUT would result in less network-wide delays than the Synchronized interchange, there was no evidence of a difference in means at the 5.0% significance level. The CGT-MUT can be viewed as an improvement of the Superstreet interchange since in terms of its effect on the network-wide delays compared to the Superstreet interchange, the CGT-MUT is likely to reduce the network-wide delays by 4.1% – 11.7%.

The CGT-MUT also leads to 2.3% – 6.2%, and 0.4% – 1.8% less network-wide delays when compared to the SPDI, and Synchronized interchanges, respectively. As for the network-wide number of stops, compared to the Superstreet, SPDI, and Synchronized interchanges, by implementing the CGT-MUT the network-wide number of stops were reduced by 5.5% – 15.0%, 5.9% – 9.2%, and 5.8% – 9.9%, respectively. This means that the CGT-MUT when compared to the Superstreet, SPDI and Synchronized interchanges should lead to fewer rear-end crashes since the network-wide number of stops would be reduced by its implementation. Regarding the network-wide speeds, implementing the CGT-MUT would increase the speeds by 3.4% – 8.3%, 3.2% – 4.4%, and 1.0% – 2.2%, compared with the Superstreet, SPDI and Synchronized interchanges, respectively. Increased speeds achieved by implementing the CGT-MUT translate to less travel time to reach between two points, thereby should lead to reduced network-wide travel times.

In Table 2, travel time results are shown for each movement. Theoretically, in terms of travel times, and since time is a function of distance and speed, the on-ramp travel times produced by a Superstreet interchange should be less than those of the CGT-MUT, given the speed is constant, especially because the CGT-MUT increases the distance travelled, thereby it should increase the travel time compared with a Superstreet.

Table 1. Network-Level Delays, Number of Stops, and Speeds.

2019 Morning Peak Results			
	Delay (s)	Number of Stops	Speed (km/h)
CGT-MUT	81.50	1.55	34.66
Superstreet	85.02	1.64	33.48
SPDI	86.02	1.67	33.29
Synchronized	82.29	1.72	34.26
2019 Mid-Day Peak Results			
	Delay (s)	Number of Stops	Speed (km/h)
CGT-MUT	87.65	1.66	33.64
Superstreet	93.22	1.80	32.07
SPDI	89.88	1.78	32.57
Synchronized	89.29	1.77	33.02
2019 Evening Peak Results			
	Delay (s)	Number of Stops	Speed (km/h)
CGT-MUT	91.94	1.78	33.35
Superstreet	102.22	2.04	30.92
SPDI	94.66	1.96	32.12
Synchronized	93.21	1.89	32.79
2029 Morning Peak Results			
	Delay (s)	Number of Stops	Speed (km/h)
CGT-MUT	83.5	1.61	34.58
Superstreet	87.69	1.71	33.29
SPDI	88.94	1.74	33.05
Synchronized	83.86*	1.78	34.24
2029 Mid-Day Peak Results			
	Delay (s)	Number of Stops	Speed (km/h)
CGT-MUT	90.89	1.75	33.40
Superstreet	97.22	1.91	31.71
SPDI	92.98	1.86	32.34
Synchronized	92.51	1.88	32.79
2029 Evening Peak Results			
	Delay (s)	Number of Stops	Speed (km/h)
CGT-MUT	96.39	1.92	32.58
Superstreet	109.21	2.26	29.90
SPDI	99.95	2.10	31.25
Synchronized	97.82	2.07	31.86

**: The mean difference is statistically insignificant at the 95% confidence level when compared to the CGT-MUT.*

The results of this study show that this is true for the morning and mid-day peaks for the WBL (intersection 2 to I-15) movement only. However, when the traffic volumes are higher at the evening peak, the CGT-MUT outperforms the Superstreet for the WBL travel times. The latter means that when traffic demands are higher, directing on-ramp traffic through a downstream U-turn with a reduced number of signal phases would provide better travel time results. In addition, the results of the study showed that the CGT-MUT outperformed the Superstreet interchange for all EBL (intersection 4 to I-15) travel times. The CGT-MUT outperformed the Superstreet by approximately 3.3% – 43.6%. On the other hand, the SPDI, and Synchronized interchanges showed a much better performance than the CGT-MUT in terms of the on-ramp travel times.

The WBL and EBL travel times for the SPDI, and Synchronized were 8.8% – 53.0%, and 12.2% – 43.3%, respectively, less than those for the CGT-MUT. This, again, is because the CGT-MUT substantially increases the on-ramp travelled distance, therefore, the travel time experienced would be higher. Regarding the off-ramp travel times, the CGT-MUT reduced the NBL (I-15 to intersection 4) and SBL (I-15 to intersection 2) travel times significantly when compared to the Superstreet and Synchronized. This is since the nature of the CGT-MUT allows the off-ramp left-turning traffic to move at the same time that the arterial's through traffic is moving.

In addition, the CGT-MUT operates with a reduced number of signal phases, therefore, it allows for more time to be allocated to the signal phases. As a result, the CGT-MUT reduced the NBL and SBL travel times by nearly 16.3% – 33.3% and 9.0% – 20.5%, when compared to the Superstreet and Synchronized interchanges, respectively. However, the nature of the CGT-MUT design requires a longer distance between the interchange ramp terminals than that required for the SPDI. Therefore, the travel time for the SPDI for NBL and SBL should theoretically be less than that for the CGT-MUT, which was observed in the results. The SPDI outperformed the CGT-MUT in terms of the off-ramp travel times by nearly 0.6% – 7.7% (some results in this range were not statistically significant).

As for the arterials' through traffic travel times, the CGT-MUT significantly outperformed all the other designs for all the tested scenarios. The CGT-MUT reduced the WBT (intersection 2 to intersection 4) and EBT (intersection 4 to intersection 2) travel times by 9.0% – 30.1%, 25.8% – 41.9%, and 12.8% – 37.5%, compared to the Superstreet, SPDI, and Synchronized interchanges. These significant travel time reductions are attributed to nature of the CGT-MUT design which reduces the number of signal phases, and allows for the through moving traffic to move at the same time with the off-ramp left-turning traffic.

It is generally known that there is no one design that would always provide the optimal travel times for all traffic movements.

Table 2. Travel Time Results.

2019 Morning Peak Travel Times (s)#							
	WBT	EBT	WBL	EBL	NBL	SBL	NBR
CGT-MUT	49.1	47.4	139.7	103.1	146.9	128.0	101.6
Superstreet	55.0	56.2	120.0	130.2	207.0	158.6	100.9*
SPDI	80.3	71.2	88.8	70.3	143.1	122.0	79.2
Synchronized	78.6	63.7	79.9	70.5	168.9	159.4	96.7
2019 Mid-Day Peak Travel Times (s)#							
	WBT	EBT	WBL	EBL	NBL	SBL	NBR
CGT-MUT	51.0	55.4	139.2	99.0	149.3	128.1	106.7
Superstreet	72.9	65.2	138.9*	137.1	178.4	159.1	109.1
SPDI	76.9	95.4	79.3	71.0	140.2	122.7	77.0
Synchronized	69.0	63.6	116.5	86.9	166.1	157.9	106.1*
2019 Evening Peak Travel Times (s)#							
	WBT	EBT	WBL	EBL	NBL	SBL	NBR
CGT-MUT	56.0	60.9	149.3	96.6	147.0	129.8	108.9
Superstreet	73.5	78.7	154.4	156.5	177.9	162.9	112.1
SPDI	75.4	104.4	71.1	80.8	146.1*	127.5	70.5
Synchronized	73.1	77.9	114.8	78.7	164.8	158.3	103.9
2029 Morning Peak Travel Times (s)#							
	WBT	EBT	WBL	EBL	NBL	SBL	NBR
CGT-MUT	51.0	48.4	144.9	103.6	147.3	128.6	101.0
Superstreet	56.1	57.4	123.2	127.5	220.8	159.0	99.8*
SPUI	76.2	74.1	76.5	72.0	139.3	124.0	78.2
Synchronized	77.4	64.5	82.2	70.6	167.4	161.7	95.8
2029 Mid-Day Peak Travel Times (s)#							
	WBT	EBT	WBL	EBL	NBL	SBL	NBR
CGT-MUT	51.8	59.7	142.6	102.3	148.0	126.4	108.4
Superstreet	72.1	71.6	140.5	141.9	178.1	161.3	107.3*
SPDI	72.0	94.2	69.7	75.2	136.6	120.3	75.7
Synchronized	66.8	69.4	121.1	88.3	162.7	159.0	106.3*
2029 Evening Peak Travel Times (s)#							
	WBT	EBT	WBL	EBL	NBL	SBL	NBR
CGT-MUT	54.8	68.7	146.0	98.0	149.1	130.3	108.7
Superstreet	76.7	90.4	155.1	173.6	181.1	163.9	111.6
SPDI	76.1	111.2	68.6	89.4	148.1*	127.6	73.7
Synchronized	75.4	88.0	117.3	80.8	164.7	162.8	100.5

**: The mean difference is statistically insignificant at the 95% confidence level when compared to the CGT-MUT.*
#: No SBR times since no SBR turning movements were not provided by UDOT.

Therefore, the suitability of a design for implementation could vary from one location to another based on the roadway and traffic conditions, in addition to other characteristics including but not limited to traffic safety, and life cycle costs, which are beyond the scope of this study. The results of this study show that the SPDI, for instance, displayed an inferior operational performance in terms of through traffic travel times compared to the CGT-MUT. This does not mean that practitioners and agencies should stop implementing SPDIs. This means that for the study location, and based on the tested roadway and traffic conditions, the CGT-MUT showed a significantly improved performance for the through moving traffic.

In a similar manner, the CGT-MUT has not always outperformed the other designs for all travel time results. This doesn't mean that the CGT-MUT should not be implemented. As mentioned previously, alternative or unconventional designs favor arterials heavy-volume through traffic, by re-routing the left-turning traffic, reducing the number of signal phases, and reducing the number of conflict points. These principles were followed when the CGT-MUT was created and resulted in a CGT-MUT providing the best performance for the through moving traffic. It should be noted that although travel times for some left or right turns would be longer with the CGT-MUT, the through traffic volumes are much higher than the left and right turning traffic volumes. Therefore, the improved operational performance for the through moving traffic which would result from CGT-MUT implementation should lead to higher benefit-cost (B/C) ratios as proven by similar previous studies (Alzoubaidi, Al-Balbissi, et al., 2021; Economic Development Research Group Inc., 2016; Schierholz et al., 2015; TIGER Grant Program, 2017). In addition, readers should take into consideration the design's impact on the network and not only focus on intersection level performance metrics. This study's results presented in table 2 have shown that the CGT-MUT resulted in the best network-wide operational performance in terms of reducing the delays and increasing the speeds, which should translate to reduced network-wide travel times, and an additional improved network-wide B/C ratio.

At the intersection level, as shown in Table 3, the only performance measure where the CGT-MUT did not perform the best for all tested scenarios was the queue lengths. Comparing the CGT-MUT with the Superstreet for instance, the Superstreet had shorter queue lengths by approximately 6.2% – 12.8% for the morning and mid-day peaks. However, it can be seen that the CGT-MUT outperformed the Superstreet and displayed shorter queue lengths by nearly 8.0% – 25.9% when the traffic volumes were higher at the evening peak. The SPDI resulted in nearly 3.1% – 12.6% shorter queue lengths than the CGT-MUT in some scenarios, whereas the CGT-MUT displayed nearly 1.4% – 12.0% shorter queue lengths than the SPDI in other scenarios.

The Synchronized interchange, on the other hand, outperformed the CGT-MUT in all scenarios by shortening the queue lengths by nearly 34.3% – 43.5%. However, the Synchronized displayed higher number of stops and significant increases in delays when compared to the CGT-MUT as discussed in the following parts.

Table 3. Intersection-Level Delays, Number of Stops, and Queue Lengths.

2019 Morning Peak Results			
	Delay (s)	Number of Stops	Queue Length (ft)
CGT-MUT	9.66	0.17	7.06
Superstreet	13.64	0.26	6.15
SPDI	25.69	0.44	8.02
Synchronized	9.92	0.25	4.00
2019 Mid-Day Peak Results			
	Delay (s)	Number of Stops	Queue Length (ft)
CGT-MUT	11.55	0.22	10.61
Superstreet	16.56	0.31	9.55
SPDI	26.99	0.49	10.76*
Synchronized	12.81	0.27	6.89
2019 Evening Peak Results			
	Delay (s)	Number of Stops	Queue Length (ft)
CGT-MUT	10.99	0.21	12.39
Superstreet	19.19	0.38	13.47
SPDI	25.26	0.48	10.83
Synchronized	12.33	0.28	7.14
2029 Morning Peak Results			
	Delay (s)	Number of Stops	Queue Length (ft)
CGT-MUT	9.86	0.18	7.90
Superstreet	14.01	0.26	6.98
SPDI	26.17	0.45	8.86
Synchronized	11.07	0.25	4.47
2029 Mid-Day Peak Results			
	Delay (s)	Number of Stops	Queue Length (ft)
CGT-MUT	11.71	0.22	11.96
Superstreet	17.19	0.33	11.22
SPDI	26.12	0.48	11.59
Synchronized	13.18	0.29	7.86
2029 Evening Peak Results			
	Delay (s)	Number of Stops	Queue Length (ft)
CGT-MUT	10.77	0.21	14.04
Superstreet	20.69	0.44	18.93
SPDI	26.7	0.49	12.71
Synchronized	13.1	0.32	8.46

**: The mean difference is statistically insignificant at the 95% confidence level when compared to the CGT-MUT.*

This means that shortening the queue lengths by the Synchronized interchange did not really help in enhancing the overall operations at the arterial. As for the number of stops at the intersection level, the CGT-MUT reduced the number of stops by approximately 29.0% – 52.3%, 54.2% – 61.4%, and 18.5% – 34.4%, compared to the Superstreet, SPDI, and Synchronized interchanges. The reduced number of stops produced by the CGT-MUT should lead to fewer rear-end crashes and, therefore, increase the safety of arterials where they will be implemented.

Similarly, the CGT-MUT outperformed all the other designs in terms of delays at the intersection level for all tested scenarios. The CGT-MUT resulted in nearly 29.2% – 48.0%, 55.2% – 62.4%, and 2.1% – 17.8% when compared to the Superstreet, SPDI, and Synchronized interchanges.

6. Conclusions

The results show that the CGT-MUT enhanced the network-wide operations by reducing delays, the number of stops and increasing speeds. The CGT-MUT reduced the network-wide delays by up to 11.7%, 6.2%, and 1.8% compared to the Superstreet, SPDI, and Synchronized interchanges, respectively. The CGT-MUT increased the network-wide speeds by up to 8.3%, 4.4%, and 2.2%, compared to the Superstreet, SPDI, and Synchronized interchanges, respectively. On the network-wide level, reducing the delays and increasing the speeds translate to reduced network-wide travel times which have been previously linked to high B/C ratios (Alzoubaidi, Al-Balbissi, et al., 2021; Economic Development Research Group Inc., 2016; Schierholz et al., 2015; TIGER Grant Program, 2017). In addition, the CGT-MUT reduced the network-wide number of stops by up to by 15.0%, 9.2%, and 9.9%, when compared the Superstreet, SPDI, and Synchronized, respectively. Such reductions in the number of stops caused by the CGT- should lead to fewer frequencies of rear-end collisions, hence, enhancing the traffic safety.

At the intersection level, the CGT-MUT also outperformed all the other designs by significantly reducing the delays by as high as 48.0%, 62.4%, and 17.8%, compared to the Superstreet, SPDI, and Synchronized interchanges, respectively. Additionally, while the CGT-MUT did not always outperform all the other designs in terms of the on-ramp turning traffic travel times, it outperformed the Superstreet and Synchronized in terms of the off-ramp turning traffic travel times and resulted in the least through moving traffic travel times for all the tested scenarios. Particularly, the CGT-MUT's through travel times were 9.0% – 30.1%, 25.8% – 41.9%, and 12.8% – 37.5% less than those for the Superstreet, SPDI, and Synchronized interchanges, respectively.

The CGT-MUT reduces the number of signal phases and allows the arterials' through moving traffic to move at the same time with the off-ramp left-turning traffic with minimal interaction. As a result, when traffic demands were higher, it was observed that directing the on-ramp traffic through a downstream U-turn with a reduced number of signal phases would make the CGT-MUT outperform the Superstreet, which is an unlikely case given the shorter distances vehicles travel when navigating a Superstreet. The results show that there are no weaving issues with the CGT-Mut, since if weaving existed then delays and travel times for the off-ramp left-turns, and arterials through movements should be the highest for the CGT-MUT which was not the case. One of the advantages of the CGT-MUT over the Synchronized interchange is that it alleviates some of the driver confusion caused by the concept of contraflow left which constitutes the basis of the Synchronized interchange.

In terms of the applicability of the results to the practice, it is important to note that the results of this study are applicable to the study area and the data provided by UDOT. It is equally important to add that as found by similar previous research Hummer (2014) that compared several alternative designs, no design would always be superior in all examined measures. The fact that there isn't always a transportation system solution that is always superior to all other solutions is also applicable to the CGT-MUT. However, based on the results of the study, the CGT-MUT is expected to outperform the Synchronized, Superstreet and SPDI when there are heavy volume through traffic demands combined with heavy off-ramp left turning traffic, and a lower on-ramp left turning traffic.

7. Limitations and Directions for Future Research

Among the limitations of this study is that the design was tested in terms of operational performance in one location only. While the traffic patterns of three peak periods for the current and future traffic conditions were tested, other locations that have different roadway and traffic patterns would provide a deeper understanding of how each of the studied designs would compare to one another including the CGT-MUT. Therefore, it is recommended that future research is performed in other locations with varying roadway and traffic conditions and possibly other alternative designs to better understand the operational performance of the presented CGT-MUT. Other directions for future research include evaluating the safety, life cycle costs and the environmental impacts of the CGT-MUT. It is also equally important that the CGT-MUT is studied in a driving simulator environment to explore the driver confusion that could result from implementing it.

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