Travel Efficiency of Unconventional Suburban Arterial Intersection Designs

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A great need exists for lower-cost design strategies to reduce congestion on major suburban arterials on which conventional techniques have been exhausted. This study examines the possible gains in travel efficiency from three unconventional strategies: the median U-turn, in which left turns are made using crossovers on the arterial approximately 180 m from the main intersection; continuous green T-intersection (CGT), in which one or two lanes at the top of the "T" receive a constant green indication; and the North Carolina State University (NCSU) Bowtie, developed during the project, in which left-turning traffic uses roundabouts on the side street approximately 180 m from the main intersection. The study used Traf-Netsim 4.0 to simulate the unconventional configurations and a conventional intersection for comparison in three factorial experiments.The experiments showed that the unconventional alternatives have the potential to provide for more efficient travel. The CGT configurations reduced travel time and stops substantially at three-legged intersections for through volumes of more than 400 vehicles per hour per lane. The median U-turn became more efficient than the CGTs at higher through volumes. An experiment with a four-legged intersection showed that the NCSU Bowtie reduced travel time and stops from the conventional configuration at about 900 or more critical through vehicles per hour. Questions remain about the unconventional strategies, but that they potentially provide for more efficient travel is clear.

Traffic congestion is a growing problem in most cities in North America, especially on major suburban arterials. Traffic engineers often face arterials on which:

- Nothing further can be done to relieve congestion with signal phasing, signal coordination, signal actuation, and other conventional operational techniques;
- Additional through or turn lanes are prohibitively expensive;
- Grade separations at intersections are too costly and are resisted fiercely by local merchants; and
- Intelligent vehicle-highway systems are not yet mature enough to provide a reliable solution.

There is a great need for a set of lower-cost operation and design strategies to reduce congestion at these locations.

North Carolina State University (NCSU) undertook a project to investigate such a set of strategies for the North Carolina Department of Transportation (NCDOT) and the FHWA. The project identified four promising unconventional strategies and investigated the key outstanding issues associated with each strategy. This project performed investigations into the travel efficiency of the strategies. There are obviously many other key variables of concern to engineers contemplating installation of an unconventional alternative, such as accident rates, acceptance by the traveling public, right-of-way costs, and construction costs. However, if an unconventional alternative does not reduce travel times, engineers will not consider it, and its effects on these other variables are unimportant. The project report (*1*) describes the effects of some of these other variables.

STRATEGIES STUDIED

The four strategies investigated during the project included the continuous green T-intersection (CGT), the median U-turn, the NCSU Bowtie, and the continuous flow intersection. The project team selected these 4 from a list of 12 initial ideas because these had the most potential for widespread application in North Carolina and provoked questions that could be addressed within the scope of the research.

Figure 1 shows the CGT commonly used in Florida. The outside through lane at the top of the "T" receives a constant green signal, whereas the rest of the intersection operates with a typical three-phase signal. Agencies use markings and reflectors to separate the free-flow lane from the through lane subject to the signal. The project also investigated a version of the CGT used at a few locations in North Carolina, in which both through lanes at the top of the T receive a constant green signal, while left turns from the side street are directed into a merging lane in the median. The project team found no existing literature on the efficiency of either version of the CGT.

Figure 2 presents a median U-turn at a four-legged intersection. At the primary intersection, engineers prohibit left turns and specify a two-phase signal. Left-turning vehicles use the crossovers on the arterial. Median U-turns are also feasible at three-legged intersections, using one crossover and one direct left turn. The project team found some speculation in the literature about efficiency gains from median U-turns, but the only systematic study documented was a preliminary one conducted by one of the authors (*2*).

Figure 3 shows an NCSU Bowtie intersection. The authors conceived this strategy during the project; to their knowledge, this strategy has not been proposed or implemented before. The NCSU Bowtie was inspired by median U-turn placements on the side street and by the "raindrop" interchange used in Great Britain and elsewhere (*3*), in which modern roundabouts are placed at the off-ramp terminals of a diamond interchange. In the United States, raindrop interchanges have been proposed in Maryland and California. At the primary intersection of an NCSU Bowtie, engineers prohibit left turns and specify a two-phase signal. Left-turning vehicles use the roundabouts on the side street. An NCSU Bowtie is feasible at a three-legged intersection, but the efficiency gains appear to be minimal and substantial extra right-of-way (ROW) is required, so this project investigated only four-legged applications. The NCSU Bowtie is intriguing because it places the roundabouts on the side

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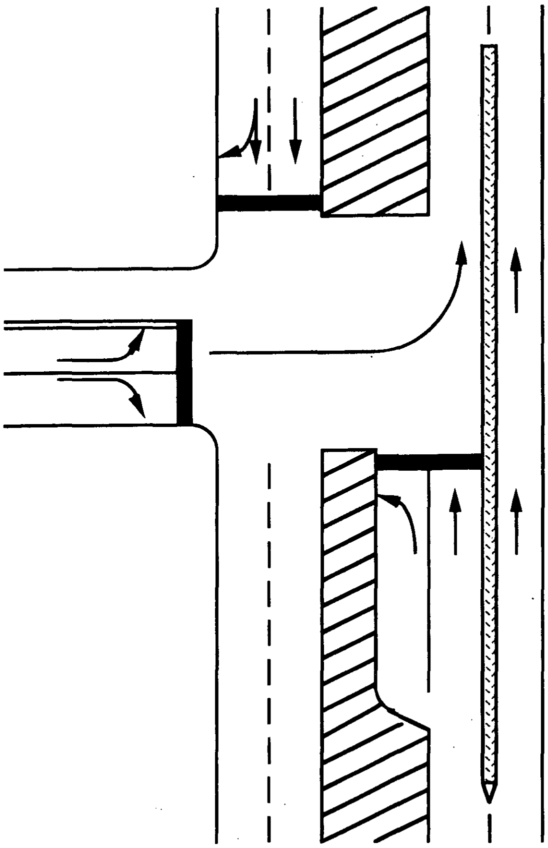


FIGURE 1 Continuous green T-intersection.

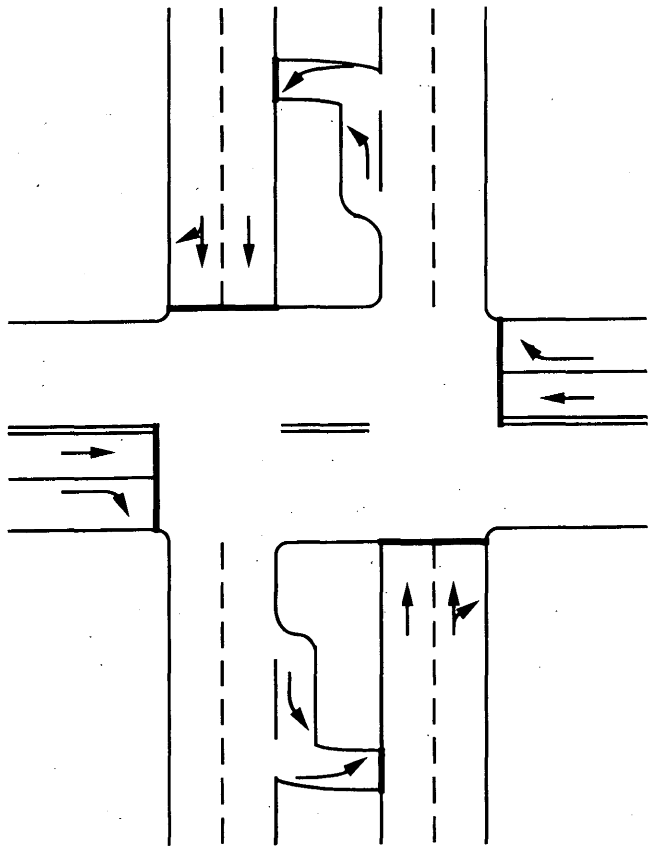


FIGURE 2 Median U-turn intersection.

street rather than the arterial [in keeping with recommended practice in Australia (*4*), for example], and because the extra ROW required for four-legged applications is not large.

The fourth strategy was a continuous flow intersection, shown in Figure 4. The continuous flow intersection crosses a left-turning movement past the oncoming through traffic at a signal upstream of the main intersection, and then guides it to the cross street near the main intersection. At the main intersection, a single signal phase then allows those left turns to move, protected, simultaneously with the through movements. This patented innovation has been implemented only once (as of November 1994), but analyses (*5,6*) and theory suggest that engineers can expect great efficiency gains from it. Since the most outstanding questions regarding this strategy center on safety and human factors, this project concentrated on those issues and did not study the efficiency of the strategy.

EXPERIMENT DESCRIPTION

The project team conducted three experiments on the efficiency of the strategies:

1. A three-legged intersection between a four-lane arterial and a two-lane side street,
2. A three-legged intersection between a six-lane arterial and a two-lane side street, and
3. A four-legged intersection between a four-lane arterial and a two-lane side street.

The primary purpose of the experiments was to determine whether the unconventional alternatives showed promise of more efficient travel within the common ranges of several key variables. The project team could not model every possible combination of volumes and did not attempt to model them all. If the unconventional alternatives showed promise, engineers could create their own models to examine conditions at the specific intersections of interest to them.

Each experiment used Traf-Netsim 4.0 (*7*) to compare the applicable unconventional strategies to a conventional design with direct, protected left turns from a single left-turn lane. Traf-Netsim was the best choice for the experiment because of its ability to simulate an entire network (needed for the unconventional alternatives), its credibility in the profession, and its large range of measures of effectiveness (MOEs).

The project team calibrated and validated Traf-Netsim for the unconventional strategies. The project team traveled to Michigan to collect data at two median U-turn intersections, to Florida to collect data at six CGT intersections, and to Maryland to collect data at the first modern roundabout in the eastern United States. The calibration data included critical gap distributions and saturation flow estimates for the median U-turn, lane distributions for the CGT, and critical gap distributions and circulation speeds for the roundabout. The validation effort encompassed travel time and stopped delay at the two Michigan median U-turn intersections and the Maryland roundabout. The results showed that field data compared reasonably well to Traf-Netsim MOEs. Model calibration and validation details are described elsewhere (*1*).

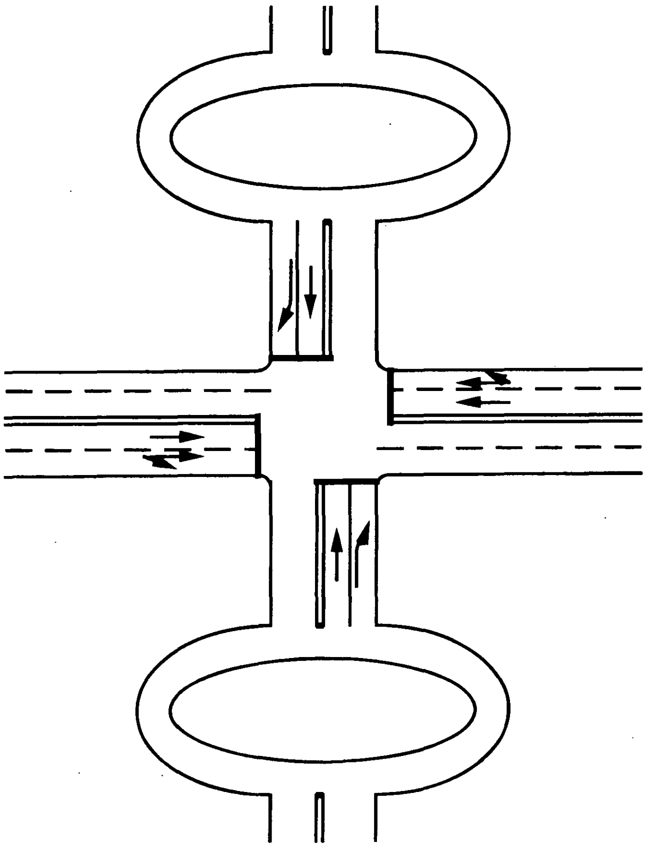
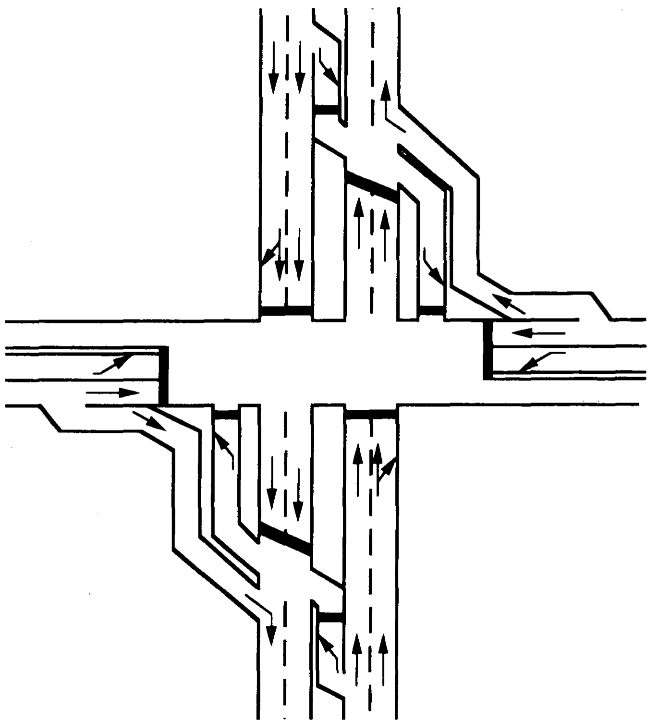


FIGURE 3 NCSU bowtie intersection.



Not to scale.

FIGURE 4 Continuous flow intersection (design patented by Mier).

The project team used 30-min simulation runs after a warm-up period that did not exceed 10 min. The team used the total travel time and the total number of stops within a constant data collection boundary, which extended 488 m in each direction from the primary intersection, as the primary MOEs. Although many analyses use delay as an MOE, total travel time allowed the analysts to compare properly strategies that require vehicles to traverse a circuitous route to execute a desired movement. The team also examined the total travel time and the total stopped delay experienced by left-turning vehicles. This allows judgments about whether methods with indirect left turns penalize those motorists too severely, which could lead to violations and negative public reactions.

The project team used fixed-time signal-phasing schemes timed with Webster's method (*8*). Fixed-time signals are appropriate because many suburban arterials have them to establish progression, because the traffic volumes are high and stable during the congested peak hours of most interest (actuated phases usually reach their maxima anyway), and because the median U-turn alternative needs to coordinate the crossover and main intersection signals. For each traffic volume combination in an experiment, the project team chose a cycle length to satisfy a minimum pedestrian crossing time and to minimize the delay for the conventional intersection treatment. The cycle length was then held constant for that volume combination across each configuration and phase times were developed. This method of signal timing ensured that any differences in the MOEs were due to the configurations, not to different cycle lengths.

To isolate the effects of the strategies, several parameters were held constant in each experiment, including:

- 90-degree intersections;
- Desired free-flow speeds (72 km/hr arterial, 56 km/hr side street);
- 200 right-turn vehicles per hour;
- Right turn on red allowed;
- No left turn on red from crossovers allowed;
- 0 percent grade; and
- Single-lane turn bays, crossovers, and roundabouts.

Each experiment was a full factorial design. The team used an analysis of variance (ANOVA) technique in SAS (*9*) on a UNIX-based workstation to draw conclusions from the data.

EXPERIMENT 1

Set-Up

Experiment 1 compared the median U-turn, the Florida version of the CGT, the North Carolina version of the CGT, and the conventional strategy at the three-legged intersection of a four-lane arterial and a two-lane side street. The three factors in the experiment included the strategy, the through volumes on the arterial, and volumes of the left turn movements. Based on the *Highway Capacity Manual* (*10*) planning analysis, a total critical volume of 1,300 vehicles per hour constitutes congested conditions. The experiment therefore included three levels of through volumes [700, 400, and

100 vehicles per hour per lane (vphpl)] and three levels of left turn volumes [300, 200, and 100 vehicles per hour (vph)] to represent congested, moderate, and uncongested conditions. The team completed two replicates of the experiment with 36 runs (4 × 3 × 3) in each replicate. The only parameters that were changed between replicates were the random number seeds (the values used to decide which vehicles turn at a given intersection, assign individual driver characteristics, etc.).

Building the simulation models presented several challenges. First, the team had to choose the distance between the crossover and the primary intersection for the median U-turn. On the basis of the literature and measurements collected during model calibration (*1*), the team selected a distance of 183 m. Second, the team selected the median U-turn configuration with the direct left turn from the arterial. If the volumes of the two left-turn movements at a three-legged intersection were similar, the direct left turn from the arterial was considered superior because a direct left turn from the side street requires a difficult merge onto the arterial. Third, the team based the percentage of traffic using the free-flow lane in the Florida CGT on fifty-four 15-min observations made at three sites in Jacksonville (*1*). Finally, although there are locations in Michigan where the median crossover is stop sign–controlled, given North Carolina's typical practice regarding left turns onto multiple lane facilities, the analysts introduced a signal to control operations for the median U-turn, at the crossover. The team chose cycle, phase, and offset times for this signal that allowed for progression of the left turn from the arterial through both signals.

Travel Time Results

The ANOVA on the travel time data showed that the configuration factor and the two-factor interaction between through volume and configuration were both significant at the 99.99 percent confidence level. Additionally, the two-factor interaction between the left-turn volume and the configuration was significant at the 95 percent confidence level.

Student-Newman-Keuls (SNK) and Tukey's (*11*) means tests indicated that the median U-turn configuration accrued significantly less travel time (a mean of 1,600 minutes per run) than the other three configurations. The Florida CGT and the North Carolina CGT provided the next lowest total travel times (1,753 and 1,855 minutes per run, respectively); they did not differ significantly from each other. The North Carolina CGT and the conventional configuration (1,913 minutes per run) did not differ significantly from each other.

Table 1 shows that the efficiency of the median U-turn increased as the through volumes increased. For the low and moderate through volumes, the CGT configurations were the most efficient. At the highest through volume level, the median U-turn reduced total travel time by 12 percent to 39 percent over the standard configuration.

Stop Results

The ANOVA on the total number of stops data indicated that the configuration factor and the two-factor interaction between through volume and configuration were significant at the 99.99 percent confidence level. In addition, the two-factor interaction between the left-turn volume level and the configuration was significant at the 99 percent confidence level, while the three-factor interaction between through volume, left-turn volume, and configuration was significant at the 95 percent confidence level.

SNK and Tukey's (*11*) means tests indicated that at the 95 percent confidence level the median U-turn (mean of 724 stops per run) required significantly fewer stops than any other configuration. The North Carolina CGT and Florida CGT had means of 843 and 856 stops per run, respectively; they did not differ significantly from each other. The standard intersection, at a mean of 965 stops per run, was significantly higher than the others.

Table 1 reveals that for the lowest through volume, the Florida CGT was clearly the most efficient, with about 20 percent fewer stops than the standard configuration and 3 to 15 percent fewer stops than the North Carolina CGT, regardless of left-turn volume. For low through volumes, the median U-turn was the least efficient. At a moderate through volume level, regardless of the left-turn volume, the CGT techniques required about 20 percent fewer stops than the standard configuration, whereas the median U-turn ranged from about 10 percent better to 10 percent worse than the standard configuration. At the highest through volume, the CGTs required slightly fewer stops and the median U-turn required 30 to 60 percent fewer stops than the conventional alternative. The median U-turn performed relatively worse as the left-turn volume increased.

Left Turn MOEs

For left-turn travel time, SNK and Tukey's (*11*) means tests revealed that, at a 95 percent confidence level, the median U-turn had the highest average left-turn travel while the Florida CGT had the lowest. The standard configuration and the North Carolina CGT did not differ significantly. Table 1 shows that these results were consistent across the through volume levels, and that the only important variation across left-turn volume levels was for the median U-turn. The relative inefficiency of the median U-turn decreased as the left turn volume increased.

For left-turn stopped delay, SNK and Tukey's (*11*) means tests revealed that, at a 95 percent confidence level, the median U-turn penalized the left-turn vehicles the most, whereas the standard, North Carolina CGT, and Florida CGT configurations did not differ significantly. The patterns in Table 1 are interesting. For the CGT configurations, the relative efficiency decreased as through volume increased. For the median U-turn, the relative efficiency decreased as through volume increased and as left-turn volume decreased.

EXPERIMENT 2

Experiment 2 compared the median U-turn, the Florida CGT, the North Carolina CGT, and the conventional strategy at the three-legged intersection of a six-lane arterial and a two-lane side street. The six-lane arterial was a concern because the relatively larger proportions of through vehicles may favor unconventional strategies more than for a four-lane arterial. The factors, levels, and analysis methods were the same for this experiment as they were for Experiment 1, and the simulation models differed only slightly.

Table 2 summarizes the results from Experiment 2. Comparing Table 2 with Table 1 for the four-lane arterial experiment reveals only two important differences. First, there was less distinction between the configurations for the travel time MOE. The median U-turn was still the best, but its overall mean was not significantly different from the CGT configurations. The standard configuration was still the worst, but its overall mean also was not significantly

TABLE 1 Summary of Experiment 1 Results

Measure of effectiveness	Through volume, vphpl	Alt. \ Left turn volume, vph	Percent difference between the alternative and the conventional configuration: 100	200	300
Travel time	100	NC CGT	- 3	- 2	- 2
		FL CGT	- 9	- 9	-13
		Median U-turn	+ 5	+ 9	+ 8
	400	NC CGT	- 5	- 4	- 4
		FL CGT	-12	-11	-13
		Median U-turn	- 4	0	- 4
	700	NC CGT	- 2	- 4	- 2
		FL CGT	- 3	- 4	-11
		Median U-turn	-39	-12	-31
Stops	100	NC CGT	-18	-11	- 8
		FL CGT	-22	-20	-23
		Median U-turn	+20	+31	+38
	400	NC CGT	-22	-17	-16
		FL CGT	-23	-19	-21
		Median U-turn	- 9	+ 8	+11
	700	NC CGT	-11	-13	- 9
		FL CGT	- 5	0	- 9
		Median U-turn	-61	-29	-46
Left turn travel time	100	NC CGT	- 3	- 2	- 1
		FL CGT	-32	-28	-33
		Median U-turn	+43	+30	+21
	400	NC CGT	- 1	- 1	+ 4
		FL CGT	-30	-25	-32
		Median U-turn	+52	+35	+19
	700	NC CGT	+ 2	- 1	0
		FL CGT	- 8	-22	-32
		Median U-turn	+62	+43	+14
Left turn stopped delay	100	NC CGT	- 8	- 4	- 2
		FL CGT	-11	- 6	-23
		Median U-turn	+56	+20	+ 1
	400	NC CGT	- 3	- 3	+ 9
		FL CGT	- 7	+ 1	-22
		Median U-turn	+82	+33	+ 2
	700	NC CGT	+ 4	- 2	+33
		FL CGT	+51	+ 2	+ 2
		Median U-turn	+105	+50	+31

different from the CGT configurations. The median U-turn and standard were still significantly different from each other. Second, the North Carolina CGT experienced relatively more left-turn stopped delay in Experiment 2 than in Experiment 1. In Experiment 2, the North Carolina CGT had an overall mean that was still significantly better than the median U-turn but now was significantly worse than the Florida CGT and the standard configuration. Other than these two differences, Experiment 2 results were very similar to Experiment 1 results.

EXPERIMENT 3

Set-Up

Experiment 3 compared a standard configuration to the median U-turn and the NCSU Bowtie at the four-legged intersection of a four-lane arterial and a two-lane side street. In developing the simulation models, several design and operation issues required attention. As in the three-legged experiments, the researchers needed to select the appropriate distance between the primary intersection and the U-turn crossovers. Ultimately, a 183-m separation between the primary intersection and the crossover was selected. The researchers verified this selection by conducting a preliminary analysis to determine the maximum queue length associated with the operation of the U-turn crossover for the heaviest volumes. This analysis revealed that a 183-m separation performed satisfactorily. There was uncertainty about the optimal separation between the primary intersection and the roundabouts for the NCSU Bowtie. Adequate storage between the primary intersection and the roundabouts was a concern. Based on preliminary simulation runs, a 183-m distance and two lanes on the approach to the primary intersection proved adequate. Finally, based on the literature and a trip to the first modern roundabout on the East Coast (in Lisbon, Maryland),

TABLE 2 Summary of Experiment 2 Results

Measure of effectiveness	Through volume, vphpl	Alt. \ Left turn volume, vph	Percent difference between the alternative and the conventional configuration: 100	200	300
Travel time	100	NC CGT	- 4	- 2	- 2
		FL CGT	-12	-10	-10
		Median U-turn	+ 1	+ 9	+ 8
	400	NC CGT	- 5	- 4	- 4
		FL CGT	-12	-12	-14
		Median U-turn	- 4	- 1	- 9
	700	NC CGT	- 7	-12	- 3
		FL CGT	-13	-11	+ 7
		Median U-turn	-37	-14	-18
Stops	100	NC CGT	-22	-12	-12
		FL CGT	-23	-11	-18
		Median U-turn	+11	+37	+29
	400	NC CGT	-22	-18	-19
		FL CGT	-20	-21	-24
		Median U-turn	-14	+ 5	+ 2
	700	NC CGT	-17	-33	- 6
		FL CGT	-19	-16	- 7
		Median U-turn	-59	-36	-44
Left turn travel time	100	NC CGT	- 2	- 1	+ 4
		FL CGT	-33	-30	-31
		Median U-turn	+42	+64	+29
	400	NC CGT	+ 1	+ 3	+ 6
		FL CGT	-29	-24	-30
		Median U-turn	+61	+42	+20
	700	NC CGT	+ 6	+ 7	+31
		FL CGT	-11	-23	-18
		Median U-turn	+66	+45	+37
Left turn stopped delay	100	NC CGT	- 8	- 2	+11
		FL CGT	-13	- 9	-14
		Median U-turn	+54	+20	+18
	400	NC CGT	+ 3	+ 7	+12
		FL CGT	- 4	+ 4	-19
		Median U-turn	+109	+52	+ 3
	700	NC CGT	+16	+16	+74
		FL CGT	+42	- 2	+ 5
		Median U-turn	+116	+54	+40

the team selected a roundabout diameter of 30 m, a vehicle speed in the roundabout of 24 km/hr, and a more aggressive gap-acceptance distribution than the default distribution (*1*).

For the experiment, the team selected five independent variables: configuration, main street through volume, main street left-turn volume, side street through volume, and side street left-turn volume. Each volume variable had three levels, with the highest levels together corresponding to a total intersection critical volume of 1,400 vph. The analysts completed one full replicate during the experiment, resulting in the analysis of $3 \times 3 \times 3 \times 3 \times 3 = 243$ runs. One full replicate of the experiment was appropriate for two reasons. First, the analysts chose to include the four- and five-way interactions into the error term in the ANOVA. Interpreting the trends associated with the higher-level interactions would be very complicated. Additional replicates are more appropriate when attempting to interpret those interactions. Secondly, by including those interactions in the error term of the model, the F statistic and therefore the analysis would be more conservative. The team examined the same four MOEs as during the first two experiments.

Travel Time Results

The ANOVA on the travel time results showed that the configuration factor; the 4 two-factor interactions involving configuration; and the three-factor interactions between configuration, main street through volume, and side street through volume were significant at the 99 percent confidence level. SNK's and Tukey's means tests indicated that the median U-turn configuration required significantly greater travel times (mean of 2,817 min per run) than the standard configuration (2,578 min per run) and NCSU Bowtie configuration (2,586 min per run) at the 95 percent confidence level. The means for the standard configuration and NCSU Bowtie did not differ significantly.

Although their overall mean travel time values were similar, the interaction results in Table 3 show that the standard configuration performed best at the low and moderate main and side street through volume levels, whereas the NCSU Bowtie configuration responded more favorably to the higher through volumes. Across the highest main and side street through volume levels, the Bowtie accumulated approximately 7 percent less total travel time than the standard configuration. Looking at the three-way interaction results in Table 3, the breakpoint at which the NCSU Bowtie begins to operate more efficiently than the conventional alternative was about 900 critical through vehicles per hour. The travel time savings were about 15 percent at the highest combination of through volume levels. There was little relative variation between the standard and NCSU Bowtie configurations across left-turn volume levels. The median U-turn required the most total travel time over almost all volume combinations considered.

Stop Results

The ANOVA on the number of stops revealed that the following factors were significant at the 99 percent confidence level: the configuration; the two-factor interactions involving configuration and each of the remaining four factors; and the three-factor interaction involving the configuration, the main street through volume, and the side street through volume. In addition, the three-factor interaction between the configuration, the main street left turn, and the side street through volume factors was significant at the 98 percent confidence level. SNK and Tukey's (*11*) means tests indicated that overall, each of the three configurations differed at the 95 percent confidence level. The median U-turn had a mean of 1,833 stops per run, the NCSU Bowtie had a mean of 1,550 stops per run, and the standard configuration had a mean of 1,503 stops per run.

Table 4 shows the two-factor interaction results. The most pronounced trend in these results suggests that the NCSU Bowtie provides the most promise at intersections with high main street through volumes. For the side street through volume, there was no strong trend for the NCSU Bowtie relative to the standard intersection. For main and side street left-turn volumes, Table 4 reveals a slight trend toward fewer stops for the Bowtie with low volumes. The significant three-way interactions yielded no noteworthy trends.

Left Turn MOEs

SNK and Tukey's (*11*) means tests indicated that, at the 95 percent confidence level, the median U-turn required the most left-turn travel time and stopped delay, the NCSU Bowtie the next highest, and the standard configuration the least. Typically, the NCSU Bowtie meant an increase of 20 percent to 60 percent and the median U-turn meant an increase of 60 percent to 130 percent for these MOEs compared to the standard configuration.

CONCLUSIONS

The results of the three experiments described above show that unconventional alternatives have the potential to provide more efficient travel at some suburban arterial intersections. The experiments with three-legged intersections revealed that the Florida and North Carolina versions of the CGT provided substantial reductions in

TABLE 3 Experiment 3 Travel Time Results for Significant Two-Way and Three-Way Interactions Involving Configuration

		Percent difference between the alternative and the conventional configuration	
Variables and units	Levels	Median U-turn	NCSU Bowtie
Main street through volume, vphpl	300	+ 12	+ 6
	400	+ 12	+ 4
	500	+ 5	- 7
Side street through volume, vph	100	+ 16	+ 5
	300	+ 12	+ 5
	500	+ 3	- 6
Main street left turn volume, vph	50	+ 6	0
	125	+ 9	+ 2
	200	+ 13	+ 1
Side street left turn volume, vph	50	+ 4	- 3
	125	+ 9	+ 1
	200	+ 14	+ 4
Main street through volume, vphpl * Side street through volume, vph	300 * 100	+ 17	+ 12
	300 * 300	+ 14	+ 8
	300 * 500	+ 5	+ 5
	400 * 100	+ 19	+ 9
	400 * 300	+ 14	+ 8
	400 * 500	+ 5	- 3
	500 * 100	+ 10	- 5
	500 * 300	+ 9	+ 1
	500 * 500	- 2	- 15

TABLE 4 Experiment 3 Stop Behavior Results for Significant Two-Way Interactions Involving Configuration

		Percent difference between the alternative and the conventional configuration	
Variable and units	Level	Median U-turn	NCSU Bowtie
Main street through volume, vphpl	300	+ 28	+ 11
	400	+ 23	+ 6
	500	+ 17	- 9
Side street through volume, vph	100	+ 31	- 3
	300	+ 24	+ 7
	500	+ 15	0
Main street left turn volume, vph	50	+ 11	- 2
	125	+ 21	+ 2
	200	+ 32	+ 4
Side street left turn volume, vph	50	+ 10	- 4
	125	+ 21	0
	200	+ 33	+ 7

travel time and stops. As through volumes grow somewhere between 400 and 700 vphpl, the median U-turn becomes more efficient than the CGT configurations. The four-legged intersection experiment showed that the NCSU Bowtie was more efficient than the standard intersection at about 900 or more critical through vehicles per hour.

Engineers should be confident of these results because of the statistical significance of the factors in the ANOVAs and because the results match previous expectations. The median U-turn and NCSU Bowtie alternatives essentially reward through travelers at the expense of left-turn travelers, so it makes sense that the relative efficiency of those alternatives rises as through volumes rise. The project team urges engineers contemplating an unconventional alternative for a particular intersection to create Traf-Netsim models of the conventional and alternative intersections with the design volume levels.

While the relative efficiency of the median U-turn and NCSU Bowtie, in terms of overall travel time and stops, varied with through volume, those alternatives consistently led to substantially more travel time and stopped delay for left-turning vehicles than the standard configuration did. It is possible that these penalties on left-turn movements would lead to violations of the left-turn prohibition at the main intersection. However, existing situations in which left-turning vehicles experience extra delay show that motorists will tolerate those penalties without many violations. First and foremost, left-turning drivers in many states tolerate longer delays from protected left turns than from permissive left turns with very low violation rates. Second, left-turning drivers in Michigan use median U-turns without major violations. Finally, left-turning drivers in New Jersey tolerate extra travel time while negotiating jughandle intersections with few violations. Although there may be some level of excessive left-turn travel time that would cause many violations, the evidence suggests that with good traffic control devices, enforcement, and more than a few isolated applications, the unconventional alternatives should not cause those violations.

Many questions remain about the unconventional alternatives. This paper is focused only on the question of travel efficiency, so safety, human factors, ROW, construction costs, and other questions are out of its scope. The project report explores some of those other questions (*1*). Remaining questions regarding the efficiency of the unconventional alternatives include the following;

- How much more efficient are the median U-turn and NCSU Bowtie with two-lane crossovers and roundabouts?
- Do the increased opportunities for progression offered by the unconventional alternatives that reduce signal phases result in still greater efficiency than that demonstrated herein for individual intersections? In particular, how well would a superstreet, made up of a series of three-legged median U-turn intersections allowing each direction of an arterial to progress independently (*12*), perform?
- Is it wise to use an unconventional intersection that is superior at the higher volumes of, for example, 4 peak hours each day, and inferior for the other 20 hours each day? How do the MOEs look over a full day or week?
- The method used to time the signals in the experiments (holding cycle length constant across different strategies) was very conservative. Would using the optimum cycle length for each strategy result in lower cycle lengths and improved MOEs for the unconventional alternatives that require only two phases? Likewise, would using actuated signals provide an advantage for the conventional and CGT configurations that use multiphase signals?

In addition, when resources allow, the project team plans additional analysis of the Experiment 3 data to determine the amounts of travel time, stops, and delay shifted from the arterial to the side street at the NCSU Bowtie. This shift may increase the arterial level of service dramatically even for cases in which there is little or no change in the intersection system-wide MOEs.

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