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Operational performance of adaptive traffic control systems: a microscopic simulation using PTV epics/balance local controllers

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Abstract

The entire priority intersection control system (Epics), supported by PTV Group, is a real-time adaptive signal control technology (ASCT) that can be used to perform real-time optimization for the signalized intersection. This study evaluated the operational performance of the ASCT using Epics/Balance Local controllers in the microsimulation environment. The analysis was based on a 4-mile corridor with ten signalized intersections along Mayport Road in Jacksonville, Florida. The VISSIM microscopic simulation model reflecting the existing condition was developed and carefully calibrated to replicate field conditions. The ASCT executed through Epics/Balance Local controllers reduced travel time, average vehicle delays, and side-street delays compared to conventional actuated-coordinated operations executed through ring-barrier controllers (RBC). Specifically, travel time was reduced by 11.1%, average vehicle delay decreased by 9.9%, and the side-street delay was reduced by up to 20%. The results were statistically significant at a 95% confidence level. These findings may provide transportation agencies and practitioners with a clear understanding of the potential of the Epics controllers in improving traffic operations at signalized intersections along the entire corridor. Also, the study results could be used by transportation agencies to justify the future deployment of adaptive traffic signals at signalized intersections.

Keywords – adaptive traffic signals, microscopic simulation, ring-barrier controllers, epics/balance controllers

1. Background

In recent years, the growth of automobile traffic on urban and suburban arterials has resulted in problems such as congestion, delays, and poor travel time reliability. These problems are aggravated, especially when the traffic is unpredictable and highly variable across the day. According to the Federal Highway Administration [14], about half of the congestion experienced by motorists in the United States (U.S.) is caused by temporary disruptions, i.e., non-recurring congestions which are associated with bad weather conditions (15%), work zones (10%), and incidents (25%). In urban areas, poor traffic signal timing at signalized intersections accounts for 5% of traffic congestion, which eventually increases travel time and delays [12]. Therefore, mitigating traffic congestion on urban arterials relies on having an efficient traffic signal control system at signalized intersections.

As the urban population grows, so does the demand for a reliable and congestion-free transportation network. Traditional solutions, such as adding lanes, are no longer considered feasible in alleviating congestion due to the limited right-of-way. As such, transportation agencies are consistently exploring strategies beyond traditional roadway infrastructure expansion projects such as Transportation Systems Management and Operations (TSM&O) [3, 4, 5, 6]. Agencies have traditionally been using conventional time-of-day (TOD) signal timing plans that are programmed based on historical turning movement counts [29]. These systems do not adjust automatically to accommodate variability in traffic demand. They remain fixed until manually adjusted by the operator. Even though the drawbacks of these TOD signal plans are well-known, the frequency of traffic signal retiming is constrained by the state and local transportation agencies' capabilities and resource limitations.

As an enhancement to the TOD plans, actuated-coordinated signals, which allow unused side-street green time to be utilized by the main-street traffic, are being deployed. However, this provides more capacity to the main-street and results in less efficient coordination since the offsets do not respond automatically in real-time to the early platoon arrival at downstream intersections [29]. These signals, which are not traffic responsive, face problems, especially when unexpected traffic patterns occur, causing delays during peak commuting periods. Advancement to the actuated-coordinated signals is the adaptive signal control technology (ASCT), the latest generation of traffic signal control systems that optimize signal timing based on the prevailing traffic flow condition [13, 26]. In contrast to the TOD, actuated, or actuated-coordinated signal timing plans, the ASCT accommodates continuously varying traffic demand by incrementally updating signal timing plans in real-time.

The ASCT uses real-time traffic data to optimize signal timing parameters such as cycle length, splits, and offsets to minimize traffic congestion, delays, and traffic stops [6, 13, 22]. These systems are expected to be more efficient for traffic signal system operations since they can detect traffic volume instantaneously and can proactively respond to real-time traffic flow fluctuations, traffic incidents, and special events [13, 34]. In the past few decades, several types of ASCT have been deployed in different arterial networks worldwide [15, 17, 34]. The most used adaptive traffic controllers include the Split Cycle Offset Optimization Technique (SCOOT), and Sydney Coordinated Adaptive Traffic System (SCATS). Other less-common controllers that are also operational are the Epics and Balance by PTV, InSync system by Rhythm Engineering, SynchroGreen by Cubic, and Centracs by Econolite. These systems are collectively in operation in more than 200 cities worldwide [10]. Each ASCT system utilizes a unique algorithm to optimize signal timing based on prevailing traffic conditions. While other systems provide an entire system solution evaluated on a second-by-second basis, other systems consider and optimize each signal on a cyclic basis. Studies have found that each approach produces similar benefits and requires a varying level of detection, communication, and processing capability that should be selected to be consistent with the agency's needs, operations, and maintenance capabilities [29, 30].

The ASCT system can be integrated and optimized to promote seamless travel along a route, thereby reducing traffic delays and significantly improving operational performance. Also, these systems can be integrated to regulate traffic control on a network of traffic signals, improving traffic flow in urban roadways and thus decreasing congestion. However, capturing real-time optimization might be difficult in the field. Simulation is advantageous in capturing phenomena such as unserved demand that is otherwise difficult to measure in the field [1, 2]. More modern traffic-adaptive optimization procedures use iterative approaches with an integrated traffic model and try to estimate the conditions on the street as realistically as possible. Based on this input, the model calculates the characteristics considered in the optimization process for various control alternatives, e.g., the waiting times of each vehicle. In this case, the solution with the shortest total waiting time is accepted and handed over to the traffic control system [27].

The entire priority intersection control system (Epics) is a traffic-model-based adaptive traffic control system created as an adaptive local control method for simultaneously optimizing signal control and level of service for all road users. While the initial version of Epics focused on public transportation vehicles, the recent enhancements included a comprehensive control method providing real-time optimization of traffic control parameters for all road users. PTV Epics, which manages individual intersection operations and PTV Balance, which operates to optimize the entire network, work together to reduce delays, travel times, and stops [27].

In general, the performance of the ASCT depends on the embedded traffic flow prediction and control algorithm. Upstream detection information predicts the vehicles' arrival time considering signal timing, vehicle trajectory, and variable queue length. The real-time signal control algorithm can be formulated based on a dynamic programming procedure, supporting the National Electrical Manufacturers Association (NEMA) phase configuration. Based on the predicted vehicular flow in the planning horizon, the signal control algorithm allocates phase sequence and duration to minimize expected vehicle delays at the intersection [8]. The signal timings for the ASCT system are updated in real-time using real-time data from a comprehensive detection system and optimization software. PTV Epics and Balance controllers integrated into the PTV VISSIM software package can be used to coordinate traffic signals along a network to allow a continuous green wave along a route. The peak direction of travel can be allocated priority along a roadway network to ensure that these vehicles stop at as few intersections as possible, thereby reducing total control delay. Signals are coordinated to ensure that signals change to green as a platoon of vehicles approaches traffic signals.

Previous studies have evaluated the safety and operational performance of the ASCT using observed field data [18, 20, 21, 23, 24]. Other researchers used the VISSIM model to evaluate the performance of the ASCT based on different controllers such as SCATS, SCOOT, ACS-Lite, and InSync [7, 9, 16, 25, 31, 32, 33]. Hansen et al. [16] evaluated the performance of the SCOOT using the CORSIM microsimulation approach. The study compared SCOOT and TRANSYT-7F performance on a 6-intersection network in an urban area. The results showed that SCOOT reduced delays and stops by up to 30%. Day et al. [9] compared the performance of the ACS-Lite on a 19-intersection corridor with the conventional signal timing in the microsimulation environment. The ACS-Lite was found to outperform the conventional signal timing. Stavanovic et al. [32] evaluated the performance of SCOOT and SCATS through microsimulation. The author indicated that both systems outperformed the conventional signal timings in terms of travel time, vehicle delay, and side-street delays for unexpected traffic demand [32].

Most recently, Stevanovic et al. [31] compared the performance of the InSync adaptive traffic control system with the TOD signal timing in response to recurring and non-recurring congestion. The InSync system outperformed the TOD signal timing in terms of travel time and delays on both recurring and non-recurring congestion. Other studies have also indicated that ASCT underperformed conventional signal timings. For instance, Stevanovic et al. [32] found that SCOOT underperformed the best offline signal timing for the expected traffic demand. The author documented that for the expected traffic demand, it is difficult for any traffic control operating in real-time to find better signal timing than that from a comprehensive optimization of the offline signal timing. Another study by Klanac et al. [19] and Stevanovic et al. [31] revealed that TOD outperformed ASCT in terms of the number of stops and side-street traffic operations.

In summary, only a few studies have evaluated the performance of local-optimization systems. To the best of the authors' knowledge, none of them assessed the performance of ASCT using Epics controllers in the microscopic simulation environment. Similar to other ASCT systems, PTV Epics has the potential to improve traffic flow over the TOD signal timing plans, which use ring-barrier controllers (RBC). Therefore, this study intended to comprehensively evaluate the performance of the adaptive traffic system using Epics controllers in VISSIM. The study used a 4-mile corridor consisting of ten signalized intersections in Jacksonville, Florida, as a case study. The ASCT using Epics controllers and TOD systems using RBC were analyzed in VISSIM for the evening peak period. This paper documents a systematic approach that contributes to an innovative procedure that can potentially be adopted for evaluating the performance of ASCT.

2. Site description

The study area included a 4-mile corridor along Mayport Road (A1A) in Jacksonville, Florida. The corridor consists of ten signalized intersections from Atlantic Boulevard to Wonderwood Drive, and the speed limit varies between 40-45 mph. The adaptive traffic signals along the study corridor were activated on June 25th, 2018. Figure 1 shows the location of the study corridor with ten signalized intersections.

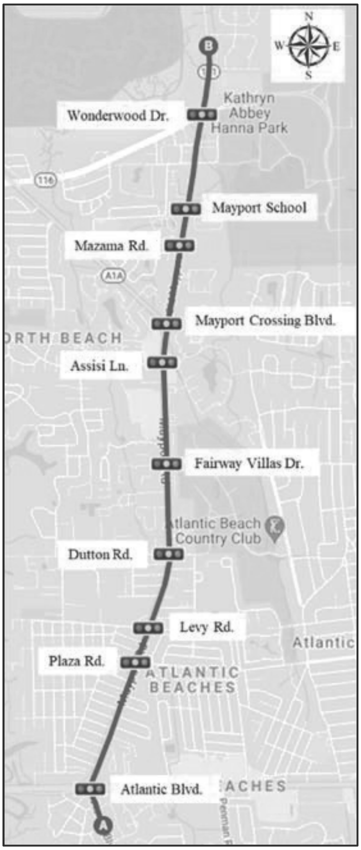


Fig. 1 - Study corridor in Mayport Road, Jacksonville, Florida

3. Methodology

A microscopic simulation approach was used to investigate the operational performance of adaptive traffic control systems using PTV Epics Balance/Local controllers. Specifically, the study compared the TOD signal timing plans that use RBC controllers and the ASCT through Epics Balance/Local controllers. In this study, the RBC-integrated model is referred to as the Base model, and the Epics-integrated model is the ASCT model. These two models were developed to evaluate and compare the performance of the ASCT and TOD signal timing plans.

3.1. Simulation model setup

The first step was to develop a simulation model representing the base condition, i.e., without the adaptive traffic controllers. The Base model was developed by incorporating relevant field data, including traffic volumes, existing roadway geometry, turning movement counts, and recently optimized TOD signal timing plans. The Base model, which replicates the current TOD signal timing, was calibrated to closely represent field conditions in terms of speed limitations, driving behavior, and saturation flow at major and minor streets using the collected field data.

Once the Base model was calibrated, the PTV Epics, which simulates the adaptive traffic systems, was interfaced with the VISSIM model using the Epics/Balance Local controllers. Generally, both models were developed following the guidelines and fundamentals described in the VISSIM manual and the Florida Department of Transportation (FDOT) traffic simulation handbook for traffic analysis tools [11, 28]. The analysis period was 3.5 hours, with the first 30 minutes used as the warm-up period in which no performance measures (i.e., output data) were recorded. The analysis was conducted during the evening peak hours (i.e., 4:00 PM - 7:00 PM).

3.2. PTV epics signal timing configuration and operation

The adaptive traffic signals were incorporated at all the ten signalized intersections along the study corridor by integrating the adaptive parameters using the Epics controllers in VISSIM. Epics was created as a model-based local adaptive control method to optimize cycle lengths based on real-time turning movement counts [27]. The control system decides in seconds whether a phase needs to be omitted, shortened, or lengthened. This system uses a deterministic model similar to the one implemented in TRANSYT [27]. Figure 2 (a) shows the Epics controller user interface. As presented in Figure 2 (a), the optimization process is repeated every second for a horizon of 100 seconds [27]. It optimizes the switching of the traffic lights at a single intersection and takes into consideration all vehicle types, including buses.

To reflect Epics requirements, the RBC controllers in the RBC-integrated Base model were modified and configured following the PTV Epics user manual [27]. The RBC detectors in the RBC-integrated Base model were adjusted to reflect the Epics configuration. Such adjustment includes the distance of the detectors from the signal head, approximately 164-262.5 ft from the stop line, which corresponds to about 4-6 seconds. Further, every intersection was configured separately to precisely correspond with the detector ports and signal heads to ensure the highest level of Epics performance. Epics use a deterministic model like the one used in TRANSYT. As stated in the Epics user manual, the counting detectors were accurately configured to best represent the operating traffic conditions for each intersection [27]. Epics repeat the optimization process every second for a horizon of 100 seconds when the distance between the detector and stop line is within 400 feet. In the case when the distance between detectors and stop line is over 400 feet, an inflow prognosis by cyclic flow profiles is used to predict the arrivals of vehicles during the next cycle. Subsequently, the *green wave* is formed automatically since Epics anticipates vehicle platoon arrivals in the following cycle at the same time as in the current cycle

Epics were designed to work based on stages (phases) and inter-stage (i.e., in between phases). Optimization in Epics is divided into two parts. First, the entire time horizon is divided into five seconds long segments where the stage sequence is determined using a branch-and-bound algorithm [19]. Second, the fine-tuning is applied by the optimized starting times for inter-stages with the precision of one second using the hill-climbing algorithm [19]. In contrast with RBC, Epics use the intergreen matrix for Epic configuration to acknowledge the interstage start and stop times (see Figure 2 (b)). The intergreen matrix timing used in this study does not represent the actual field data but is based on the sums of all-red and yellow times. Figure 2 (c) presents the configuration panel for Epics parameters and data needed for Epics simulation. It is important to note that the user needs to activate stage transition order for Epics to start functioning. After the stages were configured, the minimum green time and cycle length were entered, upon which the Epics automatically generated the stage-based signal program (see Figure 2 (d)). Note that Figure 2 was shown for visual representation purposes and does not show the actual design configuration.

Since Epics is designed to work based on stages (phases) and inter-stage, it finds a stage sequence that minimizes the performance index (PI) for the defined time horizon. The PI is the optimization function of the PTV Epics based on the total delay and the number of stops of the vehicles, which are calculated based on the summation of all detected traffic streams, each with a configurable weight. As such, PTV Epics provides the opportunity to directly adapt to the influence of the number of stops via a weight factor that has to be configured in the traffic-demands window [27]. The result of every optimization is a signal plan that fits the duration of the horizon. The PI is calculated based on Equation 1.

$$PI = \sum_{sg \in SG} \propto_{sg} D_{sg}\,(sp) + \beta\Delta(ref, sp) \tag{1}$$

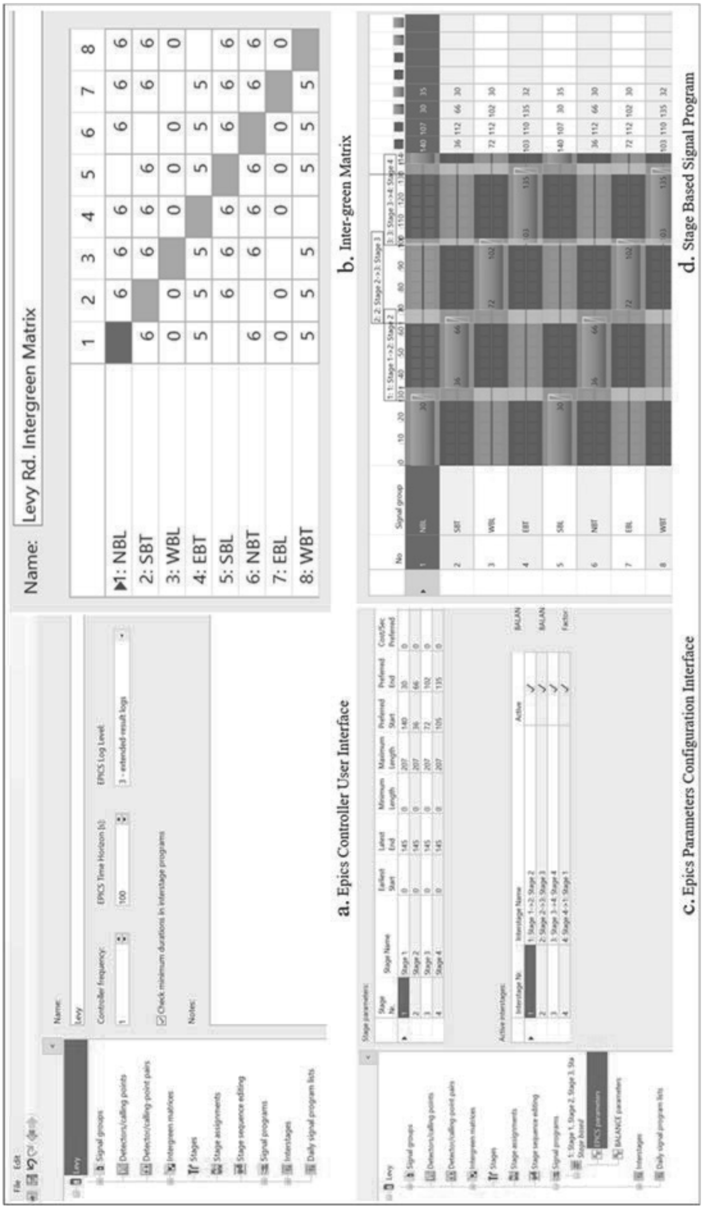
where,

SG is the set of the signal group,
sp is the signal plan to be valued,
ref represents the reference signal plan, e.g., from PTV Balance,
$\propto_{sg}$ is the weighting of the signal group sg,
D_{sg} is the sum of delay at signal group sg over the time horizon considered,
Δ represents the deviation of green time of the control alternative sp from ref, and
β is the weighting of deviation from ref.

As presented in Equation 1, the weighting of the signal group ($\propto_{sg}$), accounts for the delays or wait times for each signal group aiming at providing optimal PI. This parameter was calculated automatically by the PTV Epics algorithm. On the other hand, the weighting of the deviation from the reference signal plan accounts for the possible variation from the signal plan assigned by the PTV Balance. Similarly, this parameter was calculated automatically by the PTV Epics algorithm.

3.3. VISSIM simulation runs

To minimize the impact of the stochastic nature of traffic flow, simulation models are run multiple times with different random number seeds. A total of ten simulation runs with different random number seeds are usually adequate.



Name: Levy Rd. Intergreen Matrix

	1	2	3	4	5	6	7	8
▶1: NBL	■	6	6	6		6	6	6
2: SBT	6	■	6	6	6		6	6
3: WBL	0	0	■	0	0	0		0
4: EBT	5	5	5	■	5	5	5	
5: SBL		6	6	6	■	6	6	6
6: NBT	6		6	6	6	■	6	6
7: EBL	0	0		0	0	0	■	0
8: WBT	5	5	5		5	5	5	■

a. Epics Controller User Interface

b. Inter-green Matrix

c. Epics Parameters Configuration Interface

d. Stage Based Signal Program

Fig. 2 - Epics configuration

However, the number of required simulation runs to achieve a certain confidence level about the mean of the performance measure can be computed mathematically. VISSIM does not automatically calculate the required number of simulation runs necessary to achieve reliable results that are within the tolerable error. Therefore, the number of simulation runs was determined by using Equation 2 as provided in the FDOT Traffic Analysis Handbook [11].

$$n = \left(\frac{s * t_{\alpha/2}}{\mu * \varepsilon}\right)^2 \qquad (2)$$

where,
n is the required number of simulation runs,
s represents the standard deviation of system performance measure based on the previous simulation runs,
$t_{\frac{\alpha}{2}}$ is the critical value of a two-sided Student t-statistic at the confidence level of α and n − 1 degree of freedom (df),
μ represents the mean of the system performance measure, and
ε is a tolerable error, specified as a fraction of μ, a desirable value of 10%.

Note that the formula in Equation 2 considers the standard deviation, the 95% confidence interval, the mean, and the tolerable error of 10% for the travel speed as the performance measure used to assess the system performance. A minimum of 17 simulation runs per scenario were determined in this study.

3.4. VISSIM model calibration

The Base VISSIM model was calibrated using the turning movement counts data at each signalized intersection. Figure 3 compares the simulation model's turning movement counts and the collected field data. The coefficient of determination (R^2) was computed to assess the resemblance between the simulated and the collected field data. The value of R^2 was 0.98, indicating a high similarity between the simulated and field data. The Geoffrey E. Havers (GEH) empirical formula (Equation 3) was also used as the acceptance criteria for the model.

$$\text{GEH}=\sqrt{\frac{2(M-C)^2}{M+C}} \qquad (3)$$

where M is the traffic volume from the traffic simulation model and C is the real-world traffic count in vehicles per hour. The acceptance criterion was GEH < 5.0 for at least 85% of intersections [11]. In this study, GEH < 5.0 was observed for 95% of the intersections.

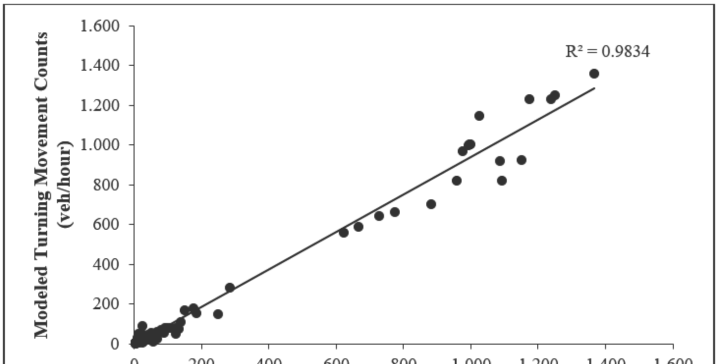


Fig. 3 - Calibration results of VISSIM base model

4. Results and discussion

The evaluation of the Epics performance through VISSIM simulation was performed for three hours with 30 minutes warm-up time for the evening peak period. The RBC-integrated Base model and Epics-integrated ASCT model were simulated for 17 differently seeded simulation runs. The mobility benefits were evaluated based on travel times, average vehicle delay, and side-street delay as the measures of effectiveness (MOEs). The following subsections discuss the simulation results.

4.1. Travel Time comparison

Travel times were measured for segments between each pair of signalized intersections along the study corridor in northbound (NB) and southbound (SB) directions. The data collection points were set in VISSIM from one signalized intersection to the next for each travel direction. Table 1 presents the travel time results along the segments for NB and SB directions. The results were statistically significant at a 95% confidence level.

Overall, based on travel time as a performance measure, the Epics-integrated ASCT model outperformed the RBC-integrated model for northbound and southbound directions. The ASCT outperformed the TOD, resulting in 11.9% and 7.6% reduction in travel time in the NB and SB direction, respectively. However, the travel time between Atlantic Blvd. and Plaza segment was lower for the RBC-integrated Base model for the SB direction. This could be attributed to the oversaturated conditions during the PM peak in the southbound direction, leading to a higher volume-to-capacity (v/c) ratio (i.e., v/c>1).

4.2. Delay comparison

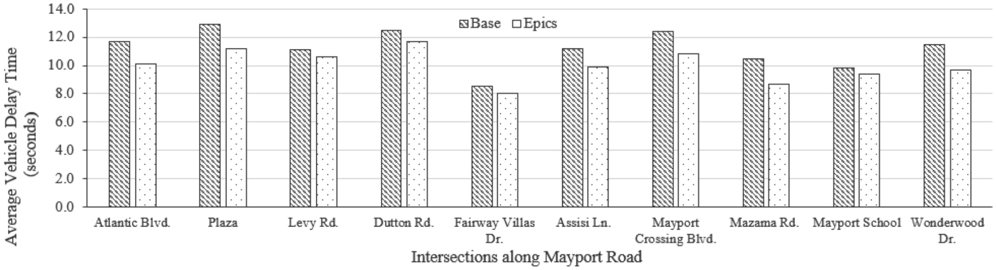
Average vehicle delay time and main-street delay were also considered as the MOEs to quantify the mobility benefits of ASCT operations. Figure 4 demonstrates Epics signal controllers' performance generated based on the average vehicle delay along the main-street in northbound and southbound directions, respectively. ASCT resulted in a lower average vehicle delay for all ten signalized intersections in NB and SB directions. The analysis results show that the ASCT resulted in a statistically significant reduction in average vehicle delay compared to the TOD signal timing plan.

Tab. 1 - Comparison of Travel Time (TT) along the study corridor

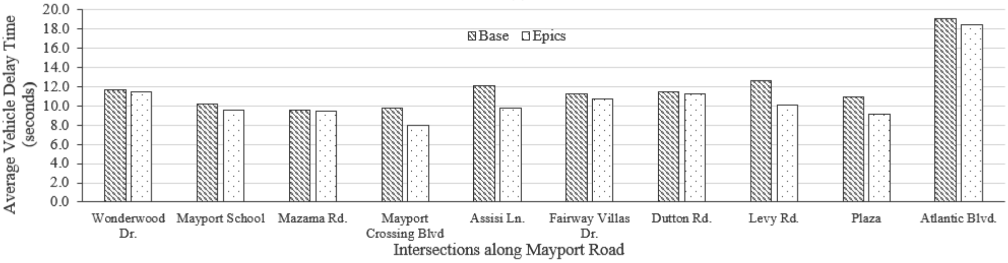
Segment Name	**Northbound TT(s)**		**Southbound TT(s)**	
	Base/RBC	**ASCT/Epics**	**Base/RBC**	**ASCT/Epics**
Atlantic Blvd.-Plaza	64	57	80	87
Plaza-Levy Rd.	26	22	33	25
Levy Rd.-Dutton Rd.	45	39	43	39
Dutton Rd.-Fairway Villas Dr.	59	53	48	37
Fairway Villas Dr.-Assisi Ln.	48	42	53	48
Assisi Ln.-Mayport Crossing Blvd.	31	35	41	37
Mayport Crossing Blvd.-Mazama Rd.	45	39	44	47
Mazama Rd.-Mayport School	22	17	17	13
Mayport School-Wonderwood Dr.	47	37	42	37
Total	**387**	**341**	**401**	**371**
Percentage Change (%)	**N/A**	**-11.9%**	**N/A**	**-7.6%**

4.3. Impacts on side-street traffic

Another essential factor in any new traffic signal control evaluation is the side-street delay. The side-street delay was recorded for all ten signalized intersections along the study corridor in eastbound and westbound directions. Figure 5 illustrates the average vehicle delay recorded in the side-street for the RBC-integrated Base model and the Epics-integrated ASCT model.

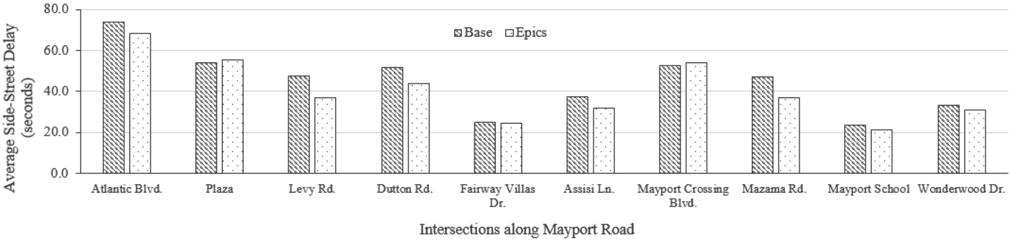


(a) Northbound

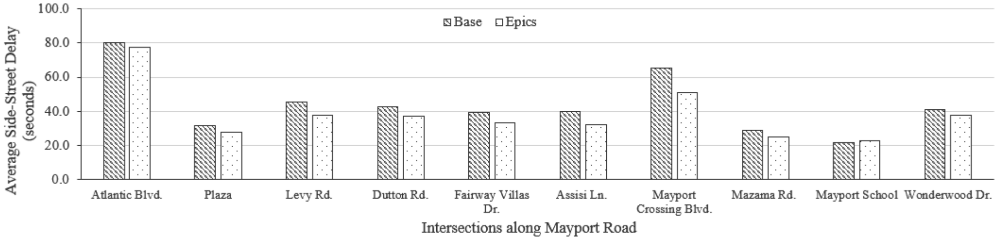


(b) Southbound

Fig. 4 - Estimated main-street delays



(a) Eastbound



(b)Westbound

Fig. 5 - Estimated side-street delays

It can be inferred from the figure that ASCT reduced side-street delays even though it favors the main-street movement. Overall results showed that ASCT significantly reduced the side-street delay for all intersections by almost 20% compared to the TOD signal timing plan. The reduction on side-street was expected since Epics operates based on prevailing traffic conditions. The actuated control system generally has detectors on the side-street, whereas the adaptive control system has sensors on both the main-street and side-street. Therefore, the ASCT provides more flexibility for the side-street users with its advanced detection in real-time than the TOD timing plans, which give little flexibility for side-street users.

4.4. Statistical analysis of the Measures of Effectiveness (MOEs)

The paired t-test was used to compare the performance of the two systems based on the selected MOEs. As stated earlier, the MOEs selected in this study include travel time, average vehicle delay, and side-street delay. The hypothesis test for the means of the MOEs between the two systems used in this study was as follows:

Null hypothesis H_0: $\bar{X}_{TOD} = \bar{X}_{ASCT}$ (4)
Alternative hypothesis H_a: $\bar{X}_{TOD} > \bar{X}_{ASCT}$ (5)

where,
$\bar{X}_{TOD}$ is the mean of the MOEs for the RBC-integrated Base model, and
$\bar{X}_{ASCT}$ is the mean of the MOEs for the Epics-integrated ASCT model.

Table 2 presents statistical test results performed based on the selected MOEs. As shown in Table 2, there is sufficient evidence to reject the null hypothesis for all MOEs since the t-statistic value (t_o) was less than the t-critical value at a 95% confidence level. This indicates that there was a significant difference in the MOEs between the two systems. More specifically, the mean travel time, main-street delay, and side-street delay were significantly lower for the Epics-integrated ASCT model than the RBC-integrated Base model at a 95% confidence level.

Tab. 2 - Statistical analysis results

Travel Time (seconds)		
	Base/RBC	ASCT/Epics
Mean	43.78	41.22
t-statistic value (t_o)	2.212	
p-value	0.020	
t-critical value	1.739607	
Main-street Delay (seconds)		
	Base/RBC	ASCT/Epics
Mean	11.55	10.41
t-statistic value (t_o)	6.700	
p-value	0.000	
t-critical value	1.729	
Side-street Delay (seconds)		
	Base/RBC	ASCT/Epics
Mean	44.10	39.26
t-statistic value (t_o)	5.222	
p-value	0.000	
t-critical value	1.729	

Tab. 3 - Performance results of the entire corridor

	Northbound		**Southbound**	
Main-street	**Base/RBC**	**Epics/ASCT**	**Base/RBC**	**Epics/ASCT**
Travel Time (seconds)	387	341	401	371
Vehicle Delay (seconds)	112.1	101	123.3	109.2
	Eastbound		**Westbound**	
Side-Street	**Base/RBC**	**Epics/ASCT**	**Base/RBC**	**Epics/ASCT**
Side-street Delay (seconds)	445.5	403.7	436.4	381.4

4.5. Corridor performance

Table 3 summarizes the performance results of the entire corridor and presents the travel time, average vehicle delay time, and side-street delay for both directions. As presented in Table 3, the ASCT significantly outperformed the TOD signal timing plan based on travel time and delay in the corridor-level performance in both travel directions. It is evident from the analysis results that the ASCT decreased travel time and delays compared to the TOD signal timing plans.

5. Conclusions and future work

This study evaluated the performance of the ASCT using microscopic simulations integrated with Epics controllers. Considering that Epics is a relatively new adaptive traffic control application, this study attempts to measure the operational benefits of this system. Epics were created as a single-intersection optimization software. Its main advantage is the second-by-second updated algorithm that generates decisions related to green time duration based on queue length and traffic demand. In this study, the performance of the Epics control system was compared to the traditional RBC-coordinated TOD signal plans for ten signalized intersections along Mayport Road in Jacksonville, Florida.

The results show that ASCT outperformed the TOD signal timing plan by reducing the travel time by 11.9% and 7.6% in the NB and the SB directions, respectively. Also, ASCT reduced the average vehicle delay on the main-street and the side-street by up to 19% and 22%, respectively. The results were statistically significant at a 95% confidence level. The study also computed MEFs to quantify the operational performance of the ASCT based on the selected MOEs. The MEF based on travel time was 0.889, and the MEF based on average vehicle delay was 0.901. Based on the MEF results for travel time and average vehicle delay time, it can be concluded that ASCT improves operational performance along the corridor.

Future research could expand the present study to evaluate the performance of Epics on other network types under various traffic conditions and different site characteristics. Also, future research should address the investigation of the combined Epics model and another embedded model known as PTV Balance to enhance network optimization. Also, different simulation software may be used to develop the model and determines the operational performance of Epics along the corridor.

Authors' contribution statement

The authors confirm their contribution to the paper as follows: study conception and design: M. Ali, J. Kodi, P. Alluri, and T. Sando; simulation model: J. Kodi and M. Ali; analysis and integration of results: J. Kodi, M. Ali, P. Alluri, and T. Sando; draft manuscript preparation: J. Kodi, M. Ali, P. Alluri, and T. Sando. All the authors reviewed the results and approved the final version of the manuscript.

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Safety performance of alternative intersection designs: techniques, current findings, and research gaps

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Abstract

The use of Alternative Intersection Designs (AIDs), traditionally known as Unconventional Arterial Intersection Designs (UAIDs), has been proposed in the past two decades to improve the operational and safety performance of at-grade signalized intersections. Alternative intersection designs typically require only minor geometric modifications and therefore are considered cost-effective. A considerable amount of valuable research has been undertaken in recent years to evaluate and compare the operational performance of AIDs. In only a few studies, the safety aspects of some AIDs were analyzed. Previous research showed operational benefits of AIDs in terms of higher capacity, lower delays, among other measures. On the other hand, the results on safety performance of AIDs were neither solid nor conclusive. This may stem from the fact that quantifying the operational benefits is far easier than estimating safety. There is currently no collective effort to review the methods used to analyze the safety impacts of AIDs and summarize the previous research findings. This paper serves as an in-depth review of the safety performance of AIDs. Also, the paper identifies areas that need further research and improvements based on the reviewed methods and results. The lack of reliable crash data and robust crash analysis procedures are the main two issues associated with the safety evaluations of AIDs.

Keywords – alternative intersection designs, road safety analysis, surrogate safety measures

1. Introduction

With the increase in traffic demand, transportation road networks suffer from traffic congestion and poor traffic safety, especially at at-grade intersections. Heavy left-turn volumes at intersections are considered the main reason for many problems. Transportation professionals have attempted to enhance the operational and safety performance of at-grade intersections by widening intersection approaches, adding protected left-turn signal phases, or ultimately constructing interchanges. These solutions might sometimes be infeasible or expensive [1-3] Recently, transportation engineers have considered alternative intersection designs (AIDs), as a solution to improve traffic operation and safety at at-grade intersections. AIDs are based on re-routing certain traffic movements from direct through and turning movements at intersections under any traffic control. As a result, the number of conflict points of an AID is typically less than a conventional counterpart. The reduction in the number of conflict points leads to a fewer signal-phases at the intersection which is traditionally associated with improved traffic operation [2].

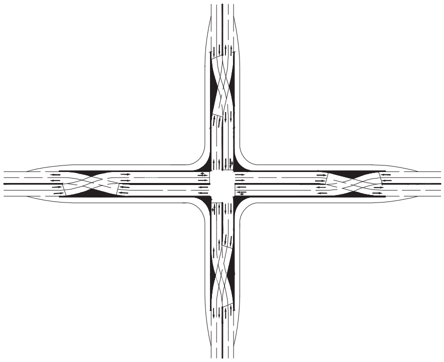
As the AIDs seem to be a valuable solution for congestion and safety problems at at-grade intersections, the efficiency and safety impacts of their implementation should be investigated and discussed. Generally, the investigation of the operational performance of AIDs have shown that they enhanced the traffic operation compared to conventional intersection in terms of reducing travel time, reducing the overall intersection delay, and increasing the capacity [4-17]. In a previous research, El Esawey and Sayed [3] described eleven different types of AIDs and presented a review of the different methods used to analyze their operational performance. Similarities and differences between various evaluation approaches were discussed and it was shown that traffic micro-simulation modeling is still the most widely used tool to analyze the operational performance of AIDs. El Esawey and Sayed [3] discussed the safety performance of AIDs only in brief. This was mainly due to the lack of studies which analyzed the safety aspect of AIDs. After almost a decade, and as more implementations of AIDs took place, a considerable body of literature became currently available on the safety performance of AIDs. This study serves as a collective effort that describes the different techniques used to evaluate the safety performance of AIDs. As well, the study presents a summary of the previous safety research findings and proposes future research directions.

2. Types of alternative intersection designs

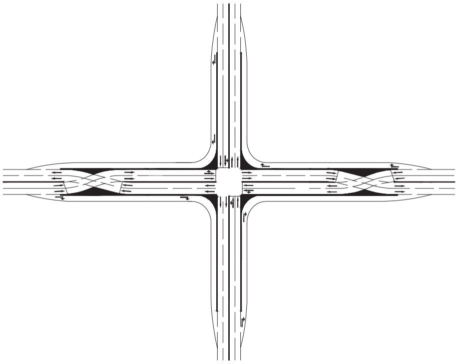
There are currently many different types of AIDs which can be applied at three or four-legged at-grade intersections. These include but not limited to: Continuous Green-T (CGT), Conventional Median U-turn (MUT), Restricted Crossing U-Turn (RCUT), Displaced Left Turn (DLT), Jughandle, Bowtie, Parallel Flow Intersection (PFI), Upstream Signalized Crossover (USC), Synchronized Split-Phasing (SSPI), Quadrant Roadway (QR), and Split Intersection. These intersections have been described and analyzed extensively in many publications in literature. Due to space limitations, only a brief background is given on each design. Interested readers are advised to refer to the original publications for a detailed description of the layout, movements, operational performance, and previous deployments of these designs.

The CGT design was described in Tabernero and Sayed [2] and Donnell et al. [3]. This innovative three-leg design is widely implemented in many states in the USA including Arizona, California, Illinois, Iowa, North Carolina, Florida and South Carolina. Jagannathan [4] and Hughes et al. [2] described the MUT intersection which has been extensively used in Michigan, Florida, Maryland, New Jersey, and Louisiana. The RCUT design was first introduced by Kramer [21], and is also known as super street median (SSM), restricted crossing intersection (RCI), J-turns (when unsignalized) [4], reduced conflict intersections, reduced conflict U-turns, and synchronized streets [22]. The DLT is known as crossover displaced left-turn (XDL) [2] and continuous flow intersection (CFI) [23] and was implemented in the USA, Mexico, and recently in the KSA. Jagannathan [20] and Bared [25] described three different types of Jughandle intersections: forward-forward ramps (Type A), reverse-reverse ramps (Type B), and reverse-forward ramps (Type C). The Jughandle intersection was implemented in many countries worldwide including Australia, Canada, Germany, Singapore, the UK, and the USA. The Bowtie design is based on placing two roundabouts on the cross-streets a few hundred feet from the main intersection to accommodate left turns [4] and is implemented in Nebraska and Utah in the USA [26].

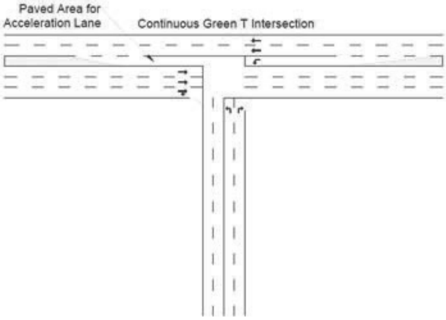
The PFI design was proposed by Parsons [27], and has not yet been implemented. The USC design eliminates conflicts between left-turn traffic and opposing traffic by redirecting both through and left-turn movements to the left side of the road through crossovers before the primary intersection [18]. The SSPI design [28] is considered as a half USC design and is also known as double crossover intersection (DXI) [29]. The quadrant roadway (QR) intersection eliminates left turns at the main intersection by providing a roadway that is located in any of the four legs [26]. In a split intersection, a two-way main road is split into two closely one-way streets before the primary intersection [30]. This design is used in Florida, Michigan, Mississippi, Pennsylvania, Texas, and Utah. Figure 1 shows the layout of different AIDs.



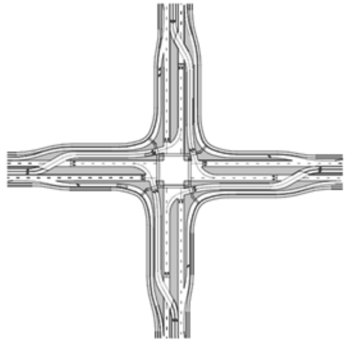
USC intersection [3]



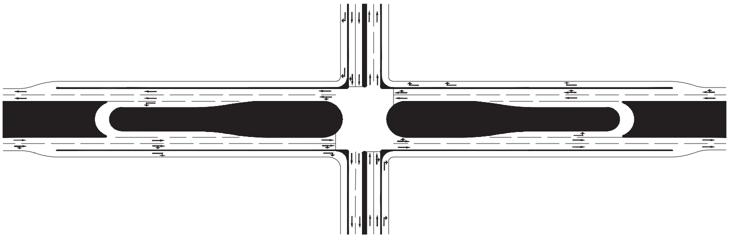
SSPI Intersection [3]



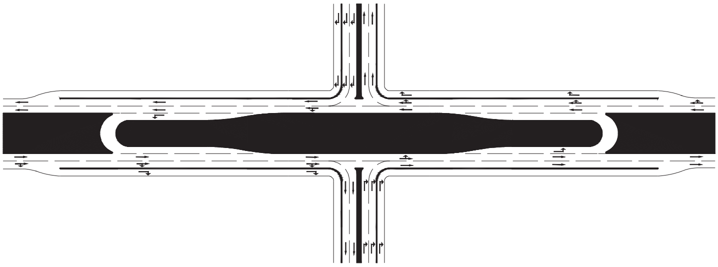
Continuous Green T-Intersection [19]



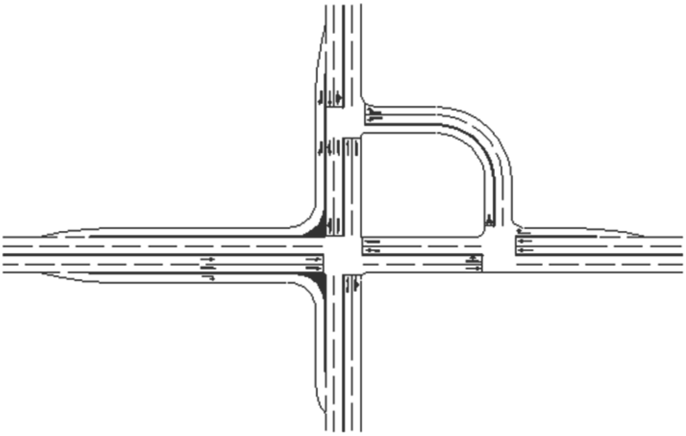
DLT with displaced left turns on all approaches, also known as CFI and XDL [31]



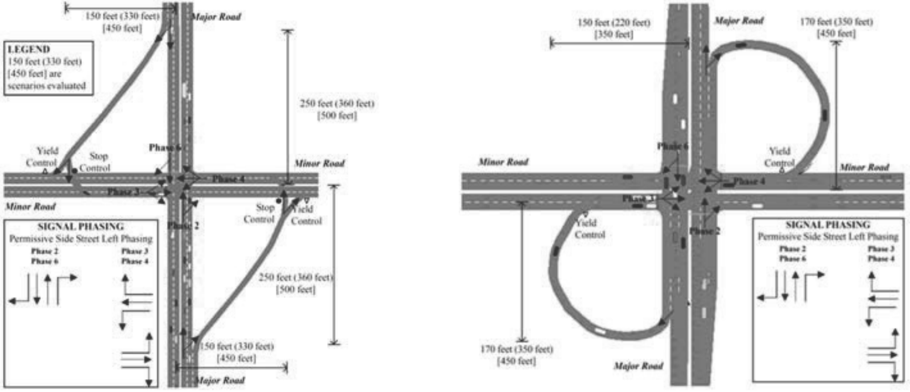
MUT Intersection with U-turn Crossover on the Major Street [3]



RCUT with restricted left-turn from the main road [3]

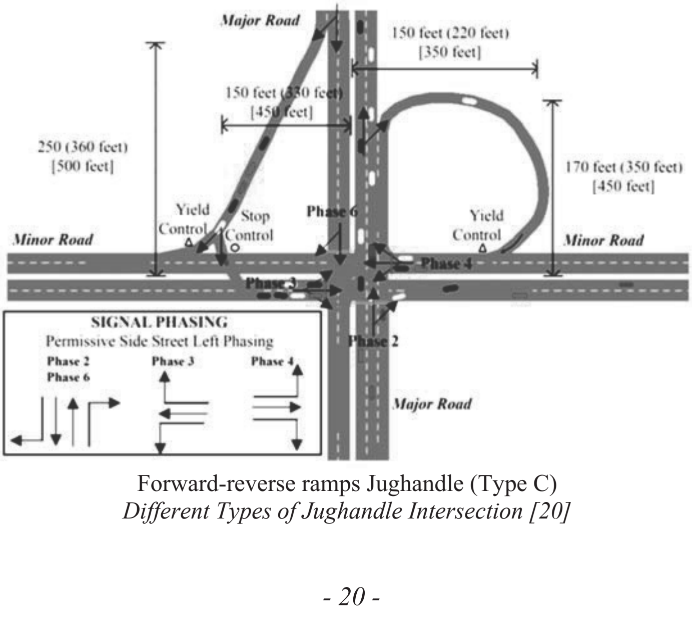


QR intersection [3]



Forward Ramps Jughandle (Type A)

Reverse Ramps Jughandle (Type B)



Forward-reverse ramps Jughandle (Type C)
Different Types of Jughandle Intersection [20]