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Operational impacts of Transit Signal Priority (TSP) in Adaptive Signal Control Technology (ASCT) environment

MS. Ali[1*] J. Kodi[1] P. Alluri[1] T. Sando[2]

[1]Department of Civil & Environmental Engineering, Florida International University, 10555 West Flagler Street, EC 3720, Miami, FL 33174
**Corresponding author, email: mali043@fiu.edu*
email: jkodi001@fiu.edu; palluri@fiu.edu
[2]School of Engineering, University of North Florida, 1 UNF Dr, Jacksonville, FL 32224
email: t.sando@unf.edu

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Abstract

The study assessed the operational performance of Transit Signal Priority (TSP) in an Adaptive Signal Control Technology (ASCT) environment using PTV Epics/Balance local controllers in a microscopic simulation setting. The analysis was based on a 4-mile study corridor in Florida. Three microscopic simulation VISSIM models, a Base model, a TSP model, and TSP operating in the ASCT environment (ATSP) model were developed. The Base model was calibrated to represent field conditions. The ATSP model provided substantial savings in travel time and average vehicle delay compared to the Base and the conventional TSP model operating in actuated conditions. Under the ATSP scenario, the study corridor experienced up to 13.40% reduction in travel times for buses and all other vehicles, and up to 11.00% reduction in average vehicle delay for buses and all other vehicles. The results were statistically significant at a 95% confidence level. To better quantify the mobility benefits of ATSP, Mobility Enhancement Factors (MEFs) were estimated. MEFs are multiplicative factors used to estimate the expected mobility level of ATSP. A MEF < 1 implies that ATSP yields mobility benefits. The MEFs based on travel time for buses and all other vehicles were estimated to be 0.8780 and 0.9100, respectively. The MEFs based on average vehicle delay for buses and all other vehicles were 0.8960 and 0.9230, respectively. The ATSP model was also found to improve cross-street delay. The study findings may provide transportation agencies with a deeper knowledge of the potential of the Epics/Balance controllers in improving traffic operations.

Keywords – transit signal priority, traffic microscopic simulation modeling, travel time, cross-street delay, PTV Epics/Balance controllers

1. Introduction

The continuous growth of automobile traffic on urban and suburban arterials in recent years has created a substantial problem for transit, especially when it operates in mixed traffic conditions. Therefore, there has been a growing interest in the use of transit signal priority (TSP) to promote transit ridership and reduce urban traffic congestion, as delays incurred by buses at signalized intersections typically account for 10 to 20 percent of bus running times [1]. TSP is an operational strategy that facilitates the movement of transit vehicles (e.g., buses) through signalized intersections [2, 3]. TSP adjusts signal timing to reduce delays for public transit [3]. It also offers the potential for a significant improvement in travel time reliability. In essence, it is anticipated that the provision of faster transit services may entice motorists to switch their travel modes to transit vehicles [4]. TSP can also help to reduce operating costs and staffing requirements. In addition, reductions in bus travel times may allow a given level of service to be offered with fewer buses. However, concerns have been frequently raised that TSP operations may interrupt the normal operation of signal control, and thus, increase delays to other traffic, particularly traffic served by the non-prioritized phases with high demand. Such delays could cause residual queues that may last for several cycles [5].

TSP operating in an adaptive signal control technology (ASCT) environment, referred to as adaptive TSP (ATSP) in this paper, has the potential to overcome the shortcomings of conventional TSP. The ATSP strategy is responsive to not only real-time transit requests but also current traffic conditions, through real-time optimization of selected performance criteria, such as vehicle delays and stops [6]. A majority of previous studies on TSP were based on pre-timed or NEMA (National Electrical Manufacturers Association) actuated controllers. Currently, the latest generation of signal control is ASCT, which could potentially generate greater benefits for TSP. With ASCT, signal timings are updated in "real-time" using real-time data from a comprehensive detection system with optimization software [7]. Well known examples of ASCT controllers include the Split Cycle Offset Optimization Technique (SCOOT), Sydney Coordinated Adaptive Traffic System (SCATS), and Real-time Hierarchical Optimized Distributed Effective System (RHODES), which are collectively operating in more than 200 cities worldwide [4]. Other ASCT controllers also operational are the Epics and Balance by PTV, InSync system by Rhythm Engineering, SynchroGreen by Cubic, and Centracs by Econolite.

When transit buses share the right-of-way with commuter traffic, their performance is affected by congestion and control delay at signalized intersections. Previous studies concluded that TSP benefits transit operations [7-12]. However, the impact of TSP on all other vehicles in the same network and at cross streets in the ASCT environment have rarely been explored [4-6, 13, 23-25, 32, 38-46]. ASCT can alter the signal timings in response to detected changes in traffic conditions, and these systems can theoretically reduce the potential for negative traffic impacts on general and cross-street traffic that may arise from the use of TSP.

The objective of this study was to quantify the mobility benefits of TSP in an ASCT environment for both the transit vehicles (i.e. buses) and all other vehicles along the corridor using PTV Epics/Balance local controllers in VISSIM. To the best of the author's knowledge, this is the first study to analyze the mobility benefits of TSP in an ASCT environment, referred to as ATSP in this paper, using Epics/Balance controllers in VISSIM. ATSP's impact on cross-street traffic was also studied. To better estimate the operational performance of ATSP, mobility enhancement factors (MEFs) for certain mobility performance measures were estimated. MEFs are multiplicative factors used to estimate the expected mobility benefit of ATSP. A MEF < 1 implies that the ATSP improves the operational performance of the corridor, while a MEF >1 implies that the ATSP deteriorates the corridor's operational performance for that particular performance measure.

2. Literature review

Recently, agencies used transportation systems management and operations (TSM&O) strategies to optimize the performance of existing multimodal infrastructure to improve the operational and safety of the transportation network. TSM&O strategies have been proven to improve mobility and safety [14-22]. In recent years, numerous transit-preferential treatments have been introduced to improve the capacity and operational performance of transit services. Examples of these treatments include, but are not limited to, TSP, queue jump, bypass lanes, etc. [26]. The impact of TSP on the operational performance of transit services has been studied since its first deployment in the 1970s [2]. Researchers have been evaluating the operational benefits of TSP using several methods, including microscopic simulation and analytical approaches. A number of studies have used the microscopic simulation modeling approach to optimize signal synchronization with TSP [4, 5, 7, 9, 27], while others have focused on resolving the concern of a system-wide traffic signal operation disrupted by the use of TSP [4, 12, 24, 28].

Microscopic simulation modeling using VISSIM has been commonly used to quantify the benefits of TSP [29]. VISSIM is a microscopic multi-modal traffic flow simulation software package developed by PTV (Planung Transport Verkehr) in Karlsruhe, Germany [7,30]. In one study, a traffic simulation model was developed in VISSIM to evaluate the performance of a proposed parallel genetic algorithm (PGA) based on adaptive traffic signal control with TSP [6]. The PGA was applied to optimize the adaptive traffic signal control in the presence of TSP. This method optimized the phase plan, cycle length, and green splits at an isolated intersection. The simulation results indicated that the PGA-based optimizer for ATSP outperformed the fully actuated NEMA control [6]. Han et al. [31] evaluated the ATSP control with an updated transit delay model in Alberta, Canada. The study also used VISSIM, with ASC/3 (advanced system controller) controllers. There were three major contributions of the study: an enhanced bus delay estimation model, a mechanism to adjust performance index weights dynamically, and optimization based on the enhanced delay-based performance index. However, the study did not describe the impact of ATSP on all other vehicles. Chen et al. [32] used VISSIM modeling and indicated that optimized TSP phasing plans reduced passenger delay by 8.38%.

Integration, a microscopic traffic simulation modeling software, was used to evaluate the TSP in an ASCT environment in Arlington, Virginia [4]. The evaluation was conducted for scenarios with no priority, priority only to express buses, and priority to all buses running along the study corridor. Three types of traffic signal control scenarios were considered in the analysis: fixed-time control, adaptive splits, and adaptive splits and offsets. The results indicated that buses typically benefitted from TSP under all types of traffic signal control. Explicitly, greater benefits were obtained by the prioritized buses under adaptive control when priority was offered to express buses. Furthermore, the study concluded that adaptive control with TSP can reduce the negative impacts on general traffic [4]. However, the study did not describe the implications of ATSP on cross-street traffic.

Using an analytical approach, Liu et al. [11] proposed a dynamic model for adaptive bus signal priority. In the study, a dynamic signal timing optimization model was developed to reallocate green times among the phases considering real-time traffic flow conditions and bus priority requests. Both arrival and departure flows were described by time-independent functions in the model. The arrival of a bus with a priority request was represented by giving a weight factor to the traffic demand of the associate approach [11]. An analytical approach was used to evaluate ATSP in El Camino Real on a 2-mile corridor with seven signalized intersections in California [5]. Findings indicated that, at a congested intersection, the average bus delay was reduced by 43% [5]. However, cross-street performance was not analyzed.

Wolput et al. [33] compared adaptive priority with conventional TSP using an analytical approach for mixed lane conditions. Results from the study indicated that the intersection flow ratio, the presence of a travel time disturbance, and the weights of the performance function helped in selecting a TSP strategy. It also described ATSP as a preferred strategy in undersaturated conditions because of the flexibility of redistribution green times. However, at saturated intersections, the study concluded that conventional priority performed better [33].

Despite the vast research in this area, the majority of previous studies have focused primarily on quantifying the impact of TSP on transit vehicles by using pre-timed or NEMA actuated controllers. Also, a few studies have focused on estimating the impact of ATSP on all other vehicles and cross-street performance. For example, researchers have commonly used transit travel time, reliability of transit vehicles, and transit delay as performance measures in evaluating TSP. Note that these measures are all related to transit and not to all other vehicles on the network. This study fills this gap in research by analyzing the impact of TSP in an adaptive signal-controlled environment for both transit buses and all other vehicles.

3. Study location and data

The analysis was based on a 4-mile corridor along Mayport Road, between Atlantic Boulevard and Edward Avenue, in Jacksonville, Florida. The corridor has two lanes in each direction of travel i.e., northbound (NB) and southbound (SB). The study corridor serves bus route #24, which is a major transit route in the area in both the NB and SB directions. The bus circulates between the Atlantic Village Shopping Center (SB) and the Wonderwood Park-n-Ride (NB). Figure 1 shows the Mayport Road study corridor with 10 signalized intersections, where section A is from Atlantic Boulevard to Fairway Villas Drive, and section B is from Fairway Villas Drive to Wonderwood Drive. As shown in Figure 1, the NB approach has seven nearside, two farside, and eight mid-block bus stops, while, the SB approach has six nearside, two farside, and four mid-block bus stops.

Section: A Section: B

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

The following data were used in the analysis.

- *Traffic flow:* Field data, such as travel time and travel speed, were extracted from the BlueToad paired devices. BlueToad pairs are Bluetooth signal receivers which read the media access control (MAC) addresses of active Bluetooth devices in vehicles passing through their area of influence. Traffic count data were collected manually from video recordings.
- *Geometric:* Google Maps and Google Earth-Street View were used to verify certain roadway geometric characteristics of the study site.
- *Transit Vehicle:* Transit information considered while developing the VISSIM simulation models include bus route, bus stops, and bus schedule. This information was obtained from the Jacksonville Transportation Authority's official website.
- *Signal Timing:* To replicate real-world conditions in the VISSIM model, the actual signal timing data for the evening peak period were obtained from the Florida Department of Transportation (FDOT) District 2.

4. Methodology

The study objective was achieved using the following six steps:

1. Develop a VISSIM microscopic simulation model for the no-TSP scenario to realistically represent existing field conditions (i.e., Base model).
2. Calibrate the VISSIM Base model to determine the model's ability to replicate field conditions.
3. Integrate the TSP scenario within the VISSIM Base microscopic simulation model by using the Ring Barrier Controller (RBC) to develop the TSP model.
4. Integrate the adaptive traffic control scenario within the TSP model using the Epics/Balance Controller in VISSIM to develop the ATSP model.
5. Analyze the data and conduct statistical tests of the network performance with and without ATSP integration.
6. Estimate MEFs for the ATSP.

4.1. Simulation model setup and the base VISSIM model

The first VISSIM model was developed to represent the Base conditions, i.e., without TSP or ASCT integration, by following the guidelines in the VISSIM manual and traffic analysis handbook [34]. The Base model included transit vehicles operating in a mixed traffic environment. The analysis was conducted for the evening peak period (4:00 PM - 7:00 PM) and was based on the existing network geometry, traffic, and transit operations. One transit line in each travel direction was added, and bus stops along the corridor in both travel directions were also included in the model (see Figure 1). The analysis period was 3.5 hours, with the first 30 minutes used as the warm-up period.

4.2. The TSP-integrated VISSIM model

For the integration of TSP operations along the study corridor, TSP parameters were integrated into the signal groups (SG) of the RBC module in VISSIM. Integrated into the VISSIM software, the RBC interface allows users to simulate actuated control in a VISSIM model. The RBC editor allows the user to set the timings used during the VISSIM simulation by the controller and stores these values in the external RBC data files with the ".rbc" file extension [35]. Programmable transit priority options for each transit SG are present in the signal controller. When a transit SG operates in a priority mode, the SGs that conflict with the parent SGs of a transit SG can be abbreviated or omitted. For transit priority, the controller attempts to adjust its operation to give a green signal, i.e., either early green or extended green, to the transit SG by the time the transit vehicle arrives at the intersection.

Check-in and check-out detectors are placed along the corridor. Check-in detectors detect the bus to grant signal priority, whereas, the check-out detector detects the bus that was already granted priority and sends back information to the controller to resume the normal signal timing plan. TSP was implemented at 10 signalized intersections along the study corridor. The model examined the transit vehicles operating in mixed traffic conditions with only TSP application.

4.3. The TSP in ASCT environment (ATSP-integrated) VISSIM model

For the integration of ASCT in the TSP model, the adaptive parameters were integrated using the Epics/Balance local controller in VISSIM. The entire priority intersection control system (Epics) was created as a model-based local adaptive control method to optimize traffic demands [36]. The control system decides (in seconds) whether a phase needs to be omitted, shortened, or lengthened. Epics use a deterministic model, similar to the model implemented in TRANSYT [36], and repeats the optimization process every second for a horizon of 100 seconds [36]. It optimizes the switching of the traffic lights at a single intersection and takes all other vehicle types into account, including public transport prioritization. Epics was designed to work based on stages (phases) and inter-stage (in between phases). The optimization in Epics is divided into two parts. First, the entire time horizon is divided into 5-second segments, where the stage sequence is determined by using a branch-and-bound algorithm [37]. Second, the fine-tuning is applied by the optimized starting times for inter-stage, with a 1-second precision, using the hill-climbing algorithm [37]. To reflect Epics requirements, the previous RBC controllers were modified for the study corridor. The RBC detectors were adjusted to Epics configuration to recognize traffic patterns and represent TSP in the ASCT environment. As shown in Figure 2(a), the intergreen matrices in Epics were configured with the actual signal timing. Intergreen matrix timing was based on the sum of all-red and yellow times and does not represent the actual field data [37]. Intergreen matrix helps to acknowledge the interstage start and stop times. Next, the stages and the stage sequence, along with minimum green time and cycle length, were configured. Upon completion of the stage sequences, Epics automatically generated the stage-based signal program (see Figure 2(b)). Subsequently, the interstages were activated in the Epics parameters. The green wave was formed automatically since Epics anticipates vehicle platoon arrivals in the following cycle, at the same time as in the current cycle.

Designed to work based on stages and inter-stage, Epics finds a stage sequence that minimizes the Performance Index (PI) for the defined time horizon. The result of every optimization is a signal plan that fits the duration of the horizon. The PI was calculated using Equation 1.

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

where,

SG is the set of the signal group,

sp is the signal plan to be valued,

ref represents 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 controlling alternative sp from ref, and

β is the weighting of deviation from ref.

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

Epics detectors are a standard detector in VISSIM, and a calling point is a public transport calling point in VISSIM [37]. Calling points can be used to define calling point pairs for public transport prioritization. Detectors for all other vehicles and calling pairs for public transport demand are present in the signal group of the Epics controller. For public transport prioritization, Epics is configured with log-in and log-off calling point pairs. The log-in points contain the pre-log-in and the main-log-in, whereas, the log-off point has only one log-off point. The log-in points are located upstream of an intersection, and it predicts the probability distribution of bus arrival times at the stop line of an intersection (Figure 3). The log-off points were placed just after the stop line of the intersection.

The standard detectors were placed in all lanes for all other vehicle detection, whereas, the calling point pairs were placed only on the outside lanes, i.e., the first and second lane for the transit buses. As per Epics configuration, a standard weight factor to all other vehicles was assigned (i.e., 1), whereas a higher weight factor was assigned to transit buses (i.e., 100) [37]. Transit buses were configured with more weights; thus, when a bus approaches a traffic light, Epics turns the relevant signal group to green. The signal group is turned green even before the actual arrival of the bus so that the vehicles in front of the bus flow off in time and do not hinder its crossing.


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. Inter-green Matrix

b. Stage Based Signal Program

Fig. 2 – Epics configuration

4.4. TSP strategy

An early green or extended green strategy was used to provide an appropriate TSP treatment to transit vehicles, depending on the time of arrival upstream of a TSP-enabled signalized intersection. An early green signal (i.e., early start or red truncation of priority phase) and extended green signal (or phase extension of priority phase) TSP strategies were implemented at the TSP-enabled signalized intersections. The early green strategy shows a green traffic light before the regular start of a priority movement phase. The extended green strategy is used when a transit vehicle approaches near the end of the green traffic light of a priority phase. This strategy holds the green light of the priority phase for a few additional seconds to allow the transit vehicle to pass through the intersection without further delay.

4.5. VISSIM simulation runs

VISSIM does not automatically calculate the required number of runs necessary to achieve good results that are within the tolerable error. Therefore, the number of runs was determined using Equation 2, in the Traffic Analysis handbook [34].

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

where,

- n is the required number of simulations runs,
- s represents the standard deviation of system performance measure based on the previous simulation runs,
- $t_{\alpha/2}$ 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 is the mean of the system performance measure, and
- ε is the 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 total of 15 simulation runs were determined for this study.

4.6. VISSIM model calibration

After the model was examined for completeness and verified for accuracy using the checklist suggested in the Traffic Analysis handbook [34], the VISSIM Base model was calibrated using the turning movement counts data at each signalized intersection. Figure 3 illustrates the comparison of turning movement traffic counts of the simulation model and the collected field data for a simulation period of 3.5 hours, during the evening peak hour. The coefficient of determination (R^2) was calculated to assess the resemblance between the simulation and the field conditions. The value of R^2 was found to be 0.98, indicating a high similarity between the field and the simulated data. The Geoffrey E. Havers (GEH) empirical formula was also used as the acceptance criteria for the model, as shown in Equation 3 [34].

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

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 [26, 34]. In this study, GEH < 5.0 was observed for 90% of the intersections.

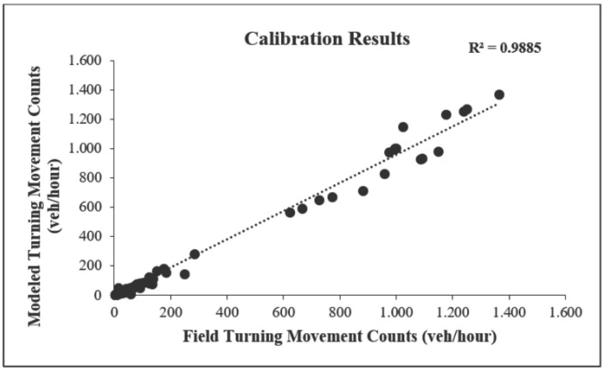

Fig 3. – Calibration results of VISSIM Base model

5. Results

The objective of this study was to evaluate the operational performance of TSP in an ASCT environment and develop MEFs. Three VISSIM models, one with no TSP strategy (i.e., Base model), a second model with only TSP strategy (i.e., TSP-integrated model), and a third model with TSP strategy operating in ASCT environment (i.e., ATSP-integrated model), were developed for a 4-mile corridor in Jacksonville, Florida. The mobility benefits were quantified based on travel times, average vehicle delay, average cross-street delay, and overall network performance of buses and all other vehicles. The three VISSIM models were run for 15 differently seeded simulations. Each model was run for 3.5 hours, where the first 30-minute period was used as the warm-up time. The following subsections discuss the simulation results.

5.1. Travel times

Travel times were measured for segments between each pair of signalized intersections along the study corridor in both directions of travel. The data collection points were set in VISSIM from one signalized intersection to the next signalized intersection, for each travel direction. Travel times collected from the three models were analyzed and compared. Travel time results for all other vehicles and buses are shown in Tables 1 and 2 for the NB and SB segments, respectively. It can be inferred from the tables that the ATSP-integrated scenario resulted in lower travel times for all other vehicles and buses, for both the NB and SB approaches. These results are statistically significant at a 95% confidence level.

Overall, the TSP in ASCT scenario outperformed the Base and the TSP scenarios in terms of travel times. Compared to the Base scenario, the implementation of TSP generated better travel time results. Also, when compared to the TSP scenario, the implementation of ATSP generated even better travel time results. For the NB approach, an 8.4% and 13.4% reduction in travel time for buses was observed with TSP and ATSP, respectively, compared to the Base scenario. A similar trend, although not to this extent, was observed for all other vehicles in the NB direction. All other vehicles experienced a 4.0%, and a 7.3% reduction in travel time with TSP and ATSP, respectively, compared to the Base scenario.

Travel times along the SB approach showed similar trends for both buses and all other vehicles. For SB approach buses, TSP and ATSP implementation resulted in a travel time reduction of 7.6% and 11%, respectively, compared to the Base scenario. For all other vehicles, the reduction in travel time with TSP and ATSP were 3% and 5.3%, respectively.

Tab. 1 - Corridor travel time for all other vehicles and buses along NB approach

Travel Time (seconds)							
	Northbound Approach	**Base Scenario**		**TSP-integrated Scenario**		**ATSP-integrated Scenario**	
Segment No.	Segment Name	All Other Vehicles	Buses	All Other Vehicles	Buses	All Other Vehicles	Buses
1.	Atlantic Blvd.-Plaza Rd.	62.9	136.9	67.0	125.9	65.2	114.1
2.	Plaza Rd.-Levy Rd.	22.3	50.9	21.1	45.7	20.0	41.9
3.	Levy Rd.-Dutton Rd.	45.4	76.3	41.0	67.4	39.2	63.3
4.	Dutton Rd.-Fairway Villas Dr.	58.2	161.9	56.0	148.9	54.0	143.8
5.	Fairway Villas Dr.-Assisi Ln.	48.4	135.6	45.0	124.8	43.3	119.9
6.	Assisi Ln.-Mayport Crossing Blvd.	31.8	54.8	27.6	50.4	26.8	47.7
7.	Mayport Crossing Blvd.-Mazama Rd.	56.5	149.0	59.1	137.1	57.6	130.0
8.	Mazama Rd.-Mayport School	21.2	67.2	19.1	61.8	17.8	59.8
9.	Mayport School-Wonderwood Dr.	47.4	63.3	42.5	58.2	41.3	55.7
	Total	**394.07**	**895.9**	**378.40***	**820.3***	**365.15***	**776.2***
	Compared to Base	**N/A**	**N/A**	**-4.0%**	**-8.4%**	**-7.3%**	**-13.4%**

* Value is statistically lower than the corresponding Base value.

Tab. 2 - Corridor Travel Time for All Other Vehicles and Buses along SB Approach

Travel Time (seconds)							
	Southbound Approach	**Base Scenario**		**TSP-integrated Scenario**		**ATSP-integrated Scenario**	
Segment No.	Segment Name	All Other Vehicles	Buses	All Other Vehicles	Buses	All Other Vehicles	Buses
9.	Wonderwood Dr.- Mayport M. School	46.2	126.2	43.1	116.7	41.2	112.9
8.	Mayport School-Mazama Rd.	21.0	41.6	18.8	38.5	16.4	36.9
7.	Mazama Rd.-Mayport Crossing Blvd.	43.4	94.5	45.2	87.4	44.3	85.1
6.	Mayport Crossing Blvd.-Assisi Ln	39.8	60.0	37.5	54.8	36.5	52.8
5.	Assisi Ln.-Fairway Villas Dr.	52.0	116.3	46.3	107.6	45.1	103.5
4.	Fairway Villas Dr.-Dutton Rd.	49.0	97.5	41.7	90.2	41.0	87.6
3.	Dutton Rd.-Levy Rd.	44.9	61.0	44.8	56.4	44.0	53.9
2.	Levy Rd.- Plaza Rd.	23.1	18.2	19.5	16.8	18.2	16.7
1.	Plaza Rd.- Atlantic Blvd.	90.0	112.0	100.3	103.6	101.0	99.7
	Total	**409.43**	**727.3**	**397.17***	**672.1***	**388.0***	**647.1***
	Compared to Base	**N/A**	**N/A**	**-3.0%**	**-7.6%**	**-5.3%**	**-11.0%**

* Value is statistically lower than the corresponding Base value.

5.2. Delays

Average vehicle delay time and average cross-street delay were also considered as the performance measures to quantify the mobility benefits of TSP in the ASCT environment. Delay, due to deceleration before a bus stop and/or the subsequent acceleration after a bus stop, was included in the average vehicle delay time. Figure 4 shows the average vehicle delay times along the main street for all other vehicles and buses in the NB and SB directions, respectively. From Figure 4, it can be inferred that the ATSP-integrated scenario resulted in a lower average vehicle delay time for all other vehicles and buses.

For the NB direction, the average vehicle delay time for buses in the Base scenario was 315.80 seconds, which is 6% and 10% higher than the average vehicle delay for buses in the scenario with TSP-integration and ATSP-integration, respectively (see Figure 4(c)). For the same direction of travel, the average vehicle delay for all other vehicles in the Base scenario was 120.6 seconds, which is 2% and 7% higher than TSP-integration and ATSP-integration, respectively (see Figure 4(a)).

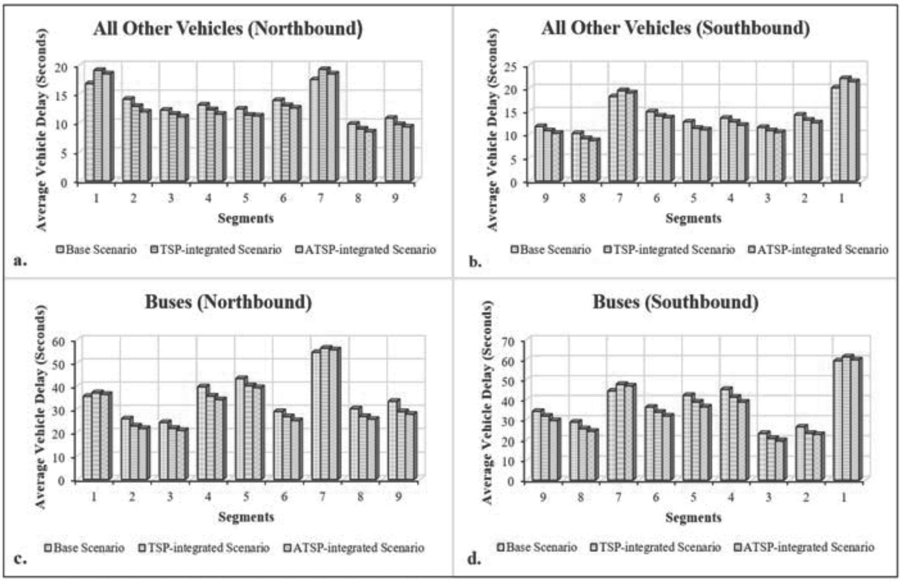

Fig. 4 – Delay time measurement along the main street for all other vehicles and buses for both travel directions

Note: segment 1(Atlantic Blvd.-Plaza Rd.), segment 2 (Plaza Rd.-Levy Rd.), segment 3 (Levy Rd.-Dutton Rd.), segment 4 (Dutton Rd.-Fairway Villas Dr.), segment 5 (Fairway Villas Dr.-Assisi Ln.), segment 6 (Assisi Ln.-Mayport Crossing Blvd.), segment 7 (Mayport Crossing Blvd.-Mazama Rd.), segment 8 (Mazama Rd.-Mayport School), segment 9 (Mayport School-Wonderwood Dr.)

Similar results, although with slightly different magnitudes, were observed for the SB direction. The average vehicle delay time for buses in the Base scenario was found to be 339.3 seconds, which is 5% and 11% higher than the average vehicle delay with TSP-integration and ATSP-integration, respectively (see Figure 4(d)). It can be inferred that the ATSP-integrated scenario generated better results. Similarly, the average vehicle delay in the SB direction for all other vehicles in the Base scenario was 127 seconds, which is 3% and 7% higher than the TSP-integration and ATSP-integration, respectively (see Figure 4(b)).

5.3. Impacts on cross-streets traffic

Another crucial factor in the performance evaluation of transit-preferential treatments is the cross-street delay. VISSIM recorded these delays at signalized intersections for all three scenarios (i.e., Base, TSP-integrated, and ATSP-integrated). Figure 5 shows the average cross-street delays at the signalized intersections in the study corridor. From Figure 5 (a, b), it is evident that transit-preferential treatment (i.e. either TSP or ATSP) caused delays on the cross streets. However, the ATSP-integrated scenario resulted in a much lower average cross-street delay at all intersections by a range from 40% to 50% (as it is site-specific), when compared to the TSP scenario which operated in an actuated environment. It is also worth noting that due to much lower demand on the cross-street compared to other intersections the average cross-street delay at the Mayport School intersection was almost equal for the Base and ATSP-integrated scenarios.

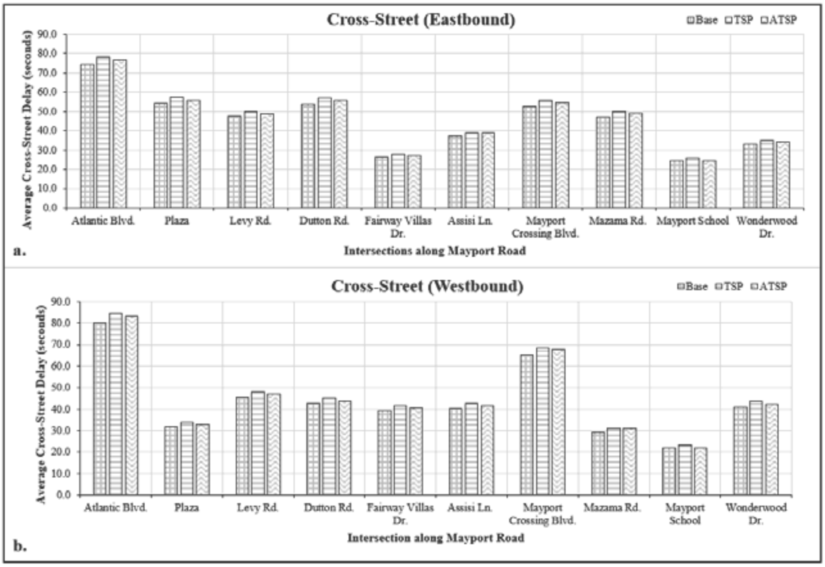

Fig. 5 – Cross-street delays

5.4. Statistical analysis of the measures of effectiveness

Student *t*-tests were performed on the raw output data from the 15 simulation runs for each scenario. The t-test was used to compare the performance of the three models (i.e., Base, TSP, and, ATSP). Note that the performance measures used in this study were travel time, average vehicle delay, and cross-street delay. However, for the cross-street delay, only two models (TSP and ATSP) were tested to determine if there was a significant difference. The hypothesis testing for the means of the performance measures among the three scenarios used in this study was as follows:

Hypothesis test for the Base and the TSP model:

Null hypothesis; H_0: $\mu_{Base} = \mu_{TSP}$ (4)

Alternative hypothesis; H_a: $\mu_{Base} \neq \mu_{TSP}$ (5)

Hypothesis test for the TSP and the ATSP model:

Null hypothesis; H_0: $\mu_{TSP} = \mu_{ATSP}$ (6)

Alternative hypothesis; H_a: $\mu_{TSP} \neq \mu_{ATSP}$ (7)

where,

μ_{Base} is the mean of the performance measure for the Base model,

μ_{TSP} is the mean of the performance measure for the TSP-integrated model, and

μ_{ATSP} is the mean of the performance measure for the ATSP-integrated model.

Table 3 presents the results of the *t*-test statistics. The t-statistic value was found to be greater than the critical t-values at a 95% confidence level for all performance measures for buses. This implies that there was a significant difference in the performance measures among the scenarios. More specifically, the mean travel time, mean average vehicle delay, and the cross-street delay were significantly lower for the ATSP-integrated scenario, compared to the Base and TSP-integrated scenarios, at a 95% confidence level.

Tab. 3 – Statistical analysis results

Travel Time					
		All Other Vehicles		Buses	
		Base	TSP	Base	TSP
Base and TSP	Mean	44.638	42.797	90.177	82.908
	Degree of freedom	179		179	
	T-Statistic value	2.319		9.588	
	p-value	0.016		0.0	
	t-critical value	1.739		1.739	
		TSP	ATSP	TSP	ATSP
TSP and ATSP	Mean	42.797	41.441	82.908	79.185
	Degree of freedom	179		179	
	T-Statistic value	11.827		6.170	
	p-value	0.0		0.0	
	t-critical value	1.739		1.739	
Average Vehicle Delay					
		All Other Vehicles		Buses	
		Base	TSP	Base	TSP
Base and TSP	Mean	13.755	13.409	36.391	34.455
	Degree of freedom	179		179	
	T-Statistic value	1.196		3.4972	
	p-value	0.123		0.001	
	t-critical value	1.739		1.739	
		TSP	ATSP	TSP	ATSP
TSP and ATSP	Mean	13.409	12.879	34.455	33.100
	Degree of freedom	179		179	
	T-Statistic value	11.089		9.528	
	p-value	0.0		0.0	
	t-critical value	1.739		1.739	
Cross-Street Delay					
		TSP	ATSP		
TSP and ATSP	Mean	46.905	45.888		
	Degree of freedom	179			
	T-Statistic value	10.987			
	p-value	0.0			
	t-critical value	1.729			

5.5. Corridor performance

Table 4 summarizes the performance results of the entire corridor and shows the travel time, average vehicle delay, and average cross-street delay in seconds. Results are shown for the Base scenario, the TSP scenario, and the ATSP scenario for each direction of travel.

The implementation of any transit-preferential treatment, such as TSP in the ASCT environment, can impact vehicular traffic at the network level, including cross-street traffic and through traffic. The corridor-level travel time was reduced significantly for buses and all other vehicles in both directions of travel for the ATSP scenario, compared to the Base and the TSP scenarios. The ATSP scenario resulted in decreased travel time along the main street. However, it reduced the available green time for turning vehicles and cross-street traffic. Consequently, increased delays were observed for the cross-street movements, especially where cross-street traffic volumes exceeded capacity. However, compared to TSP, ATSP performed better for cross-street traffic.

Tab. 4 – Performance results of the entire corridor

		Northbound			Southbound		
	Corridor Performance	**Base**	**TSP**	**ATSP**	**Base**	**TSP**	**ATSP**
All Other Vehicles	Travel Time (s)	394.07	378.4	365.2	409.4	397.1	388.0
	Average Vehicle Delay Time (s)	120.6	117.0	112.9	127.0	123.3	118.8
Buses	Travel Time (s)	1066.4	820.3	776.2	727.3	672.1	649.1
	Average Vehicle Delay Time (s)	315.8	296.63	286.7	339.3	323.5	309.1
		Eastbound			**Westbound**		
	Corridor Performance	**Base**	**TSP**	**ATSP**	**Base**	**TSP**	**ATSP**
Cross-Street	Average Cross-Street Delay (s)	450.5	476.5	465.7	436.4	461.6	452.0

6. Mobility Enhancement Factors (MEFs)

MEFs were developed to quantify the operational effectiveness of TSP in ASCT environment (ATSP). As discussed earlier, an MEF is a multiplicative factor used to estimate the expected mobility level after implementing a given Transportation Systems Management and Operations (TSM&O) strategy at a specific site, such as ATSP in this case. A MEF of 1.0 serves as a reference, where below or above indicates an expected increase or decrease in mobility, respectively, after implementation and depending on the performance metric. These MEFs will assist agencies and professionals in evaluating the effectiveness of the ATSP. In this study, MEFs for implementing ATSP were estimated based on travel time and delay measurements.

The MEFs based on the travel time and average vehicle delay were estimated using the following equations:

$$MEF_{travel-time,i} = \frac{tt_{i,ATSP}}{tt_{i,NOATSP}} \tag{8}$$

$$MEF_{delay,i} = \frac{avdt_{i,ATSP}}{avdt_{i,NOATSP}} \tag{9}$$

$$MEF = \frac{\sum_{i=1}^{n} MEF_i}{n} \tag{10}$$

where,

$MEF_{travel\text{-}time,\,i}$ is the MEF based on travel time for a particular i^{th} corridor,
$MEF_{delay,\,i}$ is the MEF based on average vehicle delay for a particular i^{th} corridor,
$tt_{i,\,ATSP}$ is the travel time along the ATSP-enabled corridor,
$tt_{i,\,NOATSP}$ represents the travel time along a corridor with no ATSP (Base scenario),
$avdt_{i,\,ATSP}$ represents the average vehicle delay time along the ATSP-enabled corridor, and
$avdt_{i,\,NOATSP}$ is the average vehicle delay time along a corridor with no ATSP (Base scenario).

Figure 6 presents the estimated MEFs for travel time for all other vehicles and buses. The MEFs for ATSP, in terms of travel time, for all other vehicles and buses were estimated to be 0.910 and 0.878, respectively. This implies that TSP in ASCT environment along a corridor would result in a 9% and a 13% decrease in travel time for all other vehicles, and buses, respectively. The MEFs in terms of average vehicle delay for all other vehicles and buses were estimated to be 0.923 and 0.896, respectively, suggesting that deploying TSP in ASCT environment along a corridor would result in a 8% and 11% decrease in average vehicle delay for all other vehicles and buses, respectively. The study results show that TSP in the ASCT environment improves the operational performance of the corridor.

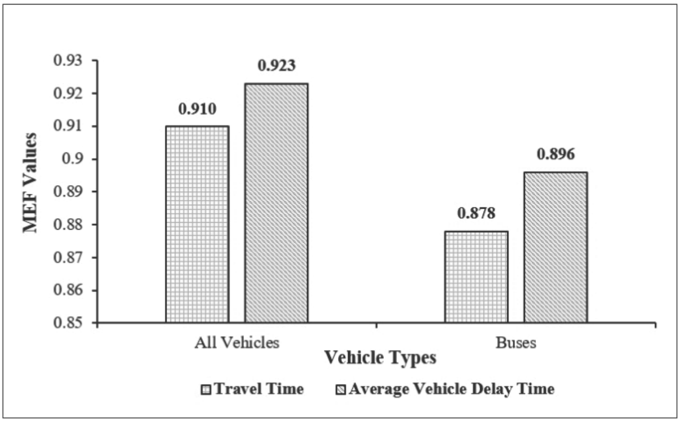

Fig. 6 – MEFs of TSP operating in ASCT environment for the performance measures

7. Discussion

The study aimed to evaluate the operational performance of TSP in an ASCT environment and develop MEFs. The analysis was performed by using a microscopic simulation approach. The mobility benefits were quantified based on travel times, average vehicle delay, average cross-street delay, and overall network performance of buses and all other vehicles.

A few of the key takeaways for practitioners and researchers are: this study showed that by incorporating TSP in an ASCT environment, the delays experienced by all other vehicles along the side streets could be decreased compared to having only TSP with no ASCT environment. Also, in an ASCT environment, TSP significantly improved traffic and transit operations along the corridor regarding travel time and delay compared to only the TSP scenario. These outcomes may also provide practitioners and researchers with a deeper insight into the potential of the Epics/Balance controllers in enhancing traffic and transit operations. The study can also justify the future deployment of the Epics and Balance controllers along an ASCT corridor with the application of TSP. The study could also be a base to explore more ability of Epics and Balance controllers integrated with TSP to improve the operational performance of buses on a network level.

8. Conclusions

The objective of this research study was to quantify the mobility benefits of TSP operating in ASCT environment (ATSP) using microscopic VISSIM simulations. This study fills the gap in the existing research by analyzing the operational effectiveness of ATSP for transit buses and all other vehicles for both the main and cross streets. Analyses were performed using the Ring Barrier Controllers and Epics/Balance Controllers in VISSIM. To the best of the author's knowledge, this is the first ATSP study using the Epics/Balance Controllers. The analysis was based on a 4-mile corridor along Mayport Road in Jacksonville, Florida. Three microscopic simulation VISSIM models were developed: a Base model with no TSP or ATSP integration, a TSP-integrated model, and a ATSP-integrated model.

One of the major findings observed from the evaluation was that TSP in the ASCT environment offers significant benefits not only for the transit buses, but also for all other vehicles along the corridor. ATSP was found to provide significant savings in travel time and average vehicle delay. For transit buses, ATSP resulted in a 13.4% reduction in travel time for the northbound direction, and an 11% reduction in travel time for the southbound direction. Also, for all other vehicles, a 7.3% reduction in travel time for the northbound direction, and a 5.3% reduction in travel time for the southbound direction was observed after the integration of the Epics controllers, which simulate adaptive traffic controls. However, the travel time of all other vehicles was better in the Base scenario on the segment between Atlantic Boulevard and Plaza Road, for both the northbound and southbound approaches. This result may be attributed to congestion during the evening peak in the southbound direction, leading to a higher volume to capacity (v/c) ratio (i.e., v/c > 1). Similarly, the travel time between Mayport Crossing Boulevard and Mazama Road was also better in the Base scenario for both approaches. For this segment, this finding may be the result of more bus stops between the two intersections (i.e., three bus stops) and higher dwell times, especially during peak hours.

ATSP also provided significant reductions in average vehicle delay. For transit buses, the presence of ATSP resulted in a reduction in average vehicle delay of 10% and 11% for northbound and southbound directions, respectively. For all other vehicles, a reduction in the average vehicle delay of 7% was observed for both travel directions. However, for both the northbound and southbound approaches, the average vehicle delay time of all other vehicles and buses between Atlantic Boulevard and Plaza Road was better in the Base scenario, when compared to the ATSP-integrated scenario. This finding may be the result of more access points and throughput vehicle volume along this segment. Similarly, compared to the ATSP-integration scenario, the average vehicle delay between Mayport Crossing Boulevard and Mazama Road was better in the Base scenario, for both approaches. This finding may be the result of higher demand on the side streets at both intersections and the presence of three bus stops along that segment in both travel directions.

Transit-preferential treatments typically cause cross-street delays. However, the ATSP results provided significant savings in cross-street delay, when compared with conventional TSP. ATSP showed a reduction between 40% to 50% (as it is site-specific) in cross-street delay when compared with conventional TSP. It is also worth noting that at one of the intersections, the cross-street delay was similar for Base and ATSP scenarios.

This study also developed MEFs for TSP operating in the ASCT environment. The MEF based on travel time was 0.910 for all other vehicles and 0.878 for buses, and the MEF based on average vehicle delay was 0.923 for all other vehicles and 0.896 for buses. Based on the MEF results, it can be concluded that TSP operating in the ASCT environment improves the operational performance of the corridor. MEF results could provide researchers and practitioners with an effective method for analyzing the economic and other benefits of the ATSP. These findings may also provide transportation agencies and professionals with a deeper understanding of the potential of the Epics/Balance controllers in improving traffic operations.

Nonetheless, it is worth mentioning that due to data availability constraints, the present study did not consider the site characteristics such as access points in modeling the VISSIM model. Future research could expand this existing study to evaluate the performance of TSP on adaptive traffic control system environment considering other network types, under a variety of traffic conditions, and different site characteristics.

Authors' contribution statement

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

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