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Supply Management of Auto Traffic to Address Starvation of Green in Multimodal Environments

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16. Abstract

Traffic congestion is challenging to resolve at closely spaced, oversaturated intersections. This condition leads to underutilization of green time at upstream intersections due to queue spillback from downstream traffic signals (green starvation). Such conditions cause significant delays and queue backups. In addition, conflicting modes of travel, such as pedestrians or rail, may exist at a site and limit available strategies to manage the green time effectively. This project explored strategies to increase utilization of green time that account for conflicting modes of travel. This project used a field deployment and hardware-in-the-loop simulation analysis to evaluate the effectiveness of strategies in reducing green starvation. In addition, the research team used the site's historically high traffic month of August to collect field data of the performance of the project's revised strategy. The goal was to identify strategies that are effective at reducing the number of phase failures caused by blocked street segments downstream despite limitations set by pedestrian timings or rail preemptions. The research team found that the priority control based flushing technique improved performance for the system overall. The team recommends exploring better back of queue detection equipment to improve the reliability and function of the system.

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Executive Summary

This research sought to address a condition where adjacent intersections are unable to service demand in part because an active rail line between the intersections disrupts traffic with frequent preemptions. The project used George Bush Dr, an arterial roadway along the south edge of the Texas A&M University campus in College Station, Texas, as a testbed for this research. Olsen Blvd and Wellborn Rd are main roadways around Texas A&M University that intersect George Bush Dr within a 1,000-foot stretch. This area suffers from traffic congestion and queue spillback during the PM peak period when classes are over, and students and staff are going to their homes from the university campus. In addition, the rail that runs parallel to Wellborn Rd has between 20 and 30 trains traveling on this segment per day, which will lead to 1 or 2 trains disrupting traffic at this portion of the network during the PM peak period.

The research team considered a variety of queue management options to address the starvation of green since the green time utilization is governed by the queue lengths backing up between the adjacent intersections. The team decided to use both field and simulation data to analyze the effectiveness of the changes in operations on the George Bush Dr corridor in College Station. The dual analysis enabled researchers to observe and note impacts of the system on field operations and utilized the simulation to determine the effectiveness of alternative operations without risk of negative impacts on field performance and with the advantage of consistent conditions between alternative scenarios.

The City of College Station determined that the preemptions at George Bush Dr and Wellborn Rd would keep the intersection on transition for long periods if the intersection operated in coordination mode, which would be a reasonable operational strategy for intersections along George Bush Dr and Wellborn Rd. Instead, the City found that the intersection would operate more consistently and service the traffic better if the intersections were in free, fully actuated control. The frequent special events near the intersections and the regularly saturated conditions in every direction of travel at the intersection of Wellborn Rd and George Bush Dr (referred to as WGB), led the City to use long maximum green times for the phases to service the high demands on normal operations and improve the process for special events. George Bush Dr and Olsen Blvd (GBO) operate in coordination during the PM peak period.

Previous research done with NICR on this testbed showed that low-level preemptions could improve performance at these intersections. However, for this field implementation, the research team decided not to use preemption since the existing operations already used many different preemptions. Given that preemption was going to impact the system more than desired, the team developed a strategy to use the priority routines in the Siemens M60 controllers used by the City of College Station.

The priority routines were developed to accomplish two objectives: metering traffic entering the link between intersections and increasing green time for the eastbound approach. Metering the traffic describes a strategy where the green time for movements feeding the link between the intersections is limited to prevent additional traffic from entering the link. When the link is full, this method is essentially meant to stop allocating green time to movements that cannot use the green time due to a lack of storage. This causes the demand to wait on the links exterior to the intersection pair of GBO and WGB. Increasing the green time between the intersections is accomplished by instituting a flushing pattern with the priority routine. This combination of metering traffic and flushing the link between GBO and WGB is referred to as the *priority queue flush strategy* in this report. For the priority flush to work, the research team added phases to WGB needed for the priority flushing pattern. To detect starvation of green at GBO, the Wavetronix radar at GBO used for detection of westbound traffic was reconfigured to detect the eastbound traffic between the two intersections. The team reconfigured the sensor such that vehicles traveling than 5 mph at the end of the link going eastbound for more than 3 seconds called a detector at GBO. The metering strategy at GBO was deployed with internal peer-to-peer commands on the GBO signal controller such that when the detector was called, the controller would omit phases at GBO. If these omitted phases were active when the detector was called, the controller would force the phases off. Then peer-to-peer communication between the signal controllers at GBO and WGB repeated the call for priority at WGB. This priority routine at WGB and the WGB signal will bring up the phases to flush the queue to begin the flushing routine.

The research team created and calibrated a baseline scenario of the model. They calibrated the model using the travel time and speed data obtained from INRIX. Alternative scenarios for simulation included the priority queue flush scenario, a retiming of the signals at GBO and WGB to have a shared cycle of 180 seconds, and a double cycle of GBO at a 90-second cycle length and a cycle length of 180 seconds at WGB. This revised strategy used information from the calibrated VISSIM model and utilized the PASSER V-09 (P5) computer program developed by Texas A&M Transportation Institute (TTI). The simulation experiment involved analyzing 10 simulation runs with different random seeds for the baseline, priority queue flush, revised timing with consistent cycle lengths, and the double cycle scenario. These simulations included two train preemptions. Each of the 10 simulations included a 900-second warm-up period to load the network and lasted a total of 4,500 seconds, meaning each run had a one-hour period of data collection. This report provides the travel time and queue length metrics for the simulation exercise. The simulation results showed that the eastbound travel times and queue lengths improved by over 50 percent. In addition, the westbound left turn movement was adversely impacted because of this strategy. The retiming and double flushing scenario had simulation results that indicated unacceptable performance for the westbound left turn movement, so these strategies were not deployed.

The research team used several data sources from the INRIX platform to analyze field performance of the deployed system. The signal analytics and corridor analytics tool with INRIX indicated an immediate improvement in performance for the eastbound direction of travel after deployment in April 2023. The roadway analytics tool was used for a travel time analysis of George Bush Dr and Wellborn Rd to compare the first weeks of the fall semester in 2022 and 2023, the known worst period for this testbed. During the peak period, eastbound travel times were generally one to three minutes lower, 38 and 41 percent lower on average on Monday and Wednesday, respectively. The eastbound afternoon peak travel times were on average 41 percent lower on Tuesday and 44 percent lower on Thursday, with the peak time down 4.8 minutes. The westbound direction of travel experienced a 10 to 18 percent reduction in travel times on average. Northbound results were similar to westbound George Bush Dr. Travel time improvements were 1 to 10 percent and there were numerous times when travel times were worse following the signal timing changes. The westbound and northbound directions were not expected to experience any large improvement from the deployed strategy since the strategy was meant to assist the eastbound direction of travel. The southbound direction experienced a large improvement (30 and 34 percent), which is somewhat surprising given the long queues observed over the spring 2023 semester on Tuesday evenings and the priority given to George Bush Dr traffic. The 30 percent average reduction could be a result of driver frustration and students and the community finding alternative routes to Wellborn Rd.

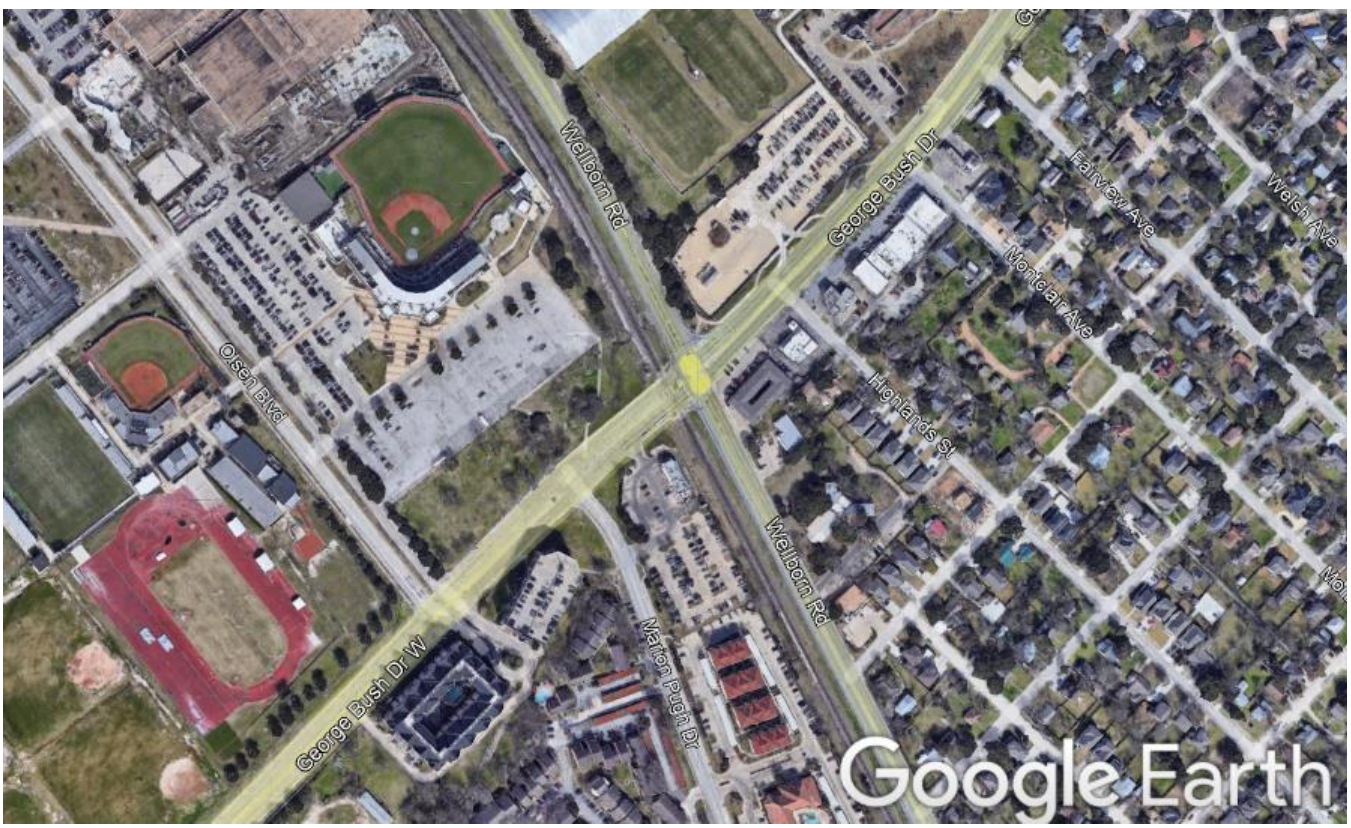
This report discusses some challenges for the operations related to the deployment. Namely some additional configuration was needed to prevent redundant queue flushing given existing queue flush operations after a train preemption already deployed at the intersections. The key takeaway from this challenge was that the Siemens M60 controllers will remember calls placed for a priority routine during preemption. The team was able to deploy a resolution to this issue. Other challenges encountered during the research effort were more difficult to resolve. The metering strategy proved to be too aggressive and generated a no-service scenario for the southbound movement at George Bush and Olsen Blvd. Given the lack of tools to put restrictions around the phase omits the metering strategy needed to be removed. This issue is likely related to the next unsolvable issue of too many priority requests. The research team found that calls would be placed for a priority check-in frequently by vehicles in motion, which the radar should not consider for the queue detection. The research team recommends identifying an alternative technology for monitoring the queue length driving the system, which should improve function from the no-service problem and the frequent priority check-ins.

Overall, this project found that the addition of a priority queue flush to the system improved performance. The eastbound direction of travel saw improved travel times and the greatest negative effect was on the westbound left turn, which saw an increase in average queue length of 90 feet (or about four vehicles) compared to the baseline. The simulation and field data both show that the eastbound direction of travel experienced improvements. Further research should consider shorter cycle lengths that better account for the westbound left turn. Shorter cycle lengths at WGB would be beneficial since long cycle lengths contribute to long queues. In addition, future research should search for a better detection unit to improve the ability to place priority requests only when queued traffic is present at the end of the link.

Chapter 1. Introduction

Roadway network geometry and traffic demand are key factors for traffic congestion. While these two factors are not easily changed, they impact the ability of traffic engineers to adjust operations that service the road users. For example, the network may require closely spaced intersections or be adjacent to a university that generates high pedestrian demand, or the network could have a railway that causes preemption operations regularly during peak periods. Each of these factors generates operational requirements for the network to service the road users. If the demands are high and there are closely spaced intersections, the network may suffer from queue spillback between intersections. This phenomenon causes vehicles to remain stopped at a green indication because of a lack of storage in the upstream link. These issues are magnified when conflicting approaches at one intersection are oversaturated and there is competition for green time.

The City of College Station, Texas, has a corridor that suffers from these issues. George Bush Dr is an arterial roadway along the south edge of the Texas A&M University campus. Olsen Blvd and Wellborn Rd are also main roadways in the area that intersect George Bush Dr within a 1,000-foot stretch, shown in Source: *Google Earth*
Figure 1. This area suffers from traffic congestion and queue spillback during the PM peak period when classes are over, and students and staff are going to their homes from the university campus. In addition, the rail that runs parallel to Wellborn Rd has between 20 and 30 trains traveling on this segment per day, which will lead to 1 or 2 trains disrupting traffic at this portion of the network during the PM peak period.



Source: Google Earth

Figure 1. Map of George Bush Drive and Wellborn Road area in College Station, TX.

The intersection of George Bush Dr and Wellborn Rd has heavy movements both eastbound and southbound, the heavier of which is southbound. However, the close spacing between Olsen and Wellborn leads to the heavy eastbound movement filling the link between the two intersections completely and causing traffic at eastbound George Bush Dr and Olsen Blvd to remain stopped on a green indication. This problem is amplified by pedestrian movements across George Bush and Olsen, which increases the duration of the cross-street phases and will lead to southbound left-turning traffic, off Olsen Blvd, to block the link between Olsen and Wellborn when eastbound traffic has the right-of-way. In addition, the Texas A&M University campus has a bus line that travels westbound on George Bush and turns onto Marion Pugh Dr, the collector road between Olsen and Wellborn. This bus line is significant because buses must stop at the rail before crossing and will limit the capacity of George Bush accordingly.

The research team aimed to use this project to develop strategies to address starvation of green in complex environments. This intersection pair served as a testbed for high volume intersections with competing directions of travel while also managing a nearby active railway, pedestrian movements, and bus routes.

Report Structure

The remainder of this report is divided into four sections. The first section describes literature relevant to addressing starvation of green and previous NICR research completed on this testbed. Next, the report explains the methodology for the research to develop control strategies for addressing the starvation of green. The fourth section presents the evaluation of the strategies via simulation and field analysis. Finally, the fifth section provides the conclusions of this research effort.

Chapter 2. Literature Review

Starvation of green at intersections is a fundamental challenge for the optimization of signal timing and control strategies. Therefore, there are many sources of literature on the topic of traffic signal optimization, gridlock, and queue management, all of which contribute to starvation of green. Numerous studies aim to generate methods to effectively manage the supply of auto traffic through signal operations.

One approach by Chen, Wu, and Xiao (2019) involved optimizing signal timing at an intersection in China using the Australian Road Research Board (ARRB) method, a modified Webster delay formula that accounts for queue spillback. This study implemented an actuated signal control scheme with a priority phase to address spillback during peak hours. By utilizing magnetic sensors to detect spillback and activate the priority phase, the study sought to employ a dynamic phase based on detected stopped traffic. This dynamic priority phase ended the green time given to the movements blocking the intersection once the queue reached the end of the link. The study showed that the introduction of a priority phase to meter traffic and avoid blocking the intersection reduced the delays for the movements blocked by the queue spillback by up to 62 percent. The minimum time between the two priority phases was 99 seconds, which lacked justification.

To improve signal control strategies, Ramezani et al. (2016) proposed integrating an arterial partitioning approach and an early detection strategy where the system detects arterial links with long queues. This approach required continuous monitoring of queue length to optimize signal settings and reduce spillback frequency in congested urban traffic conditions. The authors suggest this is possible through detection or probe vehicle data. The study evaluated two signal control strategies based on arterial partitioning: fixed timed and non-coordinated strategies. Their results demonstrated the effectiveness of utilizing arterial partitioning in managing traffic by showing reductions in queueing when the system partitions both traffic entering and exiting the corridor.

Hu, Wu, and Liu (2013) proposed a Forward-Backward Procedure (FBP) for a maximum flow model to alleviate oversaturation for real-time traffic management. This method does not rely on time-dependent traffic demand inputs. Instead, the model optimizes the signal timings using real-time information about congestion levels, as indicated by the values of temporal oversaturation severity index (TOSI) and special oversaturation severity index (SOSI) as defined by Wu, Liu, and Gettman (2010), where TOSI is the green time to discharge residual queue divided by the total available green time, and SOSI is the unusable green time due to downstream spillover divided by the total available green time. The values of TOSI and SOSI govern the appropriate amount of green or red time extension or restriction for the treated phase. Simulation tests indicated that the FBP can effectively mitigate oversaturation, however this method is yet to be validated in the field. In addition, this method focuses on a single oversaturated direction and does not address when multiple conflicting phases are oversaturated.

To enhance system reliability and address network delays, Noaeen et al. (2021) proposed a decentralized spillback resistant acyclic signal control algorithm. By utilizing a shockwave theory-based model, this approach utilized real-time data on queue lengths, spillbacks, and arrival flows to calculate minimum and maximum saturated green times and effective outflow rates for each lane. The method showed promising performance for frequent lane spillbacks and macroscopic fundamental diagrams. The challenge with each of these treatments is that the operations require specialized detection of vehicles, assume that there is only one oversaturated direction, or both. In the case presented by this research project, there are multiple directions of travel that are oversaturated in the network with already long cycle lengths and rail operations that make coordination ineffective. In addition, the rail next to this site prevents effective coordination because of almost hourly preemptions causing the controller to enter transition and fail to operate in coordination for a meaningful amount of time.

Stevanovic, Klanac, and El-Urfali (2017) tested high-resolution controller event logs to retrieve essential signal performance measures such as approach delay, volume, Purdue phase termination, split monitor, approach speed, and Purdue coordination diagram. This research utilized microsimulation experiments in a Hardware-in-the-loop (HIL) simulation lab with traffic signal controllers from six US-based intersections. The researchers documented their methods and tools for developing high-resolution data with the traffic controller and simulation tool.

Recognizing the limitations of the Arrival on Green performance measure, Dakic et al. (2017) developed models for new high-resolution Signal Performance Measures (SPMs) – Average Arrivals on Green Ratio and Average Delay. These models were based on outputs from VISSIM and validated using field data, demonstrating a reliability and accuracy rate of 93 percent for Average Delay.

Tariq (2021) proposed using high-resolution signal controller data and multilevel clustering to identify operational scenarios and calibrate a model. The study utilized signal timing, detection data, and Automated Traffic Signal Performance Measures data based on a standardized set of event parameters and identification codes. For calibration purposes, travel time, split utilization ratio, and throughput movement were used, while green occupancy ratio and percentage arrival on green were used for validation. The Elbow method was used to determine the required number of clusters, and K-means clustering was performed for pattern recognition. The data derived from the high-resolution signal controller was calibrated using the NSGA III algorithm. After developing and calibrating simulation models in VISSIM, it was found that the model produced significantly lower travel time errors. This method of utilizing cluster analysis for model calibration is similar to the recent Federal Highway Administration guidance in the *Traffic Analysis Toolbox Volume III* (Wunderlich, Vasudevan, & Wang, 2019).

The effort presented here aims to employ a queue flushing technique in an oversaturated environment and employ a longer minimum time between flushes than Chen, Wu, and Xiao (2019). In addition, this effort will utilize a radar detector to identify the location of the back of the queue. Requiring simple detection of the queue length compared to other literature will make the strategy more easily implementable elsewhere. The testbed in this condition has oversaturated eastbound and southbound movements that compete for green time, unlike other cases in the literature. This research utilizes the City of College Station's signal performance measures, which are driven off the high-resolution data from the signal controllers. The effort aims to develop and evaluate a simple approach that could be applied elsewhere to address starvation of green in a complex environment with rail, pedestrians, and conflicting oversaturated approaches.

Chapter 3. Methodology

The research team considered a variety of queue management options to address the starvation of green since the green time utilization is governed by the queue lengths backing up between the adjacent intersections. The team decided to use both field and simulation data to analyze the effectiveness of the changes in operations on the George Bush Dr corridor in College Station. The dual analysis enabled researchers to observe and note impacts of the system on field operations and utilize the simulation to determine the effectiveness of alternative operations without risk of negative impacts on field performance and with the advantage of consistent conditions between alternative scenarios. In other words, the field analysis revealed the measured impacts and the simulation provided a less noisy testbed to compare performance.

Given the timeline of the research project in relation to the academic year and the proximity of the testbed to the university, the research team decided to do an early field deployment, simulation, and a revised field deployment. This allowed them to gather field data from the end of the spring semester, run simulation during the summer break, and gather another set of field data at the beginning of the fall semester of Texas A&M University.

Control Strategies

Prior to this research, the City of College Station worked to improve operations at these intersections for many years. The operations at these intersections need to consider the frequent preemptions from rail and the high frequency of special events at sporting complexes nearby. The rail bisection at George Bush Dr is operated by Union Pacific and experiences freight trains frequently throughout any given day. Special events to the north of George Bush Dr at Kyle Field and Reed Arena generate high amounts of traffic frequently throughout the year from football games, basketball games, graduations, concerts, career fairs, and more.

The City determined that the preemptions at George Bush Dr and Wellborn Rd would keep the intersection on transition for long periods if the intersection operated in coordination mode, which would be a reasonable operational strategy for intersections along George Bush Dr and Wellborn Rd. Instead, the City of College Station found that the intersection would operate more consistently and service the traffic better if the intersections were in free, fully actuated control. The frequent special events near the intersections and the regularly saturated conditions in every direction of travel at the intersection of Wellborn Rd and George Bush Dr (referred to as WGB), led the City to use long maximum green times for the phases to service the high demands on normal operations and improve the process for special events. The ring barrier diagram for the base condition for both the signal controllers are shown in Figure 2 and Figure 3. George Bush Dr and Olsen Blvd (referred to as GBO) operate in coordination, although WGB to the east and George Bush Dr and Penberthy Blvd to the west both operate in free mode. In addition, the two intersections have different maximum cycle lengths. Each of these intersections has significant pedestrian traffic, especially GBO. Table 1 and Table 2 show the pedestrian timings for WGB and GBO.

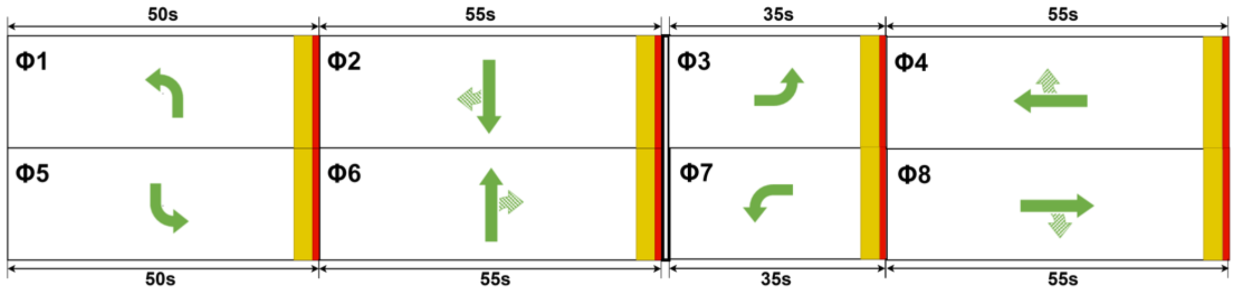


Figure 2. Ring barrier diagram for baseline operations at Wellborn and George Bush.

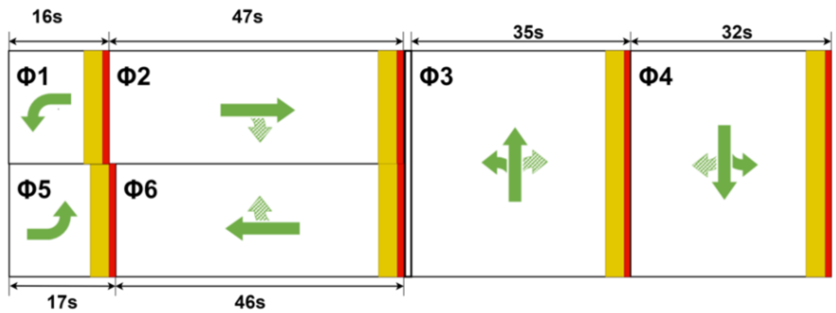


Figure 3. Ring barrier diagram for baseline operations at George Bush and Olsen.

Table 1. George Bush Dr and Wellborn Rd Pedestrian Timings

Leg	Phase	Walk	Pedestrian Clearance
North	4	7	13
West	6	7	17
South	8	7	17

Table 2. George Bush Dr and Olsen Blvd Pedestrian Timings

Leg	Phase	Walk	Pedestrian Clearance
South	2	7	21
West	3	7	20
East	4	7	17
North	6	7	25

Previous research, completed through the National Institute for Congestion Reduction, analyzed these intersections in a simulation environment utilizing software in the loop simulation with preemption routines that have a timer running limiting the number of preemptions allowed in a certain amount of time (Ziyadidegan, Florence, & Sunkari, 2021). The research effort found that the preemptions were effective at reducing delay on a network-wide basis. However, for this field implementation, the research team decided not to use preemption since the existing operations already used many different preemptions. Given that preemption was going to impact the system more than desired, the team developed a strategy to use the priority routines in the Siemens M60 controllers used by the City of College Station.

The priority routines were developed to accomplish two objectives: metering traffic entering the link between intersections and increasing green time for the eastbound approach. Metering the traffic describes a strategy where the green time for movements feeding the link between the intersections is limited to prevent additional traffic from entering the link. When the link is full, this method is essentially meant to stop allocating green time to movements that cannot use the green time due to a lack of storage. This causes the demand to wait on the links exterior to the intersection pair of GBO and WGB. Increasing the green time between the intersections is accomplished by instituting a flushing pattern with the priority routine. This combination of metering traffic and flushing the link between GBO and WGB is referred to as the *priority queue flush strategy* in this report.

The phase diagrams for the priority queue flush strategy developed in the project at both intersections are shown in Figure 4 and Figure 5. This research effort added phase 9 and phase 10 to WGB's ring structure for the eastbound left and eastbound through movements with a fixed time of 35 seconds. Figure 4 shows phases 9 and 10 in the ring structure, but these phases are only ever called during the priority routine added for the strategy. This duration allowed the detected queue to discharge until the link was a little more than halfway cleared. Phases 9 and 10 were intentionally placed before phases 4 and 8 so the phases can run and go to phases 4 and 8 until these phases either max out or gap out. The eastbound through and left movements were operated with an overlap for phases 3 and 9 together and phases 8 and 10 together. These phases enable the priority routine to trigger these phases once the eastbound movement faces starvation of green. Figure 5 shows that phases 5 and 6 were flipped, so the intersection is in lead-lag left turn operations. This enabled the research team to meter traffic by omitting Phases 2, 3, 4, and 5 when starvation of green was detected and ensure that phase 2 would receive green time after the flush was complete. Green time for phase 2 after the flush is important because the strategy deployed in this effort is meant to service the eastbound traffic at GBO more than the southbound. Therefore, GBO would rest in phases 1 and 6 while the link is full. This metered traffic that cannot enter the link between GBO and WGB.

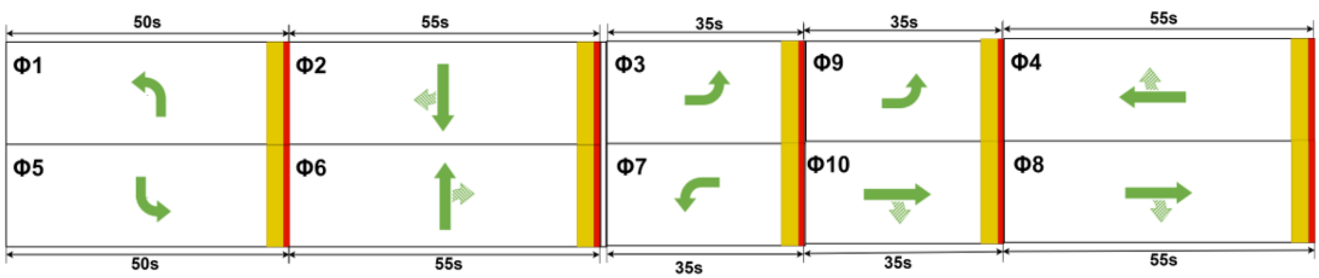


Figure 4. Ring barrier diagram for priority queue flush strategy at Wellborn and George Bush.

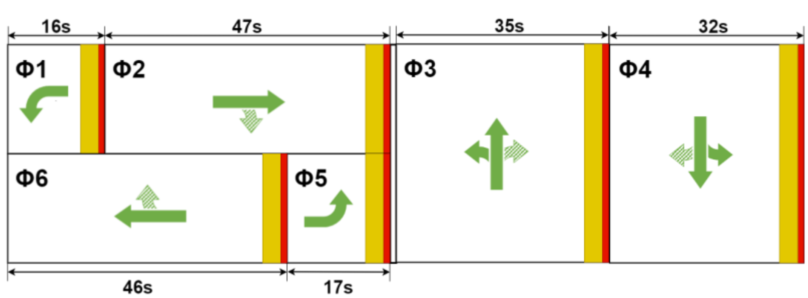


Figure 5. Ring barrier diagram for priority queue flush strategy at George Bush and Olsen.

To detect starvation of green at GBO, the Wavetronix radar at GBO used for detection of westbound traffic was reconfigured to detect the eastbound traffic between the two intersections. The research team reconfigured the sensor such that vehicles traveling with a speed less than 5 mph at the end of the link going eastbound for more than three seconds called detector 15 at GBO. The metering strategy at GBO was deployed with internal peer-to-peer commands on the GBO signal controller such that when detector 15 was called, the controller would omit Phases 2, 3, 4, and 6. If these omitted phases are active when the detector is called, the controller will force the phases off. Then peer-to-peer communication between the signal controllers at GBO and WGB repeated the call to detector 12 at WGB. Then, the controller had a priority routine added based on detector 12. This priority routine at WGB and the WGB signal will bring up Phase 9 and Phase 10 to begin the flushing routine.

The research team utilized the "Lockout A" feature in the Siemens M60 controller to limit the time between queue flush routines. The time difference between two consecutive queue flushes was limited to 360 seconds.

This control strategy was deployed on April 18, 2023, and remains operating at the time of writing this report in November 2023.

Experimental Plan

The research team created and calibrated a baseline scenario of the model. They calibrated the model using the travel time and speed data obtained from INRIX. The team selected a representative day in a week that closely represented the base scenario and determined the number of runs based on the guidelines of *Traffic Analysis Toolbox Volume III*. The baseline scenario runs were tested with four calibration criteria. The drivers and vehicle behaviors were fine-tuned until the runs of the baseline scenario cleared the calibration tests. Once the baseline scenario was calibrated, researchers worked on developing the alternative queue management strategies.

The team set up a HILS testing lab for this research. They constructed a VISSIM network to simulate and evaluate the strategies in real time. The signal timings of WGB and GBO received from the City of College Station were coded into the two Siemens controllers. These controllers were connected to VISSIM externally by means of both hardware and virtual Communication Interface Devices (CID). The virtual detectors in the simulation software detect the traffic flow and send the data to the local controllers running in real time through the CIDs. The signal controllers consider the simulation inputs in the same way real detectors work in the field and accordingly the controllers perform the signal operations. The controllers convey the same to the simulation software to simulate the signal operations.

This research effort involved enhancing the HILS tool to allow preemption calls to be placed during the simulation using a script generated by the research team. This tool allowed the HILS software to read a text file describing when a preemption should begin, end, and which preempt number and controller was used, and then place the preemption call to the controller during the simulation at the exact controller, number, and simulation time desired. This tool was used to place two preemptions in the simulation environment for analysis.

In addition, the research team used INRIX data to review and compare the field operations before and after deployment of the priority queue flush strategy.

Model Calibration

The research team used the latest *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling* software by FHWA (Wunderlich, Vasudevan, & Wang, 2019) to calibrate the VISSIM model. The calibration was done in the three recommended steps: identification of the representative day, preparation of variation envelopes, and calibration of model variant within acceptability.

Identification of the Representative Day

In the first step, the research team needed to determine a representative day to use as the calibration target. For data, the team used the travel time data from the INRIX roadway analytics for the second week of April as a key performance measure for the study area. The calibration is based on a single observed day instead of averaging multiple days together, creating a synthetic day (Wunderlich, Vasudevan, & Wang, 2019). The goal was for the representative day to have time-dependent performance measures (i.e., travel time) closest to the mean-time-dependent observed measures of all the considered days in the cluster.

The research team focused on the eastbound movement and searched for the representative day for the eastbound direction. They analyzed travel time data at 15-minute intervals for the eastbound direction during the PM peak hour from April 3 (Monday) to April 6 (Thursday). The team excluded Friday from the analysis because class schedules are lighter on Fridays and there is not much traffic observed. This exclusion was to avoid misrepresenting the existing conditions.

The key to selecting the representative day is to determine the day closest to the average day in the cluster. The research team assumed that the four days in the sample set are all in the same cluster. Therefore, the average travel time for each five-minute period for the four days was used to find the day closest to average.

Table 3. Eastbound Travel Times on George Bush Dr (Penberthy to Houston)

Trip time	Observed travel time ($m_i(t)$)				Average travel time ($\bar{m}$)
	4/3/2023 (Mon)	4/4/2023 (Tues)	4/5/2023 (Wed)	4/6/2023 (Thurs)	
5:00:00 PM	127	116	142	162	137
5:05:00 PM	121	120	130	161	133
5:10:00 PM	133	143	141	154	143
5:15:00 PM	144	126	157	132	140
5:20:00 PM	142	129	161	133	141
5:25:00 PM	142	122	160	139	141
5:30:00 PM	143	120	154	137	139
5:35:00 PM	187	127	147	134	149
5:40:00 PM	184	125	163	146	155
5:45:00 PM	187	157	184	134	166

Next, the difference between the average travel time and travel time observed on a particular day was calculated as $\dot{\boldsymbol{m}}(\boldsymbol{t})$ in Equation 1 below.

$$\dot{m}(t) = \frac{\sqrt{\left(\bar{m} - m_i(t)\right)^2}}{\bar{m}} \tag{1}$$

The representative day will be the one that minimizes the difference between the travel time of the individual day and average travel time value of the eastbound movement. As shown in Table 4, the representative day for the study is April 5, 2023, Wednesday.

Table 4. Percentage Difference Between Travel Time of Individual Days and Average Travel Time

Trip time	Difference between observed travel time and average travel time (in percentage) $\dot{m}(t)$			
	4/3/2023 (Mon)	4/4/2023 (Tues)	4/5/2023 (Wed)	4/6/2023 (Thurs)
5:00:00 PM	7%	15%	4%	18%
5:05:00 PM	9%	10%	2%	21%
5:10:00 PM	7%	0%	1%	8%
5:15:00 PM	3%	10%	12%	5%
5:20:00 PM	0%	9%	14%	6%
5:25:00 PM	1%	13%	14%	1%
5:30:00 PM	3%	13%	11%	1%
5:35:00 PM	26%	15%	1%	10%
5:40:00 PM	19%	19%	5%	5%
5:45:00 PM	13%	5%	11%	19%
5:50:00 PM	30%	15%	8%	23%
5:55:00 PM	34%	8%	1%	28%
Average	**13%**	**11%**	**7%**	**12%**

Preparation of Variation Envelopes

This step aims to establish a statistical range, derived from the observed variation, to function as the calibration target for the model variant. The simulation results are expected to align with this time-variate envelope, formulated using the standard deviation and the observed representative day value. The research team developed envelopes using one and two sigma bands for a 95th percentile variance and a single standard deviation variance. The 95th percentile variance is with a Z-statistic of 1.96, which is referred to as a 2-sigma band in the following discussion. The bands for this research are illustrated in Figure 6. These bands will be employed to evaluate the simulation results in the subsequent step. The values for the bands are given in Table 5.

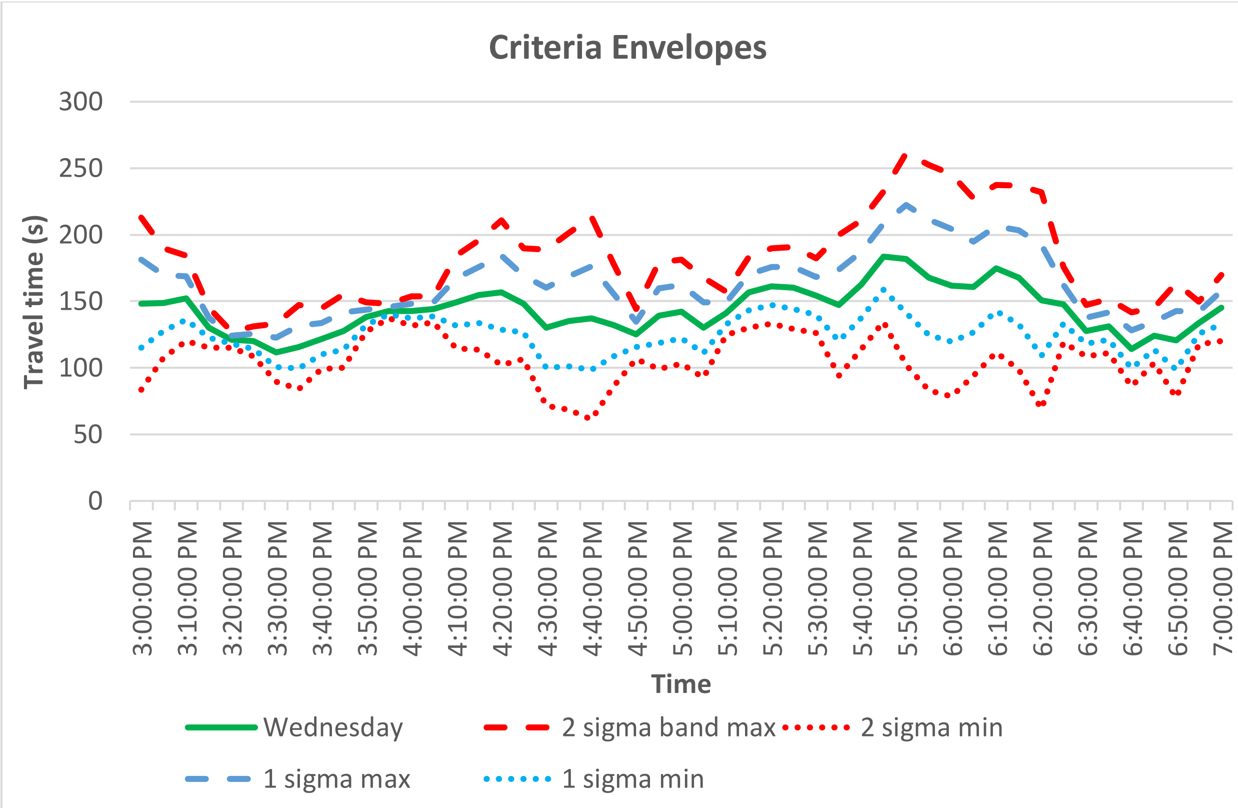


Figure 6. Variation envelope for eastbound PM travel times.

Table 5. Variation Envelope Values for Eastbound PM Travel Times

Time	Standard deviation	Eastbound travel time (Wednesday)	2 sigma max	2 sigma min	1 sigma max	1 sigma min
5:00:00 PM	20.0	142	181	103	162	122
5:05:00 PM	19.2	130	168	93	149	111
5:10:00 PM	8.4	141	157	125	149	133
5:15:00 PM	13.6	157	183	130	170	143
5:20:00 PM	14.4	161	190	133	176	147
5:25:00 PM	15.7	160	191	129	176	144
5:30:00 PM	14.2	154	182	126	168	140
5:35:00 PM	26.9	147	200	94	174	120
5:40:00 PM	24.7	163	211	114	187	138
5:45:00 PM	24.9	184	232	135	208	159

Calibration of Model Variant within Acceptability Criteria

In the concluding step for finding the calibration criteria, the research team generated variants of the baseline models. The performance of the baseline model was assessed through simulation runs with different random seeds to ensure that the simulation outputs aligned with the observed data.

Adjustments were iteratively made to the input parameters of the baseline model variant until the performance measures for each run of the model variants met the four distinct acceptability criteria established for time-dynamic profiles in relation to each measure and travel condition. Table 6 shows the travel times for each of the simulation runs for the baseline condition after calibration. This table also shows the average of the five simulation runs.

Table 6. Baseline Simulation Travel Times for Each Seed and the Average

Time	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	118	171	130	149	129	139
5:05:00 PM	132	133	123	114	121	125
5:10:00 PM	126	132	164	129	140	138
5:15:00 PM	138	129	147	113	112	128
5:20:00 PM	151	175	125	155	169	155
5:25:00 PM	137	183	173	158	131	156
5:30:00 PM	154	201	171	159	175	172
5:35:00 PM	234	178	135	136	137	164
5:40:00 PM	186	178	166	136	143	162
5:45:00 PM	184	142	141	190	166	165

These travel times were compared to the four criteria recommended in the FHWA guidance (Wunderlich, Vasudevan, & Wang, 2019). The remainder of this section discusses the baseline model's comparison to these criteria.

Criterion I: Control for Time-Variant Outliers – In the context of the first criterion, the requirement is that 95% of the simulated travel time and speed results must fall within the 2-sigma band envelope established earlier in this report. The research team assessed the output of five simulation runs for eastbound travel times against this criterion. After some calibration, the team obtained simulated travel times for 10 five-minute time intervals during the PM peak. Illustrated in Figure 7, all points fall within the 2-sigma band except for three points: 5:10 PM in simulation 3, 5:30 PM in simulation 2, and 5:35 PM in simulation 1. However, given that the number of time intervals is fewer than the recommended intervals in the guidance of 20, Criterion I was relaxed to permit one simulated time interval outside the 2-sigma band. Consequently, the baseline model passed Criterion I.

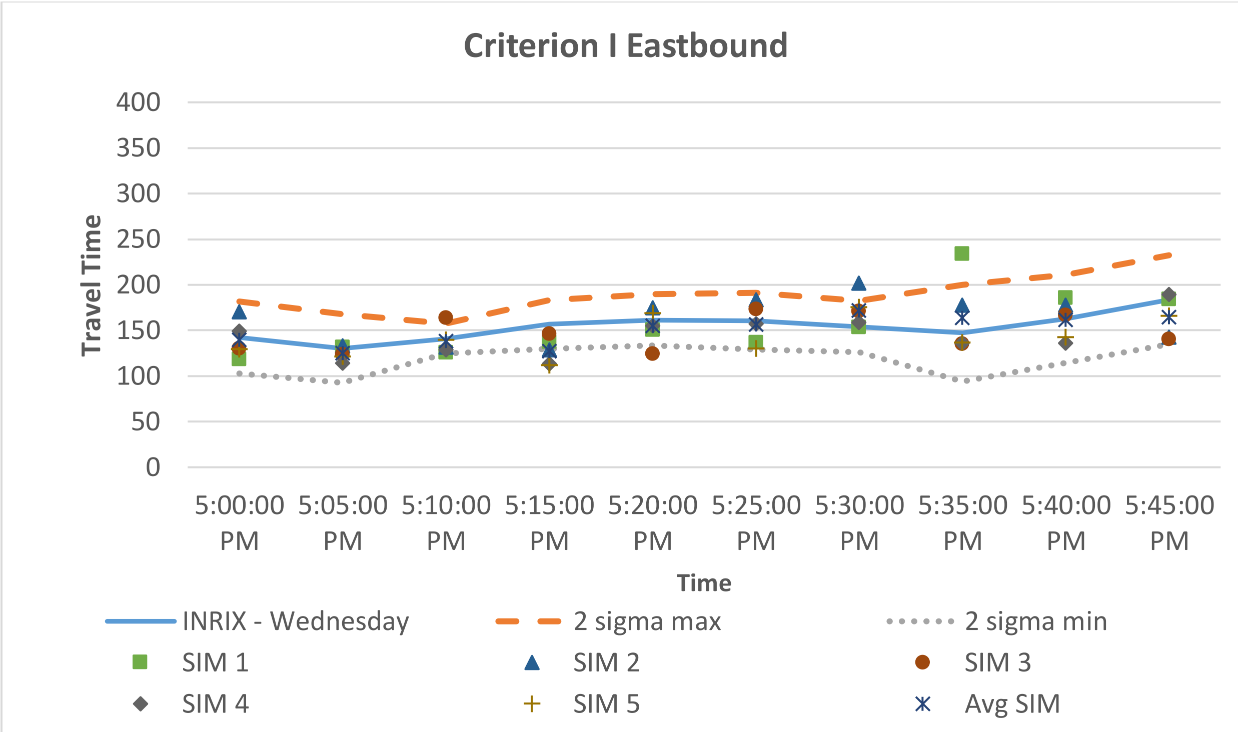


Figure 7. Chart assessing control for time-variant outliers.

Criterion II: Control for Time-Variant Inliers – In this criterion, it is stipulated that two-thirds of the simulated results must fall within the 1-sigma band for the given travel condition. As depicted in the figure, for the given model variant, three out of five simulation runs do not meet the criterion. However, considering the significantly narrow 1-sigma band based on the observed data, achieving two-thirds of the simulated output within this band is challenging. Nevertheless, the average simulation run outputs satisfy the criterion. Consequently, the baseline model passed Criterion II.

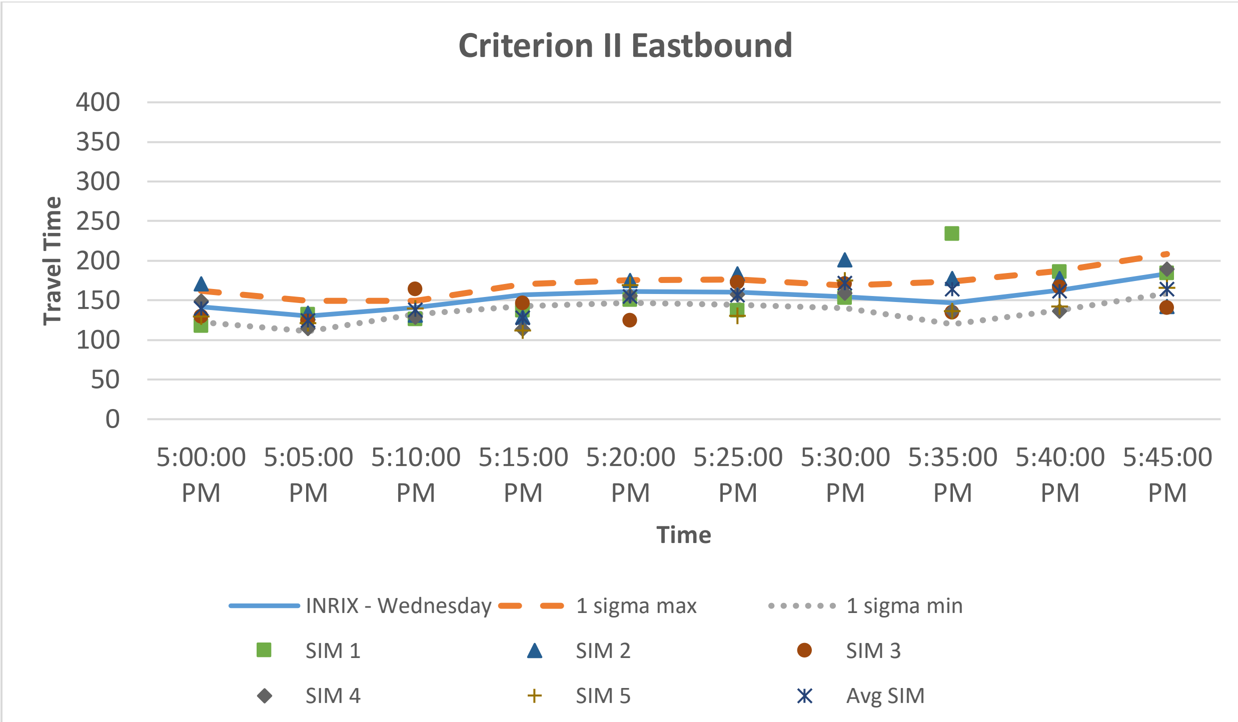


Figure 8. Chart assessing control for time-variant inliers.

Bounded Dynamic Absolute Error (BDAE) – This criterion ensures that the average simulated absolute error from the represented day for all time intervals shall be less than or equal to the Bounded Dynamic Absolute Error (BDAE) threshold; that is, the variations observed across all days compared to the representative day in each travel condition. Equation 2 shows how to calculate the BDAE threshold.

$$\frac{\Sigma_t |c_r(t) - \bar{c}_i(t)|}{N_T} \leq BDAE\ Threshold \qquad (2)$$

where, $BDAE\ Threshold = \dfrac{\sum_{i \neq r} \Sigma_t \frac{c_r(t) - c_i(t)}{N_T}}{Ncluster - 1}$

Here,

$c_r(t)$	Observed value of representative day during time interval *t*
$c_i(t)$	Observed value of non-representative day within the cluster during time interval *t*
$\bar{c}_i(t)$	Simulated performance measure during time interval *t*
N_T	Number of time intervals

In accordance with Criterion III, the research team computed the BDAE threshold for the simulated dataset using observed travel time data from both the representative day and other days in the cluster. As presented in Table 7, the average absolute difference between the simulated travel time and the representative day is below the BDAE threshold of 21.7 seconds.

Table 7. Bounded Dynamic Absolute Error Calculation

Time	4/3/2023	4/4/2023	4/5/2023	4/6/2023	Absolute difference $\lvert c_r(t) - c_i(t)\rvert$			
5:00:00 PM	127.2	115.8	142.2	162.0	15.0	26.4	-	19.8
5:05:00 PM	120.6	120.0	130.2	160.8	9.6	10.2	-	30.6
5:10:00 PM	133.2	143.4	141.0	153.6	7.8	2.4	-	12.6
5:15:00 PM	144.0	126.0	156.6	132.0	12.6	30.6	-	24.6
5:20:00 PM	141.6	129.0	161.4	133.2	19.8	32.4	-	28.2
5:25:00 PM	142.2	121.8	160.2	138.6	18.0	38.4	-	21.6
5:30:00 PM	142.8	120.0	154.2	137.4	11.4	34.2	-	16.8
5:35:00 PM	187.2	126.6	147.0	134.4	40.2	20.4	-	12.6
5:40:00 PM	183.6	125.4	162.6	146.4	21.0	37.2	-	16.2
5:45:00 PM	186.6	156.6	183.6	133.8	3.0	27.0	-	49.8
Average absolute difference					**15.8**	**25.9**	**-**	**23.3**
BDAE Threshold (sum of average absolute difference /3)					**21.7**			

Each of the simulation BDAE values is less than the threshold except simulation run 2. However, since simulation 2 exceeds the BDAE threshold by only 2.36 seconds, the research team considered Criterion III passed since the threshold was exceeded by such a small value.

Table 8. BDAE Values for Each Simulation Run

Time	Absolute error					
	SIM 1	**SIM 2**	**SIM 3**	**SIM 4**	**SIM 5**	**Avg SIM**
5:00:00 PM	24.1	28.3	12.4	6.9	12.8	2.8
5:05:00 PM	1.6	3.3	6.7	16.0	9.1	5.4
5:10:00 PM	15.1	9.4	23.0	12.4	1.4	3.1
5:15:00 PM	19.1	28.0	10.1	43.2	44.7	29.0
5:20:00 PM	10.9	13.6	36.8	6.1	7.4	6.5
5:25:00 PM	23.2	23.1	12.7	2.6	29.7	3.9
5:30:00 PM	0.6	47.3	16.8	4.5	21.0	17.8
5:35:00 PM	86.8	30.8	12.1	10.9	10.3	16.9
5:40:00 PM	23.2	15.2	3.8	26.3	20.0	0.8
5:45:00 PM	0.5	41.3	43.0	5.9	17.6	19.1
Average absolute error	**20.5**	**24.0**	**17.7**	**13.5**	**17.4**	**10.5**

Bounded Dynamic Systematic Error – This criterion makes sure that the simulation outputs do not have excessive over/under estimators. The average simulated error shall be less than or equal to one-third of the BDAE threshold using Equation 3.

$$\left|\frac{\Sigma_t c_r(t) - \bar{c}_i(t)}{N_T}\right| \leq \frac{1}{3} * BDAE\ Threshold \qquad (3)$$

As shown in Table 9, the values for the Bounded Dynamic Systemic Error in simulations 2, 4, and 5 exceed the one-third threshold value. Nevertheless, the difference is approximately 2.8 seconds, which is too small to reliably distinguish the simulation results and considered negligible. Consequently, as the average simulation meets the fourth criterion, the research team decided that this baseline model satisfies Criterion IV.

Table 9. Bounded Dynamic Systematic Error

Time	Average error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	24.1	-28.3	12.4	-6.9	12.8	2.8
5:05:00 PM	-1.6	-3.3	6.7	16.0	9.1	5.4
5:10:00 PM	15.1	9.4	-23.0	12.4	1.4	3.1
5:15:00 PM	19.1	28.0	10.1	43.2	44.7	29.0
5:20:00 PM	10.9	-13.6	36.8	6.1	-7.4	6.5
5:25:00 PM	23.2	-23.1	-12.7	2.6	29.7	3.9
5:30:00 PM	0.6	-47.3	-16.8	-4.5	-21.0	-17.8
5:35:00 PM	-86.8	-30.8	12.1	10.9	10.3	-16.9
5:40:00 PM	-23.2	-15.2	-3.8	26.3	20.0	0.8
5:45:00 PM	-0.5	41.3	43.0	-5.9	17.6	19.1
Absolute Average Error	**1.9**	**8.3**	**6.5**	**10.0**	**11.7**	**3.6**
BDAE Threshold/3	**7.2**					

This calibration methodology was applied to other directions of travel across George Bush Dr and Wellborn Rd, and the summary of calibration results is presented in Table 10. Detailed results for each direction can be found in Appendix A. It is evident from the calibration results that both westbound and northbound directions did not meet the calibration criteria because the standard deviation observed between the individual days and the representative day was too low, resulting in a narrower variation envelope. Hence, the majority of simulation runs fell out of the acceptable range. In the case of the southbound direction, the simulation runs cleared Criteria I and III, but Criteria II and IV failed by only few seconds, which can be considered negligible as in the failures in the eastbound direction. Given the primary emphasis of this study on the eastbound and southbound directions, the research team decided to accept these results as passing calibration for the purpose of further analysis.

Table 10. Summary of Calibration Results for Westbound, Northbound, and Southbound

Direction	Criterion I	Criterion II	Criterion III	Criterion IV
Westbound	**Fail**	**Fail**	**Fail**	**Fail**
Northbound	**Fail**	**Fail**	**Fail**	**Fail**
Southbound	**Pass**	**Fail**	**Pass**	**Fail**

Revised Strategies

The research team also attempted to develop additional changes to operations to further improve operations. During the PM peak period, the intersection at Wellborn Rd is oversaturated in all approach directions, as highlighted by red arrows in Figure 9. An at-grade railway crossing located on the west side of this intersection (highlighted using red-shading) serves 27 to 30 trains daily. This further aggravates the congestion problem by reducing the capacity of George Bush Dr approaches to zero for several minutes during each train preemption, which may occur more than once during the peak period on any given day. Texas A&M buses crossing the railway tracks cause additional capacity loss because of the legal requirement for them to stop prior to crossing. As highlighted with green arrows in Figure 9, the intersection at Olsen Blvd is undersaturated during the peak period. However, queues at the eastbound Wellborn approach often spill into the Olsen Blvd intersection and cause starvation of green. Under these conditions, vehicles entering the intersection often get trapped within the intersection and block other movements at Olsen Blvd.

The City of College Station always operates the intersection at Wellborn Rd as Free. During the PM peak period where all phases max out, this intersection runs at an effective cycle length of 195 seconds. During the PM peak period, the City operates the intersection at Olsen Blvd using a time-of-day coordination plan with a cycle length of 130 seconds. The net effect of these different cycle lengths is that it is impossible to predict or control which movement (eastbound through or southbound left) gets to use the downstream storage when it becomes available.

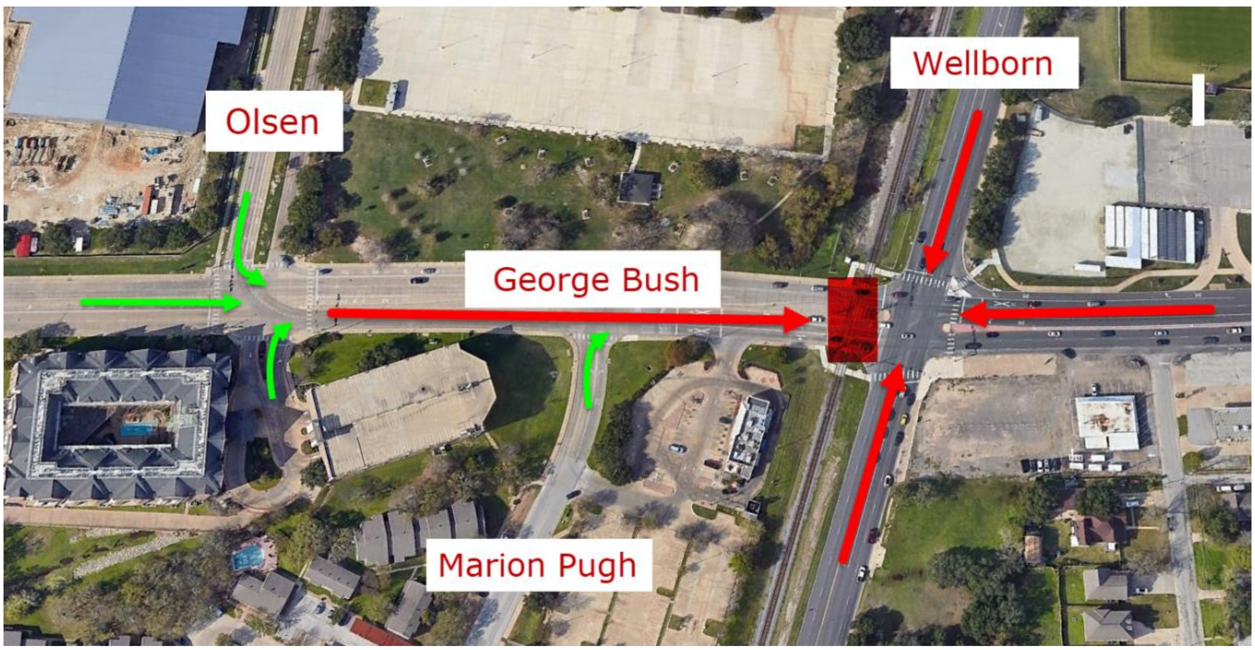


Figure 9. Saturated and undersaturated movements at George Bush testbed.

The potential solution requires a two-pronged approach:

1. Bring regularity to traffic control. This can be achieved by using the same effective cycle lengths at the two intersections.
2. Manage queues to minimize detrimental effects of queue spillback/starvation. This objective can be achieved only if the interior approach (in this case, eastbound left and through movements) has sufficient capacity to handle the traffic allowed to enter from the upstream intersection. It could be achieved as follows:
    a. Increase capacity of interior movements by taking time from conflicting approaches (southbound, northbound, and westbound phases) at the Wellborn Rd intersection.
    b. Reduce capacity of Olsen Blvd movements feeding traffic to the downstream link. Potential ways of achieving this objective are:

i. Increase green times for westbound left and though movements as necessary.
ii. Introduce all-red time, where no one is moving.
iii. Introduce additional lost time at Olsen by serving selected phases multiple times during one cycle at Wellborn.

c. A combination of the above two approaches.

The research team first selected approaches 1 and 2a. This revised strategy used information from the calibrated VISSIM model and utilized the PASSER V-09 (P5) computer program developed by TTI. The simulation data includes 12 sets of five-minute volumes at each network entry point (origin) and origin-destination distributions of traffic along each vehicle path. Demand calculations involved the following steps:

1. For each set, researchers began by calculating five-minute traffic volumes/demand at each intersection in the entire network. A spreadsheet was used to add traffic demand contributing to each movement from all paths.
2. In the next step, researchers added 5-minute traffic volumes/demands for sets of three consecutive periods to obtain four sets of 15-minute volumes.
3. In the last step, researchers selected the most critical (maximum) 15-minute demand for each movement at each intersection and multiplied it by four to obtain hourly demand for that movement.

Researchers developed signal retiming calculations using P5. The first step for P5 developing the revised signal timing required entering the geometric characteristic, phase clearance times and traffic demands calculated using the steps described above for both intersections. P5 uses this information to calculate saturation flow rates and green splits for all phases for user-specified cycle length. Based on engineering judgement, researchers selected a cycle length of 180 seconds for both intersections. For the Wellborn Rd intersection, this maximum background cycle length is 15 seconds less than the current maximum of 195 seconds. However, the overall impact of this reduction is 2.25 seconds per phase.

Figure 10 shows the timings calculated by P5 for the two intersections. Note that the volume to capacity (V/C) ratios for all phases at Olsen Blvd (top part of figure) are less than one. In other words, this signal has sufficient capacity to handle demands for all phases, especially eastbound through. However, as shown in the bottom portion of this figure, at least one movement in each direction at the Wellborn Rd intersection is over capacity. Note that the through phase for the eastbound approach has a V/C ratio of 1.07, indicating that this approach does not have the capacity to handle the demand from Olsen Blvd. In the next step, researchers manually adjusted the phase times at this intersection to increase the capacity of eastbound through movement.

Artery	George Bush						Olsen Blvd					
Movement	EBL	EBT	EBR	WBL	WBT	WBR	SBL	SBT	SBR	NBL	NBT	NBR
Lane Assignment	1	2 >	< 1	1	2	1	2 >	< 1	1	1 >	< 2 >	< 1
Volume (vph)	91	799	18	100	832	255	683	40	80	8	8	8
SatFlow (pcphg)	1769.61	3629.30	81.76	1769.61	3725.49	1583.33	3352.68	196.35	1583.33	1153.72	1153.72	1153.72
Green Splits (sec)	21	49	49	52	80	80	41	41	41	38	38	38
Delay (sec/veh)	89.96	76.88	226.79	52.32	39.96	37.46	103.51	210.37	61.62	59.94	59.94	59.94
Delay LOS	F	E	F	D	D	D	F	F	E	E	E	E
V/C Ratio	0.54	0.88	0.88	0.21	0.53	0.38	0.99	0.99	0.25	0.04	0.04	0.04

Artery	George Bush						Wellborn Rd					
Movement	EBL	EBT	EBR	WBL	WBT	WBR	SBL	SBT	SBR	NBL	NBT	NBR
Lane Assignment	1	2 >	< 1	1	2	1	1	2 >	< 1	1	2 >	< 1
Volume (vph)	146	1152	146	125	582	125	467	975	589	153	701	90
SatFlow (pcphg)	1769.61	3242.09	410.89	1769.61	3725.49	1583.33	1769.61	2177.75	1315.58	1769.61	3236.62	415.54
Green Splits (sec)	29	66	66	16	53	53	53	79	79	19	45	45
Delay (sec/veh)	82.89	106.77	155.62	183.74	60.95	55.22	98.84	104.48	112.49	166.90	91.61	148.33
Delay LOS	F	F	F	F	E	E	F	F	F	F	F	F
V/C Ratio	0.59	1.07	1.07	1.06	0.60	0.30	0.97	1.07	1.07	1.04	0.95	0.95

Figure 10. Signal timing calculations using PASSER V.

Figure 11 shows the adjusted green times at the Wellborn Rd intersection. This adjustment reduced the V/C ratios for the eastbound movements to 0.94 at the expense of other movements from where time had to be taken away. This adjustment significantly penalized the westbound left movement.

Artery	George Bush						Wellborn Rd					
Movement	EBL	EBT	EBR	WBL	WBT	WBR	SBL	SBT	SBR	NBL	NBT	NBR
Lane Assignment	1	2 >	< 1	1	2	1	1	2 >	< 1	1	2 >	< 1
Volume (vph)	146	1152	146	125	582	125	467	975	589	153	701	90
SatFlow (pcphg)	1769.61	3242.09	410.89	1769.61	3725.49	1583.33	1769.61	2177.75	1315.58	1769.61	3236.62	415.54
Green Splits (sec)	31	74	74	13	56	56	51	75	75	18	42	42
Delay (sec/veh)	78.85	68.98	112.00	325.19	57.85	52.59	111.06	129.53	136.80	192.81	112.19	174.34
Delay LOS	E	E	F	F	E	D	F	F	F	F	F	F
V/C Ratio	0.55	0.94	0.94	1.41	0.56	0.28	1.01	1.14	1.14	1.11	1.03	1.03

Figure 11. Manually adjusted splits at Wellborn Rd intersection in PASSER V.

The above results show the worst possible scenario, peak 15-minute demand at all phases simultaneously for the assumed demand. However, this solution would not work if peak eastbound demand was higher than that assumed here. The reason is that the eastbound through phase causes significant unused green time, which would be detrimental if drivers used it to block the intersection.

Researchers made one final change to the timings by changing the phasing sequence at the Wellborn intersection to provide leading left turn (swapping Phases 7 and 8), as shown in Figure 12. This change provides two benefits:

1. Interior left and through traffic start moving together and minimize friction between the two movements.

2. Any time not used by phase 8 is available for use by phase 7, especially when phase 4 demand is high.

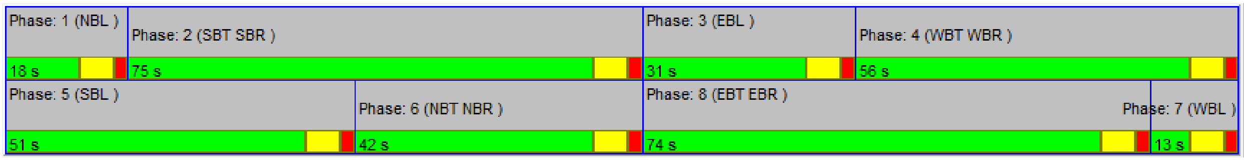


Figure 12. Revised ring structure for Wellborn-George Bush intersection.

Another way to accomplish metering for GBO would be to use double cycling. A double cycle strategy is where the higher demand intersection, in this case WGB, operates at a cycle length twice that of the nearby lower demand intersection, in this case GBO. The research team used P5 to generate a signal timing plan where GBO would operate at a 90-second cycle length and WGB would operate at the 180-second cycle length explained above. The net effect of this change should be a metering effect, resulting in a reduction in the number and severity of starvation at GBO at the expense of increased stops. It should be noted that a 90-second cycle length at this intersection is not sufficient to adequately serve some pedestrian movements and as such is not a practical option for the subject signal system. However, double cycling a signal may be a useful strategy where pedestrian traffic is minimal. The research team analyzed this option in simulation since the double cycle method may work in an alternate scenario where the pedestrian timings are not as large.

Chapter 4. Evaluation Results

This section describes the data gathered to assess the performance of the strategies proposed in both the simulation and field, as applicable. The simulation tools were used to analyze an array of strategies, which may or may not have been deployed in the field. The simulation results section describes the performance of the strategies, and the field analysis section describes the deployed strategies. The field data were collected through the INRIX platform. The section ends with a discussion on miscellaneous field adjustments based on input from road users and the City on the deployed system.

Simulation Results

The simulation experiment involved analyzing 10 simulation runs with different random seeds for the baseline, priority queue flush, revised timing with consistent cycle lengths, and the double cycle scenario where GBO had a cycle length of 90 seconds and WGB had a cycle length of 180 seconds. These simulations included two train preemptions. One train preemption of 216 seconds starting at simulation second 1293 and another of 267 seconds starting at simulation second 3403. Each of the 10 simulations included a 900-second warm-up period to load the network and lasted a total of 4500 seconds, meaning each run had a one-hour period of data collection. The models were generated and calibrated to represent the testbed network in April 2023. However, the research team noticed that the model did not generate congestion consistent with the field conditions in the fall, when the starvation of green is at its worst, so they increased volumes in the simulation to generate additional queues. All the simulation results presented here describe the increased volume scenarios.

This report provides the travel time and queue length metrics for the simulation exercise. The eastbound travel times across George Bush Dr from before Penberthy Blvd to past Houston St are provided in Figure 13. The travel times for the baseline scenario increase gradually throughout the simulation, indicating that the corridor is over-capacity. Each of the strategies analyzed that reduced travel times compared to the baseline scenario experienced a significant reduction in eastbound travel times with no consistent upward trend in travel times. The priority queue flush alone scenario had the highest average travel time of about 3.7 minutes, but still represented a reduction of 53 percent of the baseline average travel time at 7.9 minutes. The best strategy for the eastbound travel times were the signal retiming and queue flush scenario with an average travel time of 2.6 minutes and a reduction of travel time of 67 percent. The impacts of the trains are visible in Figure 13 at the 5:10 PM and 5:45 PM intervals. Table 11 lists the travel time values for each scenario with asterisks to represent the statistical significance for the difference in travel time between the scenario and the baseline using a student's t-test. Each of the scenarios has significantly lower travel times than the baseline at a 99 percent confidence level, except for the first 10 minutes of the simulation for the priority queue flush scenario.

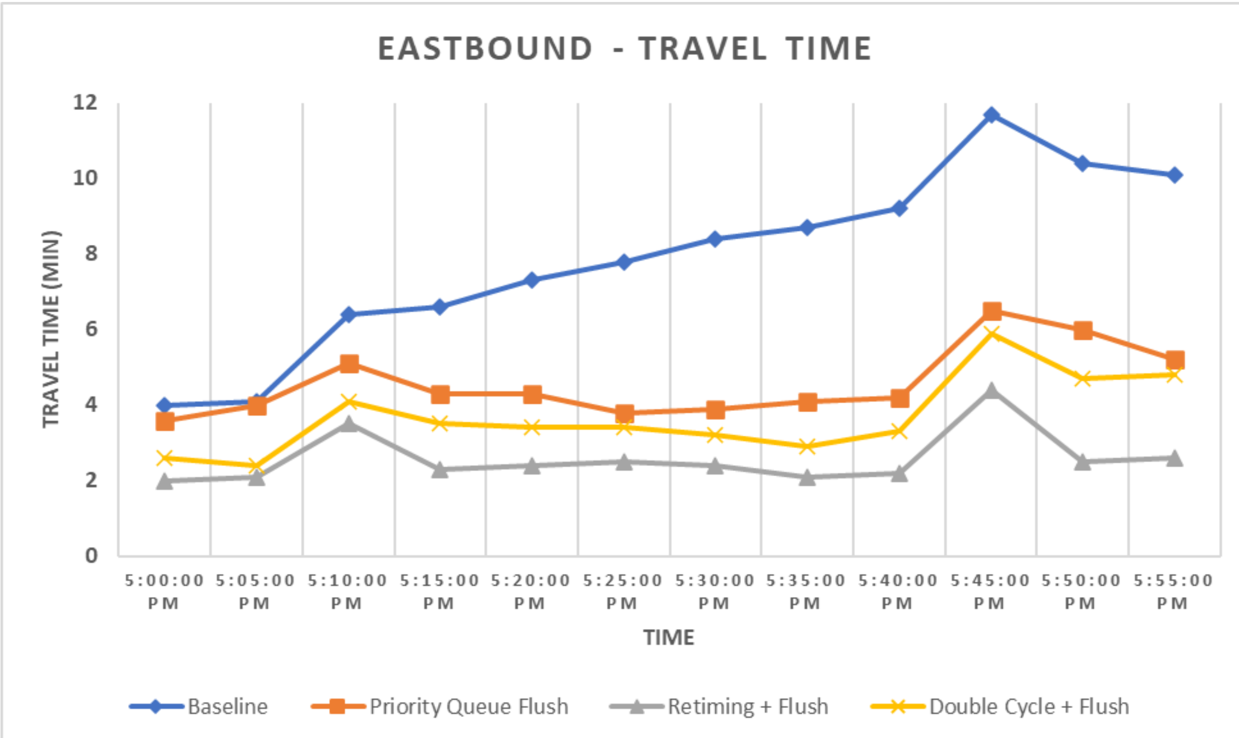


Figure 13. Eastbound travel times for the analyzed queue management strategies.

Table 11. Eastbound Travel Time Averages (Minutes) with Statistical Significance

Time Interval	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
5:00 PM – 5:05 PM	4.0	3.6	2 ***	2.6 ***
5:05 PM – 5:10 PM	4.1	4	2.1 ***	2.4 **
5:10 PM – 5:15 PM	6.4	5.1 **	3.5 ***	4.1 ***
5:15 PM – 5:20 PM	6.6	4.3 ***	2.3 ***	3.5 ***
5:20 PM – 5:25 PM	7.3	4.3 ***	2.4 ***	3.4 ***
5:25 PM – 5:30 PM	7.8	3.8 ***	2.5 ***	3.4 ***
5:30 PM – 5:35 PM	8.4	3.9 ***	2.4 ***	3.2 ***
5:35 PM – 5:40 PM	8.7	4.1 ***	2.1 ***	2.9 ***
5:40 PM – 5:45 PM	9.2	4.2 ***	2.2 ***	3.3 ***
5:45 PM – 5:50 PM	11.7	6.5 ***	4.4 ***	5.9 ***
5:50 PM – 5:55 PM	10.4	6 ***	2.5 ***	4.7 ***
5:55 PM – 6:00 PM	10.1	5.2 ***	2.6 ***	4.8 ***

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

Figure 14 shows the westbound travel times from before Houston St to past Penberthy Blvd. The impacts of the train are visible for the westbound direction in the 5:10 PM and 5:45 PM intervals too. The baseline scenario has an average travel time of 4.2 minutes. The double cycle scenario shows consistently higher travel times than the baseline. The priority queue flush westbound travel times are similar to the baseline, with consistently lower travel times than the baseline scenario in the later half of the simulations. The retiming scenario shows even more consistently lower westbound travel times than the baseline scenario through the simulations. Table 12 lists the westbound travel time values for each scenario with asterisks to represent the statistical significance for the difference in travel time between the scenario and the baseline using a student's t-test. Different portions of the retiming and double flush scenarios are statistically significant, but the overall trends are the same. The priority queue flush scenarios do not have any statistically significant differences in travel time from the baseline.

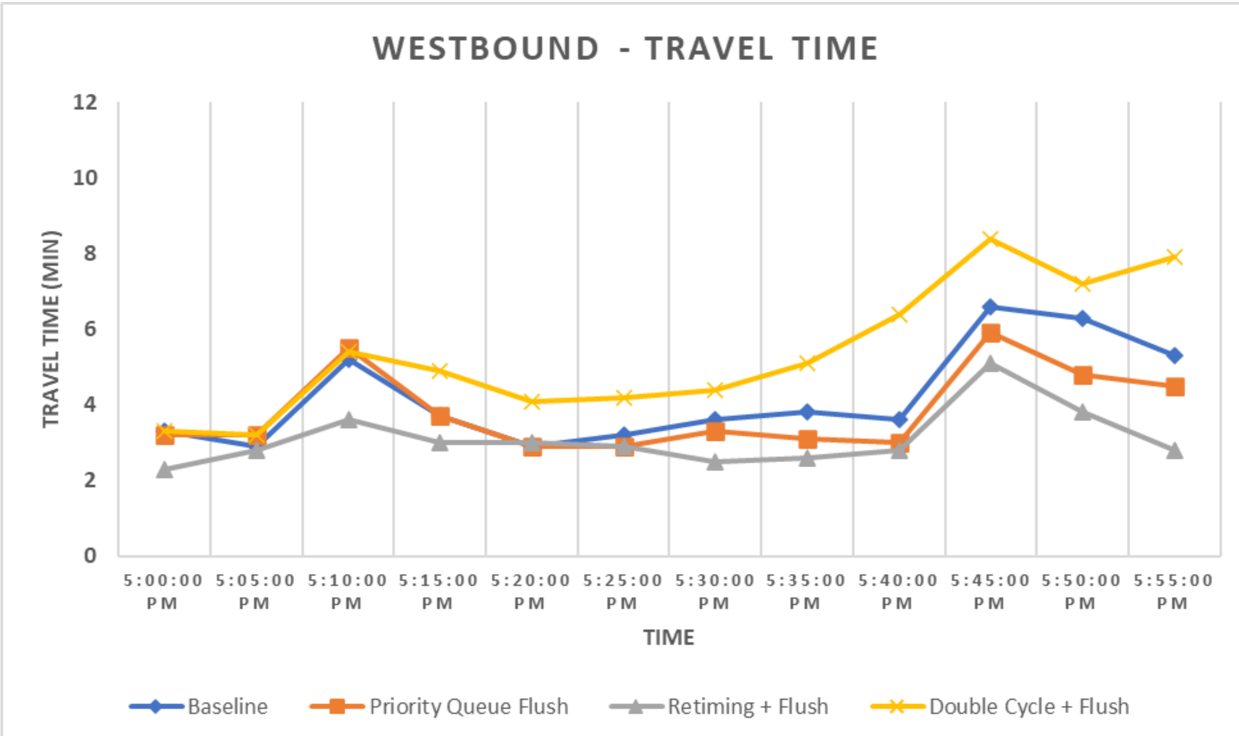


Figure 14. Westbound travel times for the analyzed queue management strategies.

Table 12. Westbound Travel Time Averages (Minutes) with Statistical Significance

Time Interval	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
5:00 PM – 5:05 PM	3.3	3.2	2.3 ***	3.3
5:05 PM – 5:10 PM	2.9	3.2	2.8	3.2
5:10 PM – 5:15 PM	5.2	5.5	3.6 ***	5.4
5:15 PM – 5:20 PM	3.7	3.7	3 **	4.9 **
5:20 PM – 5:25 PM	2.9	2.9	3	4.1 **
5:25 PM – 5:30 PM	3.2	2.9	2.9	4.2 *
5:30 PM – 5:35 PM	3.6	3.3	2.5 ***	4.4
5:35 PM – 5:40 PM	3.8	3.1	2.6 **	5.1
5:40 PM – 5:45 PM	3.6	3	2.8	6.4 ***
5:45 PM – 5:50 PM	6.6	5.9	5.1 ***	8.4 **
5:50 PM – 5:55 PM	6.3	4.8	3.8 **	7.2
5:55 PM – 6:00 PM	5.3	4.5	2.8 ***	7.9 **

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

Figure 15 shows the southbound travel times from the simulation experiment for the different strategies. These travel times record the time from north of Joe Route Blvd down to Holleman Dr. The priority queue flush scenario caused an increase in southbound travel times of about 15 percent on average compared to the base network. This was expected because the queue flush was only intended to improve performance for the eastbound movement. The other strategies indicated a reduction of 15 percent in southbound travel times were possible for the double cycle scenario and a 28 percent reduction in southbound travel times for the retiming scenario. Table 13 lists the southbound travel time values for each scenario with asterisks to represent the statistical significance for the difference in travel time between the scenario and the baseline using a student's t-test. This illustrates that many of the differences in travel time between the scenario and the baseline in the middle of the simulation are statistically significant at some level. The retiming scenario remains statistically significant different from the baseline for the last 45 minutes of the simulated peak period.

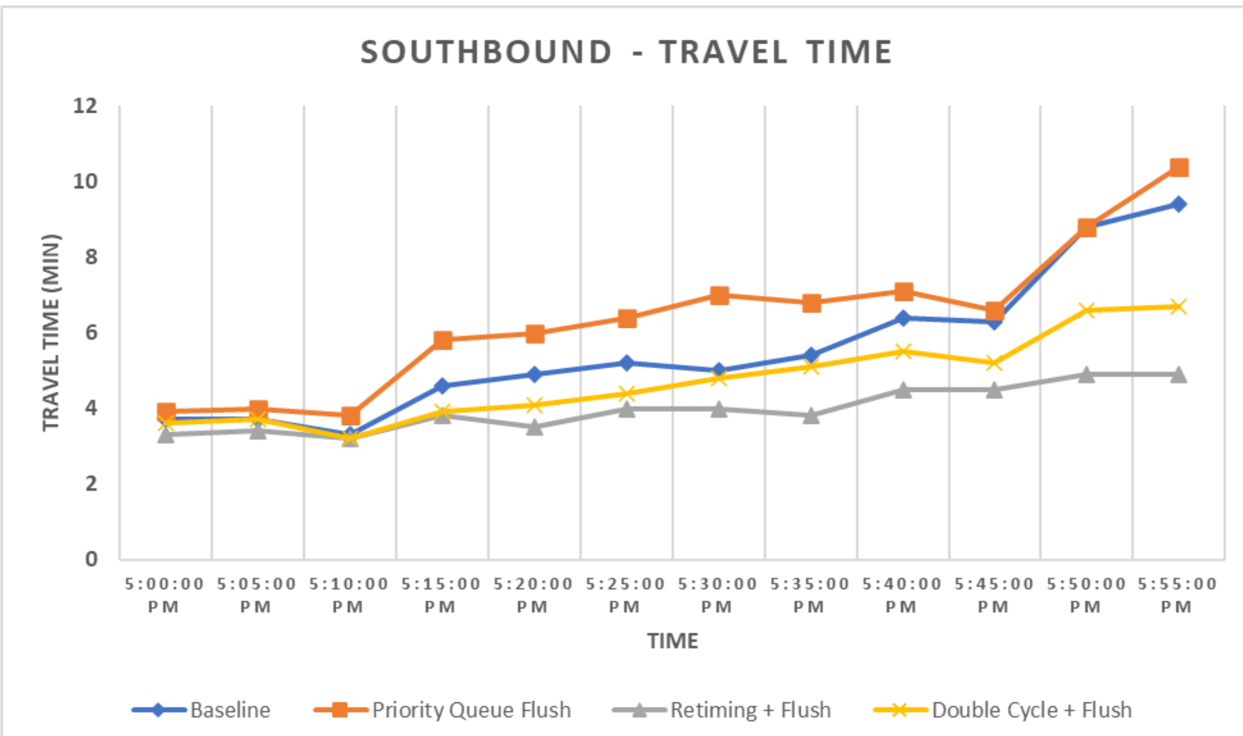


Figure 15. Southbound travel times for the analyzed queue management strategies.

Table 13. Southbound Travel Time Averages (Minutes) with Statistical Significance

Time Interval	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
5:00 PM – 5:05 PM	3.7	3.9	3.3 **	3.6
5:05 PM – 5:10 PM	3.7	4	3.4	3.7
5:10 PM – 5:15 PM	3.3	3.8	3.2	3.2
5:15 PM – 5:20 PM	4.6	5.8 **	3.8 ***	3.9 **
5:20 PM – 5:25 PM	4.9	6 **	3.5 ***	4.1 **
5:25 PM – 5:30 PM	5.2	6.4 ***	4 ***	4.4 ***
5:30 PM – 5:35 PM	5.0	7 ***	4 ***	4.8
5:35 PM – 5:40 PM	5.4	6.8 ***	3.8 ***	5.1
5:40 PM – 5:45 PM	6.4	7.1	4.5 ***	5.5
5:45 PM – 5:50 PM	6.3	6.6	4.5 ***	5.2
5:50 PM – 5:55 PM	8.8	8.8	4.9 ***	6.6 *
5:55 PM – 6:00 PM	9.4	10.4	4.9 ***	6.7 *

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

The northbound travel times from Holleman Dr to past Joe Route Blvd are presented in Figure 16. Each of the northbound travel times overlap, with some scenarios showing reduction in travel time compared to the baseline scenario at one point in the simulation and increased at other points. The retiming scenario shows more consistently lower northbound travel times compared to the baseline than the other scenarios. Table 14 lists the northbound travel time values for each scenario with asterisks to represent the statistical significance for the difference in travel time between the scenario and the baseline using a student's t-test. It is noteworthy that very few of the travel time intervals have statistically significant differences and those that do have a significant difference still do not have a large average difference in travel times.

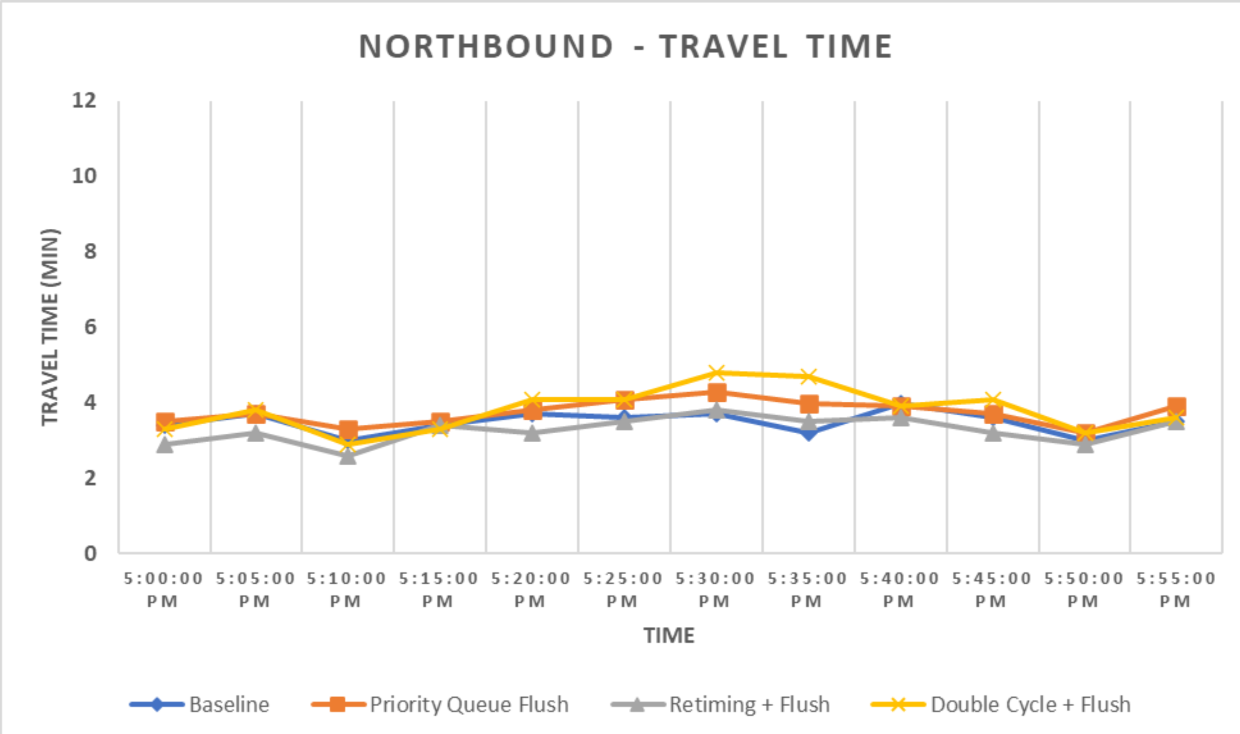


Figure 16. Northbound travel times for the analyzed queue management strategies.

Table 14. Northbound Travel Time Averages (Minutes) with Statistical Significance

Time Interval	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
5:00 PM – 5:05 PM	3.4	3.3	3.5	2.9 ***
5:05 PM – 5:10 PM	3.7	3.8	3.7	3.2
5:10 PM – 5:15 PM	3.0	2.9	3.3	2.6 *
5:15 PM – 5:20 PM	3.4	3.3	3.5	3.4
5:20 PM – 5:25 PM	3.7	4.1	3.8	3.2 ***
5:25 PM – 5:30 PM	3.6	4.1	4.1 **	3.5
5:30 PM – 5:35 PM	3.7	4.8 ***	4.3 ***	3.8
5:35 PM – 5:40 PM	3.2	4.7 ***	4 ***	3.5
5:40 PM – 5:45 PM	4.0	3.9	3.9	3.6 *
5:45 PM – 5:50 PM	3.6	4.1 **	3.7	3.2 *
5:50 PM – 5:55 PM	3.0	3.2	3.2	2.9
5:55 PM – 6:00 PM	3.5	3.6	3.9 ***	3.5

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

The next set of figures shows the average queue lengths for the simulated PM peak hour on different movements and approaches. Figure 17 shows the overall intersection average queue lengths for each intersection in the model. GBO exhibits reductions in queue lengths overall with the strategies. The queue lengths are reduced for WGB between the baseline and the priority queue flush scenario but are increased for the retiming scenario, and no notable change in queue length is indicated for the double cycle scenario. The George Bush Dr and Houston St (GBH) intersection shows increases in queue lengths for the retiming and double cycle scenario compared to the baseline scenario. The Wellborn Rd and Joe Route Blvd (WJR) intersection reveals a slight increase in average queue lengths between the baseline and the priority queue flush scenario but a decrease in queue lengths between the baseline and the retiming scenario and the double flush scenario. There are no notable changes in average queue lengths for each of the scenarios at the Wellborn Rd and Holleman Dr (WHO) intersection. The George Bush Dr and Penberthy Blvd (GBP) intersection shows reductions in average queue lengths for the three treatment scenarios compared to the baseline. The results for the four intersections outside of the testbed (GBH, WJR, WHO, and GBP) indicate that there are no drastic changes in queue lengths at the intersections that do not have changes in operations as a result of these considered strategies.

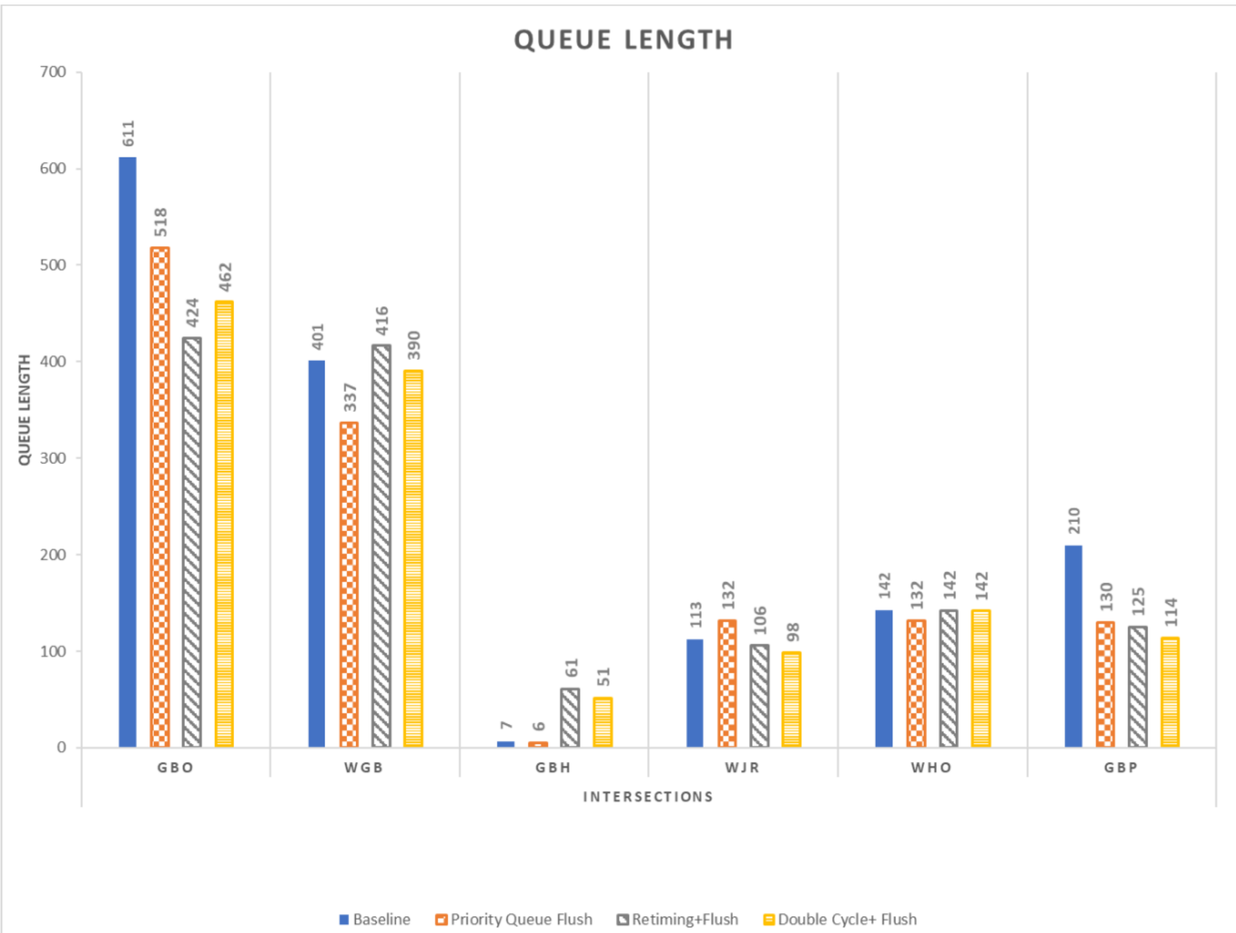


Figure 17. Average queue length at all the simulated intersections for the analyzed queue management strategies.

Table 15 lists the average queue length values at each intersection for each scenario with asterisks to represent the statistical significance for the difference between the scenario and the baseline using a student's t-test. Overall, few intersections have any statistically significant difference in average travel times for the intersection, except for George Bush and Houston, which is one of the low queue length intersections.

Table 15. Average Queue Lengths (Feet) for Each Intersection with Statistical Significance

Intersection	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
George Bush & Olsen	611	424	424	462
Wellborn & George Bush	401	416	416	390
George Bush & Houston	7	61 ***	61 ***	51 **
Wellborn & Joe Route	113	106	106	98
Wellborn & Holleman	142	142	142	142
George Bush & Penberthy	210	125	125	114

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

Figure 18 shows the average queue lengths for left turn movements at GBO. This figure illustrates that the eastbound and northbound left turns are not impacted by the changes in operations. The westbound left turn shows a consistently reduced average queue for each scenario. The southbound left turn has an extremely long average queue length in all the scenarios. Table 16 lists the average queue length values for each left turn movement for each scenario with asterisks to represent the statistical significance for the difference between the scenario and the baseline using a student's t-test. The westbound left turn has a significant reduction in queue lengths at a 90 percent confidence. The southbound left turn has slightly lower queue lengths for the retiming and double cycle scenarios, but these are not statistically significant.

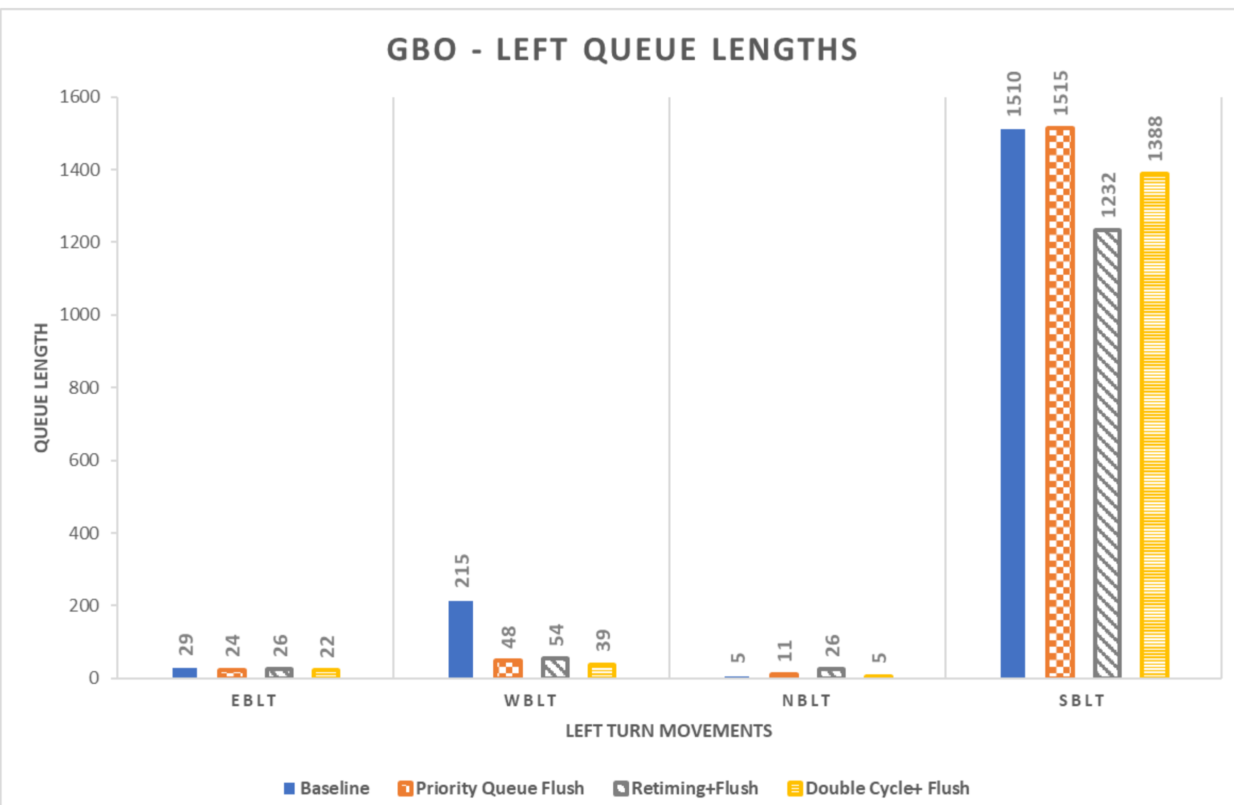


Figure 18. Queue lengths of left turn movements for four queue management strategies at GBO intersection.

Table 16. Queue Lengths at George Bush and Olsen Left Turn Movements with Statistical Significance

Movement	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
Eastbound Left Turn	29	24	26	24
Westbound Left Turn	215	48 *	54 *	48 *
Northbound Left Turn	5	11	26 **	11
Southbound Left Turn	1510	1515	1232	1515

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

Figure 19 displays the average queue lengths for through movements at GBO. Table 17 lists the average queue length values for each through movement for each scenario with asterisks to represent the statistical significance for the difference between the scenario and the baseline using a student's t-test. The eastbound through movement has a drastically and significantly reduced queue length due to the evaluated strategies. The westbound through movement also has a reduced queue length. The northbound through movement experienced little changes in the average queues. The southbound through movement also has high queue lengths since the southbound through movement is a shared lane with the southbound left turn movement.

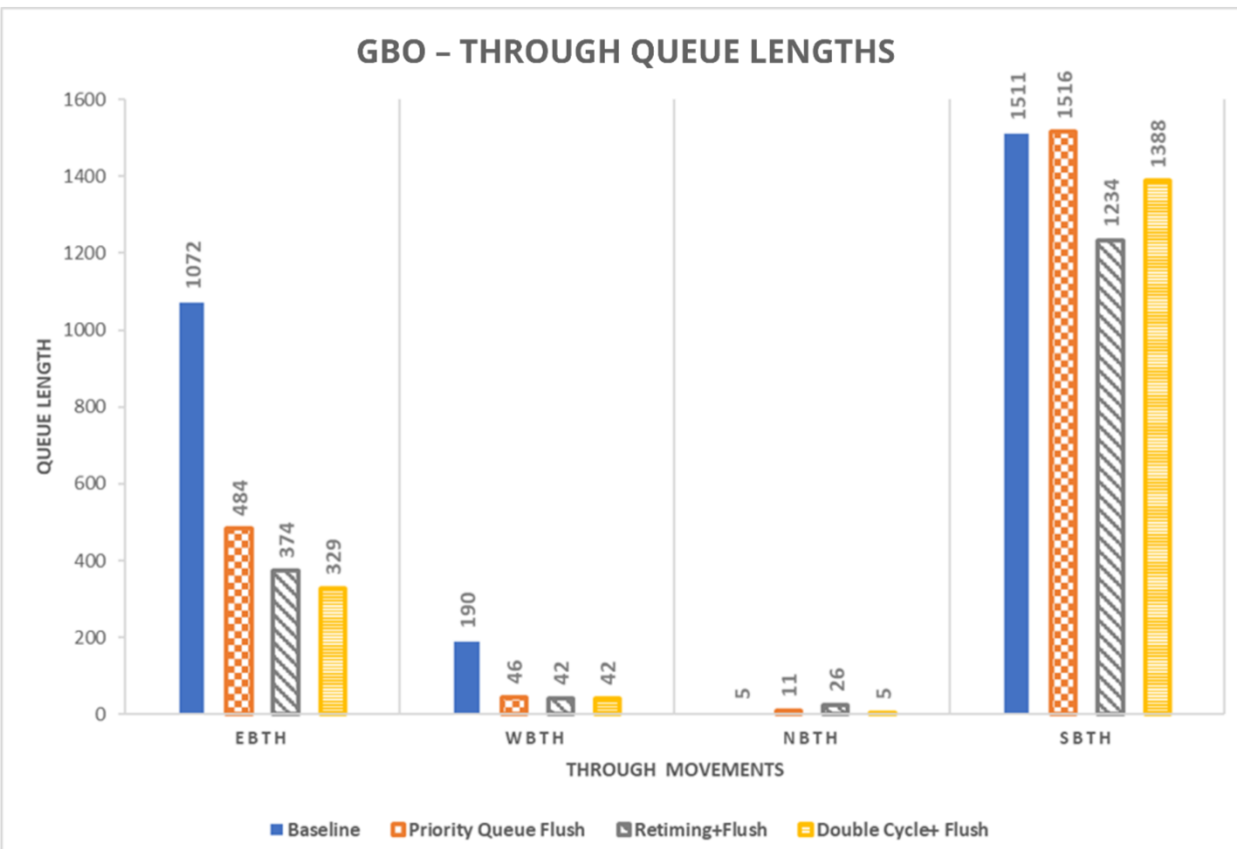


Figure 19. Queue lengths of through movements for four queue management strategies at GBO intersection.

Table 17. Queue Lengths at George Bush and Olsen Through Movements with Statistical Significance

Movement	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
Eastbound Through	1072	484 ***	374 ***	329 ***
Westbound Through	190	46 ***	42 **	42 **
Northbound Through	5	11 ***	26 ***	5
Southbound Through	1511	1516	1234 ***	1388 **

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

Figure 20 focuses on the average left turn queue lengths for the four approaches in each scenario. Table 18 lists the average queue length values for each left turn movement for each scenario with asterisks to represent the statistical significance for the difference between the scenario and the baseline using a student's t-test. The eastbound left turn average queue length reduces, but not at a statistically significant amount. The westbound and northbound left turn average queue lengths increase some between the baseline and the priority queue flush scenarios and then increase drastically for the retiming and the double cycle scenarios. The southbound left turn queue length also shows signs of increase in response to the treatment scenarios.

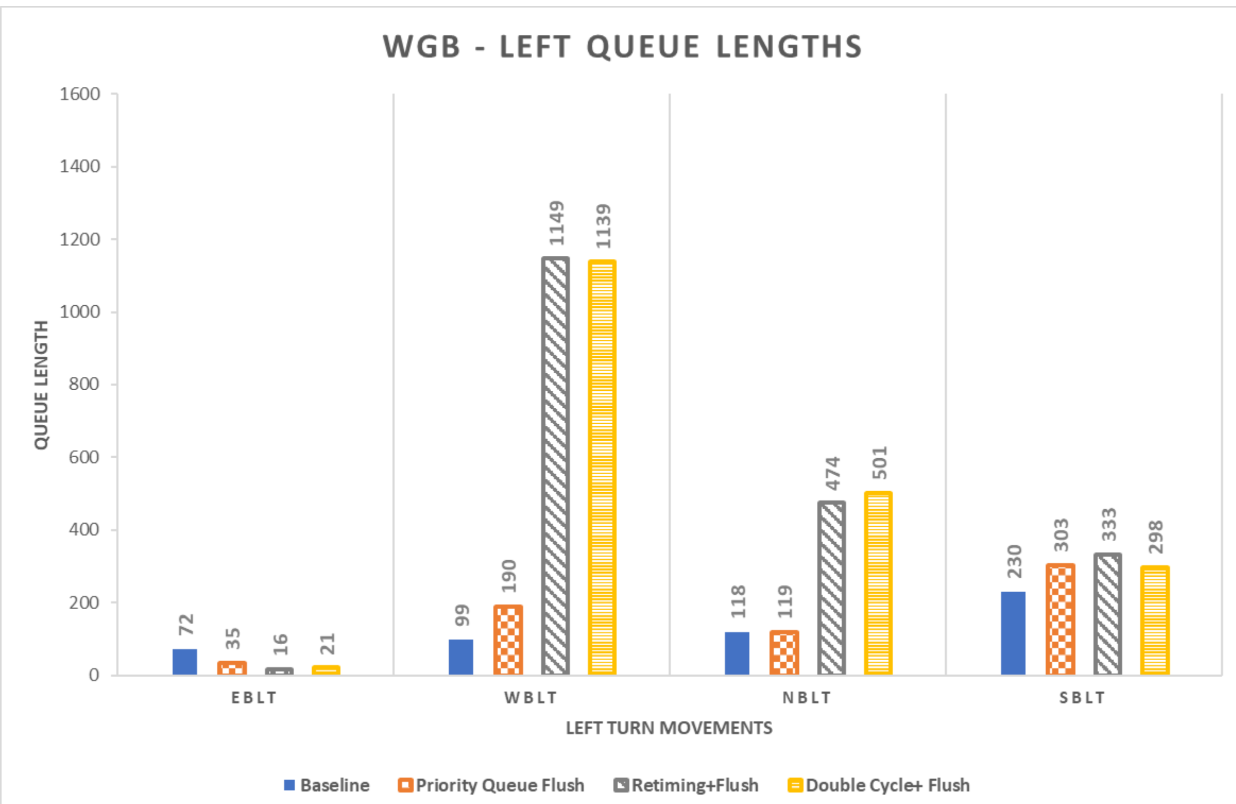


Figure 20. Average queue lengths of left turn movements for the analyzed queue management strategies at Wellborn-Bush intersection.

Table 18. Queue Lengths at Wellborn and George Bush Left Turn Movements with Statistical Significance

Movement	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
Eastbound Left Turn	72	35	16	21
Westbound Left Turn	99	190	1149 ***	1139 ***
Northbound Left Turn	118	119	474 **	501 **
Southbound Left Turn	230	303	333 *	298

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

The WGB through movement average queue lengths are shown in Figure 21. Table 19 lists the average queue length values for each through movement at WGB for each scenario with asterisks to represent the statistical significance for the difference between the scenario and the baseline using a student's t-test. These results indicate that the eastbound through movement would experience a significant reduction in queue lengths from the deployed scenarios. The priority flush would increase green time for this movement. Westbound through movements would have about the same queue lengths between the baseline and the priority queue flush, but the retiming and the double cycle scenarios would triple the queue lengths, which is statistically significant. The northbound through queue length would remain smaller than the others but increase with the scenarios. The southbound through queue lengths would remain long, with notable reductions in queue lengths for the retiming and double cycle strategies.

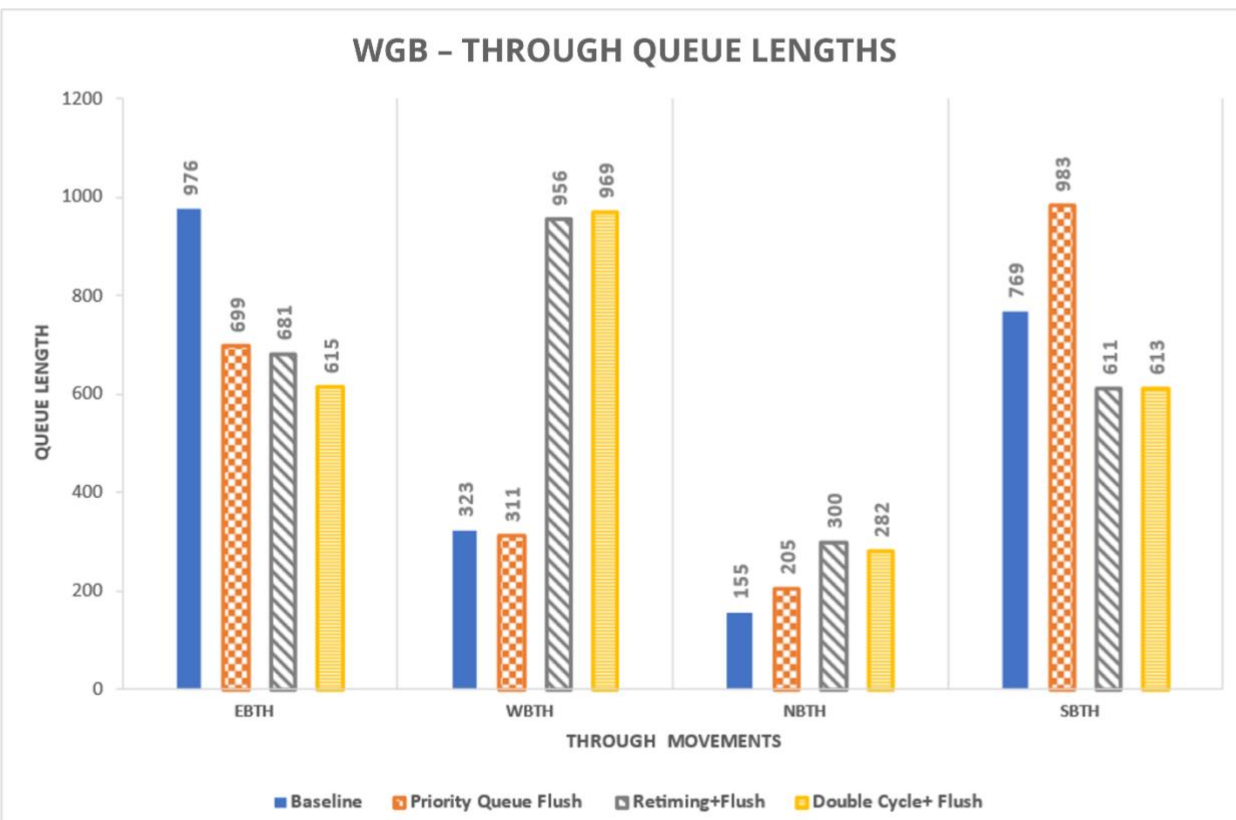


Figure 21. Average queue lengths of through movements for the analyzed queue management strategies at the Wellborn-Bush intersection.

Table 19. Queue Lengths at George Bush and Olsen Through Movements with Statistical Significance

Movement	Baseline	Priority Queue Flush	Retiming + Flush	Double Cycle + Flush
Eastbound Through	976	699 ***	681 ***	615 ***
Westbound Through	323	311	956 ***	969 ***
Northbound Through	155	205 ***	300 **	282 **
Southbound Through	769	983 ***	611 ***	613 **

** Statistically significant at 90%; ** statistically significant at 95%; *** statistically significant at 99%.*

The research team considered these simulation results and reports from the City of College Station about complaints from the local transit operators that the westbound left turn at WGB seemed worse and decided not to change the deployment in the field from the priority queue flush scenario. The team saw the increases projected for the westbound left turn in the retiming and double cycle scenarios unacceptable for deployment. In addition, the 90-second cycle length for GBO would not be able to service pedestrians, so this strategy is not eligible for deployment since it harms the westbound and northbound left turn movements at WGB and it cannot service pedestrians at GBO.

INRIX Signal Analytics

INRIX is one of the largest transportation on-demand crowd sourced data service providers, offering a suite of tools to monitor and analyze performance trends on the transportation network. Using anonymous data from connected vehicles, researchers and transportation operators can identify and visualize year-over-year or day-over-day trends. Vehicle speed and travel time information are available on individual street segments in 1-, 5-, and 15-minute as well as one-hour intervals, 365 days per year, significantly enhancing planning and monitoring capabilities. This section and the following sections provide an analysis using several of the tools available on the INRIX platform.

INRIX offered access to their Traffic Signal Analytics platform for the three intersections along George Bush Dr to evaluate the before and after signal performance measures for the corridor and at the individual intersection level. INRIX developed a method to obtain traffic signal analytics data without installation of field detection equipment. To obtain this data, INRIX collects anonymous vehicle waypoint “breadcrumbs” at three- to five-second intervals from probe vehicles. Individual vehicle waypoints are used to calculate travel times through intersections. Within the Traffic Signal Analytics application, INRIX uses the following assumptions when estimating vehicle attributes such as turning movements, vehicle stops, approach speed, and traffic signal split failures.

1. Shown in Figure 22, the intersection influence area is 150 meters upstream and 80 meters downstream of the intersection. All data are aggregated together at the node (signal) for all intersecting roadways.
2. The 5th percentile travel time is used to define the limit of unimpeded travel time, so vehicles traveling slower than the 5th percentile travel time are considered to be delayed.
3. Vehicles that slow below 6 MPH for three seconds or more are considered stopped vehicles. This metric aligns with Advanced Traffic Signal Performance Measures (ATSPMs) in a detector-based system.

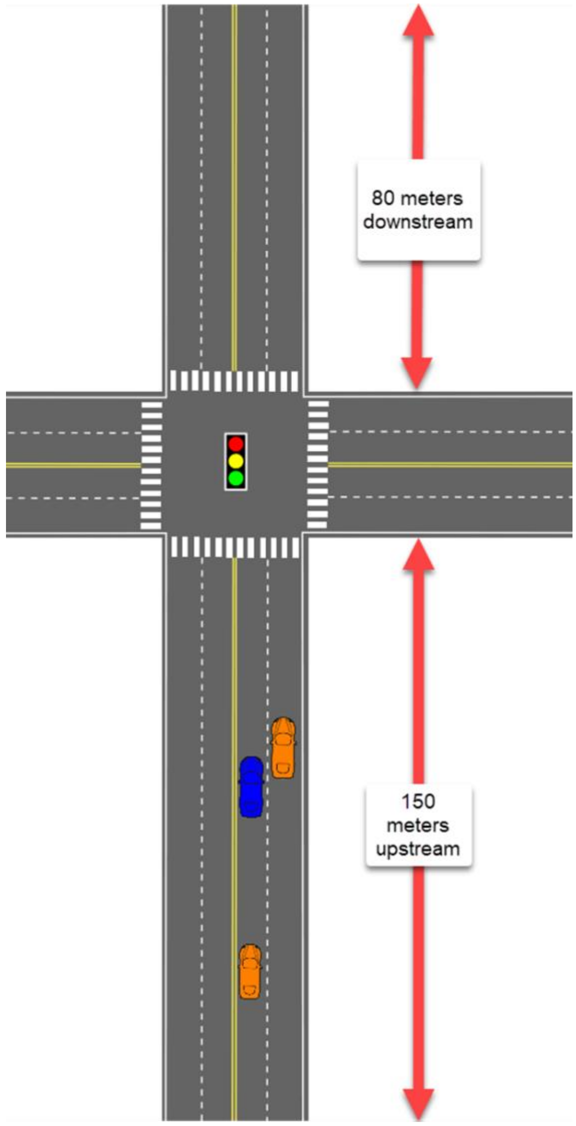


Figure 22. INRIX signal analytics intersection influence area.

The data are aggregated by intersection and summarized over time periods (INRIX, 2021). The following performance metrics are reported on the platform in summary and detailed reports.

The research team focused on the average control delay per vehicle metric. The average delay per vehicle is a measure of a traffic signal operation that is useful to understand the mean wait time for each vehicle at an intersection. Commonly, motorists wait longer at intersections with a higher delay per vehicle regardless of traffic volume at the intersection. This could be attributed to poor signal timing, preemption, or other factors that influence signal operation (INRIX, 2021).

The team investigated the control delay according to the INRIX Signal Analytics tools for GBO and WGB since these are the key intersections in the testbed. Figure 23 shows the average control delay for the approaches at GBO, where all the movements are combined to increase the sample size, for the week of April 25–29, 2023, with a filter to reduce the times to the PM peak of 4:00–7:00 PM, since the PM peak was of the most interest to this research effort. This timeframe is the week after the revised operations were deployed. The figure shows the number of observations, or individual vehicles recorded, for each approach gathered throughout the week. Overall, the southbound approach has the highest delays, which is expected given the metering techniques employed.

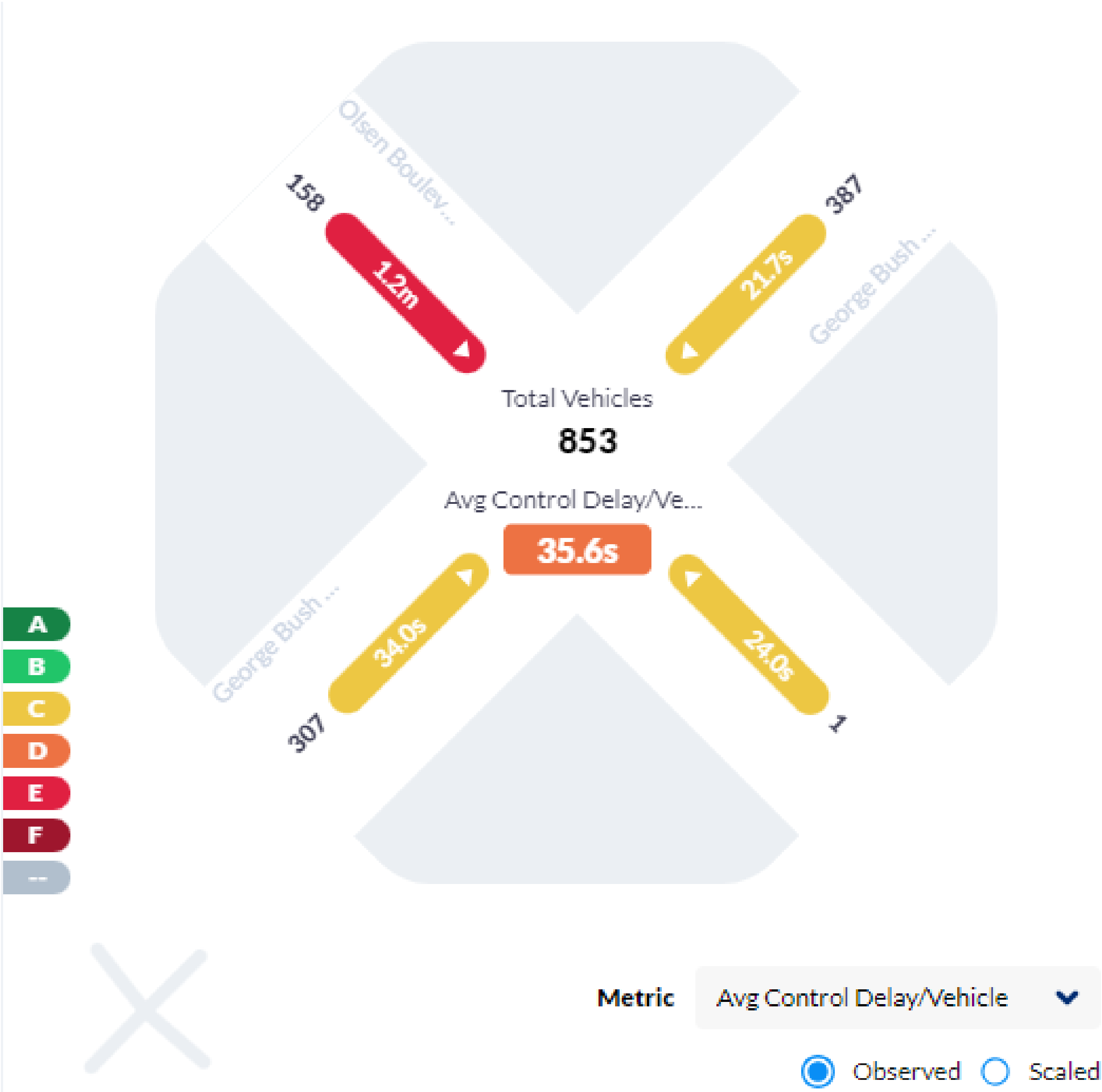


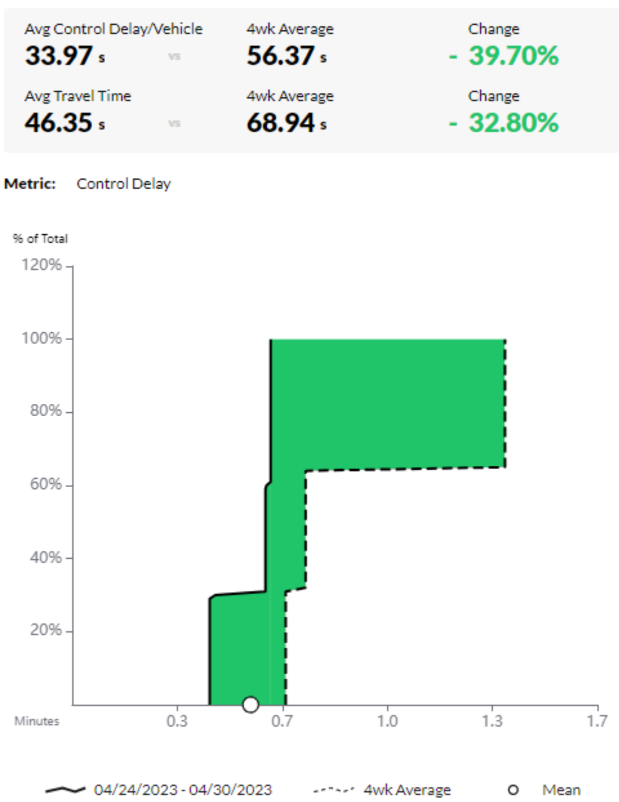
Figure 23. INRIX signal analytics average control delay per vehicle for George Bush and Olsen at the PM peak.

The signal analytics tool also allows users to generate cumulative distribution graphs comparing the average metrics for a given period to the previous four weeks' worth of data.

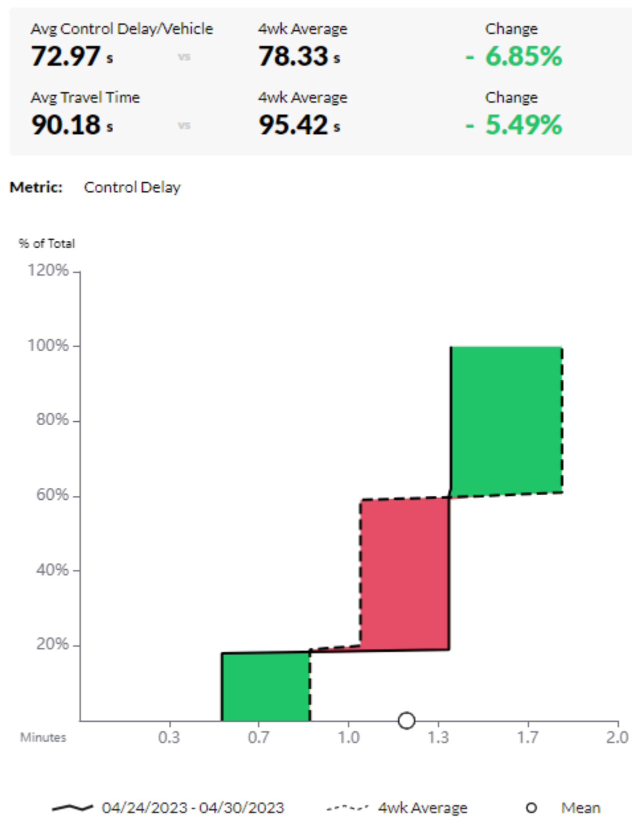
Figure 24 (a) and (b) shows the details of control delay for the eastbound and southbound approaches. This figure displays the distribution of control delay, which reveals that the eastbound control delay is consistently lower post deployment. The post deployment data reduced delay the most for the users at the highest end of the distribution, starting at the 65th percentile, which experienced an average of 84 seconds of delay per vehicle in the four-week average but only 38 seconds of delay on April 20, 2023.

Figure 24 (a) also shows that the average travel time reduced from about 69 seconds for the eastbound approach to about 46 seconds. The southbound approach a five-second reduction in delay and travel time according to

Figure 24 (b), which is surprising since this approach should have been metered and, as a result, penalized. The raw data for the measurements in this dataset were not available, so the research team could not run a statistical analysis on these metrics. The team believes that this lack of negative impact is because the volumes at the end of the spring semester at Texas A&M University were not high enough to stress the system.



(a) Eastbound Approach



(b) Southbound Approach

Figure 24. INRIX signal analytics cumulative distribution graphs for eastbound (a) and southbound (b) approaches at George Bush and Olsen at the PM peak.

The control delay for the four approaches at WGB is shown in Figure 25, illustrating that there is delay in all four approaches with the highest delays per vehicle on the northbound and westbound approach. As expected, the delays are higher at WGB. Figure 26 (a) and (b) shows the cumulative distribution graphs of the eastbound and westbound approaches at WGB. This figure reveals that the eastbound approach does experience a reduction in delay and travel time, and the westbound direction experiences an increase. Figure 26 (a) shows that the decrease in delay kept the same variance in travel times, while Figure 26 (b) shows that the variance in delay increased post deployment.

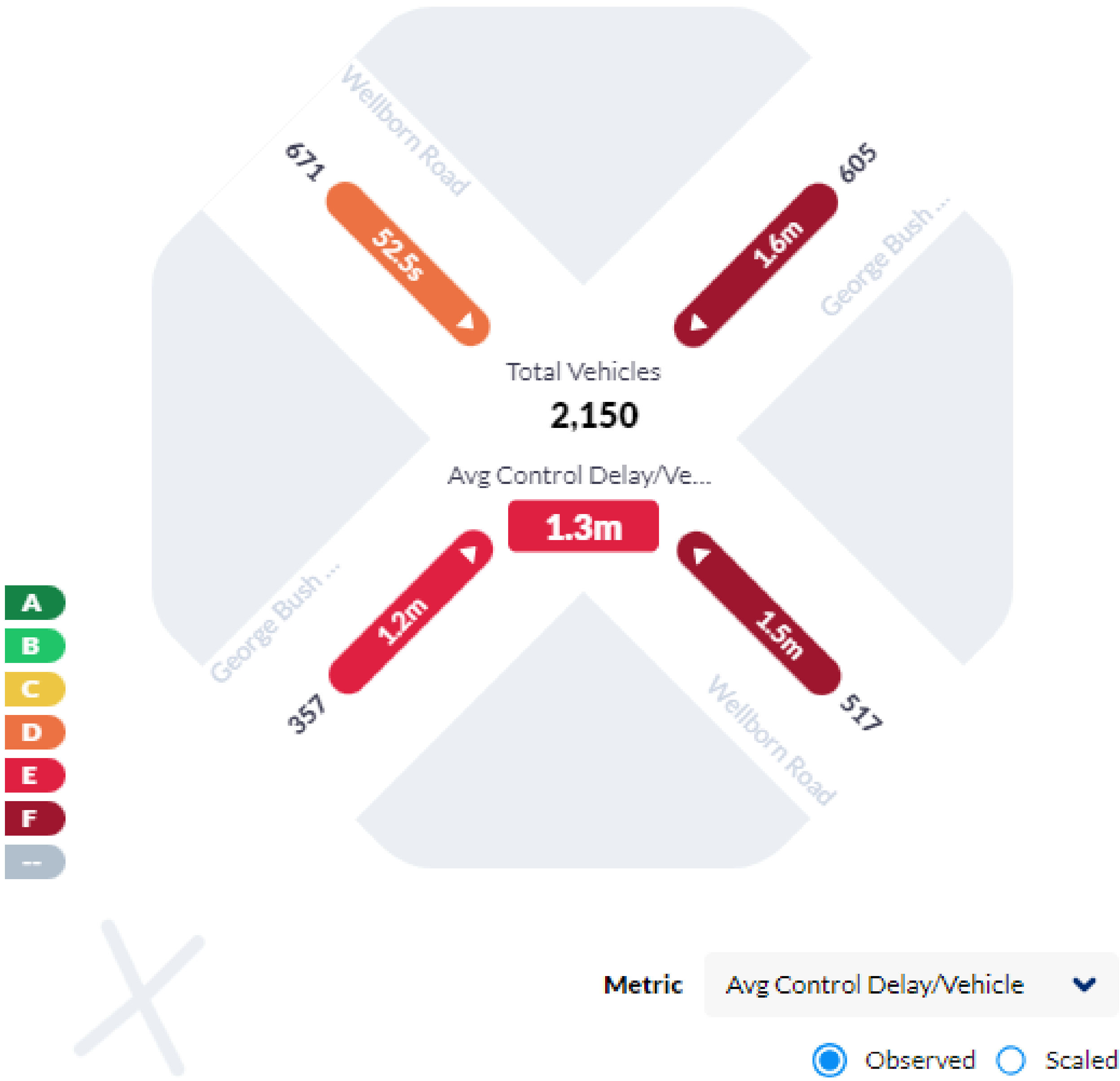
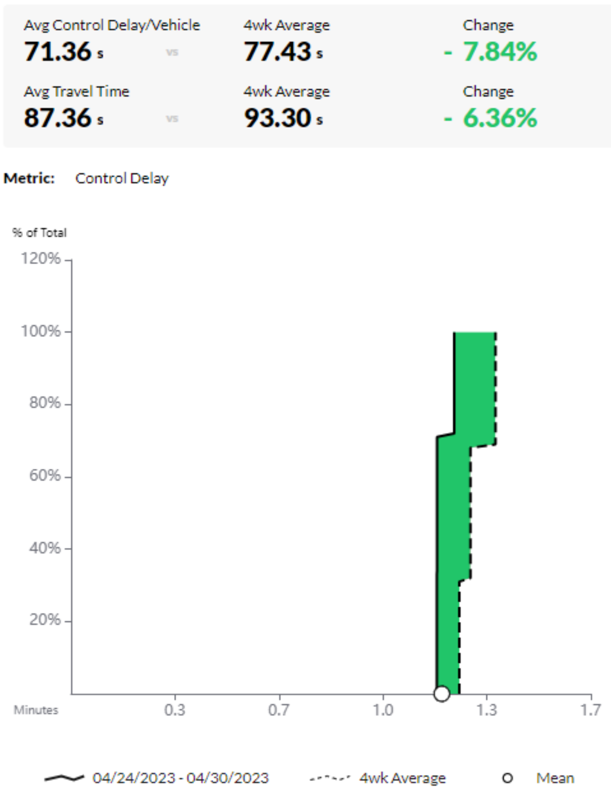
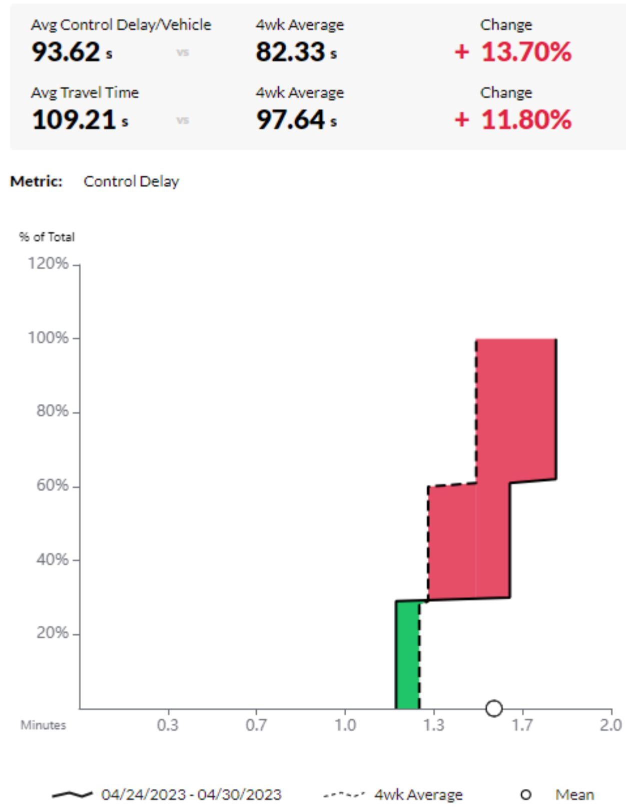


Figure 25. INRIX signal analytics average control delay per vehicle for Wellborn and George Bush at the PM peak.



(a) Eastbound Approach



(b) Westbound Approach

Figure 26. INRIX signal analytics cumulative distribution graphs for eastbound (a) and westbound (b) approaches at Wellborn and George Bush at the PM peak.

INRIX Corridor Analytics

The research team also analyzed the George Bush corridor from Penberthy past Wellborn using the INRIX corridor analytics tools. This tool compiles data for vehicles traveling through each of these intersections. Since the corridor analysis tool limits the sample size to users who travel the entire length of the corridor, the team used the 24-hour period for the week of April 25–29, 2023, for the corridor analysis. The INRIX tool provides similar cumulative distribution graphs for the corridor travel times and charts on the hourly vehicle counts. For brevity, the eastbound vehicle counts and corresponding travel times are shown in Table 20. The data show that there is an increase in vehicles observed going the eastbound direction and a decrease in travel times of about 30 seconds. The increase in vehicles counted does not indicate an increase in throughput because this increase could mean that more vehicles sending INRIX data traveled this corridor; that is, there could have been an increase in market penetration but the same number of vehicles. The changes in travel time, on the other hand, are notable and show that there is a decrease in travel time for eastbound traffic. It is noteworthy that the raw data for the measurements in this dataset were not available, so the research team could not run a statistical analysis on these metrics.

Table 20. INRIX Corridor Analytics for Eastbound George Bush Dr – Week of April 25, 2023

Metric	Observation	Four-Week Average	Change	Percent Change
Vehicle Count	515 vehicles	450 vehicles	+65 vehicles	+14.4%
Travel Time	3.2 minutes	3.7 minutes	-29.8 seconds	-13.4%

The westbound corridor analytics results are shown in Table 21. Overall, the westbound corridor vehicle counts and travel times did not reveal any notable changes.

Table 21. INRIX Corridor Analytics for Westbound George Bush Dr – Week of April 25, 2023

Metric	Observation	Four-Week Average	Change	Percent Change
Vehicle Count	398 vehicles	406 vehicles	-8 vehicles	-1.9%
Travel Time	3.6 minutes	3.5 minutes	+4.8 seconds	+2.3%

INRIX Roadway Analytics Travel Time Analysis

INRIX's Roadway Analytics tool was used to build the street network shown in Figure 27 for this analysis along with the data download. This tool allowed the research team to compare the operations of the deployed strategy in between the fall semester of 2022 to the fall semester of 2023. The beginning of the fall semester is the time of year that this testbed experiences the highest demand, excluding special events. Five-minute data were downloaded and analyzed for the second week of the Texas A&M University's fall semester in 2022 (August 29 – September 2) and 2023 (August 28 – September 1) to evaluate any effects the modification in signal timing had on directional corridor travel times. The analysts generated graphics and performed the analysis using standard Microsoft Excel features.

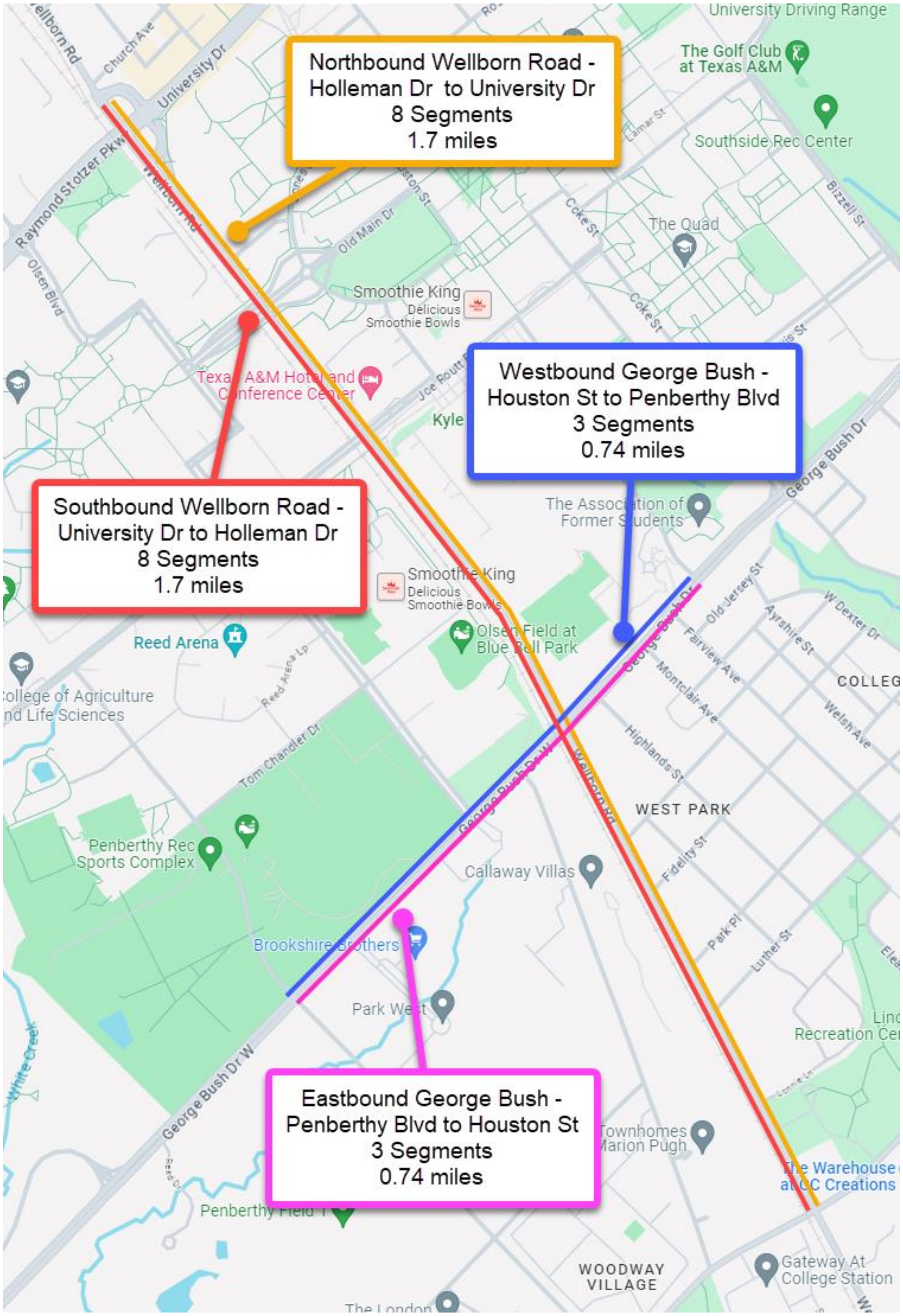


Figure 27. INRIX roadway network.

Since traffic along the George Bush Dr and Wellborn Rd corridors is heavily affected by students and faculty attending classes, classroom enrollment and typical weekday traffic congestion were reviewed to determine the best time to evaluate travel time patterns. Figure 28 shows the number of students enrolled in 2023 fall semester classes by time of day and day of week along with historical traffic congestion on major streets in Bryan and College Station, Texas, from 2022. The highest block of enrollment is on Tuesdays and Thursdays, with 11:15 AM and 12:30 PM having the highest number of potential students in the classroom. Conversely, Fridays have the lowest enrollment during any time period and it drops off to minimal levels after 4:00 PM. Classroom occupancy has a direct relationship to traffic congestion as there is an early morning peak when students are going to class that tapers off for most of the day when classrooms are fullest. Congestion again rises around 4:00 PM, peaking at 5:30 PM when there are fewer students in class. Congestion dissipates at about 6:30 PM when classes are done for the day.

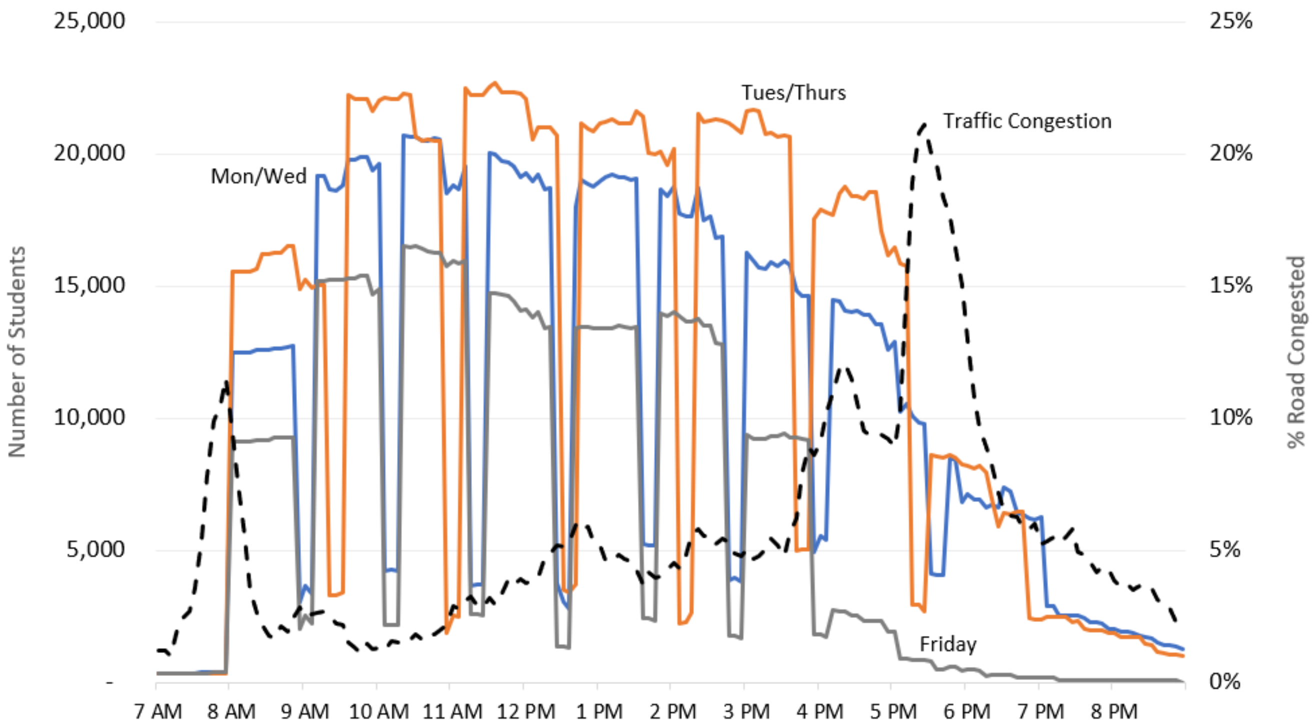


Figure 28. Texas A&M University class and lab enrollment vs. typical day traffic – fall 2023 semester.

Figure 29 shows the travel times for eastbound George Bush Dr from 12:00 AM until 11:59 PM on Monday and Wednesday for the second week of class, while Figure 30 includes just the afternoon peak hour travel time (4:00–7:00 PM) data. Travel times fluctuate throughout the day but are highest during the afternoon peak for both days in 2022. Travel times in 2023 are lower in general throughout the day with the largest change during the afternoon peak. During the peak period, travel times were generally one to three minutes lower (38 and 41 percent lower on average on Monday and Wednesday, respectively). The exception is around 6:10 PM on Wednesday when post signal modification (2023) travel times were higher than before the changes (2022). This could be attributed to a train event or other anomalies as it only lasted for one five-minute interval.

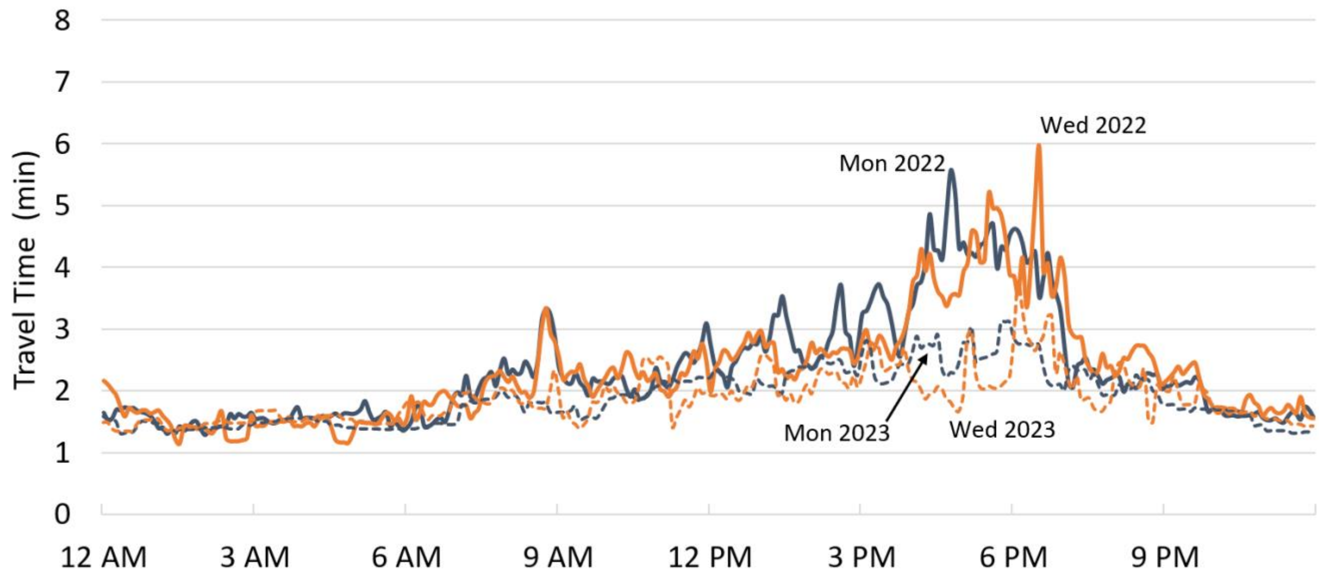


Figure 29. George Bush Dr eastbound travel time – Monday & Wednesday 2nd week of fall semester.

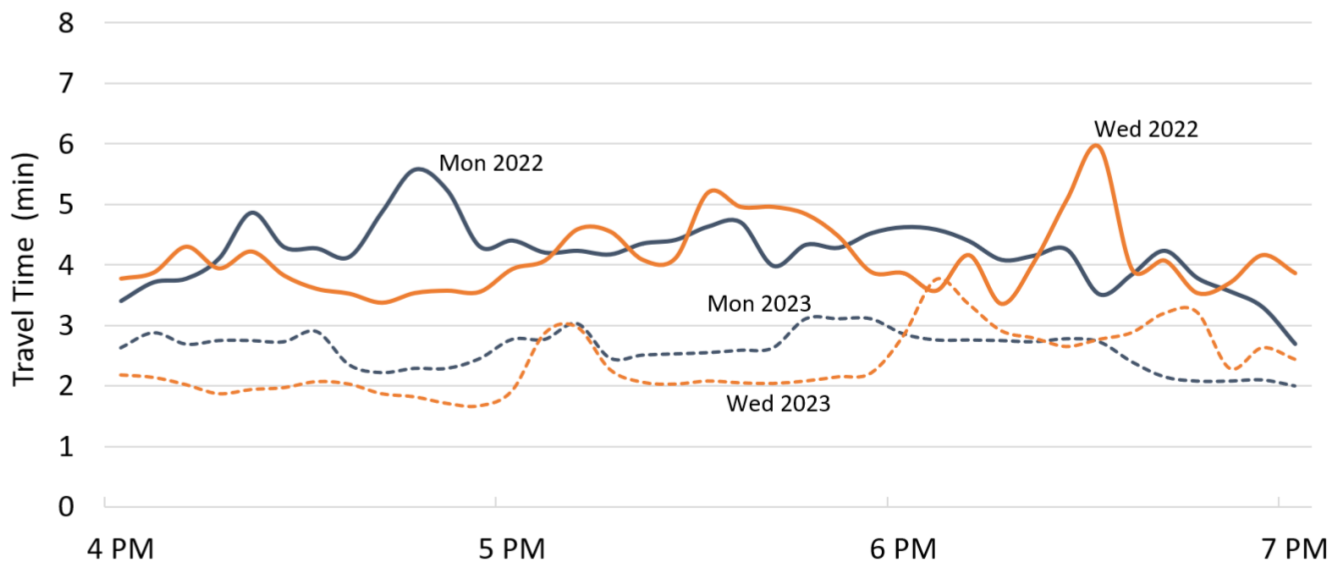


Figure 30. George Bush Dr eastbound PM peak period travel time – Monday & Wednesday 2nd week of fall semester.

All day Tuesday/Thursday travel times for eastbound George Bush Dr are shown in Figure 31, while Figure 32 includes only the afternoon peak period data. The data resemble the Monday/Wednesday data with the overall peak about one minute longer. Afternoon peak travel times were on average 41 percent lower on Tuesday and 44 percent lower on Thursday, with the peak time down 4.8 minutes.

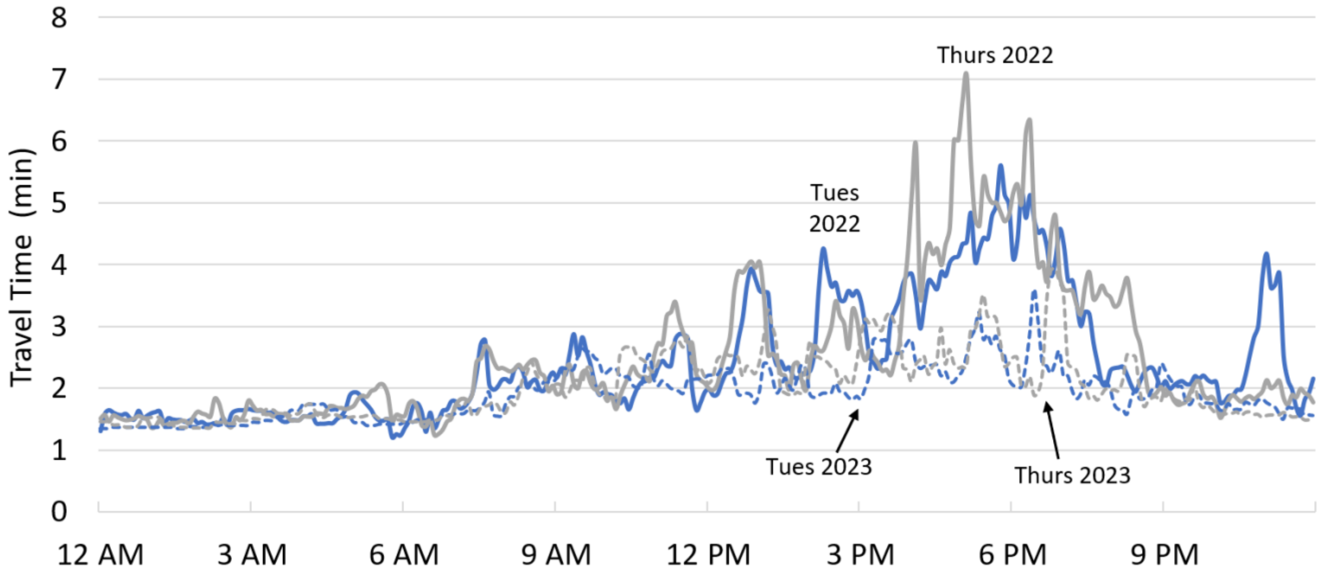


Figure 31. George Bush Dr eastbound travel time – Tuesday & Thursday 2nd week of fall semester.

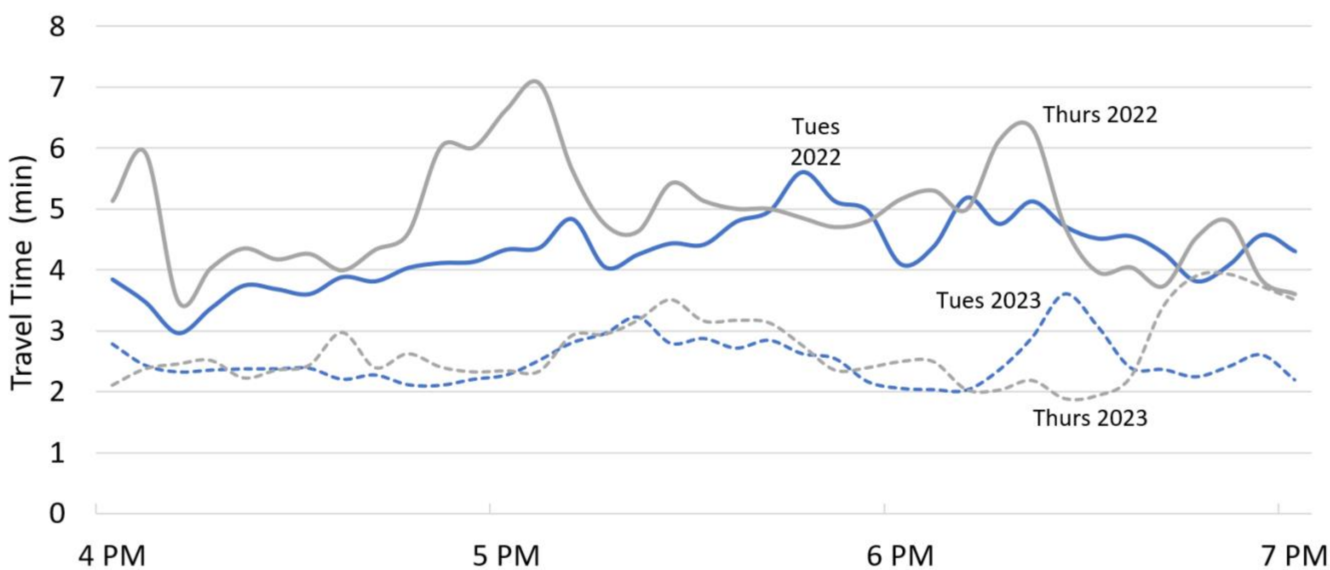


Figure 32. George Bush Dr eastbound PM peak period travel time – Tuesday & Thursday 2nd week of fall semester.

Based on this information comparing eastbound travel times on Monday/Wednesday and Tuesday/Thursday all day versus the afternoon peak, as well as the traffic congestion and enrollment data presented earlier, the targeted analysis period was 4:00 PM to 7:00 PM on Tuesday and Thursday. The remaining graphics for westbound George Bush and northbound and southbound Wellborn Rd are shown for this time period.

Travel times for westbound George Bush Dr are included in Figure 33. As expected, there was a 10 to 18 percent improvement in travel times on average, but it is not as clear and there are more instances where it was lower in the before condition. This is because priority was given to eastbound traffic with the new signal timing operation.

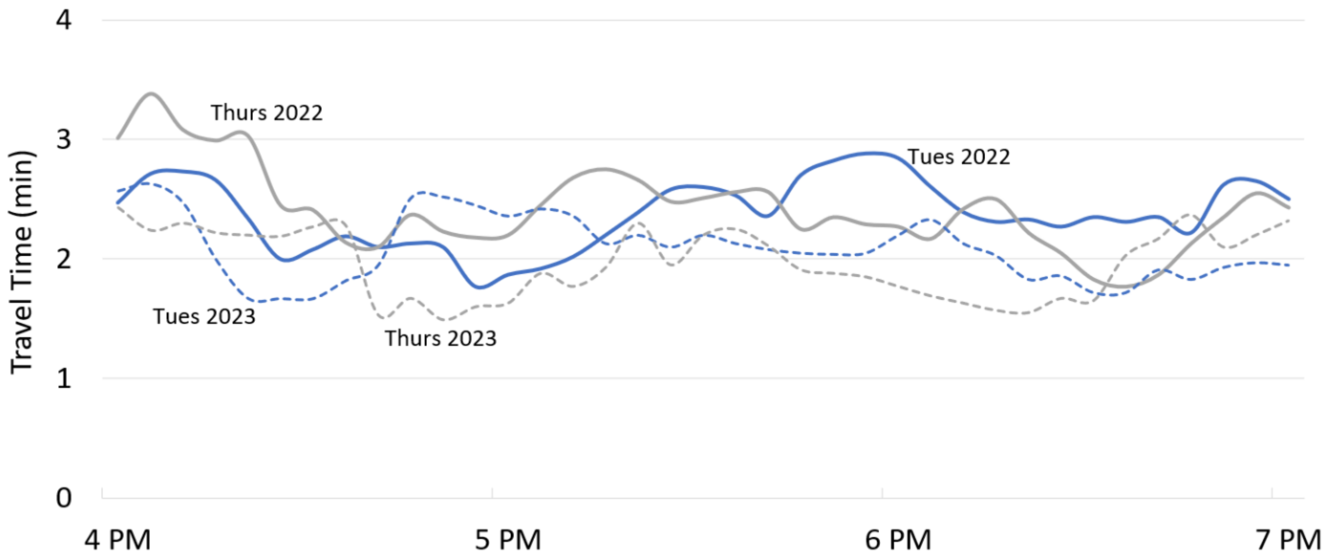


Figure 33. George Bush Dr westbound PM peak period travel time – Tuesday & Thursday 2nd week of fall semester.

Figure 34 and Figure 35 show northbound and southbound Wellborn Rd afternoon peak travel times, respectively. Northbound results are similar to westbound George Bush Dr. Travel time improvements were 1 to 10 percent and travel times were often worse following the signal timing changes, particularly on Tuesday between 5:00 PM and 5:30 PM and after 6:15 PM. Thursday 2023 traffic was overall an improvement over 2022.

Southbound travel times displayed a more obvious improvement except on Tuesday from 5:25 PM to 5:35 PM. Interestingly, southbound travel times are nearly double northbound and at the peak are 2.2 times longer. The large improvement (30 and 34 percent) is somewhat surprising given the long queues observed over the spring 2023 semester on Tuesday evenings and the priority given to George Bush Dr traffic. The 30 percent average reduction could be a result of driver frustration and students and the community finding alternative routes to Wellborn Rd.

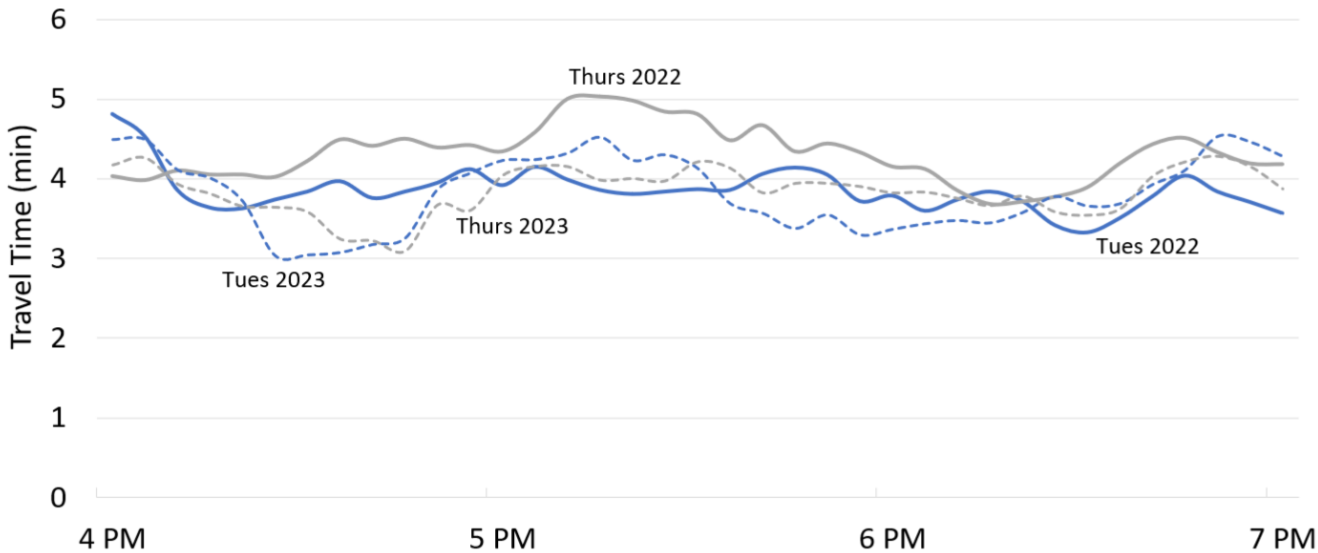


Figure 34. Wellborn Rd northbound PM peak period travel time – Tuesday & Thursday 2nd week of fall semester.

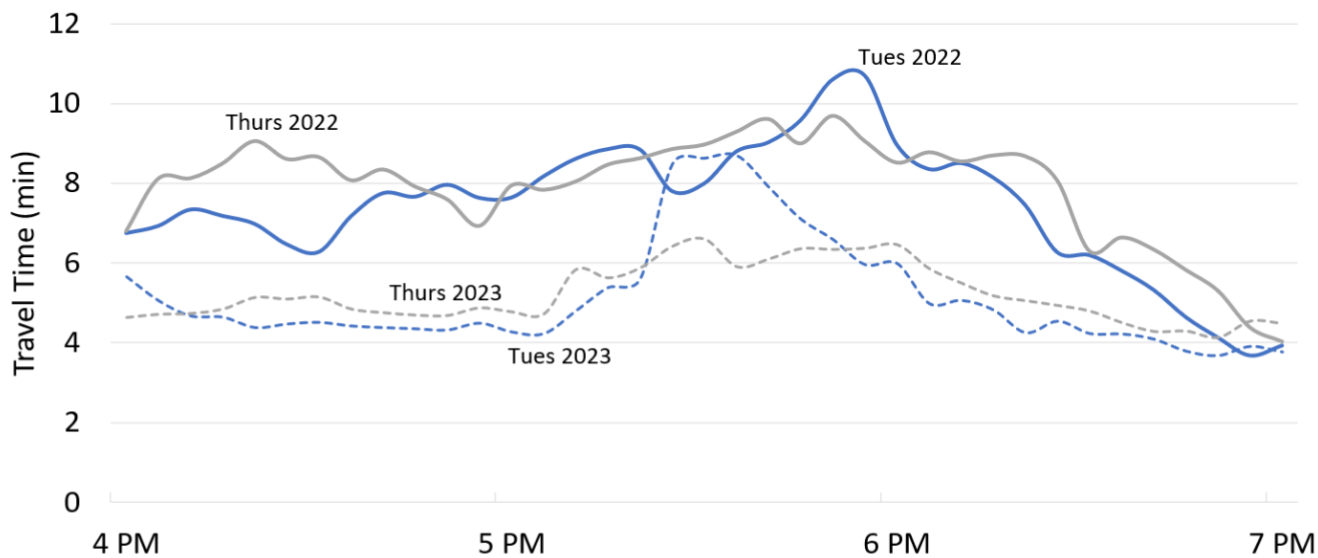


Figure 35. Wellborn Rd southbound PM peak period travel time – Tuesday & Thursday 2nd week of fall semester.

Miscellaneous Field Adjustments

This section discusses adjustments made to the deployed strategy given observations in the simulation environment, complaints from motorists, and field observations. Three undesirable operations are identified and the attempts to address the behavior are discussed. The three phenomena include redundant queue flushing, lack of service for Olsen Blvd, and unreasonable queue flushes.

Redundant Queue Flushing

An analyst on the research team reviewed the simulation animation during a simulation run for evaluation and noticed that the behavior following a train preemption was undesirable. The normal operations for the corridor included a strategy to clear queues after a train preemption at WGB. This was a strategy deployed before the research effort that involved entering a different preempt after the train preemption, preempt 1, that called the eastbound movements to flush the queue that built up while the train blocked the intersection. The signal controller contained some logic that determined how long a queue flush to call after different durations of preempt 1. The queue flushes were operated with preempts 9 through 12.

The analyst observed that after a simulated train preemption ended, preempt 11 would activate, calling the eastbound phases 3 and 8, and then go to phases 2 and 6. However, phases 2 and 6 were served for the minimum time and phases 9 and 10 would then activate as a priority flush. Therefore, the eastbound movement would be flushed twice for the same train. This observation was noted and confirmed with review of the field data and bench testing. Figure 36 shows the PM peak period for September 1, 2023, and that there were TSP check-ins while the controller was in preempt, shown by the orange bars. The TSP check-in during the preemption would be remembered and enacted at the earliest opportunity once the controller exited preemption. Thus, the controller would service the redundant priority flush once the preemptions ended.

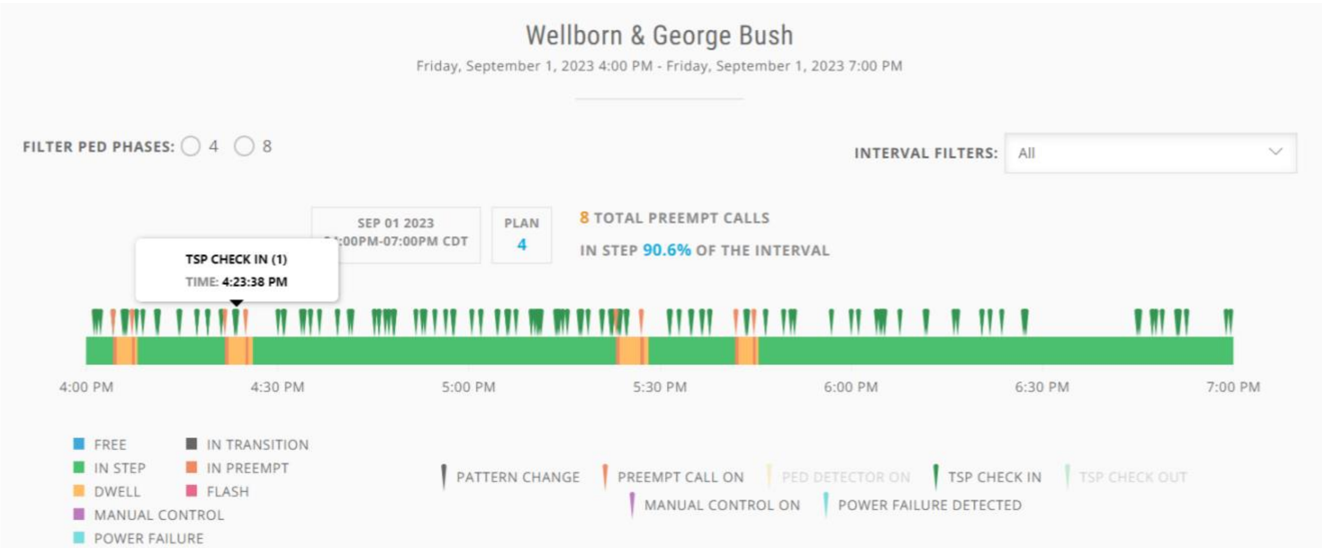


Figure 36. Priority routine check-ins during train preemptions – September 1, 2023.

The research team worked with local operations experts at Iteris, Inc., to develop a solution to this back-to-back flushing behavior. The developed solution involved introducing a Special Function 8, which called unit bank 2. Unit bank 2 was a copy of unit bank 1, but it didn't have the logic to begin a priority flush. Therefore, if the detector driving the priority flush was occupied and a preempt related to the train was active, the priority flush would not be called. The steps to accomplish this logic were developed into instructions based on bench testing. The research team used the test bench to confirm that this mitigation strategy worked in the lab and then deployed the change in the field, on September 15, 2023.

The team then used the signal performance metrics available through Iteris and the City of College Station and confirmed that the priority flush was not happening immediately after a train preemption. Figure 37 shows an example day after implementing the change where there are long preemptions related to trains but no priority check-ins during the preemptions.

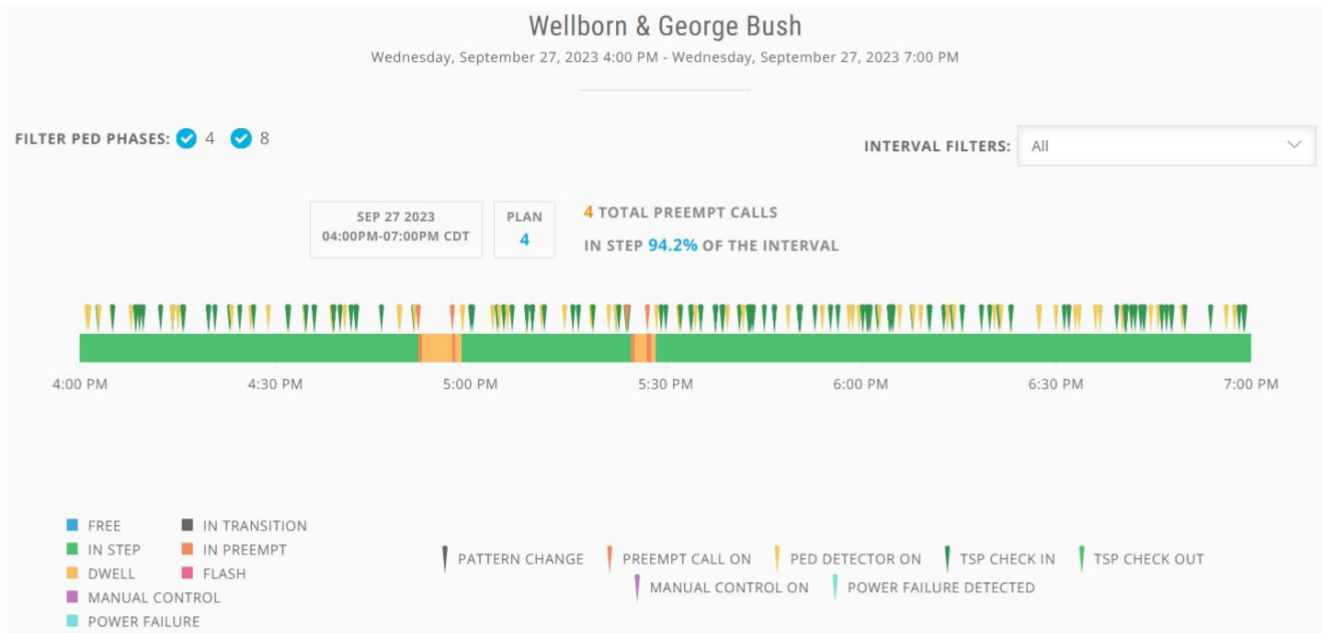


Figure 37. No priority routine check-ins during preemptions – September 27, 2023.

Lack of Service for Olsen Boulevard

Over the course of the project, the City of College Station received three complaints about phases being skipped at GBO. Each complaint claimed 10 minutes between green indications. The first complaint was confirmed for phase 3 with a wait time of 671 seconds with service twice between 5:18 PM and 5:30 PM on September 6, 2023. The research team identified that these were caused by multiple adjacent preemptions and the redundant queue flushes. Nonetheless, the team decided to rearrange the ring structure of GBO so that phase 3 was lagging and the cycle would bring up phase 2 before phase 4 if phase 3 was active. The team then removed the omit for phase 3 from GBO.

On October 12, 2023, and on October 25, 2023, the City of College Station received complaints about the signal not changing for southbound Olsen. The research team confirmed that phase 4 was receiving a wait time in excess 600 seconds for phase 4. For the October 25 complaint, the City was able to confirm with its recorded video that traveler was facing a perceived no-service scenario since the eastbound traffic continually triggered metering at the end of phase 2. Video of the condition on October 25 also indicated that pedestrians and cyclists were crossing the intersection on a “Don’t Walk” indication due to impatience.

The research team investigated how to establish effective metering but still provide occasional service to phase 4 and reduce frustration. However, the Siemens M60 controller did not offer the ability for users to easily customize the metering technique to be more conditional. Thus, the team decided to remove the metering technique deployed at GBO.

Unreasonable Priority Flushes

The research team observed on many occasions that the priority check-ins were happening more frequently than expected. In a four-hour period there could be more than 150 check-ins (see Figure 36 and Figure 37). During field visits, analysts also observed check-ins for priority flushes happening from turning traffic in motion despite the configuration of the radar unit searching for a queue. The team tried changing the configuration and shape of the detection zone for the radar unit but was unable to determine the settings that reduced the frequency of check-in requests from vehicles in motion.

Chapter 5. Conclusions

This research effort sought to evaluate and recommend operations for an interaction pair struggling to manage demand and regular interruptions from a train preemption between the intersections. Previous efforts at these intersections show that the major intersection could not operate in coordination since it would spend too much time in transition to make coordinated operations worthwhile. The goal of the strategies considered in this research were to increase service for the eastbound direction along George Bush Dr in College Station, Texas, at the intersection of George Bush Dr and Wellborn Rd. The effort included a simulation analysis and a field deployment and analysis. The simulation tools revealed that the deployed scenario would be most effective with mitigation of negative impacts to conflicting movements, especially the westbound left turn movement. Retiming the signals at these intersections may still be beneficial to reduce the cycle lengths, but the proposed signal timings in the simulations did not provide enough green time to the westbound and northbound left turn phases to lead to an overall positive impact on the network. On the other hand, simulation results showed that the introduction of queue flush with a priority routine would benefit the network.

The field analysis, using INRIX data, confirmed the simulation results. The eastbound direction of travel experienced reductions in travel times both at the end of spring and beginning of fall semesters for Texas A&M University.

The deployment did present some challenges for operations. Namely, some additional configuration was needed to prevent redundant queue flushing given existing queue flush operations after a train preemption already deployed at the intersections. The key takeaway from this challenge was that the Siemens M60 controllers will remember calls placed for a priority routine during preemption. The team was able to deploy a resolution to this issue. The other challenges were not solved during the project. The metering strategy proved too aggressive and generated a no-service scenario for the southbound movement at George Bush and Olsen Blvd. Given the lack of tools to put restrictions around the phase omits, the metering strategy needed to be removed. This issue is likely related to the next unsolvable issue of too many priority requests. The research team found that calls would be placed for a priority check-in frequently, even by vehicles in motion, which the radar should not consider for the queue detection. The team recommends identifying an alternative technology for monitoring the queue length driving the system, which should improve function from the no-service problem and the frequent priority check-ins.

Overall, this project found that the addition of a priority queue flush to the system improved performance. The eastbound direction of travel saw improved travel times and the greatest negative effect was on the westbound left turn, which saw an increase in average queue length of 90 feet (or about four vehicles) compared to the baseline. The simulation and field data show that the eastbound direction of travel experienced improvements. Further research should consider shorter cycle lengths that better account for the westbound left turn. Shorter cycle lengths at WGB would be beneficial since long cycle lengths contribute to long queues. In addition, future research should search for a better detection unit to improve the ability to place priority requests only when queued traffic is present at the end of the link.

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Appendix A – Additional Calibration Results

Calibration Results for Westbound

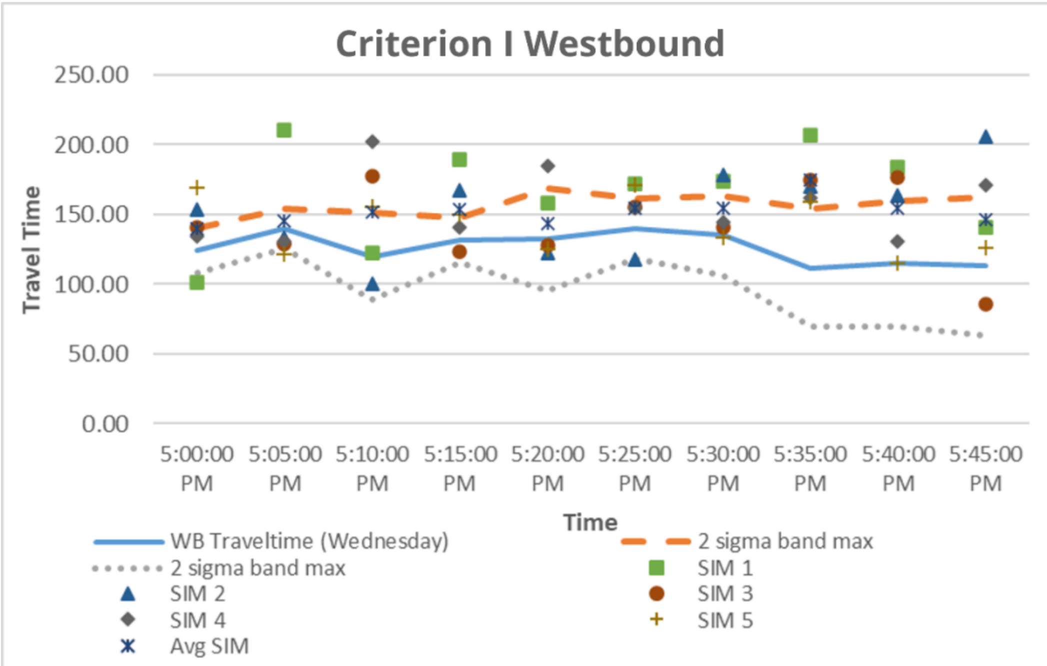


Figure 38. Chart assessing control for time-variant outliers for westbound.

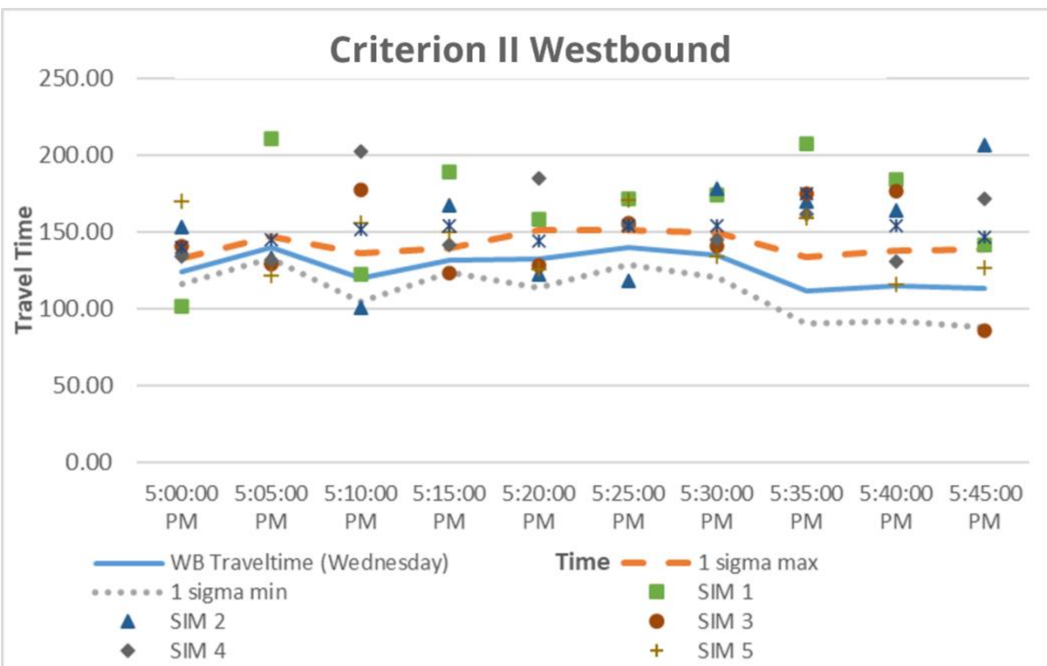


Figure 39. Chart assessing control for time-variant inliers for westbound.

Criterion III Westbound						
Time	Absolute error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	**23.0**	**29.1**	**16.6**	**10.1**	**45.4**	**15.6**
5:05:00 PM	70.4	6.7	11.2	8.7	18.2	5.1
5:10:00 PM	2.4	19.6	56.9	82.1	35.5	31.5
5:15:00 PM	57.5	35.8	8.4	9.7	18.3	22.6
5:20:00 PM	26.0	9.8	4.0	53.1	6.5	11.8
5:25:00 PM	31.8	22.1	16.0	14.5	31.1	14.2
5:30:00 PM	38.8	43.4	5.3	9.8	1.2	19.2
5:35:00 PM	95.4	58.4	63.2	49.9	47.4	62.9
5:40:00 PM	69.3	49.2	62.0	15.7	0.9	39.4
5:45:00 PM	28.3	93.4	27.3	58.5	13.5	33.3
Average absolute error	**44.3**	**36.8**	**27.1**	**31.2**	**21.8**	**25.6**
BDAE Threshold	**17.1**					

Criterion IV Westbound						
Time	Average error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	23.0	-29.1	-16.6	-10.1	-45.4	-15.6
5:05:00 PM	-70.4	6.7	11.2	8.7	18.2	-5.1
5:10:00 PM	-2.4	19.6	-56.9	-82.1	-35.5	-31.5
5:15:00 PM	-57.5	-35.8	8.4	-9.7	-18.3	-22.6
5:20:00 PM	-26.0	9.8	4.0	-53.1	6.5	-11.8
5:25:00 PM	-31.8	22.1	-16.0	-14.5	-31.1	-14.2
5:30:00 PM	-38.8	-43.4	-5.3	-9.8	1.2	-19.2
5:35:00 PM	-95.4	-58.4	-63.2	-49.9	-47.4	-62.9
5:40:00 PM	-69.3	-49.2	-62.0	-15.7	-0.9	-39.4
5:45:00 PM	-28.3	-93.4	27.3	-58.5	-13.5	-33.3
Absolute average error	**39.7**	**25.1**	**16.9**	**29.5**	**16.6**	**25.6**
BDAE Threshold/3	**6.2**					

Calibration Results for Northbound

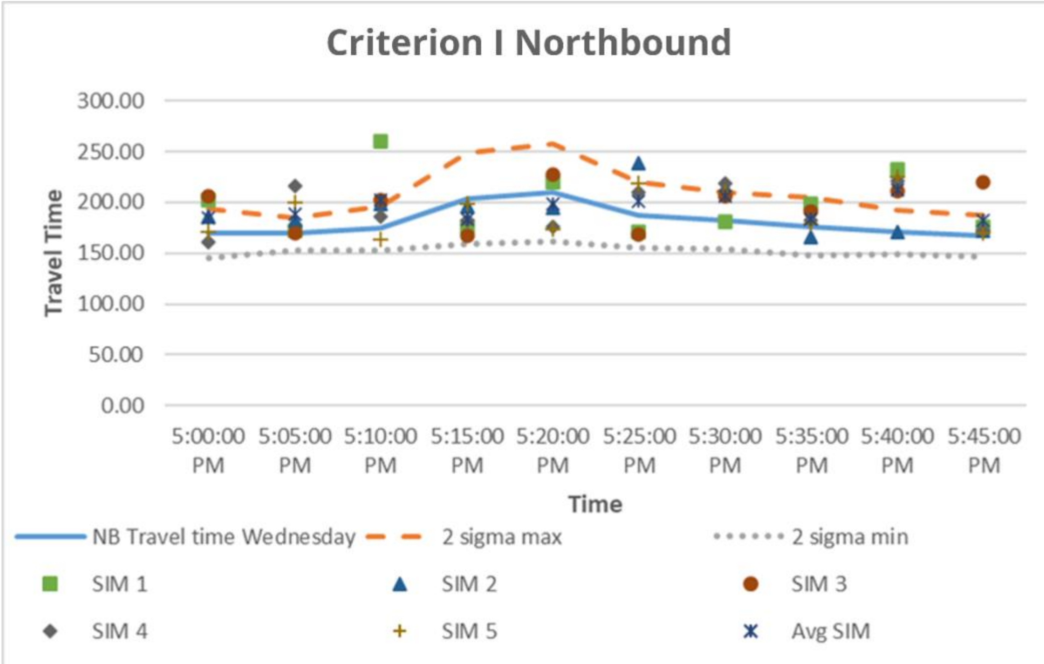


Figure 40. Chart assessing control for time-variant outliers for northbound.

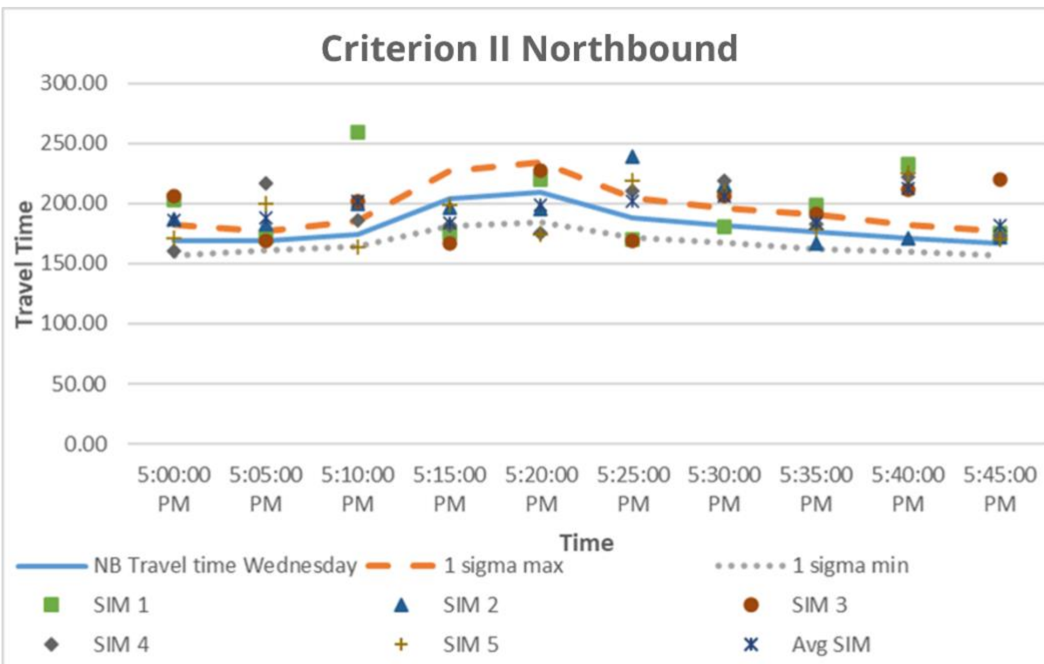


Figure 41. Chart assessing control for time-variant inliers for northbound.

Criterion III Northbound						
Time	Absolute error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	33.8	17.3	36.5	8.4	1.8	16.2
5:05:00 PM	3.0	13.5	0.1	47.4	30.8	19.0
5:10:00 PM	85.0	24.6	27.5	11.1	10.9	27.4
5:15:00 PM	28.5	7.7	37.3	22.2	5.8	20.3
5:20:00 PM	10.5	14.1	17.8	33.8	35.6	11.0
5:25:00 PM	17.3	51.0	19.3	22.2	31.0	13.5
5:30:00 PM	1.1	33.7	23.9	36.9	27.8	24.3
5:35:00 PM	21.8	10.1	15.3	6.2	1.7	7.0
5:40:00 PM	61.8	0.4	40.0	50.8	54.3	41.5
5:45:00 PM	9.0	4.9	53.1	6.0	2.8	15.2
Average absolute error	**27.2**	**17.7**	**27.1**	**24.5**	**20.2**	**19.5**
BDAE	22.9					

Criterion IV Northbound						
Time	Average error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	-33.8	-17.3	-36.5	8.4	-1.8	-16.2
5:05:00 PM	-3.0	-13.5	-0.1	-47.4	-30.8	-19.0
5:10:00 PM	-85.0	-24.6	-27.5	-11.1	10.9	-27.4
5:15:00 PM	28.5	7.7	37.3	22.2	5.8	20.3
5:20:00 PM	-10.5	14.1	-17.8	33.8	35.6	11.0
5:25:00 PM	17.3	-51.0	19.3	-22.2	-31.0	-13.5
5:30:00 PM	1.1	-33.7	-23.9	-36.9	-27.8	-24.3
5:35:00 PM	-21.8	10.1	-15.3	-6.2	-1.7	-7.0
5:40:00 PM	-61.8	-0.4	-40.0	-50.8	-54.3	-41.5
5:45:00 PM	-9.0	-4.9	-53.1	-6.0	-2.8	-15.2
Absolute average error	**17.8**	**11.4**	**15.8**	**11.6**	**9.8**	**13.3**
BDAE Threshold/3	5.7					

Calibration Results for Southbound

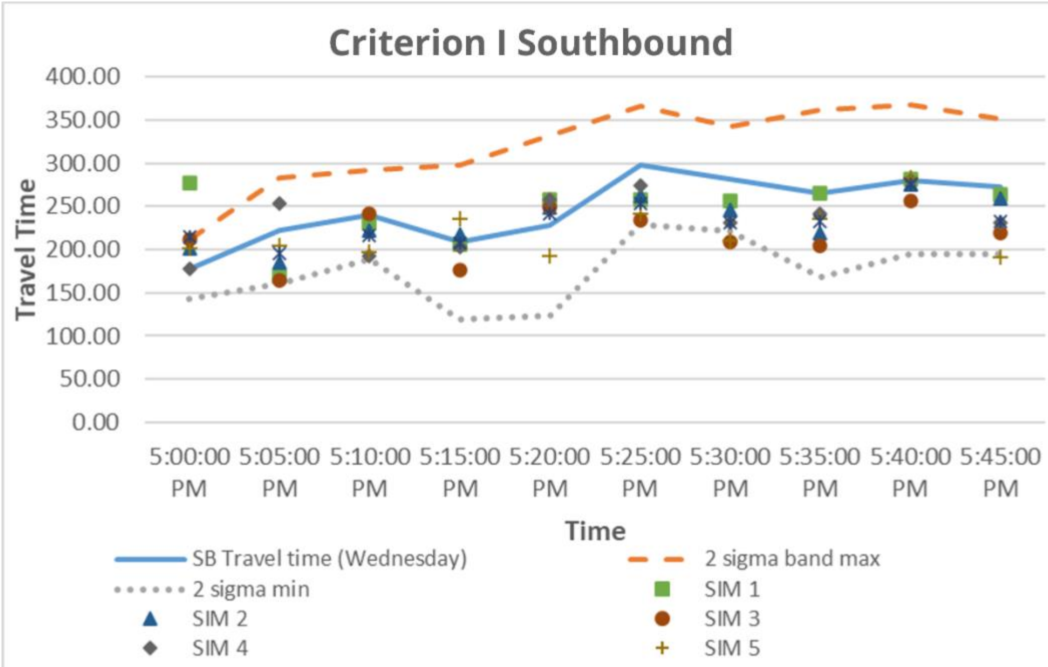


Figure 42. Chart assessing control for time-variant outliers for southbound.

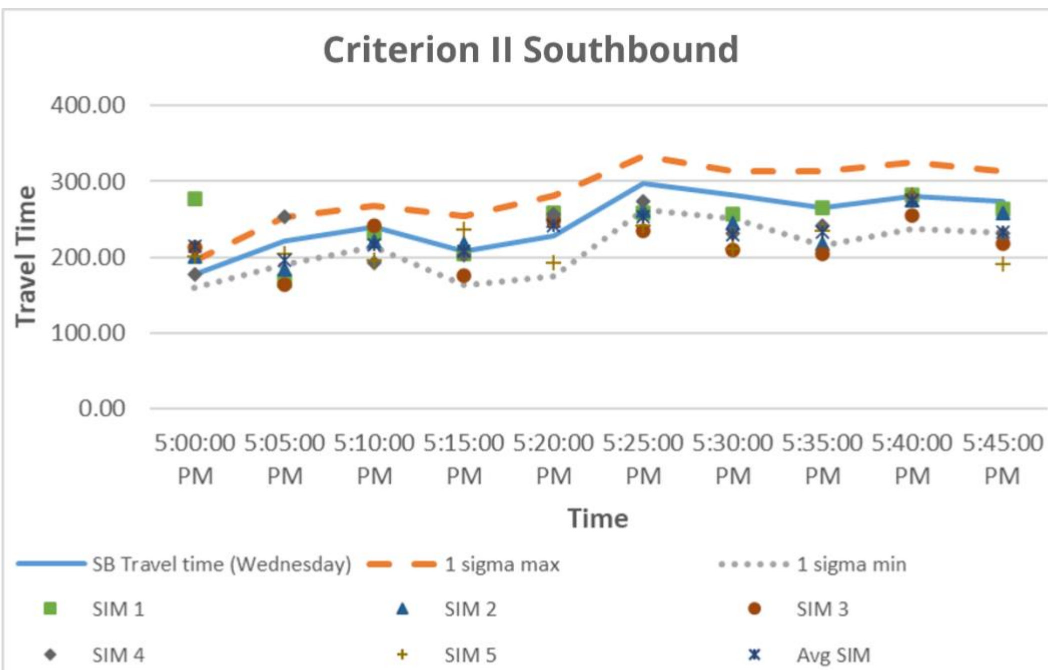


Figure 43. Chart assessing control for time-variant inliers for southbound.

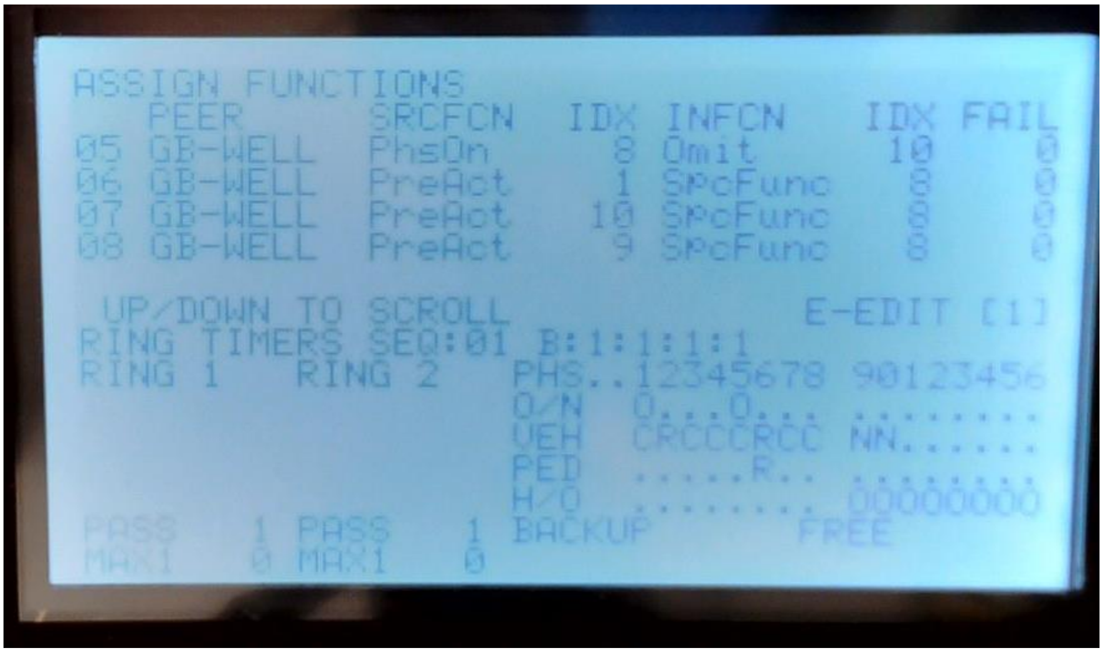
Criterion III Southbound						
Time	Absolute error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	100.0	24.7	35.2	0.7	24.9	37.1
5:05:00 PM	53.2	37.0	57.5	31.6	17.3	26.7
5:10:00 PM	9.8	18.5	0.4	48.5	43.8	24.0
5:15:00 PM	3.0	10.0	32.0	5.9	27.5	0.7
5:20:00 PM	30.0	20.9	20.6	29.4	35.7	13.1
5:25:00 PM	39.9	35.7	62.9	23.5	56.4	43.7
5:30:00 PM	25.6	36.3	73.1	51.3	71.3	51.5
5:35:00 PM	0.9	46.1	59.6	22.4	29.5	31.4
5:40:00 PM	0.7	5.7	24.9	0.5	1.7	5.8
5:45:00 PM	9.6	14.1	54.4	41.5	81.9	40.3
Average absolute error	27.3	24.9	42.1	25.5	39.0	27.4
BDAE	41.1					

Criterion IV Southbound						
Time	Average error					
	SIM 1	SIM 2	SIM 3	SIM 4	SIM 5	Avg SIM
5:00:00 PM	-100.0	-24.7	-35.2	-0.7	-24.9	-37.1
5:05:00 PM	53.2	37.0	57.5	-31.6	17.3	26.7
5:10:00 PM	9.8	18.5	-0.4	48.5	43.8	24.0
5:15:00 PM	3.0	-10.0	32.0	5.9	-27.5	0.7
5:20:00 PM	-30.0	-20.9	-20.6	-29.4	35.7	-13.1
5:25:00 PM	39.9	35.7	62.9	23.5	56.4	43.7
5:30:00 PM	25.6	36.3	73.1	51.3	71.3	51.5
5:35:00 PM	-0.9	46.1	59.6	22.4	29.5	31.4
5:40:00 PM	-0.7	5.7	24.9	0.5	-1.7	5.8
5:45:00 PM	9.6	14.1	54.4	41.5	81.9	40.3
Absolute Average Error	0.9	13.8	30.8	13.2	28.2	17.4
BDAE Threshold/3	10.3					

Appendix B – Instructions to Remove Double Flushing

These instructions were developed, bench tested, and utilized to address a back-to-back eastbound George Bush flush observed first in the HITL simulation environment and confirmed in the field. These instructions were used to adjust the field controllers and remove the double queue flushing behavior.

1. On MM 4-4-2, add commands for special function 8 when preempt 1 ,9, 10, 11, and 12 are active in unit back 1.



2. At MM 4-C, copy bank 1 to 2.

3. At MM 4-4-2, press "-" to go to phase bank 2 and then delete the VehDet 15 to 12 by pressing "E", navigating to the row, and pressing "NEXT" and "ENTER".

4. At MM 6-0, scroll down to unit bank 2 and enter "1" at function 8.

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