# Effects of Queue Jumpers and Transit Signal Priority on Bus Rapid Transit

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## ABSTRACT

Preferential treatments for transit are needed for high-occupancy transit vehicles to improve their operations. However, these treatments are often not effective in saturated traffic conditions when transit operates in mixed traffic. Additional Right-of-Way (ROW) for transit at intersections can be achieved with Queue Jumpers. They allow buses to bypass the waiting queues by using queue jumper lanes and getting an early green signal. The goal of this paper is to evaluate individual and combined effects of Queue Jumpers and Transit Signal Priority (TSP) on performance of a Bus Rapid Transit (BRT) system and vehicular traffic along 3500 S in West Valley City, Utah. Four VISSIM microsimulation models were developed for evaluation: the existing scenario without special treatments for transit (Base), the QJ scenario that introduced Queue Jumpers only, the TSP scenario that implemented TSP only, and a combination of Queue Jumpers and TSP (QJ & TSP). The implementation of any transit strategy resulted in significant improvements in BRT operations. The QJ & TSP scenario yielded highest benefits: 13-22% reduction in BRT travel times, better corridor progression, lower intersection delays and number of stops, increased speed (22%), and better travel time reliability and headway adherence. Transit treatments did not affect private traffic along the corridor. These strategies, however, had certain impacts on side streets. QJ & TSP scenario increased average delays for cross-street traffic by 15%. However, with small improvements in QJ and TSP settings, the combination of the two strategies can be most beneficial and highly desirable for implementation.

# INTRODUCTION

A constant growth of automobile traffic on urban streets in recent years has created a significant problem for transit, especially when it operates in mixed traffic. The negative impacts include an increase in transit travel times and reduction in its reliability and punctuality, bus crowding, and an increase in passengers' bus stop waiting times. Many public transit agencies have been introducing high-capacity rapid transit modes, along with other operational strategies, as a potential solution to these impacts on transit service.

Bus Rapid Transit (BRT), one such high-capacity rapid transit mode, has gained popularity and a significant number of BRT lines have been deployed in the US in the last few decades *(1)*. The BRT Implementation Guideline defined BRT as: "A flexible, rubber-tired rapid-transit mode that combines stations, vehicles, services, running ways, and Intelligent Transportation System (ITS) elements into an integrated system with a strong positive identity that evokes a unique image"*(2)*. It provides quality of rail transit at much lower construction and operational costs and combines it with the flexibility of buses. A BRT system is generally combined with ITS technology, as well as signals and roadway designs that prioritize transit. The designation of exclusive bus lanes and the provision of Transit Signal Priority (TSP) on arterial streets are the two major bus preferential treatments that have received increasing attention in North America. In practice, however, it is often difficult to justify the use of an exclusive lane for buses during peak hours. Studies have also shown that TSP is ineffective during peak hours, because buses are not able to bypass the long waiting queues at intersections (*3, 4*).

A special type of bus-preferential treatment that has the potential to improve transit performance at signalized intersections is the Queue Jumper lane. This treatment combines a short stretch of special lane with a leading transit signal phase interval to allow buses to bypass a waiting traffic queue. Usually, a bus utilizes a right-turn bay (if present) to advance ('jump') in front of the queue by getting a leading green interval. These bays usually consist of a nearside right-turn only lane, and a far-side open bus bay. Role of the nearside right-turn only is to enable buses to circumvent traffic queues. Far-side bus bay serves to avoid blockage of through traffic by a stopped bus. The literature has shown that queue jumper lanes, or simply "Queue Jumpers", are the most effective during congested traffic conditions, when long queues prevent transit vehicles to efficiently clear an intersection *(5)*.

In addition to Queue Jumpers, public transit performance at intersections can be further improved by ensuring that an arriving bus enjoys a preferential signal treatment – e.g. by either extending green of the corresponding phase, or reducing the greens of conflicting phases. However, while Queue Jumpers sometimes require a major reconstruction of the intersection, a TSP deployment can be done with installation of ITS hardware at signal controllers and on TSP-enabled vehicles. There are several studies that evaluated effects of TSP strategies on performance of different transit modes *(6-8)*. There are also several studies that investigated effects of Queue Jumpers and TSP on transit performance *(5, 9, 10)*. However, there are only few studies that comprehensively evaluate combined effects of Queue Jumpers and TSP on transit performance.

The goal of this study is to evaluate individual and combined effects of TSP and Queue Jumpers on performance of a BRT system and vehicular traffic. A high-fidelity microsimulation model is used as a mean to conduct the evaluation. The test-bed for the research is a part of the BRT line along 3500 S in West Valley City, Utah.

The remainder of the paper is divided into four sections. The next section provides a literature review on BRT and transit preferential treatments. It is followed by the description of the applied methodology for the model building and scenario development. The major results and findings are presented in the Results section, followed by the Discussion. The main conclusions of the paper are presented in the last section.

## LITERATURE REVIEW

In this section, the authors first review a few major BRT evaluation studies. Then, a review of studies which addressed various transit preferential treatments is provided. Authors conclude this section by identifying contribution of the presented work in the field of BRT operations and bus preferential treatments.

### BRT Evaluations

The Metro Orange Line in Los Angeles, CA, opened in October 2005, is one of the first full featured BRT in the US. It experienced a big gain in ridership during its first year of operation *(11)*. About 17% of the ridership gains were new riders, while 33% of riders were diverted from cars. The new BRT service reduced transit travel times by 66% when compared to the corresponding vehicular travel times. The TransMilenio BRT line in Bogota, Colombia, is another great example of BRT success, carrying about 1.4 million passengers per day *(12)*. The implemented BRT features had the following effects: reduced transit travel times by more than 32%; increased transit travel speeds by approximately 78%; reduced operational costs; and reduced the number of collisions by 79%. The first BRT line in Utah was launched in 2008 in West Valley City *(13)*. Preliminary survey results showed significant improvements in transit operations, with a 33% increase in ridership, 15% reductions in travel times, and improved travel-time reliability. Dwell times were reduced, mostly due to the new fare collection process and improved accessibility at bus stops. Passenger surveys revealed a high degree of acceptance of the new system.

### Transit Preferential Treatments

TSP at signalized intersections has been studied in the US since the 1970s *(14)*. Case studies have shown successful implementation and quantifiable benefits of TSP. Green extension and early green strategies were implemented in Tualatin Valley Highway, Portland, for thirteen signalized intersections. Bus travel time savings varied between 2% and 14% per trip, with a two to thirteen seconds reduction in average intersection delays *(6)*. The same strategies were implemented along Powell Blvd. in Portland for four signalized intersections. The reported reduction of bus travel time and bus person delay was 5 - 8% *(7)*. Green extension and early green strategies were implemented at twenty intersections along Rainer Avenue in Seattle. The implementation resulted in a 5-8% reduction in travel times, 25-34% reduction in average intersection bus delay, and $40,000 passenger benefit per intersection *(8)*.

The success of the TSP implementation vary with the characteristics of traffic environment of the deployment site, such as transit usage, the time of day when used, and the characteristics of the transit service. Garrow and Machemehl *(3)* used a TRAF-Netsim microsimulation model to evaluate TSP along urban arterials. They reported that the negative impact on the cross-street traffic is "significant" if the cross-street saturation levels are high, with volume-to-capacity (v/c) ratio of 0.9-1.0. Ngan et al. *(4)* determined that TSP had a moderate impact on cross-street performance where the v/c ratio was above 0.8, while this impact was significant for v/c greater than 0.9.

Studies have also find difficulties in justifying the use of exclusive lanes during peak hours, while TSP is ineffective when traffic flow is saturated. Queue Jumpers are often cited as a solution that can overcome these problems. Nowlin and Fitzpatrick *(15)* performed field and simulation studies of Queue Jumpers performance. They found that Queue Jumpers work well in under-saturated traffic conditions. However, when the through traffic volume exceeded 1,000 vehicles/hour/lane (near saturation), the benefit of Queue Jumpers began to decrease quickly.

Zhou and Gan *(5, 9)* evaluated the impacts of various parameters on Queue Jumpers. The evaluations were performed under different TSP strategies, traffic volumes, bus volumes, dwell times, and bus stop and detector locations. It was found that Queue Jumpers without TSP were ineffective in reducing bus delay, as opposed to including TSP strategies such as phase insertion, green extension, red truncation, and phase skipping. Nearside bus stops upstream of the check-in detectors were preferred for jumper TSP over far-side bus stops and nearside bus stops downstream of the check-in detectors. The optimal detector location was found to be about 500 feet before the stop line. Through vehicles on the bus approach were found to have only a slight impact on bus delay when the v/c ratio was below 0.9. However, when v/c exceeded 0.9, the bus delay increased quickly. Right turn volumes did not have impacts on bus performance.

Lahon *(10)* evaluated impacts of TSP and Queue Jumpers at six signalized intersections on the BRT system in Pleasanton, California. Two VISSIM models were developed for the alternative analysis: one with TSP operations and right-turn Queue Jumpers only, and the other with TSP operations and both right-turn and left-turn Queue Jumpers. Results showed that TSP and Queue Jumpers reduced bus travel times by 30%, without adversely affecting vehicular traffic. Interestingly, this study showed that intersections with higher v/c ratios for corresponding through movement offer higher travel time savings for the bus when the intersection has TSP and/or Queue Jumpers.

The practice around the world shows that investing in BRT deployments pays off. Studies on various transit preferential treatments show that most of their benefits are achieved at lower traffic intensities, and that sometimes cross-street traffic suffers due to the deployment of those treatments. The combined effects of Queue Jumpers and TSP are still not well known. This study fills the gap in the existing research by adding the combined effects of QJ and TSP strategies using a real-world network, and analyzing both transit and vehicular modes. The combined effects of various transit preferential treatments are analyzed on multiple levels, such as network-wide, mainline, side-street, and intersection. It evaluates individual effects of Queue Jumpers and TSP, as well as their combined effect on BRT and vehicular traffic performance. The study is using VISSIM microsimulation models of a BRT line in West Valley City, Utah as the test- bed network. The study makes an effort to identify the best transit preferential treatment that would provide the most benefit for BRT, with minimal impacts on vehicular traffic.

## METHODOLOGY

The test-bed network for this study is a BRT corridor on 3500 S in West Valley City, Utah. The BRT line was introduced in 2008. It operates six days a week on a 15-minute-headway-based schedule. The total length of the line is 10.8 miles, with a total of twenty-nine stops (fourteen westbound (WB) and fifteen eastbound (EB)). The average weekday ridership is approximately 3,000 passengers per day. TSP is implemented in the field and it provides 10 seconds of extra time (either for green extension or for red truncation) for BRT (*13*). The corridor analyzed in this study includes thirteen signalized intersections from 2700 W to 5600 W, with a small digression from 2700 W to 2820 W, where the line makes a turn to the West Valley Fair Mall. During the most congested PM peak hours, the average Level of Service at these intersections varies between C and D. The PM peak traffic is directed WB. The study corridor is given in Figure 1.

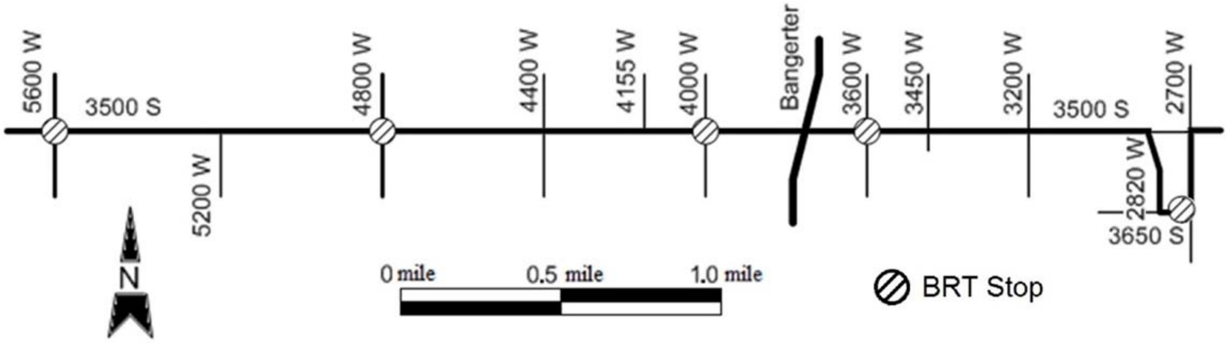


**FIGURE 1 Test-bed network along 3500 S in West Valley City, UT.**

A regular bus line (RT 35) operates parallel with the BRT line. RT 35 operates on a schedule-based time table, with designed headways of 30 minutes. This line uses thirty-nine bus stops within the field of study (twenty WB and nineteen EB). The BRT stops are shared with RT 35.

The methodology of this study has four basic steps:

1. Development of a VISSIM microsimulation model to realistically represent field conditions.
2. Calibration and validation of the simulation model to present model's ability to replicate field conditions.
3. Development of various BRT operational scenarios to evaluate impacts of Queue Jumpers and TSP.
4. Analysis of data and statistical testing to document differences among the scenarios.

## Development of the Base VISSIM Model

The base VISSIM model was developed for the PM peak period (4:00 – 6:00 PM), based on the existing network geometry, traffic and transit operations. The simulation network included the busiest 4-mile section, as shown in Figure 1. All signalized intersections in the test-bed network are actuated-coordinated, except the intersection of 3650 S and 2700 W, which is a free-running intersection. Signal timing data were obtained from UDOT's SYNCHRO files, and the i2 software which enables a direct on-line connection to the field traffic controllers. Both transit lines (BRT and RT 35) are included in the model.

## Calibration and Validation of the Base VISSIM Model

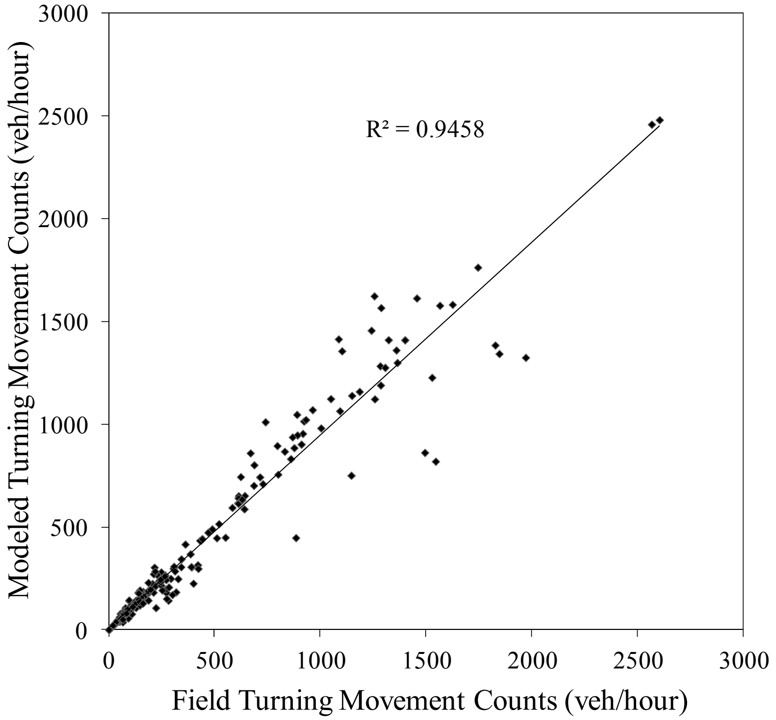
The data used in model development were collected by UDOT in the period between 2006 and 2008. The data included turning movement counts at signalized intersections, and vehicular travel times along the corridor collected using the floating car technique and GPS devices. The calibration of the existing VISSIM model was performed for the turning movement counts at each signalized intersection. Figure 2 (a) shows a comparison of turning movement traffic counts from the simulation and the field for the 2-hour simulation period. The coefficient of determination ($R^2$) was close to 0.93, indicating a high resemblance between the field and simulation conditions.

For the purpose of validating corridor travel times, the 3500 S segment from 2700 W to 5600 W was split into twenty-two segments between signalized intersections (eleven in each direction), where the measurement points in VISSIM were set. Travel times from the field were used to validate those from the model. Figure 2 (b) shows the comparison of the travel time data from the two sources with a very high $R^2$ value (0.96).

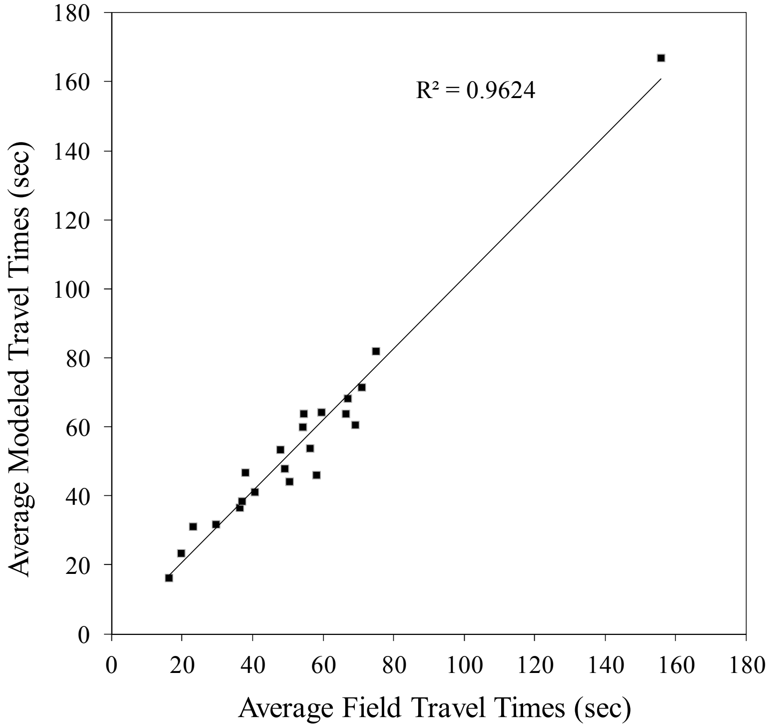
## Simulation Scenarios

Four scenarios were developed to analyze impacts of Queue Jumpers and TSP on the performance of BRT and private traffic:

- **Base Case Scenario** (Base) – Represents field conditions for which the model was calibrated and validated. It includes both transit lines (BRT and RT 35), operating in mixed traffic. There are no Queue Jumpers or TSP.
- **Queue Jumpers Scenario** (QJ) – Queue Jumper lanes are introduced at each intersection, along with special 8 seconds Queue Jumper leading signal phase interval. The leading bus interval is activated only by the waiting BRT bus. The 8 seconds leading interval is taken as the average time for the bus waiting at red light in the QJ lane to accelerate, cross the intersection and return to the regular lane, before the waiting cars catch up to the bus, due to the cars' faster acceleration rates. This setting is also implemented for intersections with far-side BRT stops, because BRT buses can skip stations if no passenger demand exists. This leading bus interval is the part of the through phases along the main corridor, so it only impacts those phases. Both transit lines are routed to utilize the Queue Jumpers lanes, but only BRT receives the leading bus interval. Queue Jumper bays were not developed for intersections where the BRT makes left or right turns.
- **TSP Scenario** (TSP) – Green extension and red truncation TSP strategies are introduced at signalized intersections for BRT only. Each strategy provided a maximum time span of 10 seconds, which is the setting adopted from the field. The redistribution of times when TSP is active is among all other phases proportional to the phase durations (i.e. all phases are shortened proportional to their duration). This is the standard setting in the used traffic control emulators in VISSIM. Queue Jumper lanes and leading bus interval are not implemented in this scenario.
- **Queue Jumpers & TSP Scenario** (QJ & TSP) – Queue Jumper lanes, leading bus interval and TSP are implemented simultaneously. TSP and the leading bus interval are activated by BRT only, while both lines use the Queue Jumper lanes. This scenario is a combination of the previous two scenarios.



a) Calibration results



b) Validation results

**FIGURE 2 Calibration and validation of VISSIM Base Model.**

For the QJ and QJ & TSP scenarios, the Queue Jumper bus bays were modeled according to the guidelines provided by Transit Cooperative Research Program *(16)*. These bus bays consist of a nearside right-turn only lane, and a far-side open bus bay. Role of the nearside right-turn only lane (whose minimum length should be 240 ft) is to enable buses to circumvent traffic queues. Far-side bus bay serves to avoid blockage of through traffic due to a stopped bus.

The minimum lengths of 100, 90, and 150 feet were used for the bus stop zones for nearside, far-side and middle-block bus stops, respectively. The far-side bus stops were placed 70-200 ft after the end of the curb, whereas the nearside bus stops were placed 30-100 ft before the beginning of curb. Locations of the bus stops, with respect to the intersections, were in the shoulder lanes for all non Queue Jumper scenarios, while for the Queue Jumper scenarios the bus stops were placed in the Queue Jumpers. The researchers looked into the existing geometry at each intersection, access to businesses and parking lots along the corridor, as well as the designed locations for bus stops when creating the model. Queue Jumpers at each intersection are designed to avoid disruptions in regular traffic operations.

## RESULTS

For the purpose of evaluating the impacts of Queue Jumpers and TSP, VISSIM was coded to record travel times (private traffic and BRT), BRT time-space positions, cross-street delay, and overall network performance. Each scenario was run for ten differently seeded simulations (with the same sequence of random seeds among scenarios), each of which was 2 hours and 15 minutes long (15 minutes – warm-up time). The results of the experiments were averaged and divided into separate categories.

### Corridor Travel Times

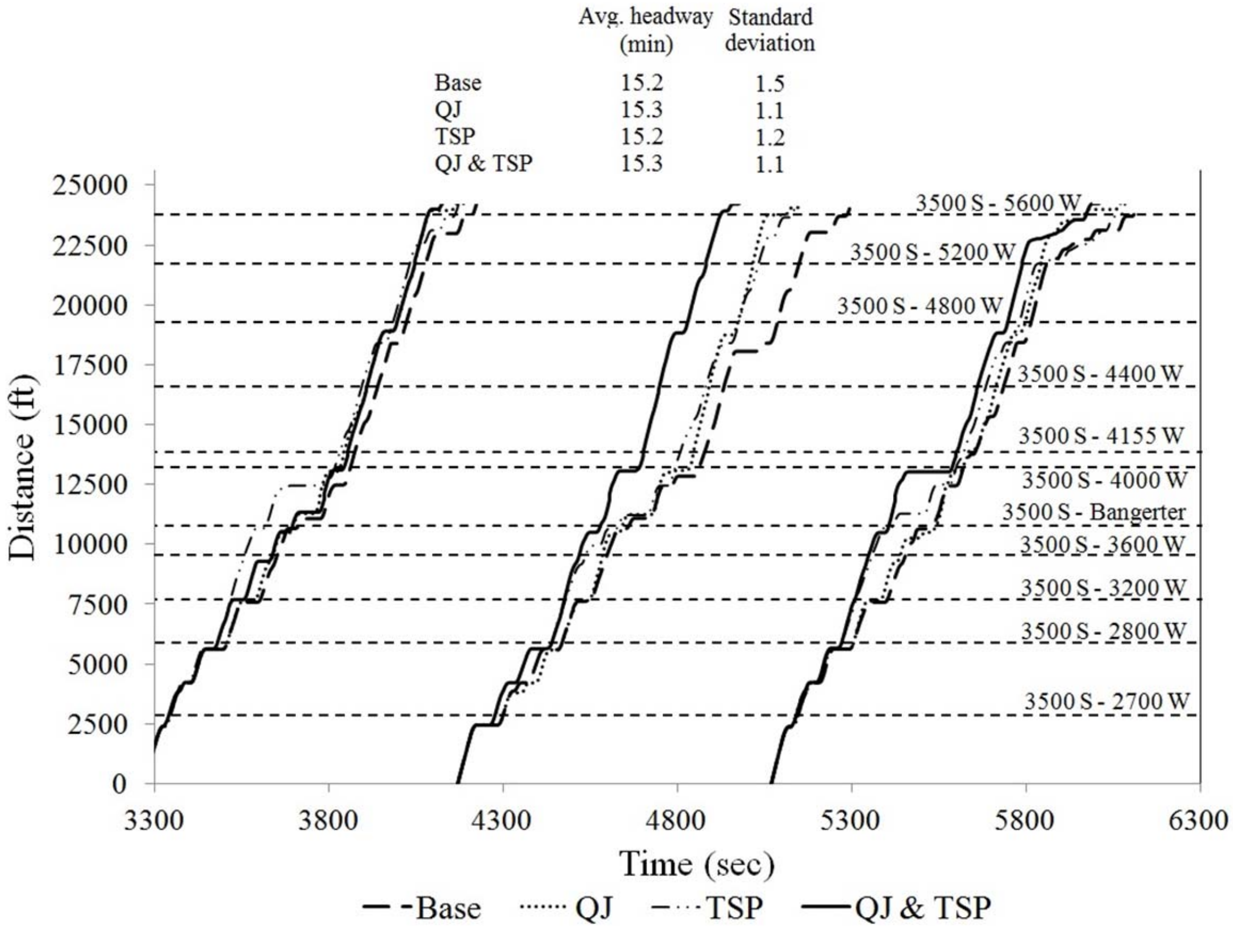
Travel times for private traffic and BRT vehicles were measured for segments between each pair of signalized intersections in both directions. The average travel times obtained through simulations are given in Table 1 for each scenario.

**TABLE 1 Corridor Travel Times for BRT and Passenger Cars**

| Travel times (s) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Segments** | **Base** | | **QJ** | | **TSP** | | **QJ & TSP** | |
| WB | BRT | Cars | BRT | Cars | BRT | Cars | BRT | Cars |
| 2700W-2820W | 167 | 16 | 167 | 17 | 146 | 17 | 149 | 17 |
| 2820W-3200W | 99 | 64 | 84 | 69 | 46 | 65 | 57 | 67 |
| 3200W-3450W | 44 | 48 | 35 | 48 | 47 | 48 | 43 | 48 |
| 3450W-3600W | 32 | 44 | 31 | 45 | 35 | 43 | 28 | 43 |
| 3600W-Bangerter | 87 | 46 | 77 | 46 | 87 | 47 | 77 | 48 |
| Bangerter-4000W | 82 | 47 | 75 | 49 | 108 | 46 | 95 | 48 |
| 4000W-4155W | 32 | 32 | 26 | 34 | 29 | 31 | 24 | 33 |
| 4155W-4400W | 43 | 41 | 37 | 42 | 41 | 41 | 33 | 42 |
| 4400W-4800W | 70 | 72 | 68 | 71 | 60 | 70 | 57 | 70 |
| 4800W-5200W | 86 | 54 | 86 | 53 | 81 | 54 | 83 | 54 |
| 5200W-5600W | 180 | 192 | 172 | 178 | 153 | 183 | 148 | 187 |
| **Total** | **916** | **652** | **859** | **642** | **836** | **640** | **795** | **654** |
| **Compared to Base** | **N/A** | **N/A** | **-6%** | **-2%** | **-9%** | **-2%** | **-13%** | **0%** |
| EB | BRT | Cars | BRT | Cars | BRT | Cars | BRT | Cars |
| 5600W-5200W | 63 | 60 | 56 | 57 | 50 | 59 | 51 | 56 |
| 5200W-4800W | 89 | 82 | 85 | 78 | 59 | 76 | 53 | 74 |
| 4800W-4400W | 82 | 54 | 84 | 54 | 79 | 52 | 80 | 52 |
| 4400W-4155W | 35 | 37 | 34 | 37 | 36 | 37 | 33 | 37 |
| 4155W-4000W | 48 | 39 | 45 | 39 | 36 | 37 | 37 | 37 |
| 4000W-Bangerter | 106 | 61 | 92 | 60 | 108 | 62 | 98 | 61 |
| Bangerter-3600W | 49 | 43 | 55 | 45 | 38 | 43 | 31 | 43 |
| 3600W-3450W | 57 | 24 | 55 | 23 | 59 | 23 | 56 | 23 |
| 3450W-3200W | 97 | 92 | 64 | 87 | 78 | 84 | 50 | 80 |
| 3200W-2820W | 56 | 64 | 50 | 62 | 79 | 79 | 67 | 74 |
| 2820W-2700W | 324 | 68 | 234 | 62 | 261 | 74 | 220 | 70 |
| **Total** | **1005** | **625** | **850** | **613** | **887** | **628** | **783** | **610** |
| **Compared to Base** | **N/A** | **N/A** | **-15%** | **-2%** | **-12%** | **0%** | **-22%** | **-2%** |

### BRT Progression and Intersection Performance

BRT positions were recorded in VISSIM for every simulation step. They were used to plot and compare BRT trajectories for the four scenarios. There were eleven BRT vehicles in the WB direction and eight in the EB direction that started and completed their trips during the evaluation interval in each simulation. The example diagram for one randomly seeded simulation is given in Figure 3. The diagram shows the progression of three consecutive WB BRT vehicles along the corridor. Another indicator of the transit reliability is the actual headway and its deviations from the designed headway (which is 15 minutes for BRT). The obtained results are also shown in the figure.



| | Avg. headway (min) | Standard deviation |
|---|---|---|
| Base | 15.2 | 1.5 |
| QJ | 15.3 | 1.1 |
| TSP | 15.2 | 1.2 |
| QJ & TSP | 15.3 | 1.1 |

FIGURE 3 Example BRT trajectories and headway adherence.

Table 2 summarizes stopping percentages and times that BRT vehicles spent waiting at the red light at intersections. The example is for one random seed only, but the similar patterns exist for all simulations. Two-tail t tests for paired samples with α = 0.05 were used to perform statistical analyses of the results and determine if statistically significant differences existed among scenarios. The t tests are performed on the raw output data from the 10 simulation runs for each scenario.

**TABLE 2 BRT Stopping Percentage and Intersection Waiting Times (WT)**

| WB | BRT stop location | Base | | QJ | | TSP | | QJ & TSP | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stop (%) | WT (s) | Stop (%) | WT (s) | Stop (%) | WT (s) | Stop (%) | WT (s) |
| 2700 W | N/A | 89 | 494 | 100 | 313 | 67 | 204 | 78 | 223 |
| 3650 S | N/A | 0 | 0 | 33 | 57 | 0 | 0 | 33 | 52 |
| 2820 W | N/A | 100 | 424 | 100 | 340 | 89 | 230 | 89 | 181 |
| 3200 W | N/A | 100 | 386 | 100 | 272 | 0 | 0 | 33 | 80 |
| 3450 W | N/A | 22 | 51 | 11 | 2 | 33 | 32 | 33 | 62 |
| 3600 W | FS | 0 | 0 | 22 | 50 | 56 | 71 | 44 | 92 |
| Bangerter | N/A | 44 | 154 | 44 | 148 | 78 | 271 | 22 | 63 |
| 4000 W | NS | 22 | 21 | 22 | 84 | 22 | 16 | 0 | 0 |
| 4155 W | N/A | 22 | 14 | 0 | 0 | 33 | 7 | 0 | 0 |
| 4400 W | N/A | 33 | 26 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4800 W | FS | 33 | 64 | 33 | 57 | 11 | 11 | 0 | 0 |
| 5200 W | N/A | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 1 |
| 5600 W | FS | 100 | 740 | 89 | 574 | 78 | 232 | 78 | 226 |
| **Avg/Total** | | **44** | **2374** | **43**[1] | **1897**[1] | **36**[1,2] | **1074**[1,2] | **32**[1,2,3] | **980**[1,2,3] |
| **Compared to Base** | | **N/A** | **N/A** | **-2%** | **-20%** | **-18%** | **-55%** | **-27%** | **-59%** |

| EB | BRT stop location | Base | | QJ | | TSP | | QJ & TSP | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stop (%) | WT (s) | Stop (%) | WT (s) | Stop (%) | WT (s) | Stop (%) | WT (s) |
| 5600 W | NS | 100 | 382 | 100 | 426 | 0 | 0 | 100 | 131 |
| 5200 W | N/A | 86 | 25 | 0 | 0 | 0 | 0 | 14 | 1 |
| 4800 W | FS | 100 | 174 | 100 | 214 | 57 | 46 | 0 | 0 |
| 4400 W | N/A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4155 W | N/A | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 4 |
| 4000 W | FS | 43 | 143 | 43 | 80 | 43 | 57 | 57 | 100 |
| Bangerter | N/A | 71 | 173 | 43 | 155 | 86 | 237 | 86 | 305 |
| 3600 W | FS | 57 | 94 | 86 | 210 | 29 | 24 | 43 | 19 |
| 3450 W | N/A | 29 | 43 | 29 | 48 | 0 | 0 | 0 | 0 |
| 3200 W | N/A | 86 | 318 | 43 | 101 | 57 | 110 | 14 | 45 |
| 2820 W | N/A | 0 | 0 | 0 | 0 | 57 | 52 | 14 | 14 |
| 2700 W | N/A | 86 | 802 | 86 | 327 | 100 | 713 | 100 | 198 |
| 3650 S | N/A | 0 | 0 | 0 | 6 | 14 | 1 | 0 | 0 |
| **Avg/Total** | | **51** | **2154** | **41**[1] | **1561**[1] | **34**[1,2] | **1240**[1,2] | **34**[1,2,3] | **817**[1,2,3] |
| **Compared to Base** | | **N/A** | **N/A** | **-20%** | **-28%** | **-33%** | **-42%** | **-33%** | **-62%** |

1 - value statistically different from the corresponding Base value
2 - value statistically different from the corresponding QJ value
3 - value statistically different from the corresponding TSP value
NS – Near-side bus stop
FS – Far-side bus stop

## Impacts on Cross-Street Traffic

Another important factor in the evaluation is the cross-street delay, since the implementation of transit preferential treatments can impact cross-street traffic. VISSIM recorded these delays at signalized intersections where QJ and/or TSP were implemented. The results are shown in Figure 4. The figure also shows the recorded volume-to-capacity (v/c) ratios for the side streets.

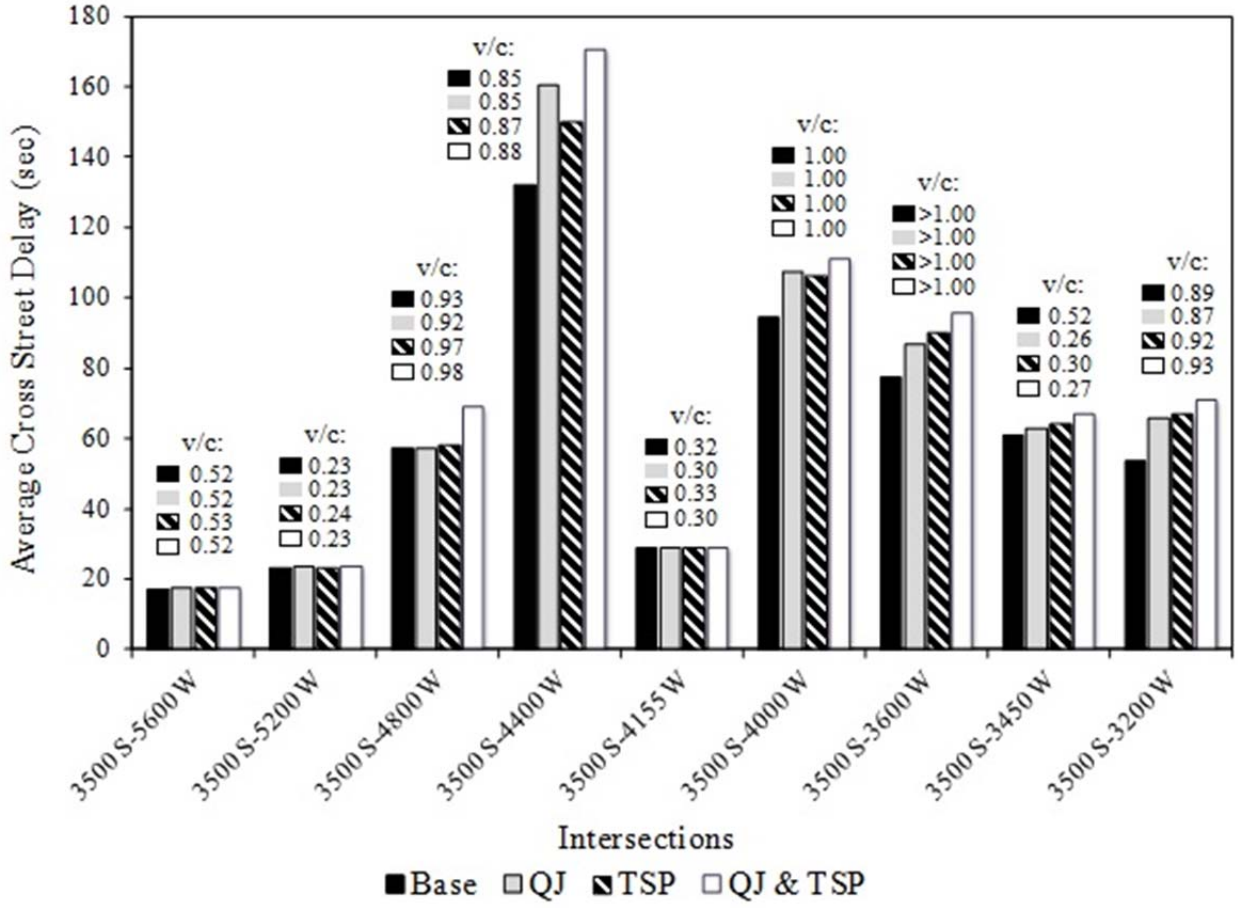


FIGURE 4 Cross-street delays and v/c ratios.

### Network Performance

The effects of the analyzed strategies were assessed on a network-wide level through a comparison of the most relevant parameters, such as the average values of delay, number of stops, stopped delay, and speed. The data were summarized separately for passenger cars and BRT and presented in Table 3. The results were tested with a t test for paired samples to assess potential statistically significant differences among the scenarios.

**TABLE 3 Network Performance**

| **Passenger cars** | **Base** | **QJ** | **TSP** | **QJ & TSP** |
|---|---|---|---|---|
| Average delay time per vehicle (s) | 179 | 191 | 183[2] | 201 |
| Average number of stops per vehicle | 4.1 | 4.2[1] | 4.1[1,2] | 4.4 |
| Average stopped delay per vehicle (s) | 106 | 116 | 109 | 123 |
| Average speed (mph) | 16.9 | 16.3 | 16.7[2] | 15.9 |

| **BRT vehicles** | **Base** | **QJ** | **TSP** | **QJ & TSP** |
|---|---|---|---|---|
| Average delay time per vehicle (s) | 534 | 456 | 388 | 355 |
| Average number of stops per vehicle | 9.0 | 7.2 | 6.7 | 6.2[3] |
| Average stopped delay per vehicle (s) | 246.8 | 198.7 | 122.4 | 105.1 |
| Average speed (mph) | 15.8 | 17.4 | 18.3 | 19.3 |

1 - value statistically different from the corresponding Base value
2 - value statistically different from the corresponding QJ value
3 - value statistically different from the corresponding TSP value

## DISCUSSION

### Corridor Travel Times

The results show improvements in BRT travel times in each direction of travel, and for every scenario that implemented some of the transit preferential treatments, when compared to the Base scenario. The implementation of Queue Jumpers resulted in a BRT travel time reduction of 6% (WB), and 15% (EB). The implementation of TSP only reduced BRT travel times by 9% in the WB and 11% in the EB direction. QJ and TSP strategies implemented individually yielded similar results for BRT travel times. When implemented together, QJ & TSP resulted in the reduction in BRT travel times of 13% in the WB and 22% in the EB direction, compared to the Base scenario. The combined implementation of QJ & TSP shows significant improvements in transit travel times over any strategy implemented individually. Therefore, from the perspective of the transit system, the combination of these two strategies is highly desirable.

Vehicular traffic did not experience any negative impacts on travel times along the corridor. The implementation of Queue Jumpers actually reduced vehicular travel times 1-2%, even with the implementation of the Queue Jump phases. When TSP only is implemented, the vehicular traffic along the corridor can benefit from the extra green time given to BRT. The simultaneous implementation of QJ & TSP has combined (positive) effects on vehicular traffic.

Since vehicular travel times along the corridor were not negatively affected, any preferential treatment for transit should be recommended on this corridor.

## BRT Progression and Intersection Performance

The progression of BRT vehicles along the corridor shows improvements in all transit scenarios. QJ and TSP yield similar effects on the BRT vehicle progression when implemented individually. In the peak WB direction, TSP implementation only provides a better progression on the segment between 2800 W and Bangerter Highway. The intersections are spaced more closely in this segment, so BRT benefits from the extra time provided by TSP and the coordination between intersections. QJ only allows BRT busses to bypass the queues. However, because of the earlier green start, the buses do not enjoy the full benefit of signal coordination. On the other hand, the segment between Bangerter Highway and 5600 W is characterized by a greater distance between intersections. This makes signal coordination less effective, resulting in a worse performance of TSP-only scenario when compared to QJ-only scenario. QJ on the other hand enjoys full benefits of the QJ lanes and QJ phases. These differences are less noticeable in the EB direction, because of the lower traffic volumes. The combination of QJ & TSP offers cumulative benefits of each strategy individually, resulting in the best progression of BRT vehicles. The variation of travel times along the corridor is the smallest with QJ & TSP, offering much better travel time reliability and headway adherence than any other scenario.

The implementation of transit preferential treatments offers significant improvements to the BRT stopping percentage and red light waiting times when compared to the Base scenario, as shown in Table 2. QJ-only scenario reduced the number of BRT stops up to 20%, and BRT waiting times between 20% (WB) and 28% (EB). The implementation of TSP-only scenario reduced the number of BRT stops between 18% (WB) and 33% (EB), while the waiting times were reduced respectively 55% and 42% in the WB and EB direction. The combined implementation of QJ & TSP provided the most benefits to BRT intersection performance. The number of BRT stops was reduced by 27% in the WB and 33% in the EB direction. The waiting time was reduced by 59% and 62% in the WB and EB direction, respectively. The results also show that any transit preferential treatment reduces deviations from the headway. The implementation of QJ is the most beneficial from this standpoint.

Statistical tests that compared four scenarios found significant differences for each comparison. It means that each strategy had different impacts on BRT intersection performance. QJ & TSP offered the most benefit to BRT operations, justifying its implementation from the transit standpoint.

## Impacts on Cross-Street Traffic

While the transit preferential treatments provided major benefits for BRT and did not affect the vehicular traffic along the corridor, certain impacts were observed on the cross-street traffic. The effects of transit treatments on cross-street delays are given in Figure 4. All intersections, except 4155 W, experienced a certain increase in delays in any transit scenario. QJ-only and TSP-only scenarios had the same effects on cross-street traffic, with the exceptions at 3600 W and 4400 W. For these two scenarios, the average increase in cross-street delay was about 8%. The highest impact of QJ-only was at 3200 W, where the cross-street delays were increased about 23% (or 12 seconds). Similar observations were made for TSP-only, where the highest impact was also on

3200 W, with a 25% (13 seconds) increase in cross-street delays. The combination of QJ & TSP increased the cross-street delay for about 15% on average along the corridor. The highest impact on cross-street traffic was again at 3200 W, where the cross-street delay increased about 32% (17 seconds).

However, the analysis of v/c ratios on side streets shows that these streets have enough capacity to alleviate negative impacts of preferential transit strategies. QJ & TSP scenario had the biggest impacts on higher volume cross-streets.

### Network Performance

On the network level, any transit preferential treatment imposes certain impacts on vehicular traffic, as shown in Table 3. TSP-only scenario has the smallest impacts, followed by QJ-only scenario and QJ & TSP. The average delay per vehicle was increased between 2% (TSP) and 12% (QJ & TSP);the number of stops per vehicle was increased up to 7% (QJ & TSP); and the average speed was reduced from 1% (TSP) to 6% (QJ & TSP). Since the previous results showed that transit treatments did not cause any significant impact on vehicular traffic along the corridor, the majority of impacts on the network level came from the cross-streets traffic. The statistical analysis showed differences between most of the outputs of the QJ and TSP scenarios, implying that these two treatments generate different performances.

On the other hand, the transit preferential treatments provide major benefits for BRT on the network level. QJ-only resulted in a 15% reduction in the average BRT delays, a 20% reduction in the number of stops, and a 10% increase in BRT speeds. TSP-only reduced the average BRT delays by 27%, the number of BRT stops by 26%, and increased BRT speed by 16%. The highest improvement in BRT operations on the network-wide level were observed in the QJ & TSP scenario, where the average BRT delays were reduced by 34%, the number of BRT stops was reduced by 31%, and BRT speed was increased by 22%. A statistically significant difference was observed only in the average number of BRT stops between the QJ & TSP and TSP scenarios. It should also be noted that the average number of stops recorded for BRT buses included stopping at BRT stations. It means that for the QJ & TSP scenario, only one out of six stops was at signalized intersections.

## CONCLUSIONS

The goal of this paper is to evaluate individual and combined effects of Queue Jumpers and TSP on BRT and vehicular traffic along 3500 S in West Valley City, Utah. This was achieved through the comparison of four different scenarios in VISSIM microsimulation: Base, QJ-only, TSP-only, and QJ & TSP. The main conclusions observed in this study are as follows:

- Each transit preferential scenario offers significant benefits for BRT and imposes certain impacts on vehicular traffic.
- The implementation of QJ only and TSP only has similar end effects on BRT operations. The implementation of TSP only showed slightly better performance for BRT than QJ only.
- The greatest benefits for BRT are observed in the combined QJ & TSP scenario, where the BRT travel times were reduced 13-22%, the progression of BRT vehicles through the network was significantly improved, intersection delays and waiting times were reduced, speed was significantly increased (22%), and the travel time

reliability and headway adherence were significantly better than for any other scenario.

- The implementation of any transit preferential treatment (QJ, TSP, or both) did not negatively affect vehicular traffic along the main corridor. In fact, some small improvements were observed in each transit scenario.
- Cross-street traffic experienced some deterioration in performance for scenarios which facilitated preferential transit treatments. TSP-only scenario had the smallest impact on cross-street traffic, while the impacts were highest in QJ & TSP scenario. Higher volume cross-streets were more affected by preferential transit treatments.
- Some deterioration in vehicular traffic performance was observed on the network-wide level. The majority of impacts came from the worsened traffic conditions on cross-streets.
- Network-wise, performance of BRT vehicles was much better in any of the scenarios with transit preferential treatments than in the base case. The highest benefits for BRT operations were observed in the combined QJ & TSP scenario.

This study fills the gap in the existing research by adding the combined effects of QJ and TSP strategies using a real-world network, and analyzing both transit and vehicular modes. It shows that the combined benefits of QJ and TSP for transit are somewhat cumulative. This means that transit operations exploit the best features of the two transit preferential strategies. The study also shows that TSP should always be implemented if QJ lanes exist: this will provide most benefits for transit, without a major deterioration in vehicular traffic performance. The combination of QJ & TSP is a preferred treatment for the 3500 S BRT corridor. QJ phases and TSP can be further improved to minimize impacts on cross-street traffic for high volume side streets.

The study looked only into green extension and red truncation TSP strategies, combined with Queue Jumpers. In future research, some other TSP strategies, such as phase rotation, phase insertion, and/or phase skipping and their combination with QJ should be assessed. Also, a comparative evaluation between QJ & TSP and exclusive bus lanes should be performed from operational and cost/benefit standpoints.

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