Simulation Testing of No Ride Free Area at Selected Critical Bus Stops in the Seattle CBD

Volume 2: Downtown Seattle Transit Tunnel (DSTT), 4th Avenue, and Spot Locations

King County Metro Transit
Service Development
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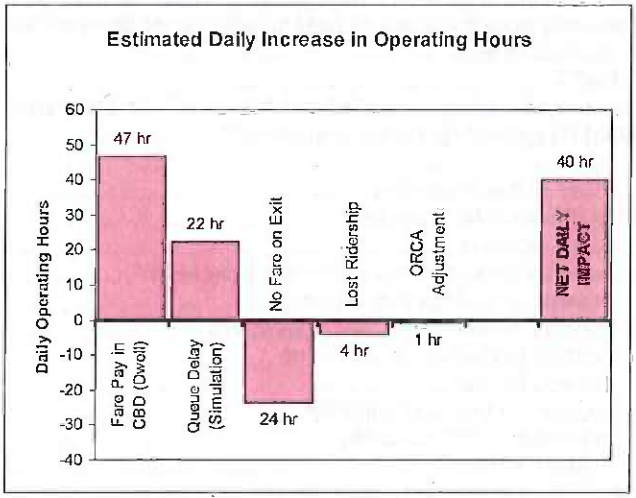
Executive Summary

Impacts to Transit Operation

Lesson learned from the simulation was that additional dwell time with pay on entry could negatively impact to bus and train operations in the DSTT. Delays experienced by buses and trains were increased between two to eight minutes per trip (compared to 9 minutes current travel time between International District and Convention Place Stations). Of the total 60[1] buses per hour during the afternoon peak hour traveling in the DSTT, only 50-52 coaches were able to be accommodated during the testing simulation. Reduction of bus volumes and/or increase of train headways in the tunnel during the peak hour are required to minimize delay and congestion at the platforms. The estimated number of coaches that can be accommodated in the DSTT ranges from 40 to 45 coaches per hour, although some improvements have been identified that could potentially increase capacity.

On surface streets, elimination of the RFA will increase dwell time and corridor travel time within the CBD, and will result in queuing problems at closely-spaced bus stops. Under current service levels, southbound 3rd Avenue would likely operate in a borderline acceptable condition as long as transit volumes remain the same. Without the RFA, 3rd Avenue would lose the ability to absorb additional coach volumes, whether due to planned Rapid Ride implementation, future tunnel routes being moved to the surface when Link frequency increases, or in the event of an emergency tunnel closure. Operations on 3rd Avenue southbound could completely break down in the event of an emergency tunnel closure without the RFA. Several measures are proposed to increase capacity of these critical bus stops that could help to mitigate the impacts of eliminating the RFA. On other corridors, bus travel time is also expected to increase without causing any major breakdown in the system.

Cost



The projected daily increase in operating hours from elimination of the RFA system wide is about 40 hours. Of the total 40 hours projected increase in daily operating hours, about 24 hours increase is due to delay on the surface streets and the remainder increase delay of 16 hours is projected to occur in the DSTT. The total increase in annual[2] operating cost using the average system wide marginal cost of $89.00 per hour is equal to 250 weekdays/year x 40 hours x $89.00 per hour = $890,000 annually.

Without mitigation measures, under current service levels, the annual operational cost to eliminate the RFA is projected to be **$890,000 annually**. This amount would be offset by additional fare revenue. This is a significant increase since the September 2010 report, which estimated this operating cost at $545,680; the increase is largely due to the delays in the DSTT that were measured during the recent simulations.

Potential Mitigation Measures

A set of improvements on both surface streets and DSTT should be considered to minimize transit delay and travel time due to pay on entry operation in downtown Seattle when no RFA is implemented. These are discussed in more detail in the last section of the report.

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[1] An agreement between Metro and Sound Transit sets a limit of 60 buses per hour per direction (10 of which are designated to be Sound Transit buses).

[2] The total increase in annual hours that would be incurred if the RFA were discontinued was calculated by multiplying daily impact hours by 250 weekdays/year; excluding weekends and holidays.
Annual hours = 250 weekdays/year x 40 hours = 10,000 annual hours

Surface Streets

- Adjust bus schedules to help reduce instances when groups of four buses arrive at critical bus stops at the same time
- Increase bus zone capacity at the critical zone on Third Avenue/Pike southbound to accommodate three coaches at a time by relocating loading zone closer to Pike St or removing the loading zone
- Implement ticket vending machines and/or ORCA readers at high boarding locations along Second, Third and Fourth Avenues.
- Implement additional traffic restrictions and enforcement on Third Avenue between Stewart St and Yesler Way.

Improve Columbia St traffic flow in order to increase bus zone capacity at Columbia and 2nd Ave bus zone.

DSTT

Evaluate the signal operation at the stub tunnel to reduce gridlock at stub tunnel and northbound coaches

- Reduce the number of Link Train/coaches operating in the DSTT - Without additional mitigation in place, the estimated number of coaches that can be accommodated in the DSTT ranges from 40 to 45 coaches per hour.
- Reconfigure staging area at IDS to help prioritize the order of buses entering the tunnel in the order of bay assignments
- Reevaluate bay assignments for buses serving bay A/B and bay C/D
- Implement second sweeper for Link at Westlake Station northbound to reduce Link dwell time at the platform.
- Change bus operation in the DSTT to allow all terminating coaches to drop off passengers anywhere on the platform.
- Add digital signs to display bus route number in the order of buses entering the tunnel for each platform in both directions.

What is the No Ride Free Area Simulation project?

On September 15, 2009, the King County Auditor's Office released its Performance Audit of Transit. This audit included recommendation A13, which states that,

> "A13: Transit should update and fully document the formula used to assess the City of Seattle's payment for the Downtown Seattle Ride Free Area to reflect current ridership and operating conditions including trips that are attracted by virtue of free fares. Transit and the council should then consider revising the agreement with the City of Seattle."

Metro submitted an executive response to the Auditor's report on September 9, 2009. In this response, Transit agreed to implement this finding, stating that it would be completed by the 3rd Quarter of 2010.

To address this recommendation, Metro began conducting studies to evaluate and update the costs and benefits of the ride free area (RFA). In September 2010, Volume 1 of the *Simulation Testing of No Ride Free Area at Selected Critical Bus Stops in the Seattle CBD* report was issued. This report addressed how transit operations without a ride free area would impact Second and Third Avenues and estimated the potential operating cost of eliminating the RFA. After consideration of the impacts described in this initial report, it was determined that additional analysis was necessary.

This report, Volume 2, builds upon the findings of the previous report to address the Downtown Seattle Transit Tunnel (DSTT), 4th Avenue, and other selected spot locations. It evaluates the impact that eliminating the ride free area would have on transit delay and operating costs. This report provides an updated operating cost estimate, based on the results of the additional simulations.

As with Volume 1, this report does not address the second part of the audit recommendation relating to fare revenue and policy issues, which will be addressed in a companion report.

What is the scope of this project?

During RFA hours (6 a.m. to 7 p.m.), no fares are collected within the Seattle Central Business District (CBD) area. Inbound trips that travel to the RFA require people to pay-on-entry until they reach the RFA and outbound trips are pay-on-exit after leaving the RFA. Trips not serving the CBD area are always pay-on-entry. If the RFA were to be discontinued King County Metro, as well as other partner agencies operating transit within the Seattle CBD, would likely convert to a fully pay-on-entry fare payment policy. If all passengers were required to pay fares upon boarding, dwell times would likely increase at busy bus stops in the CBD, due to the time required to pay the fare, and to single-door boarding.

Coach simulations have been conducted to assess the magnitude of increased delay and bus queuing that would occur because of increases in dwell time at bus stops. During the simulations, buses were deliberately delayed at selected bus stops in downtown Seattle by prescribed amounts during the afternoon peak commute hour. These simulations helped determine whether additional dwell time would cause severe queuing, compounding delays for buses as coaches wait for other vehicles to depart from the critical bus stops.

Data collected during the simulation includes:

- Amount of increased coach delay on surface streets due to additional dwell time

- Impact of dwell time to bus stop capacity
- Number of buses queuing that would occur as coaches wait for other coaches to depart at critical bus stops
- Coach travel time within and between DSTT stations, and between selected points on surface streets

The results of this simulation were used as assumptions in estimating the operating cost associated with potential RFA elimination.

What data and references are used for the assumptions and analysis in this project?

Throughout the study, a combination of resources were used to validate assumptions and to analyze transit delays and projected travel time. These resources and their specific uses pertaining to this study are described below.

- *Transit Capacity and Quality Service Manual*, TCRP Report 100 sponsored by the Federal Transit Administration. This manual was used as a reference for estimating passenger service time under various fare-payment scenarios. The relevant data presented in this manual was verified and refined in the field.

- Automatic Passenger Count (APC) database. The APC database was used to gather historical trends for numbers of boarding and alighting passengers. A regression analyses for dwell time information at selected bus stops was then performed with the data. This analysis was completed for system wide bus stops within and outside RFA area.

- Automatic Vehicle Identification (AVI) database. A network of AVI readers is installed throughout the Seattle CBD area to monitor transit travel times. Data from these readers was used to gather bus travel time along the corridors in the RFA and to determine typical day-to-day travel time variation.

- Automatic Vehicle Location (AVL) database. Metro's AVL system was used to determine typical day-to-day bus travel times through the DSTT. Due to limitations in the AVL system, data was often manually filtered to remove outliers, especially when a timepoint at the beginning or end of the trip was used. By using a consistent approach to filtering data, meaningful comparisons can be made.

- LINK SCADA logs. Detailed travel time and schedule time data are available for Sound Transit Link Light Rail trains (LRT) operating in the DSTT. This data was used to compare Link operations during the simulations with typical day-to-day operations. SCADA data was also used to verify and supplement the field data collected in the DSTT.

- Field Data (surface). At surface locations, data collectors were stationed just upstream of the zone (arrival) and at the head of the zone (departure). The arrival data collector recorded the time when each bus arrived at the bus stop or joined the queue of buses waiting to enter the bus stop, along with the queue position of the coach upon arrival. The departure data collector recorded the time that each bus departed from the bus stop. The arrival and departure data collectors had synchronized clocks, so that the times recorded could be compared to determine the total delay for each bus stop.

- Field Data (DSTT). In the tunnel, arrival and departure data collectors were positioned at each station and recorded the times that each bus and train entered or departed each station. From this data, a matrix of travel times was developed, showing the travel time of each bus and train trip within each of the tunnel segments.

No Ride Free Area Simulation Testing

How was the simulation methodology adjusted for the DSTT?

Surface bus zones on 4th Avenue and spot locations were simulated in a similar fashion as the previous simulations on 2nd and 3rd Avenues. More details about the surface zone simulation methodology are

available in Volume 1 of this report. Simulations in the DSTT required a different approach, described below.

- All four joint bus-rail operations stations were simulated at the same time in one direction. These stations are International District Station (IDS), Pioneer Square Station (PSS), University Street Station (USS) and Westlake Station (WLS). Convention Place Station (CPS) was not considered since it does not have rail operations. An additional simulation was conducted in both directions concurrently at USS and WLS only.
- Additional dwell time was determined based on the route number and its APC boardings Buses operating through the DSTT are not through-routed and are considered either inbound or outbound. Thus, the added dwell time for inbound coaches is lower than the added dwell time for outbound coaches. This assumption simplified the procedure and is valid in a controlled environment such as the DSTT.
- Two teams were assigned to Bays A and C to intercept the first and second coach. while one team was assigned to Bay B and D. Bay A (northbound) and Bay C (southbound) required more personnel because they handle a higher volume of buses than Bays B or D.
- For simulations involving northbound WLS, two security guards were employed to sweep trains at the end of the line. Under current operations, one security guard sweeps the second car while the train operator sweeps the first car. Employing a second guard to sweep the first car saves dwell time since the operator does not have to get out of his/her seat. A second security guard was incorporated into the assumptions for this study because this was identified as an easy measure that could be taken to mitigate increased bus dwell time at WLS.
- Data collectors were positioned at the station entrances and exits, recording the total time each vehicle spent in the station and in the tunnel bore sections between stations. Coaches will often have to wait in the tunnel bore section before a station is clear, something that may not be visible to observers in the stations. Passing is normally not allowed in the DSTT, therefore vehicles pass through the tunnel in strict first in first out (FIFO) queuing order.

Figure 1 below illustrates how staff were arranged in each station during the tunnel simulations.

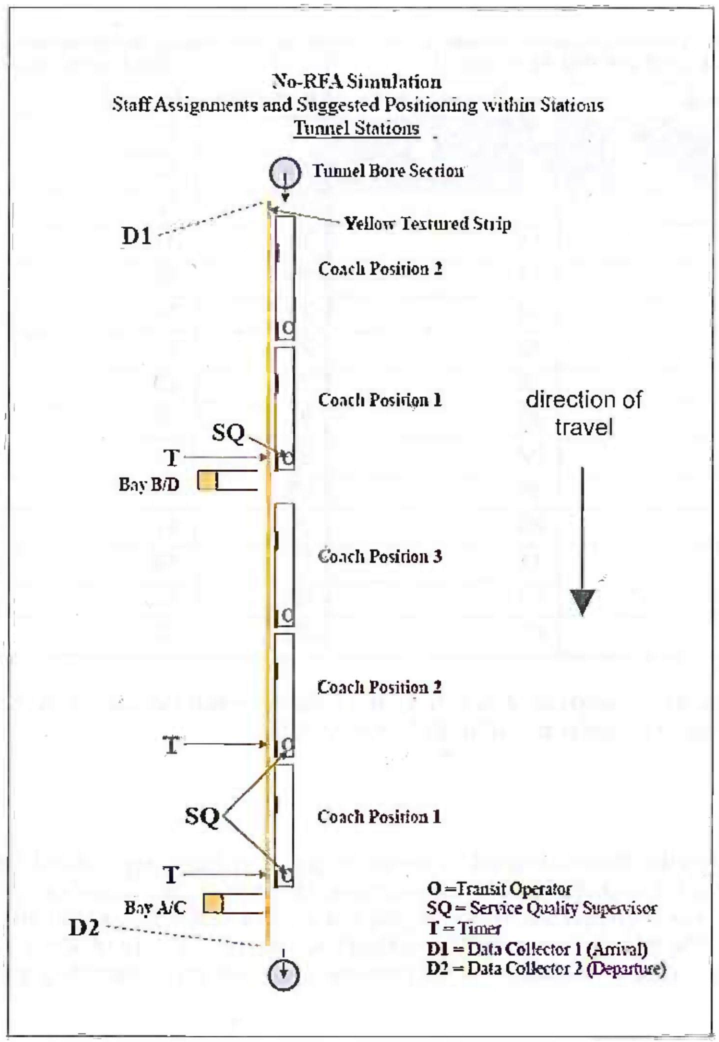

Figure 1: Simulation Setup in DSTT

How long were the coaches held to reflect operations without the RFA?

Surface Streets

The dwell time increase formula that was used for the previous simulations on 2nd and 3rd Avenues was used for the 4th Avenue and spot locations simulations on surface streets. The Volume 1 Report contains an in-depth discussion of how this formula was determined. The table that shows the increased dwell time for surface zones is included below for reference.

# of boardings	Dwell Time Increase [seconds] Normal	w/ lift/ramp use*	# of boardings	Dwell Time Increase [seconds] Normal	w/ lift/ramp use*
0	NO ADDED DELAY		15	29	49
1			16	30	52
2	4	7	17	32	56
3	6	11	18	34	59
4	8	14	19	35	62
5	10	18	20	37	65
6	12	22	21	39	69
7	14	25	22	40	72
8	16	29	23	42	75
9	18	32	24	44	79
10	20	36	25	46	82
11	22	39	26	47	85
12	23	41	27	49	88
13	25	44	28	51	92
14	27	46	29	52	95

* Additional dwell time for lift/ramp use was considered only at the two bus zones on Jackson Street, due to the observed frequency of lift/ramp use at these two bus stops.

DSTT

To determine additional dwell time required for people to pay upon boarding at DSTT stations, the above formula was applied to the average number of boardings, as measured by Metro's APC system at each station. The results were then rounded up to simplify the procedure and to account for platform congestion at Westlake station. The table below shows the added dwell times that were used for each bus route at each station. Note that Link Trains were not held for any amount of time, since they would continue to use prepaid boarding.

			Seconds of added dwell time			
Direction	In/Out	Routes	IDS	PSS	USS	WLS
Northbound	Outbound	41, 17, 72, 73, 74, 76, 77, 255, 301, 316	25	25	25	35
	Inbound	101, 106, 150, 212, 217, 550	10	5	5	5
Southbound	Outbound	101, 106, 150, 212, 216, 218, 225, 229, 550	25	25	25	35
	Inbound	41, 71, 72, 73, 74, 255	5	5	5	12

Where was testing conducted and how long? And why were these locations selected?

DSTT simulations were conducted according to the following schedule:

DSTT Simulation 1: Thursday, January 20
- Northbound direction: 3:30-4:30pm
- Southbound direction: 4:45-5:45pm

DSTT Simulation 2: Tuesday, January 25
- Southbound direction: 3:30-4:30pm
- Northbound direction: 4:45-5:45pm

DSTT Baseline Data Collection
- Data collection only, no holding coaches
- Northbound and Southbound at all stations: 3:30-5:45pm

DSTT Simulation 3: Wednesday, February 2

- Additional simulation added at request of LCC staff
- Northbound and Southbound at USS and WLS only: 4:00-5:45pm

Surface bus zone simulations and baseline data collection sessions were scheduled based on staff availability. The table below lists when each surface location was simulated and when baseline data was collected. All surface locations were simulated between 4:30-5:30pm.

Location	Simulation Date	Baseline Data
NB 4th Ave FS Union St (White zone)	Wed. 1/19/11	Tue. 1/25/11
NB 4th Ave FS Pike St (Orange zone)	Wed. 1/19/11	Wed. 1/26/11
EB Olive Way NS 6th Ave	Wed. 1/19/11	Tue. 2/1/11
WB Columbia St NS 2nd Ave	Wed. 1/19/11	Tue. 2/1/11
SB 3rd Ave NS Main St	Wed. 1/26/11	Tue. 2/1/11
EB Jackson St NS 5th Ave	Wed. 1/26/11	Tue. 2/1/11
WB Jackson St FS 5th Ave	Wed. 1/26/11	Tue. 2/1/11
EB Terrace St NS 5th Ave	Wed. 1/26/11	Tue. 2/1/11

The first three locations shown in the table are considered to be the critical bus stop locations for the 4th Avenue corridor. These bus stops are also used by Community Transit outbound trips and Pierce Transit inbound trips.

What Happened during the Simulation?

DSTT

Single-direction test

On the first day of the simulation, the northbound simulation was conducted first and then followed by the southbound simulation. On the second day of the simulation, the order was reversed, so that the southbound simulation was conducted first, and then followed by the northbound simulation. This strategy was conducted in order to capture the operational impacts to both buses and Link Trains when additional dwell time was added to buses during the afternoon peak commute hour in the tunnel in both directions.

The results of the single direction tests show an increase in average travel time in both directions, ranging between 2.1 and 2.5 minutes for buses, and 0.8 and 1.8 minutes for trains. The total amount of added dwell time for all stations was 1.8 minutes for outbound trips, and 0.4 - 0.5 minutes for inbound trips. The average added dwell time for all trips combined was between 1.3 – 1.4 minutes per trip in both directions. During the simulation, observations from the Link traffic control center noted that on occasions trains experienced delay between one and four minutes. During the test, occasional back ups occured at WLS in the southbound direction with more buses waiting at CPS to enter the tunnel. No significant problems were noted in the northbound direction.

At WLS, northbound trains had a second security guard to sweep the first car before trains leave WLS to enter the stub tunnel. Under normal operations, one security guard stationed at WLS sweeps the second car, while the train operator sweeps the first car. The average train dwell time during this normal operation procedure is 60-70 seconds. During the simulation, a second security guard swept the first car so that the train operator could remain in the cab. This action was observed to reduce train dwell time to 40-45 seconds or 20-25 seconds reduction of train dwell time.

Two-direction test

From the single-direction tests, it was observed that there was occasional back up occurring at WLS in the southbound direction with more buses waiting at CPS to enter the tunnel. The two-direction test was conducted to simulate the cumulative impact of buses backing up at WLS southbound and northbound. The test was run from 4 p.m. to 5:45 p.m.

After 45 minutes of simulation, occasional grid lock occurred when a train departing the stub tunnel was delayed while waiting for buses to clear out of the tunnel section between CPS and WLS; northbound buses had to wait until the southbound train fully departed the stub tunnel before they could proceed to CPS. The current signal logic is set up so when a train places a call to leave the stub tunnel, a red light is displayed for

northbound buses and southbound buses entering at CPS. However, the train at the stub tunnel cannot leave until the cut-and-cover section approaching WLS is cleared of all vehicles. See Figure 2.

As a result, northbound bus travel times between USS and WLS increased by 3.3 minutes, while an average of only 0.8 minutes of dwell time was added at these two stations (1.0 minutes to outbound trips, and 0.2 – 0.3 minutes to inbound trips). The added travel time resulted in roughly 42% of northbound buses experiencing 5 minutes or longer than scheduled time in the tunnel.

The measured delay of the two direction simulation between USS to WLS combined with the measured delay of the single direction simulation from IDS to USS resulted in an estimated travel time increase of 4.3 minutes per northbound trip and 1.9 minutes per southbound trip. The current scheduled time is 9 minutes per trip in each direction. This added time represents an almost 150% increase in travel time through the tunnel in the northbound direction.

The simulations were not able to capture delay to buses entering the tunnel southbound at CPS. It is possible that additional delay was occurring in the southbound direction when buses were waiting for clearance to enter the tunnel.

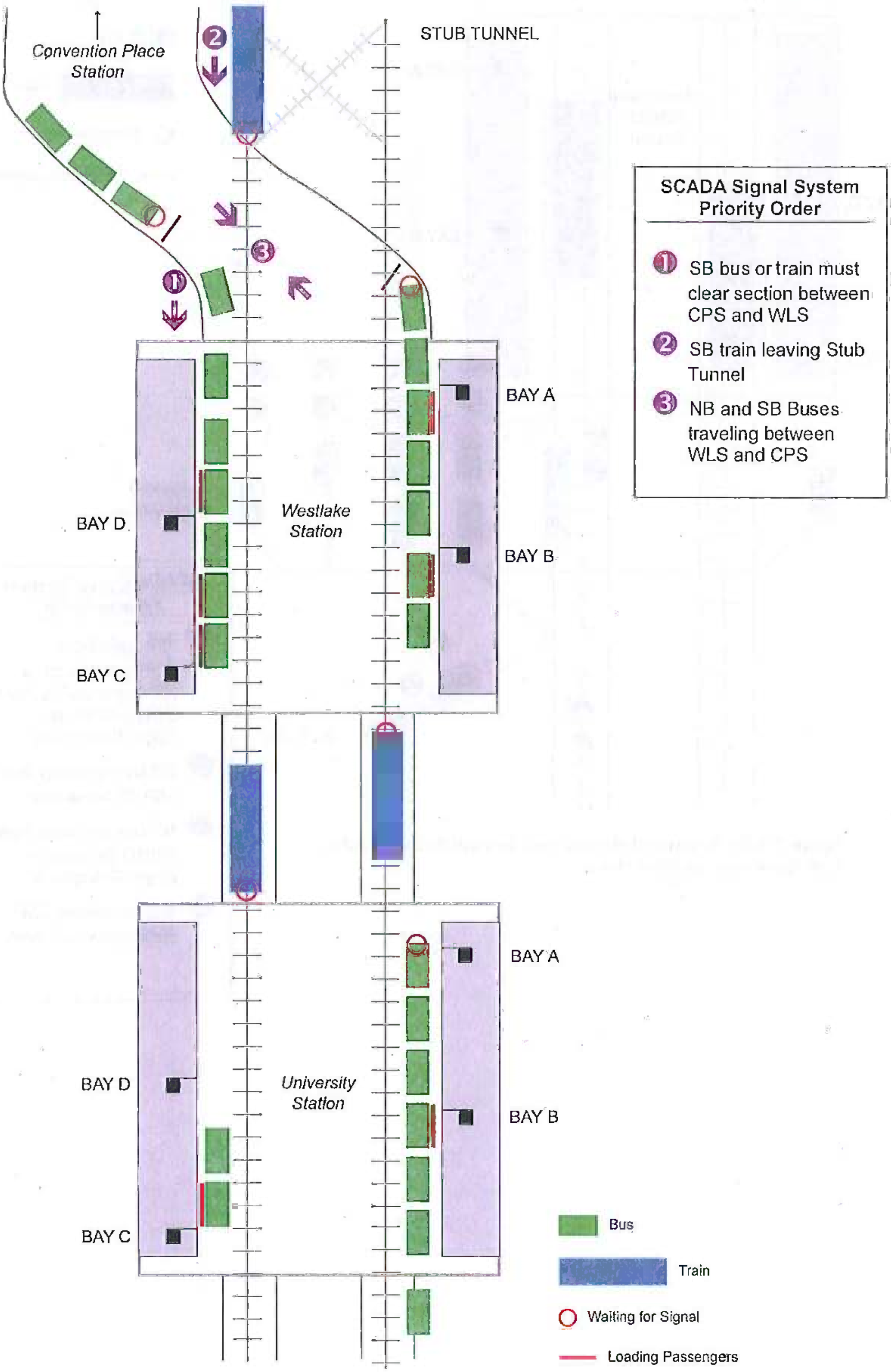

Figure 2: Typical bus and train queuing observed during two-direction simulation at USS and WLS

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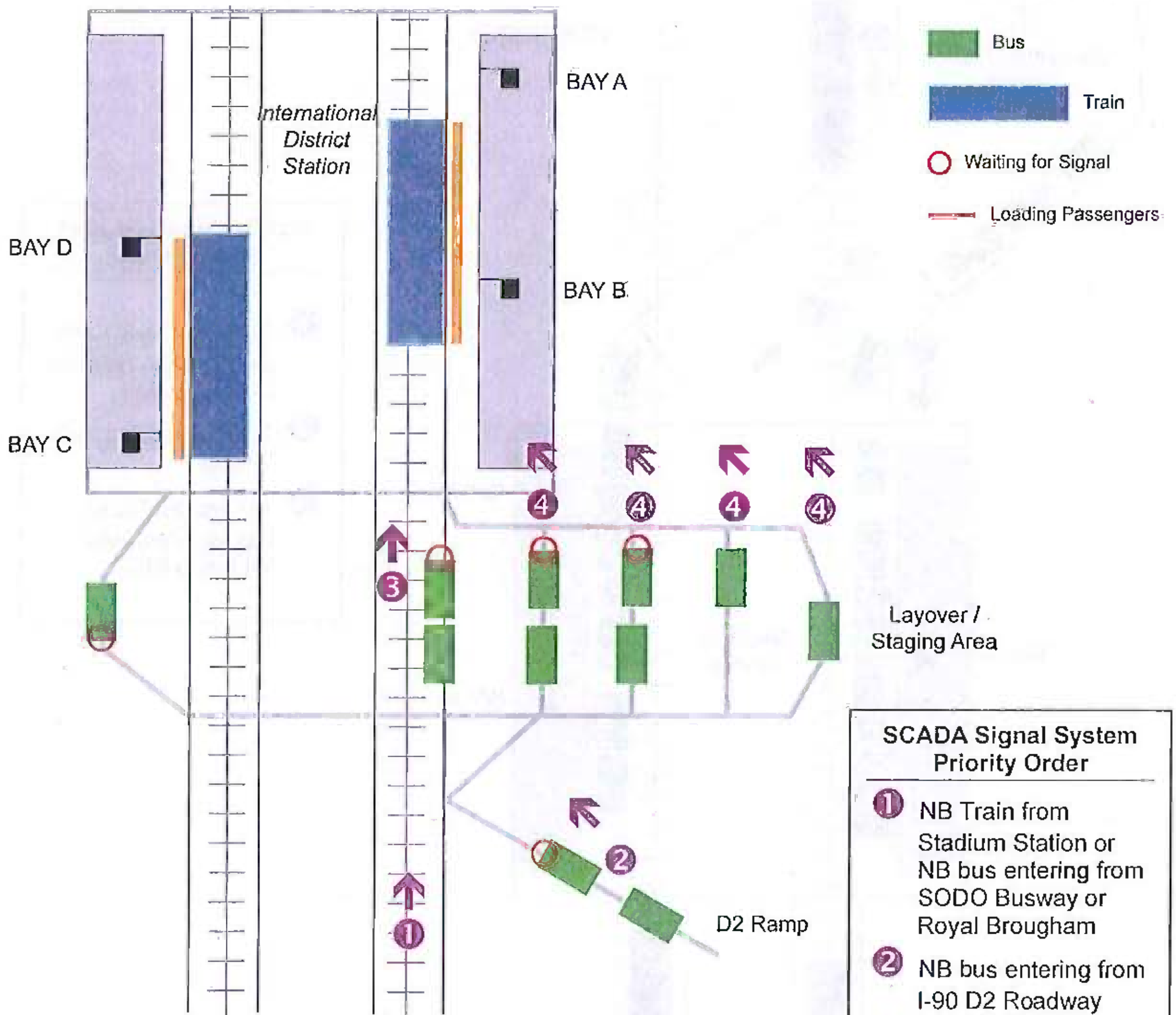

Figure 3: IDS Station and staging area for northbound coaches, typical queuing condition shown.

SCADA Signal System Priority Order

1. NB Train from Stadium Station or NB bus entering from SODO Busway or Royal Brougham
2. NB bus entering from I-90 D2 Roadway
3. NB bus entering from SODO Busway or Royal Brougham
4. Buses leaving IDS staging/layover area

King County METRO

Effect of the Simulation

The subsequent series of charts illustrate the effects of the simulation on bus and train travel times within the DSTT.

Figures 4a and 4b show overall travel time from one end of the tunnel to the other, for every bus and train trip observed during the single direction tests portion of the simulation. These charts show how travel time and delays unfold over time. It also provides information about the interaction between bus and train arrivals.

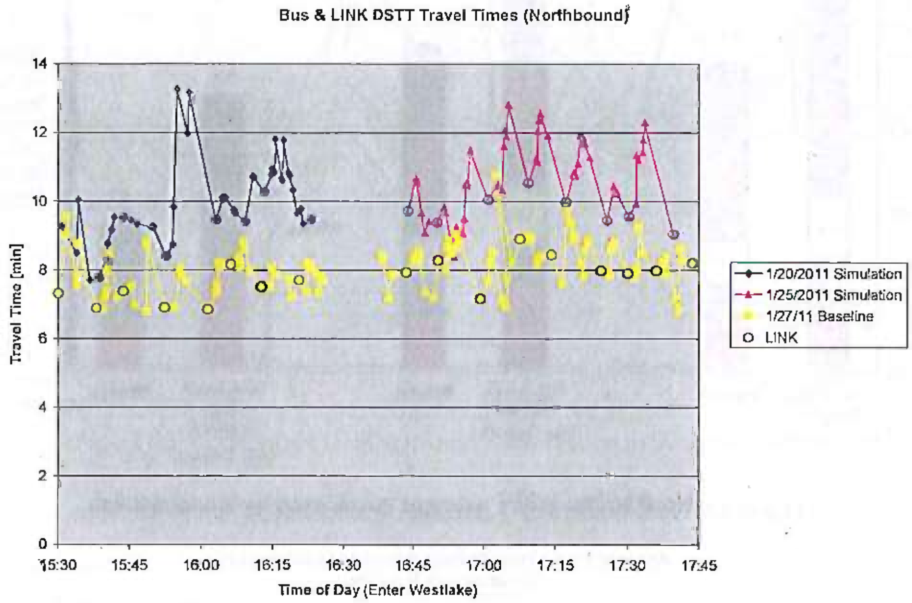

Figure 4a: Northbound DSTT Bus and Train end-to-end travel times by trip

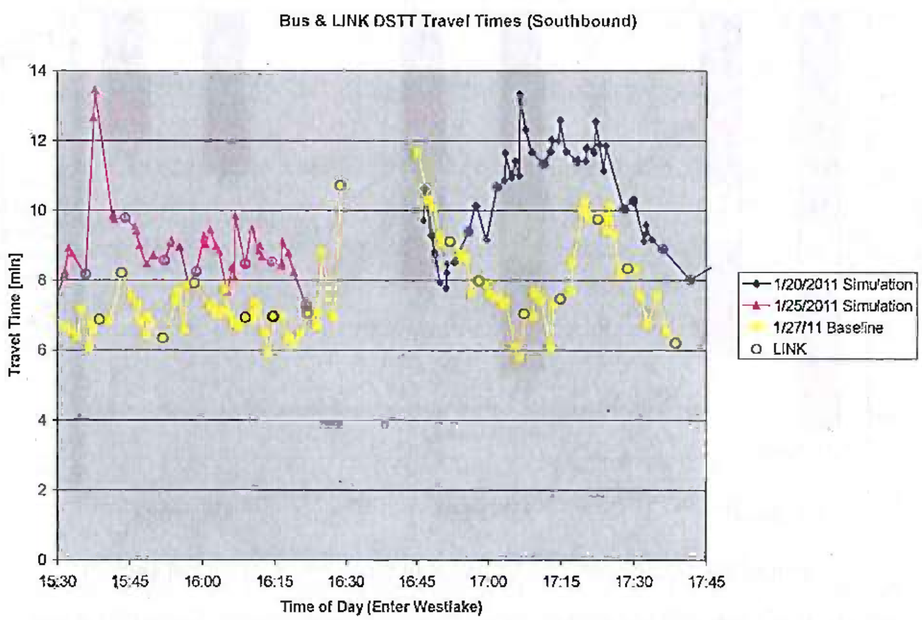

Figure 4b: Southbound DSTT Bus and Train end-to-end travel times by trip

Figures 5a and 5b show average travel times broken down by tunnel section, comparing each simulation period with the equivalent baseline period. These charts show where delay is occurring within the tunnel. The results of the two-direction test, which included WLS and USS only, are also shown.

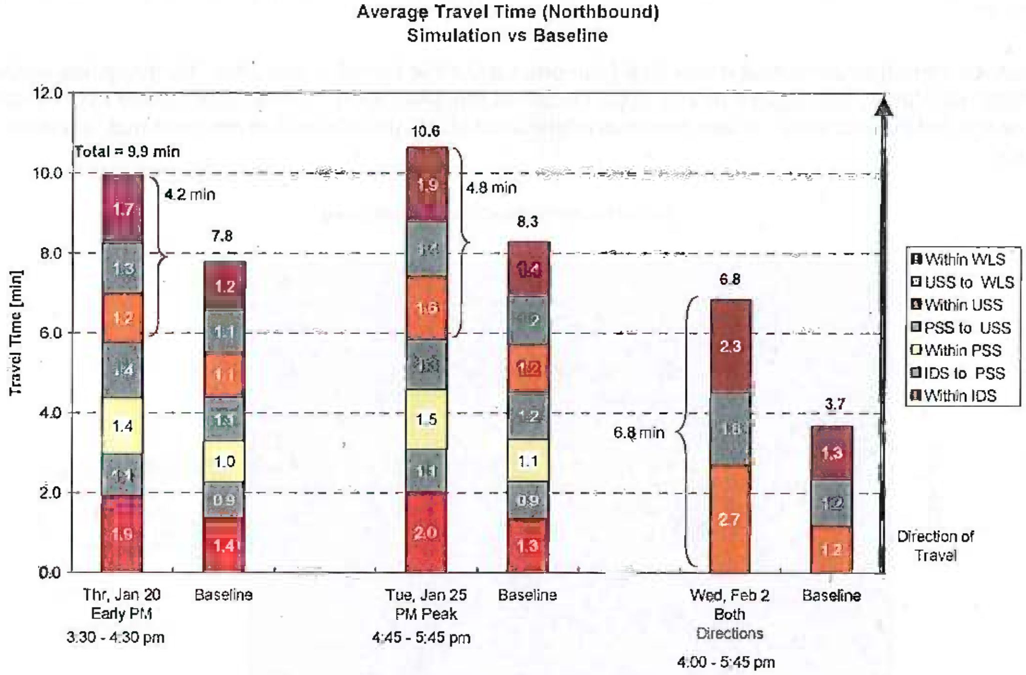

Figure 5a: Northbound DSTT average travel times by tunnel section

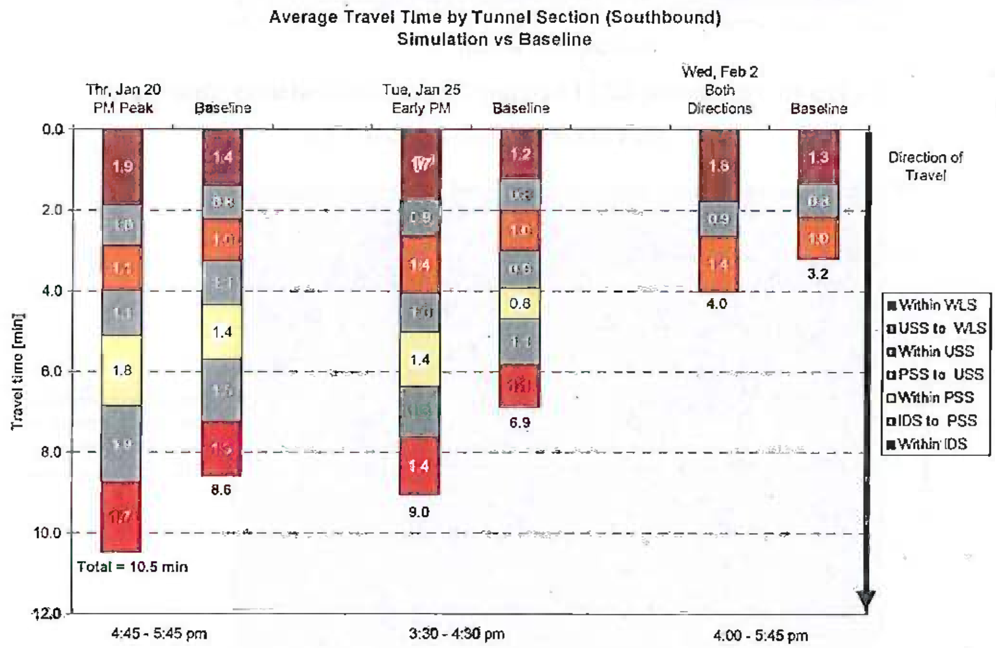

Figure 5b: Southbound DSTT average travel times by tunnel section

Figures 6a and 6b show LINK schedule adherence at Westlake Station based on SCADA logs over a 3-week period. Each line on the chart illustrates the difference between scheduled and actual arrival times during the PM peak period of one day of operation. The grey lines represent non-simulation days, and the blue lines indicate simulation days. Note that this chart captures the effects of a blocking incident, unrelated to any simulations, which occurred on 1/28/11 due to a bus breakdown in the southbound direction.

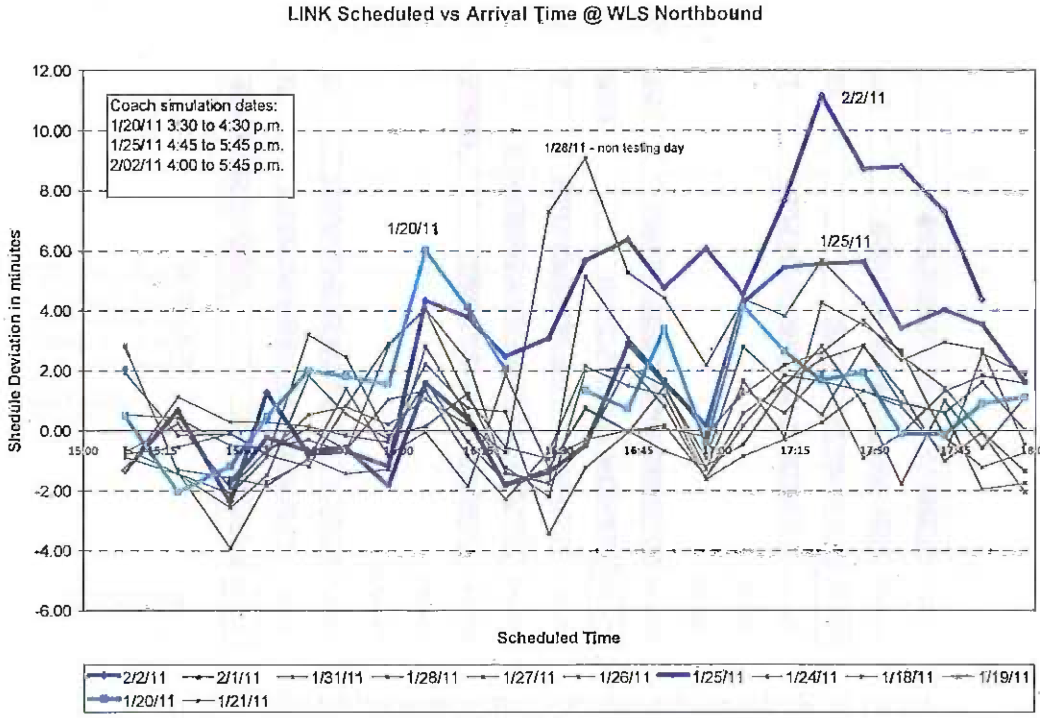

Figure 6a: Northbound LINK schedule performance at Westlake Station

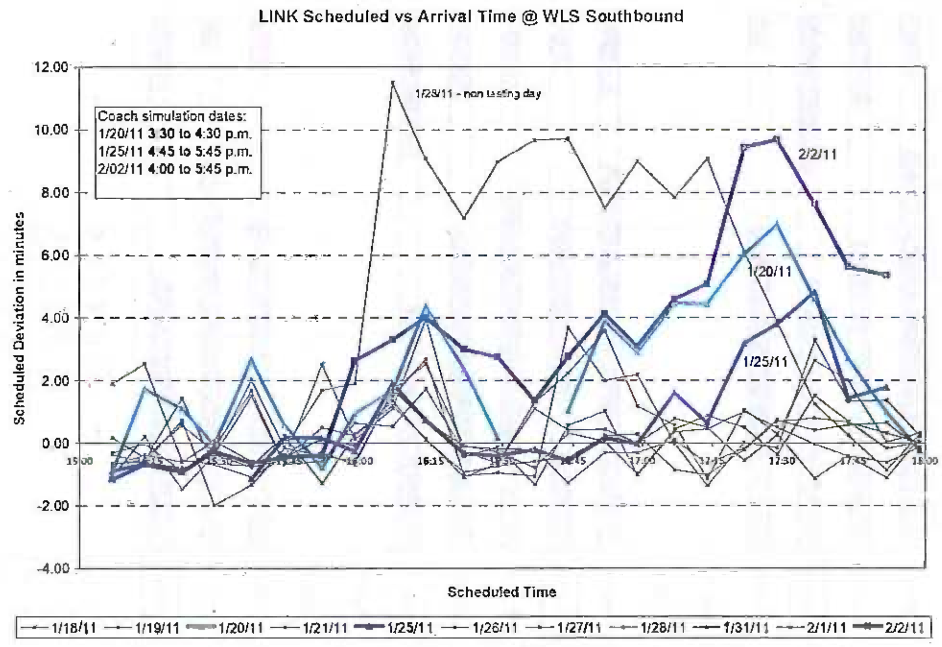

Figure 6b: Southbound LINK schedule performance at Westlake Station

Figures 7a and 7b show the distribution of bus schedule adherence over a three-weak period. This distribution is based on AVL data for travel times between CPS and IDS. The scheduled time for all bus trips is 9 minutes in both directions. These charts also show the effect of the blocking incident on 1/28/11.

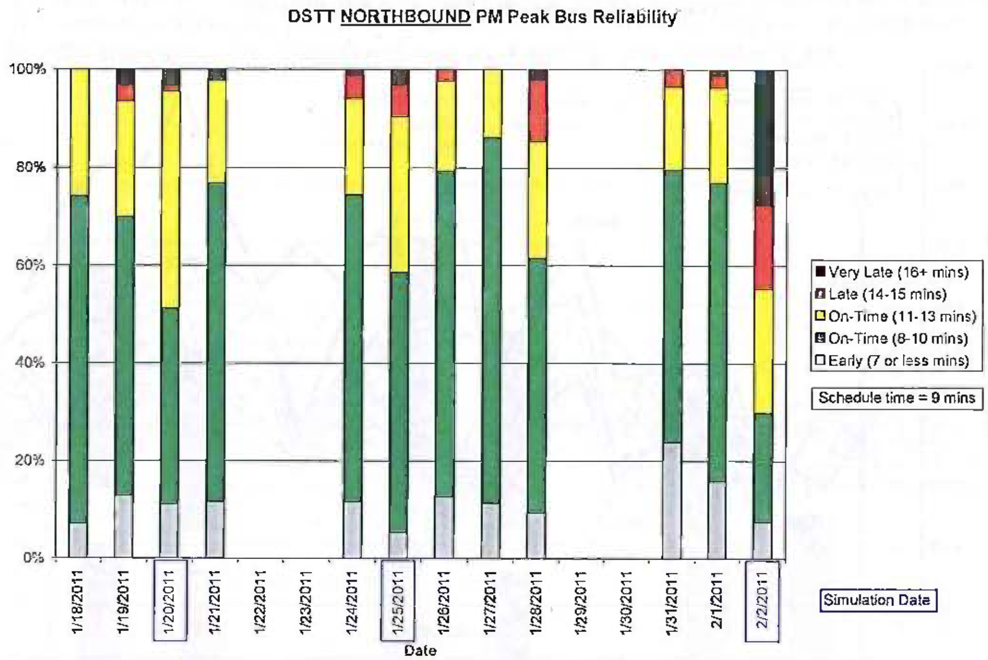

Figure 7a: Northbound bus schedule performance within DSTT (IDS to CPS)

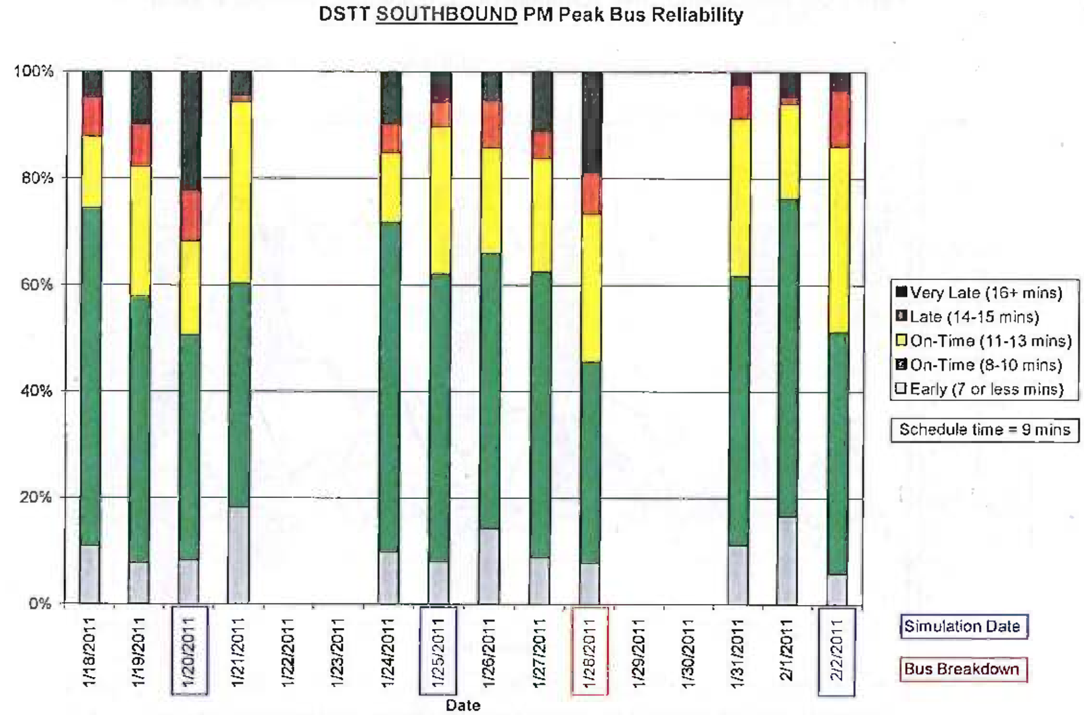

Figure 7b: Southbound bus schedule performance within DSTT (CPS to IDS)

Northbound 4th Avenue

The coach simulation in the northbound direction on 4th Avenue was conducted simultaneously at three adjacent bus stops. These stops were located at farside Union Street (White skip-stop zone), farside Pike Street (Orange skip-stop zone), and on Olive Way nearside 6th Avenue (unique skip-stop operation).

All three bus zones operated well under capacity with no queuing problems during both the baseline and simulation periods. Most buses arrived and were able to take either the first or second position, with a rare bus arriving in the third and fourth position. Instances of third or fourth position arrivals seemed to increase slightly at Union Street during the simulation.

At each bus stop, an average of 13-14 seconds of dwell time delay was intentionally added. This delay impacted these three stops as follows:

- Average bus stop delay at 4th Avenue and farside Union Street increased by 12 seconds during the simulation compared to baseline; while an average of 13 seconds of dwell time delay was intentionally added. A total of 32 buses were observed at the Pine Street bus stop during the simulation.

- At 4th Avenue farside Pike Street, no additional bus stop delay was observed during the simulation compared to the baseline, even though an average of 13 seconds of additional dwell time was added. A total of 37 buses were observed at this bus stop during the simulation.

- At Olive way nearside 6th Avenue, average bus stop delay increased by 5 seconds during the simulation compared to baseline; while an average of 14 seconds of additional dwell time was added. The additional dwell time often occurred while the bus was already waiting at a red signal, therefore the observed delay increase is less than the added dwell time. A total of 38 buses were observed at this bus stop during the simulation.

Figures 8a, 8b and 8c show how queues developed over the course of the simulation period in comparison to baseline conditions at these three bus zones. They also show the number of buses per minute that are expected to arrive based on the schedule. As noted previously, the current policy allows two coaches to load and unload passengers at a given time at each bus stop. When curb length is long enough to accommodate third and fourth coaches, these coaches are required to make second stops. Coaches arriving in position three and beyond are considered "over capacity" because they become affected by congestion at the bus stop.

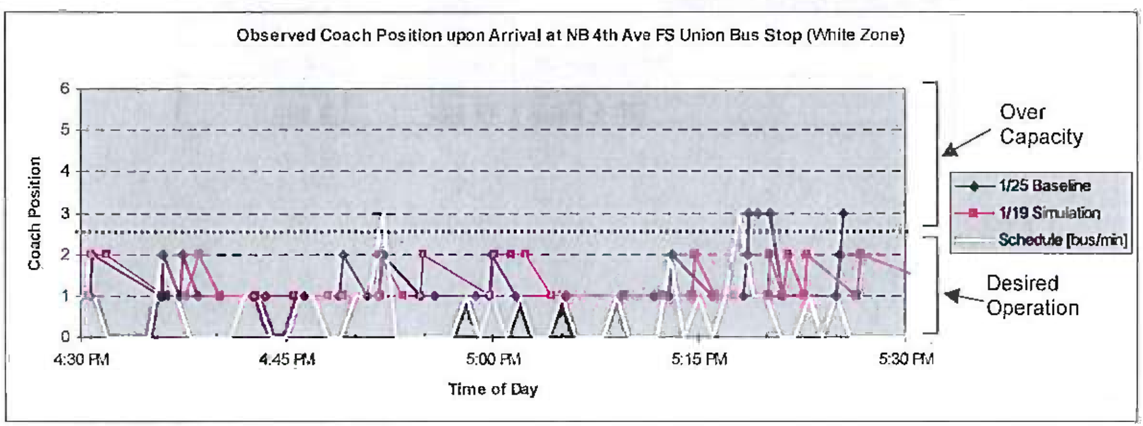

Figure 8a – Northbound 4th Avenue & Union Street baseline and simulation conditions, with scheduled arrivals

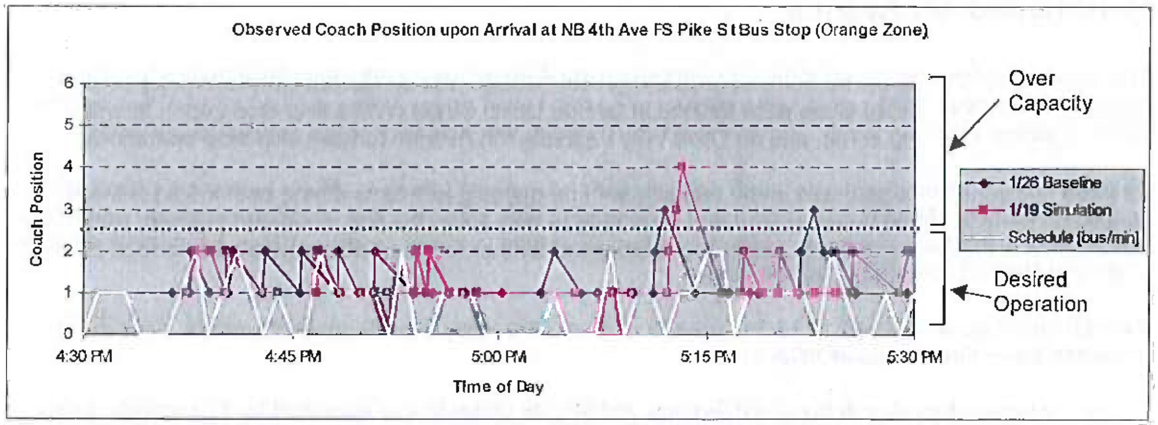

Figure 8b – Northbound 3rd Avenue and Pike Street baseline and simulation conditions, with scheduled arrivals

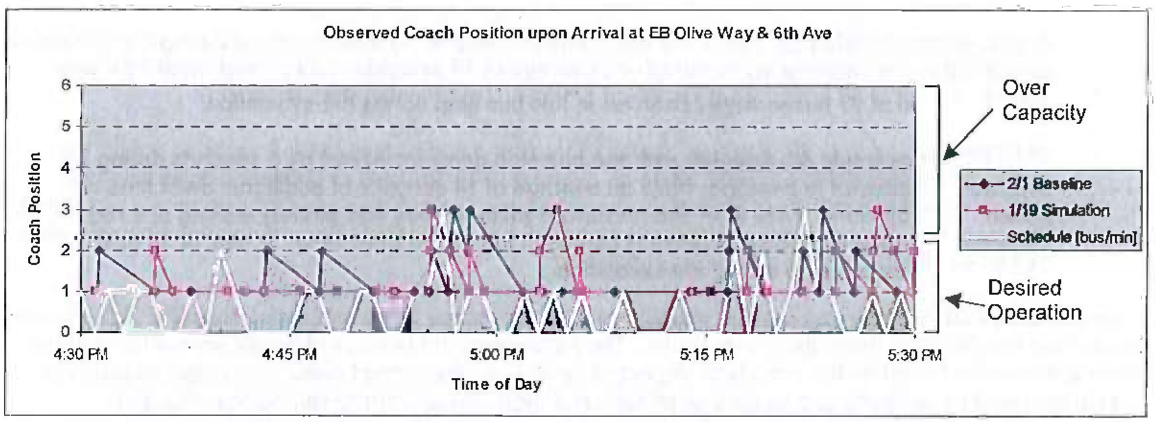

Figure 8c – Northbound 3rd Avenue and Pike Street baseline and simulation conditions, with scheduled arrivals

Bus Stop Delay Increase	Added Dwell Time	Simulation Result
NS Union St:	13 sec	12 sec
FS Pike St:	13 sec	none
6th & Olive	14 sec	5 sec

Figure 9 shows average bus travel times measured by the downtown AVI system between available readers at 4th Avenue & Seneca Street and 8th Avenue & Olive Way, over a four week period including the simulation date. Each bar represents the average travel time of all trips observed between 4:30 and 5:30pm. The simulation date is noted with an arrow. This chart demonstrates that the amount of additional delay resulting from the RFA simulation falls within a typical day-to-day travel time variation.

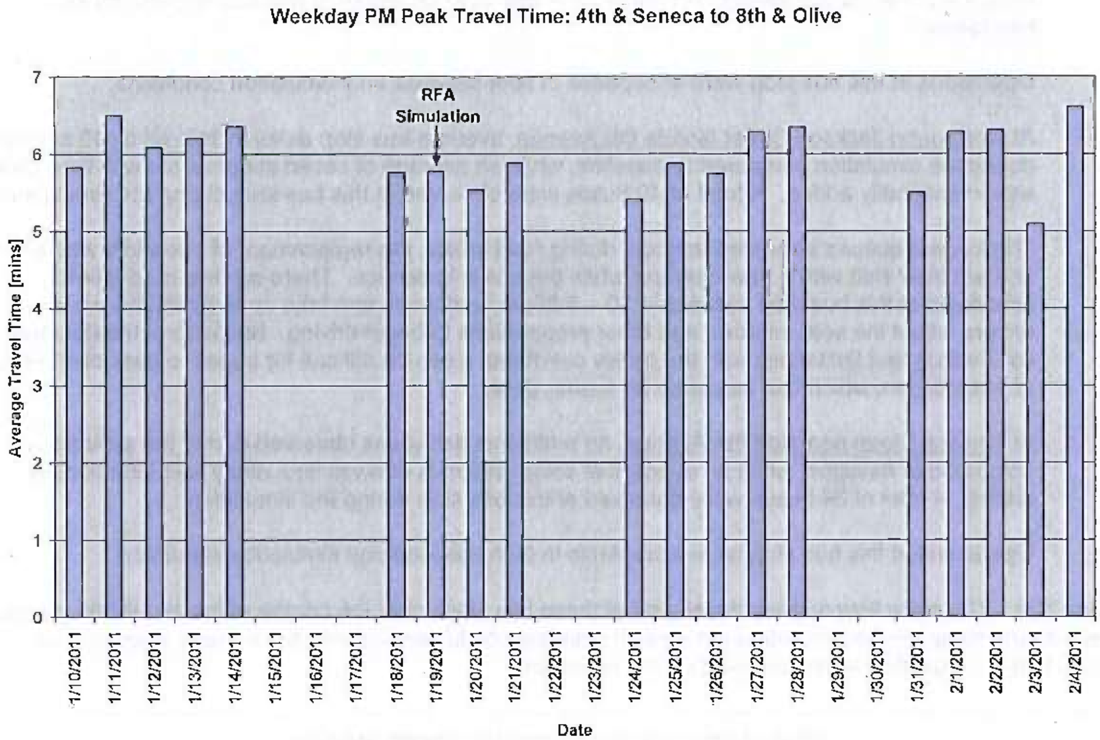

Figure 9 – Average Travel Times on 4th Avenue between Seneca Street and 8th Avenue & Olive Way across a four week period

Spot Locations

A handful of spot location bus zones were chosen and simulated to provide further insight into surface street operations without the RFA. These locations were identified as choke points outside of the primary CBD corridors, where bus stop queues are known to develop. Buses were intentionally delayed to simulate conditions that could occur without the RFA. Buses were held if there were two or more boardings at the stops. The results of the individual locations are as follows:

- At Columbia Street nearside 2nd Avenue, average bus stop delay increased by 55 seconds during the simulation compared to baseline, while an average of 19 seconds of dwell time delay was intentionally added. A total of 34 buses were observed at this bus stop during the simulation.

  This bus stop is subject to chronic over-capacity conditions during the PM peak, due to a combination of factors including the short length of the bus zone, alleys and driveways that interfere with passenger loading, the high number of boardings, and heavy traffic volumes in the adjacent lane. Queues of over five buses were observed developing during both baseline and simulation conditions. A bus lane and queue jump signal were recently installed at this location, which should help buses move out of the bus zone area easily and help queues dissipate more quickly; the simulation was conducted prior to the completion of the bus lane and queue jump.

- At 3rd Avenue nearside Main Street, average bus stop delay increased by 17 seconds during the simulation compared to baseline, while an average of three seconds of dwell time delay was intentionally added. A total of 42 buses were observed at this bus stop during the simulation.

Although this bus stop is a bottleneck where queues often develop, the bottleneck is largely due to the traffic signal at this location. The bus stop has a relatively low number of boardings, so the impact of RFA elimination would be relatively small.

- At eastbound Jackson Street nearside 5th Avenue, average bus stop delay increased by 13 seconds during the simulation compared to baseline, while an average of 11 seconds of dwell time delay was intentionally added. A total of 27 buses were observed at this bus stop during the simulation.

  Operations at this bus stop were acceptable in both baseline and simulation conditions.

- At westbound Jackson Street farside 5th Avenue, average bus stop delay increased by 13 seconds during the simulation compared to baseline, while an average of seven seconds of dwell time delay was intentionally added. A total of 40 buses were observed at this bus stop during the simulation.

  The longest queues appeared to occur during road reliefs, the replacement of operators who have finished their shift with a new operator while the bus is in service. There are two road reliefs scheduled at this bus stop between 4:30 – 5:30pm, and these can take up to 5 minutes while drivers adjust the seat, mirrors, and other preparations to begin driving. Because of the right turn at 4th Avenue and limitations with the trolley overhead, it can be difficult for buses to pass each other at this location, which can be cause for further delay.

- At Terrace Street nearside 5th Avenue, no additional delay was observed during the simulation compared to baseline, while an average of seven seconds of dwell time delay was intentionally added. A total of 34 buses were observed at this bus stop during the simulation.

  Operations at this bus stop were acceptable in both baseline and simulation conditions.

Figure 10a – 10e show how queues developed at these bus stops over the course of the simulation period. These charts compare the simulation period with baseline conditions and with the number of buses per minute that are expected to arrive based on the schedule.

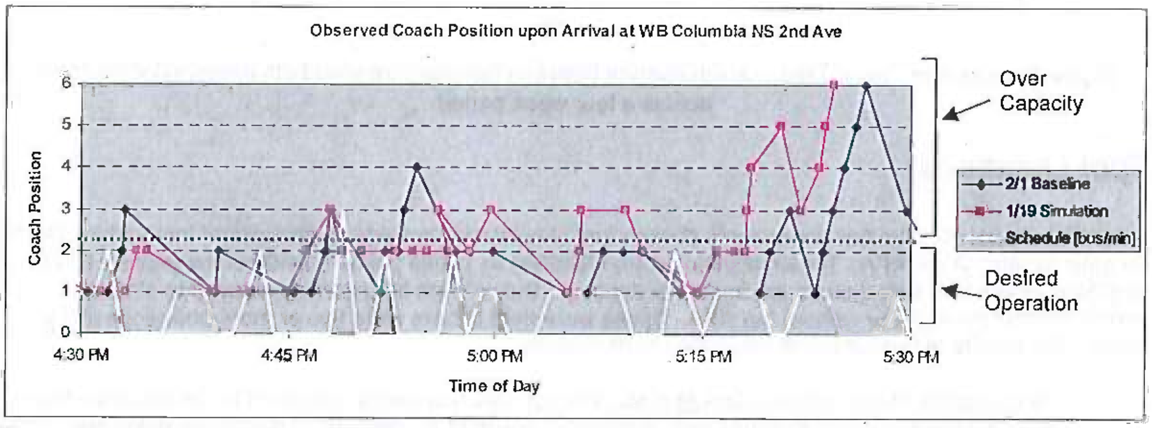

Figure 10a – Westbound Columbia Street nearside 2nd Avenue baseline and simulation conditions

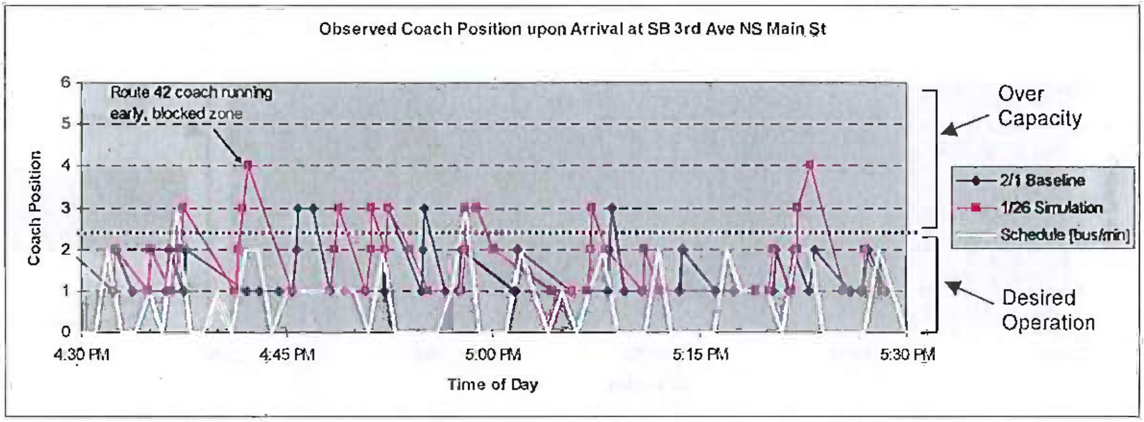

Figure 10b – Southbound 3rd Avenue nearside Main Street baseline and simulation conditions

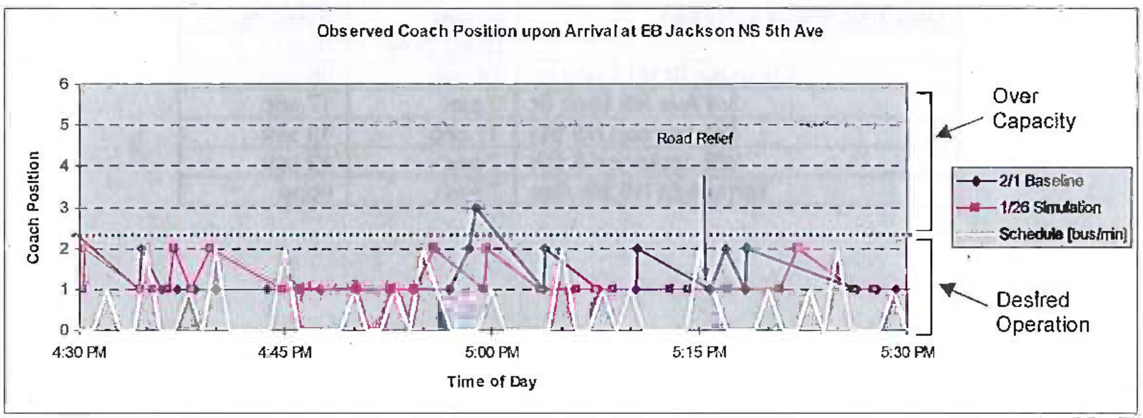

Figure 10c – Eastbound Jackson Street nearside 5th Avenue baseline and simulation conditions

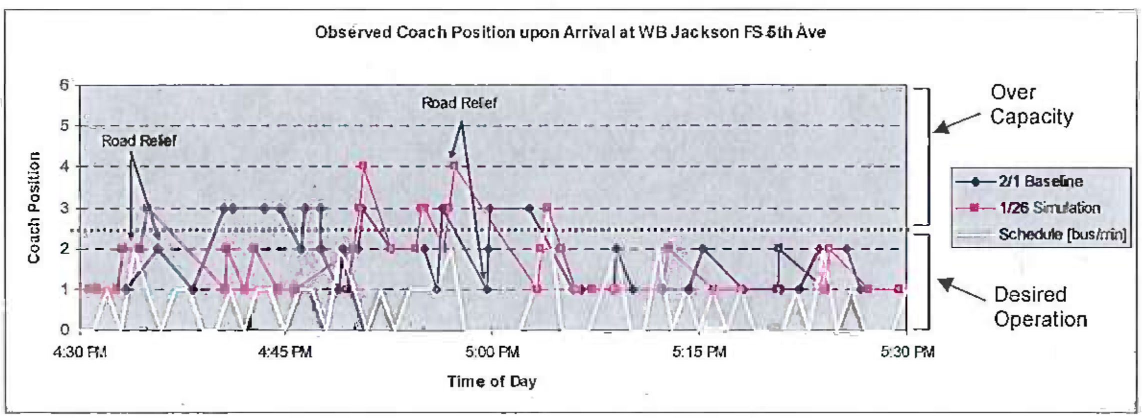

Figure 10d – Westbound Jackson Street farside 5th Avenue baseline and simulation conditions

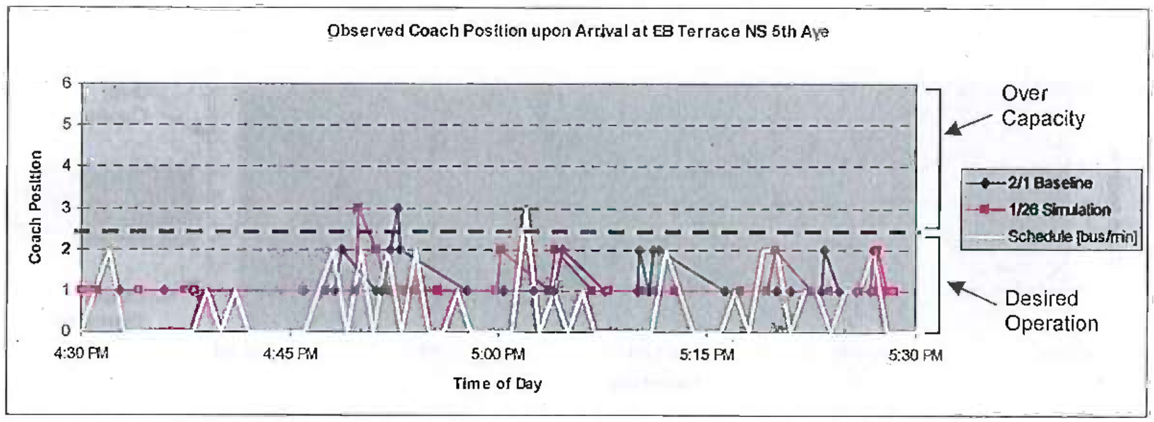

Figure 10e – Eastbound Terrace nearside 5th Avenue baseline and simulation conditions

Bus Stop Delay Increase	Added Dwell Time	Simulation Result
Columbia St NS 2nd Ave	19 sec	55 sec
3rd Ave NS Main St	3 sec	17 sec
EB Jackson NS 5th	11 sec	13 sec
WB Jackson FS 5th	7 sec	13 sec
Terrace St NS 5th Ave	7 sec	none

King County
METRO

What are the Impacts of No Ride Free Operation?

Impacts at Surface Bus Stops

The previous simulations on 2nd and 3rd Avenues demonstrated varying degrees of increased travel times and congestion at bus stops during the one hour afternoon peak hour from 4:30 p.m. to 5:30 p.m., although overall travel times fell within typical day-to-day variation. The second set of simulations shows that impacts on 4th Avenue and most spot locations are less than the impacts on 2nd and 3rd Avenues. The most significant issue would occur at the Columbia Street & 2nd Avenue bus zone, one that is currently experiencing capacity problems. These problems would likely be exacerbated should the RFA be eliminated. However this bus zone will no longer be used when the Alaskan Way Viaduct is taken out of service in 2015.

The projected daily increase in operating hours is 24 hours from the removal of ride free area due to higher dwell time at surface bus stops.

Impacts to DSTT and LINK Operations

The two-direction test in the DSTT demonstrated the potential for a grid-lock condition and significant increases in delay to both buses and trains operating through the DSTT. The impact will not be as severe as a bus or train breakdown, which can block tunnel operations and create significant delays even after the blockage has cleared.

Current scheduled travel time for buses through the tunnel is 9 minutes in each direction. Of the total 60[3] scheduled buses per hour during the afternoon peak hour, only 50-52 coaches were accommodated during the testing simulation with increase of delay by 4-5 min in the northbound direction and 2-3 min in the southbound direction.

Impacts to Corridor Travel Time

The simulation only addressed no-RFA conditions at one pair of bus stops along each corridor. To project total travel time increases along the entire length of the RFA corridors, delays at the other bus stops need to be considered as well. At these other bus stops, dwell time increases were calculated based on the number of APC boardings and assumptions about boarding times per person using the same formulas used to develop the dwell time increase charts for the simulation. A delay factor was added to account for additional signal delay in the CBD. This factor is based on the probability that the additional dwell time will cause a coach to miss a green light, multiplied by an average red light time. Delays recorded during the simulation were also incorporated into the projected corridor travel times.

The table below shows projected delays and travel times on the main north-south corridors within the RFA, and compares these with baseline conditions. This table incorporates results from the earlier simulations on 2nd and 3rd Avenues.

Corridor	from	to	No-RFA Delay [min]	PM Peak Travel Time [min]		
				Baseline	No RFA	Δ%
NB 3rd Ave	S Jackson St	Battery St	1.6	15.2	16.8	11%
SB 3rd Ave	Battery St	S Jackson St	1.8	15.2	17.0	12%
SB 2nd Ave	4th & Stewart	S Jackson St	1.7	14.9	16.6	11%
NB 4th Ave	S Jackson St	6^{th} & Olive	1.2	12.1	13.3	10%

[3] An agreement between Metro and Sound Transit sets a limit of 60 buses per hour per direction (10 of which are designated to be Sound Transit buses).

Impacts to riders

Riders with monthly passes and riders travelling from the Seattle CBD to a destination outside of the RFA, representing 89% of the current RFA boardings, will not likely make any changes in their travel behavior. The other 11% of riders, those paying cash and those travelling only within the RFA, may decide not to make their trips.

Implementing a pay-on-entry policy throughout the system would simplify fare payment and make the system more intuitive for new riders. In addition, there may be benefits from improved circulation within coaches and better utilization of the back doors. The all pay-on-entry policy is also likely to reduce fare evasion rates. For further details, refer to the report *2010 Ride Free Area Ridership and Revenue Estimates, September 14, 2010.*

Impacts on bus stop capacity

Increasing dwell time at critical bus zones will decrease the potential capacity of the bus stops and the downtown corridors overall. Bus stop capacity refers to the theoretical maximum number of buses per hour that the bus stop is able to reliably serve. Because of limited capacity in Downtown Seattle, many of the buses operate on a skip-stop pattern, where the buses only serve every other stop. Where skip-stops are used, corridor capacity refers to the maximum number of buses per hour that the skip-stops operating together are able to accommodate.

Bus stop and corridor capacity can be determined using dwell time, traffic signal timing information, clearance time (time needed to re-enter traffic), number of loading areas, and other traffic parameters. This methodology is outlined in Part 4 of the TCRP Transit Capacity & Quality of Service Manual. The bus stop capacity calculation also requires the assumption of an acceptable failure rate. This rate defines failure as a condition where a bus arrives at a bus stop but is unable to serve it until other buses move out of the bus zone. On 3rd Avenue, a failure rate of 25% is considered an acceptable failure rate based on previous analysis and field observation.

For the no-RFA condition, the reduction in capacity can be calculated based on the average number of boardings recorded during the simulation and the corresponding average dwell time increase. The tables below summarize the reduction in capacity when compared to existing bus volumes. The volume to capacity (v/c) ratio shown in the tables provides an indication of how close to capacity the bus stop is currently operating. Since the previous report, 3rd Avenue volumes and v/c ratios have been updated to reflect the February 2011 service change, and 4th Avenue has been added.

Elimination of the RFA would reduce bus zone capacity, which will become more of a problem as RapidRide C, D, and E lines are implemented and bus volumes increase further on 3rd Avenue. When Link Light Rail is extended and train frequencies are increased, it is anticipated that some or all of the bus volume currently using the DSTT will be routed to surface streets. At the same time, some of the current DSTT bus volume may be eliminated to avoid duplication with Link service. Although some routes can be moved to 2nd/4th Avenues, it will become increasingly difficult to preserve some of the attributes of transit service that make it easier to understand and use, such as groupings of routes serving similar geographic areas. Some measures could be taken to increase bus stop capacity, which are discussed in the Volume 1 report.

Northbound 3rd Avenue	Pike		(#590)	Pine		(#578)	Corridor		
Buses per PM peak hour	vol	Cap	v/c	Vol	cap	v/c	vol	cap	v/c
Existing Service Level (Spring 2011)	44	65	0.68	63	85	0.74	107	130	0.82
Existing Service Level Without RFA	44	40	1.10	63	65	0.97	107	95	1.13

Southbound 3rd Avenue	Pine		(#430)	Pike		(#431)	Corridor		
Buses per PM peak hour	vol	Cap	v/c	Vol	cap	v/c	vol	cap	v/c
Existing Service Level (Spring 2011)	60	80	0.75	61	65	0.94	121	130	0.93
Existing Service Level Without RFA	60	70	0.86	61	50	1.22	121	100	1.21

Southbound 2nd Avenue[4]	University (#315)			Pike (#300)			Corridor		
Buses per PM peak hour	vol	Cap	v/c	Vol	cap	v/c	vol	cap	v/c
Existing Service Level (Spring 2010)	52	85	0.61	29	105	0.28	81	160	0.51
Existing Service Level Without RFA	52	70	0.74	29	75	0.39	81	120	0.66
Northbound 4th Avenue[1]	Union (#690)			Marion (#660)			Corridor		
Buses per PM peak hour	vol	Cap	v/c	Vol	cap	v/c	vol	cap	v/c
Existing Service Level (Spring 2011)	32	65	0.49	42	109	0.34	74	135	0.55
Existing Service Level Without RFA	32	49	0.65	42	80	0.53	74	100	0.74

Impacts to DSTT Capacity

An agreement between Metro and Sound Transit sets a limit of 60 buses per hour per direction that are allowed to operate in the DSTT during peak hours (10 of which are designated to be Sound Transit bus trips). Current scheduled bus volumes during the PM peak are nearly at the 60 bus/hour limit in both directions. Based on the results of the simulation, reduction of bus volumes and/or increase of train headway in the tunnel during the peak hour are required to minimize delay and congestion at the platforms. Without additional mitigation in place, the estimated number of coaches that can be accommodated in the DSTT ranges from 40 to 45 coaches per hour. Reducing bus volumes would require that specific routes be identified and alternative surface street pathways be used for those routes. Metro and Sound Transit would also have to negotiate new cost sharing agreements due to the change in bus volumes.

Another way to improve operations in the DSTT would be to reduce Link volumes. In terms of operational impact, one train is equivalent to about 3 buses.

System Impacts

The simulation focused on potential impacts to the most congested bus stops in the RFA. The corridor results focused on the most congested transit corridors within the RFA. In order to understand the full costs of eliminating the RFA and converting to an all pay-on-entry system, the entire transit system needs to be considered. While travel times within the CBD and DSTT will increase, there will be a corresponding savings to outbound trips that are currently pay-on-exit. In addition, the number of boardings would likely decrease should the RFA were eliminated, resulting in some additional operational savings.

System-wide impacts are computed in terms of daily platform hours, which can then be converted into annual hours and operating cost. This is not a complete re-blocking analysis, where actual bus schedules are reworked to determine operational cost impacts, but it is an approximation. In reality, some of the additional delay may be absorbed into layover without affecting service. In other cases, coaches may need to be added into the schedule in order to maintain existing service levels, which would incur additional costs.

This report updates the previous analysis completed on total system impacts by incorporating simulation results from the DSTT, 4th Avenue, and spot locations. In addition, other assumptions such as percentages of boardings continuing outside the RFA, and number of boardings with a transfer were updated based on recent surveys.

Figure 11 shows a breakdown of RFA boardings based on surveys conducted in 2010. The majority of boardings are of passengers continuing beyond the RFA boundary, and another large proportion is composed of trips within the RFA by people with a transfer or monthly pass; it is assumed that these people will not change their trip behavior. Of the remaining 12%, it is assumed that 7% will no longer ride in the RFA, while 5% will now pay a fare for

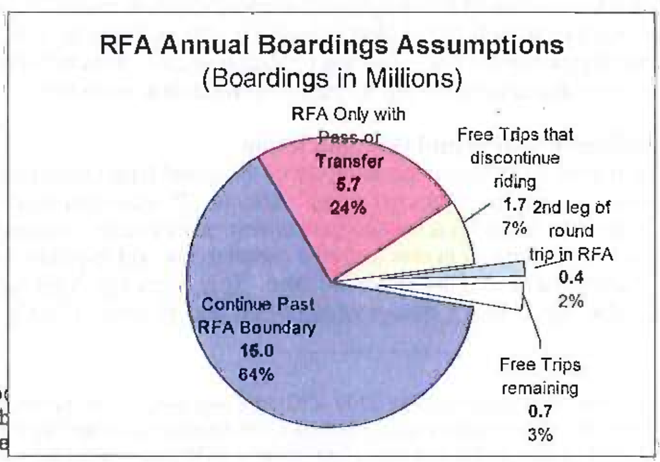

Figure 11: RFA boardings breakdown

4 NOTE: Bus stop capacity on 2nd and 4th Ave is rep
simulation on 2nd Avenue. Capacity without RFA is b
stops would be equivalent to the dwell time increase
zone.

their trip (with 2% making a second trip in the RFA with a transfer). These assumptions are all important for RFA revenue projections, which are addressed in the companion report, however the 7% reduction in boardings is incorporated for the system-wide operations analysis completed below.

Total RFA Delay
In general, the simulation results indicate that the additional bus stop delay resulting from pay-on-entry closely equals the intentionally added dwell time. Exceptions to this general rule occur when bus stops are currently operating close to capacity and/or bus stop queues interfere with the operation of other bus stops, such as at SB 3rd Avenue and Pike Street and Westlake Station. The system-wide impact of eliminating the RFA can be computed by multiplying the number of affected boardings by the change in boarding time per person. Adjustments were made to capture increased delay at bus zones with queuing/capacity issues, which will be added separately. The delay due to dwell time increase in the RFA is computed as follows:

Service Time per Boarding Passenger[5]		APC observations used
No fare payment:	1.42 sec/pass	RFA Boardings + Alightings
Pay-on-Entry:	3.76 sec/pass	Inbound trip Boardings
Difference:	+2.25 sec/pass	
Number of boardings:	74,000	Total RFA boardings[6] – 7% lost trips
Daily Operating Delay:	**47 hours increase**	

No Fare Pay on Exit
With the pay-on-entry fare policy, there would be some delay savings in places where passengers currently pay-on-exit. Based on additional regression analyses, service time per alighting passenger (pay on exit) is compared with the service time per deboarding passenger on inbound trips outside of Downtown (no fare payment). It is assumed that the rear door can be more efficiently used on these outbound trips, so alighting time per passenger in this scenario is similar to current RFA boarding/alighting times.

Service Time per Alighting Passenger		APC observations used
Pay-on-Exit:	3.09 sec/pass	Outbound trip Alightings
No Fare Payment:	1.42 sec/pass	RFA Boardings + Alightings
Difference:	-1.67 sec/pass	
Number of boardings:	51,000	RFA trips to outside of RFA (64%)
Daily Operating Savings:	**24 hours decrease**	

Lost Ridership
Eliminating the RFA is expected to reduce the total number of boardings and alightings within the current RFA, because some passengers will choose not to ride. Based on the estimated 7% reduction in the number of boardings, and the RFA boarding/alighting passenger service time noted above, the estimated savings would be approximately **four hours travel time decrease** in daily operating hours.

Smart Card Implementation
Increased use of the ORCA smart card was also considered and incorporated into the potential savings. Service time projections were based on Fall 2009 data, though ORCA use has increased since that period. ORCA use in Fall 2009 in the CBD was estimated to be 17%, while the full implementation target of ORCA is 25%[7]. Based on the projection of riders who will switch to ORCA and an assumed 1.5 second savings[8] for each cash or ticket paying passenger who switches to ORCA, the resulting savings is a **one hour travel time decrease** for the RFA trips analyzed above. This includes only boardings within the RFA, which could be considered to offset the 47 hours of dwell time increase.

Additional Traffic and Queuing Delay
Simulation results and the analysis of the travel time increases along the congested corridors during the PM peak were added to the net delay increase. The corridor travel time projections were first adjusted to remove the dwell time component, which was already accounted in the dwell time delay calculation above. The resulting delay is due to traffic signal delay and queuing at congested bus stops, and amounts to a **22 hour increase** in daily operating time. This figure has increased since the previous report, largely due to the addition of DSTT delays which alone add 13 hours of daily operating cost.

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[5] Service times based on Fall 2009 APC data regression, 1-10 boardings data range used
[6] Does not include boardings on Sound Transit service operated by King County
[7] Based on Spring 2010 analysis by Research & Management Information
[8] Based on national standards presented in TCRP Report 100

Conclusion
Without the ride free area operation in downtown Seattle, the projected transit delay and operating hours combined will increase by 40 hours each weekday. Details of the projected hours are summarized in Figure 12 below.

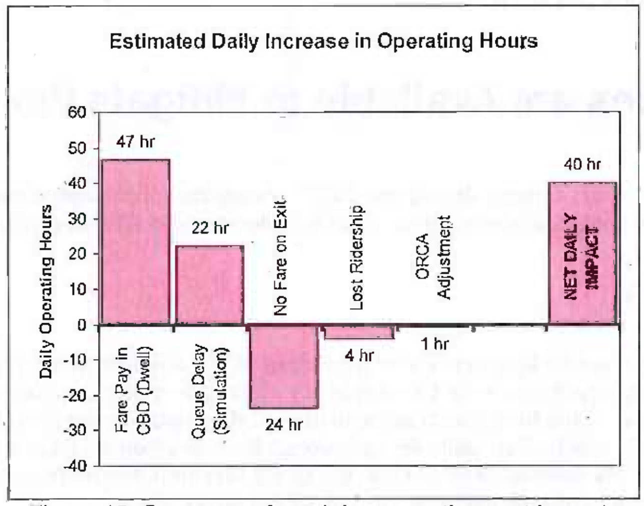

Figure 12: Summary of weekday operating cost impacts

Of the total 40 hours projected increase in daily operating hours, about 24 hours is due to delay on the surface streets and the remainder of 16 hours is projected to occur in DSTT.

The calculated annual increase in the operating cost is about $890,000; excluding weekends, holidays, and reduced weekdays. The daily operating delay is translated into annual hours by multiplying by 250 weekdays per year. Annual cost is determined by multiplying the annual hours increase by the average system wide marginal operating cost that includes a factor for additional deadhead trips ($89.00 per hour in year 2010). The annual hours of delay and cost that would be incurred if the RFA were discontinued are as follows:

Annual Hours of Delay	Annual Operating Cost (2010 dollars)
10,000 hrs.	$890,000

What do the Simulation Results Mean?

Based on the previous simulation, the following conclusions were made regarding surface street operations:

- Elimination of the Ride Free Area will increase delay and reduce reliability of transit service along the most congested corridors with the Seattle CBD.
- The level of increased delay due to payment-on-entry and single door boarding falls within typical day-to-day variation of average PM travel times.
- Southbound 3rd Avenue demonstrated operations during the simulation that borderline on acceptable and would leave no room for additional bus volumes.
- In a situation where the RFA is eliminated, and there in an emergency tunnel closure during the PM peak, significant queuing would be expected on southbound 3rd Avenue, with moderate queuing to northbound 3rd Avenue and southbound 2nd Avenue operations.
- A set of mitigation on the surface streets should be implemented to increase bus stop capacity at critical bus zones on 3rd Avenue

Based on the results of the new simulations, the following conclusions can be added to the above:

- DSTT operations without RFA, without reducing the number of buses in the tunnel or implementing other improvements, will result in frequent grid-lock conditions at Westlake Station and the cut-and-cover tunnel section between WLS and CPS. Delays will not be as severe as those that occur during a bus or train breakdown.

- Without implementing mitigation measures, travel time increases of up to five minutes (56%) per trip can be expected through the DSTT.
- 4th Avenue and other surface locations will be able to absorb additional dwell time without significant impacts to operations, except where existing issues exist such as the bus zone on Columbia nearside 2nd Avenue.

What Measures are Available to Mitigate the NO-RFA Impacts?

A set of improvements on both surface streets and DSTT should be considered to minimize transit delay and travel time due to pay on entry operation in downtown Seattle when no RFA is implemented.

Surface Streets

- Adjust bus schedules to help reduce demand at bus stops at a given time when groups of four buses arrive at critical bus stops the same time. Current policy allows two coaches at a time to load and unload passengers at bus stops. If the third coach stops to load and unload passengers, it is required to make a second stop. The fourth coach often waits for curb space to clear when an adjacent traffic signal is green but has nowhere to go. As coaches start to clear out of the bus stop, the fourth coach cannot proceed because the traffic signal turns red and it has to wait for the next cycle.

Responsibility party: Metro Schedulers

- Increase bus zone capacity at the critical zone on Third Avenue/Pike southbound to accommodate three coaches at a time by relocating loading zone closer to Pike St or removing the loading zone

Responsibility party: City of Seattle and Metro

- Implement ticket vending machines and/or ORCA readers at high boarding locations along Second, Third and Fourth Avenues.

Responsibility party: City of Seattle and Metro

- Implement additional traffic restrictions and enforcement on Third Avenue between Stewart St and Yesler Way.

Responsibility party: City of Seattle

- Improve Columbia St traffic flow in order to increase bus zone capacity at Columbia and 2nd Ave bus zone. The current operation has a limited gap for buses to merge to next lane of traffic before entering SR 99 on-ramp and it frequently prevents a bus leaving the zone and then buses behind it form a queue on Columbia St and southbound on Third Avenue.

Responsibility party: City of Seattle and Metro

DSTT

A set of improvements listed below should be considered to alleviate congestion in the tunnel if no RFA is in operation. Each improvement is expected to provide a small benefit and the cumulative benefits of all improvements are expected to help reduce the impact to transit and train operations. In a situation where only a handful of improvements are deployed, further assessment and/or field testing may be required to make sure bus/train operation in the DSTT with no-RFA will operate within an acceptable level.

- Evaluate the signal operation at the stub tunnel to reduce gridlock at stub tunnel- Adjust the signal operation at the merge point near the stub tunnel to reduce delays to northbound buses and trains leaving the stub tunnel. Southbound buses queuing at Westlake Station frequently back up into the cut and cover ("chute") area. When a southbound Link Train sends a call to put signals at Convention Place Station signals to stop, it has to wait for buses to clear the chute area before receiving a green signal. After 90 seconds, if queuing buses are still present in the chute area, the call times-out and the train has to wait for the next cycle to leave the stub tunnel. In the meantime, northbound buses frequently are held while the southbound train has an active call but cannot move.

Responsibility party: Sound Transit Signal Engineers

- Reduce the number of Link Train/coaches operating in the DSTT - Reduce the number of coaches operating in the tunnel in order to reduce queuing of buses at the platform with no RFA operation. Of the total 60[9] buses per hour scheduled during the afternoon peak hour, only 50-52 coaches were accommodated during the testing simulation with increase of delay by 4-5 min in the northbound direction and 2-3 min in the southbound direction. Reduction of buses volumes and/or increase of train headways in the tunnel during the peak hour are required to minimize delay and congestion at the platforms. Without additional mitigation in place, the estimated number of coaches that can be accommodated in the DSTT ranges from 40 to 45 coaches per hour.

Responsibility party: Sound Transit and Metro planners

- Reconfigure staging area at IDS to help prioritize the order of buses entering the tunnel in the order of bay assignments - Reconfigure station area at IDS to designate lane four as a through lane. Currently, lane 4 is used for route 255 and 256 layover. The benefit of lane designation of lane four is to prioritize buses entering the IDS platform in the order of bay routes. Bay A buses currently get stuck behind Bay B buses stopping at each station. Drivers are not required to open doors while waiting for the Bay B buses. This improvement would require modification to the signal system and wiring to regulate buses in the staging area and northbound Link Trains before entering IDS. Further assessment is required to find displaced layover location and to estimate the additional operating hours needed to route the displaced routes outside the tunnel.

Responsibility party: Sound Transit Operations and Metro to find layover replacement

- Reevaluate bay assignments for buses serving bay A/B and bay C/D - when reduction of bus volume in DSTT is implemented. Analyze the number of buses serving each bay and balance the volumes to spread out the congestion evenly on the platform.

Responsibility party: Metro and Sound Transit

- Implement second sweeper for Link at Westlake Station northbound to reduce Link dwell time at the platform. The reduction of dwell time for Link will reduce wait time for buses to enter the Westlake Station northbound.

Responsibility party: Sound Transit Operations

- Change bus operation in the DSTT to allow all terminating coaches to drop off passengers anywhere on the platform. Further assessment may be required to mitigate impact to visually impaired and ADA riders. Inconsistent drop off location posts a challenge for visually impaired riders to access elevators in DSTT. Public outreach and operators training work plans are needed to be in placed prior to the removal of RFA in DSTT.

Responsibility party: Metro

- Implement dynamic bay assignment system - Add digital signs to display bus route number in the order of buses entering the tunnel for each platform in both directions. The signs will provide information to riders waiting at the platform of the order of incoming buses and will give riders enough time to get to the right position at the station before the bus arrives.

Responsibility party: Sound Transit Operations

[9] An agreement between Metro and Sound Transit sets a limit of 60 buses per hour per direction (10 of which are designated to be Sound Transit buses).