Analysis of Transit Signal Priority Using Archived TriMet Bus Dispatch System Data

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Findings are presented on changes in bus running times, on-time performance, and excess passenger wait times following implementation of transit signal priority (TSP) in select bus corridors in the Portland metropolitan region. Analysis of the effectiveness of TSP is often undertaken by using simulation techniques or empirical studies that are limited in either scope or data availability, or both. The current research uses an abundance of trip-level data collected from TriMet's Bus Dispatch System, in Portland, Oregon. The study focuses on the most common performance measures of interest to both transit operators and passengers and shows that the expected benefits of TSP are not consistent across routes and time periods, nor are they consistent across the various performance measures. The authors believe that benefits of TSP will accrue only as the result of extensive evaluation and adjustment after initial deployment. In most cases, an ongoing performance monitoring and adjustment program should be implemented to maximize TSP benefits.

Many transit agencies have implemented transit signal priority (TSP) programs in recent years. The success of TSP in reducing running time delay is widely recognized in the literature, though estimated and actual running time savings vary considerably across studies (*1, 2*). Analysis of the benefits of TSP can be differentiated according to those based on analytical studies, simulation, or empirical analysis with data collected in the field. Analytical studies use mathematical techniques to derive theoretical results. These models can then be tested in more real-world settings by using simulation. Simulation studies tend to focus on either a single intersection or a series of signalized intersections within a corridor. Costs associated with manual data collection efforts may necessitate the use of simulation for quantifying TSP benefits (*3*). Simulation studies undertaken with empirical studies are often limited with respect to the duration, amount, and type of data collected (*1, 2*).

Analysis of the benefits of TSP is often helped by the collection of preliminary baseline data that can be used for comparison purposes following implementation (*4–8*). Transit agencies with automatic vehicle location (AVL) systems in place are much more likely to undertake before-and-after studies as well as collect data for longer time durations. The majority of empirical studies are "one off" studies in that benefits are measured immediately following TSP implementation and not at subsequent time intervals. Ongoing performance monitoring programs are needed in order to provide feedback for adjusting schedules (*9*) and signal timing so as to maximize TSP system performance. Limited data availability tends to hinder statistical analysis. Although the majority of TSP studies show positive changes in certain key performance measures following implementation, the real question is whether the differences are statistically significant. Previous studies finding statistically significant changes in service reliability and efficiency resulting from TSP implementations include both simulation analysis (*3, 10*) and field studies (*11*); however, the practice of testing for significant differences is the exception (*4, 8*) rather than the rule.

This study differs from previous ones primarily in that analysis of TSP is undertaken on a large number of route segments, and operations data derived from the TriMet Bus Dispatch System collected before and after TSP implementation are compared. The TriMet Bus Dispatch System, in Portland, Oregon, is inimitable among North American transit agencies in that detailed operations data are collected for each bus in the system at every stop on a continuous basis. These data provide a unique opportunity for comprehensively analyzing changes in bus performance following TSP implementation. The current study analyzes changes in the mean and variance in bus running times, changes in on-time performance (OTP), scheduling benefits, and passenger wait times. The study also includes a regression model to consider the effect of the after-TSP implementation period on actual running times.

From a transit standpoint, TSP falls within the domains of service planning, scheduling, performance monitoring, field supervision, and operator training. Before implementation, it is important that transit agencies adequately identify the bus routes that could benefit the most from TSP. These routes should be exhibiting poor performance due to operational problems and not inadequate scheduling or operator management issues. Buses that are consistently early or late would indicate a scheduling or supervision problem. Accurate schedules are critical since they are not exogenous to the process. Portland's TSP system (*12*) is based on conditional priority, whereby late buses beyond a certain delay threshold value request priority until buses are no longer deemed excessively late. Since schedule delay is determined by relating actual to scheduled service, the accuracy of the reference point (the schedule time) has important implications for determining whether TSP is even requested in the first place or for how long and for monitoring the effectiveness of TSP through performance analysis.

EMPIRICAL ANALYSIS

Study Characteristics

Select TriMet bus routes with TSP coverage are represented in the analysis. The characteristics of the analysis segments are presented in

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TABLE 1 Analysis Segments

Segment[a]	Name	Dist. (mi)	Bus Stops	Traffic Signals	Priority Signals	Nearside Stops
12-0	Barbur Blvd.	6.2	29	13	13	5
12-1	Barbur Blvd.	6.1	30	13	13	6
14-0	Hawthorne	5.9	46	25	18	5
14-1	Hawthorne	5.9	44	25	18	14
72-N/W	82nd Ave./Killingsworth	13.1	95	47	32	17
72-E/S	82nd Ave./Killingsworth	13.0	95	46	32	20
94X-0	Sherwood–Pacific Hwy.	8.4	5	19	13	1
94X-1	Sherwood–Pacific Hwy.	8.2	6	19	13	2
109-0	Powell	4.0	30	17	13	3
109-1	Powell	4.0	30	17	13	3
112-0	Sandy Blvd.	5.2	36	28	19	7
112-1	Sandy Blvd.	5.2	37	28	19	14

[a] Segment naming convention is route-direction (e.g., 12-0). For radial route segments, 0 = outbound or 1 = inbound. For cross-town routes segments, the actual direction is used.

Table 1, with Figure 1 showing the locations geographically. Table 1 presents information about the individual route segments including distance, the number of scheduled stops, the number of signalized intersections, the number of priority intersections, and the number of priority intersections with nearside bus stops. Six bus routes were analyzed broken out by time of day and direction. For peak time periods of operation, bus performance on radial route segments in the primary direction of travel was analyzed. Both directions of travel were analyzed on radial route segments in the midday time period as well as on crosstown route segments in all time periods since there is no primary travel direction. A total of 24 analysis segments are included in the study.

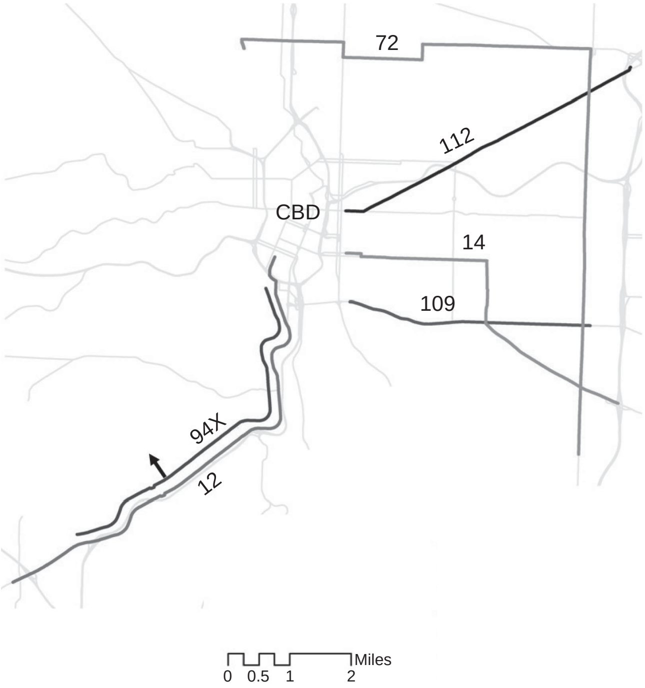

FIGURE 1 Study area map (CBD = central business district; light gray lines are major arterials).

The 12-112 Barbur Blvd.–Sandy Blvd. route is a double-spoke, radial through route connecting the two suburbs of Sherwood and Gresham with downtown Portland. Each spoke is treated as an individual segment in the analysis. The 109 Powell route links Gresham and close-in urban neighborhoods with downtown. The Broadway portion of the 9-109 was excluded from the analysis because of an extended reroute related to light-rail construction affecting one of the data collection periods. Route 14 Hawthorne is a high-frequency single-spoke radial route serving dense urban neighborhoods in southeast Portland. Route 72 Killingsworth–82nd Ave. is a high-demand, dogleg-shaped crosstown route connecting Clackamas Town Center with the Swan Island industrial area. The 94X is a single-spoke, radial express route operating on a major urban arterial. The 94X operates on the same street as the 12 Barbur Blvd. route.

The before-and-after samples form a panel in that individual trip-level observations in the before sample have a corresponding element in the after sample. This arrangement helps ensure that any differences in bus running times between the before and the after TSP implementation periods are due to factors other than sample size discrepancies or representative bus trips. Each trip was matched according to a unique identifier consisting of route segment, direction, trip, day of week, and a randomly assigned counter variable. This same approach was employed by the authors in a previous analysis of bus running times (*13*). Of the 13,868 trip-level observations in the before sample, a direct match was found with 9,066 observations, for a 65.4% success rate. To control for seasonal effects between the two sampling periods, data were processed for similar months.

At the time of data collection, signal priority was initialized by means of an emitter if a bus was 90 s late or more. The emitter was turned on at that point and remained on until delay became 30 s or less. The current analysis considers the effectiveness of TSP by comparing bus performance following TSP implementation with baseline conditions before the system was turned on. It was not possible to collect information on the number of times a particular bus trip received priority. As such, the current analysis cannot directly measure the effects of TSP on bus performance. A number of confounding factors exist, including changes in schedules, operators, signal phasing, and traffic levels to name several; however, these are the conditions that exist in the real world.

Testing for Differences in Mean and Variance of Running Times

Transit operations personnel are interested in utilizing limited resources in an efficient manner. Bus running time is a performance measure that is of particular interest to schedulers. Excessive running time variability forces schedulers to add excess recovery-layover time to schedules. Since this time is nonrevenue service, the costs of unreliable service can add up quickly. The data were analyzed to see if there were any changes in the mean and variance of running time between the periods before and after TSP implementation. A test for difference in means for paired samples was used to determine whether changes in mean running times were statistically significant. To test for the difference between two variances, an *F*-test was employed. The statistical tests were based on the 95% level of confidence under the null hypothesis that the measures were not statistically different between the two time periods.

Descriptive statistics for mean scheduled running time, mean actual running time, running time variation, and the coefficient of variation of running time are presented in Table 2. All values are presented in minutes. The coefficient of variation provides a useful measure of relative dispersion, allowing comparison across analysis segments that vary by the amount of scheduled running time. Although scheduled running times changed slightly between the before and after TSP implementation periods at the segment level, the differences were relatively small. Over all observations, mean actual running time showed a negligible decrease from 33.2 to 33.1 min following TSP implementation. When weighted by the number of trips, running time variation decreased from 13.2 min to 12.6 min. The weighted coefficient of variation of running time over all segments was the same for both time periods.

Percentage differences for the mean and variance of running times and the results of the means and variances tests are presented in Table 3. The largest percentage reductions in mean running times were associated with Barbur Blvd. in the afternoon peak outbound direction, where the 12 and 94X experienced double-digit reductions. These same two routes also experienced reductions in running time variation of approximately 85%. In contrast, the 112 Sandy Blvd. segment in the morning peak inbound direction and the 12 Barbur Blvd. segment in the midday inbound direction experienced increases in running time variation greater than 110%. With respect to the coefficient of variation of running time, only 44% of the segments exhibited a decrease following TSP implementation.

The results of the statistical tests for differences in the mean and variance of running time by time period of operation are presented in Table 4. Eleven of the 24 analysis segments showed a statistically significant difference in mean running time, with eight segments showing significant decreases and three segments showing significant increases. The most striking improvements in mean running times were associated with the afternoon peak time period, in which all five significant differences are reductions. Routes associated with the morning and midday time periods were evenly split between statistically significant winners and losers, both with few significant differences to begin with. Only eight of the 24 analysis segments showed a statistically significant change in running time variability, with five experiencing an actual increase. Only one segment in each time period was associated with a significant reduction in running time variability following TSP implementation.

TABLE 2 Descriptive Statistics

			Mean Scheduled Run Time (min)		Mean Actual Run Time (min)		Var. Actual Run Time (min)		C.V. Actual Run Time (min)	
TOD	Segment	*N*	Pre	Post	Pre	Post	Pre	Post	Pre	Post
a.m.	12-1	136	22.1	21.8	20.0	20.2	6.3	3.6	12.5	9.4
	14-1	350	31.3	31.3	30.2	29.9	5.1	4.2	7.5	6.8
	72-N/W	203	51.8	51.8	55.4	54.4	13.0	12.1	6.5	6.4
	72-E/S	194	54.1	54.1	55.2	55.6	6.8	12.2	4.7	6.3
	94X-1	138	20.8	22.8	22.7	22.7	9.5	8.2	13.6	12.6
	109-1	218	18.3	18.3	19.0	19.4	3.5	4.8	9.9	11.2
	112-1	177	24.5	25.5	25.5	25.9	4.1	8.8	7.9	11.4
Midday	12-0	538	20.2	20.3	19.3	19.1	7.7	8.5	14.4	15.3
	12-1	548	20.4	19.6	17.8	17.8	3.0	6.3	9.7	14.1
	14-0	658	26.8	26.8	28.6	28.8	14.1	19.4	13.1	15.3
	14-1	651	29.3	29.6	29.6	29.3	6.1	5.5	8.3	8.0
	72-N/W	800	55.6	55.6	59.4	59.4	32.8	31.4	9.6	9.4
	72-E/S	776	57.5	57.5	60.0	60.5	23.8	26.9	8.1	8.6
	109-0	538	16.6	16.5	18.2	18.0	6.4	6.7	13.9	14.4
	109-1	539	17.2	17.2	18.4	18.5	5.0	4.2	12.2	11.1
	112-0	517	21.2	21.1	22.8	22.5	8.9	7.7	13.1	12.4
	112-1	551	22.0	22.6	22.9	23.2	3.9	5.2	8.6	9.8
p.m.	12-0	156	24.7	24.7	25.6	22.6	49.0	6.6	27.4	11.4
	14-0	373	30.0	30.0	32.1	32.4	7.1	11.3	8.3	10.4
	72-N/W	243	59.1	59.1	63.0	62.3	15.9	12.5	6.3	5.7
	72-E/S	211	58.8	58.8	62.9	63.3	24.1	38.8	7.8	9.8
	94X-0	198	18.8	20.4	24.5	20.3	59.7	8.8	31.6	14.6
	109-0	143	20.1	18.7	21.4	20.2	5.4	5.6	10.9	11.7
	112-0	210	23.3	23.1	25.8	24.1	7.2	6.6	10.4	10.7
Total	All	9,066	31.8	31.9	33.2	33.1	13.2[a]	12.6[a]	10.9[a]	10.9[a]

C.V. = coefficient of variation.

[a] Denotes weighted total (weighted by the number of trips for each segment in time period).

TABLE 3 Running Time Analysis

			Mean Actual Run Time (min)		Var. Actual Run Time (min)		C.V. Actual Run Time (min)
TOD	Segment	*N*	% Diff.	Sig. (*t*-test)	% Diff.	Sig. (*F*-test)	% Diff.
a.m.	12-1	136	0.9	.	–42.2	**	–24.6
	14-1	350	–0.8	.	–18.3	.	–8.8
	72-N/W	203	–1.9	**	–7.6	.	–2.1
	72-E/S	194	0.9	.	77.7	**	32.2
	94X-1	138	0.2	.	–13.3	.	–7.1
	109-1	218	2.2	**	35.6	.	13.9
	112-1	177	1.9	.	116.8	**	44.5
Midday	12-0	538	–1.0	.	10.5	.	6.2
	12-1	548	0.1	.	111.6	**	45.3
	14-0	658	0.6	.	37.3	**	16.5
	14-1	651	–1.3	**	–10.1	.	–3.9
	72-N/W	800	0.0	.	–4.2	.	–2.1
	72-E/S	776	0.7	**	12.7	.	5.4
	109-0	538	–0.9	.	5.4	.	3.6
	109-1	539	0.6	.	–16.1	**	–9.0
	112-0	517	–1.4	**	–13.3	.	–5.6
	112-1	551	1.3	**	32.8	**	13.7
p.m.	12-0	156	–11.8	**	–86.4	.	–58.2
	14-0	373	0.9	.	59.6	.	25.2
	72-N/W	243	–1.1	**	–21.4	.	–10.3
	72-E/S	211	0.7	.	60.8	**	26.0
	94X-0	198	–17.0	**	–85.3	**	–53.8
	109-0	143	–5.6	**	2.2	.	7.1
	112-0	210	–6.4	**	–8.1	.	2.5
Total		9,066	–0.6	**	–4.5[a]	.	0.0[a]

C.V. = coefficient of variation.
[a]Based on weighted totals.
**Denotes statistically significant difference at the 95% level of confidence.

These results indicate that the changes in bus transit performance following TSP implementation are mixed with respect to the mean, variation, and coefficient of variation of bus running times. The benefits are largely contingent on the particular segment under consideration and time period of operation, maybe because of physical factors such as route characteristics and system design (e.g., AVL and signal controller logic) as well as operational factors such as excess traffic congestion, delay-causing events, changes in passenger demand, operator effects, or inadequate schedules.

Scheduling Implications

The 50th, 80th, and 95th percentile running times were computed in order to estimate potential savings in scheduled running time and recovery-layover time for each of the analysis segments in each time period. Scheduled running time savings were calculated by using Equation 1 and recovery time savings by using Equation 2. Both of these formulas were derived from previous work by Levinson (*14*) and presented in more detail by Strathman et al. (*15*). The optimal scheduled running time should be set at slightly less than the mean or median running time so that the majority of operators do not have to kill time to maintain schedule adherence. The optimal recovery time is calculated as the difference between the median and the 95th percentile running time.

$$\text{SRT savings} = \text{ART50}P_{\text{Post}} - \text{ART50}P_{\text{Pre}} \tag{1}$$

where SRT is the scheduled running time and ART50*P* is the 50th percentile actual running time.

$$\text{R/L savings} = \left(\text{ART95}P_{\text{Post}} - \text{ART50}P_{\text{Post}}\right) - \left(\text{ART95}P_{\text{Pre}} - \text{ART50}P_{\text{Pre}}\right) \tag{2}$$

where R/L is the recovery-layover time and ART95*P* is the 95th percentile actual running time.

The difference in the median running times between the two periods indicates the amount of scheduled running time that can be added to or subtracted from schedules. Table 5 shows which routes serve as the best candidates for adjusting scheduled running time and recovery-layover time following TSP implementation.

The majority of scheduled running time savings were associated with the afternoon peak outbound direction, for which three route segments (94X, 109, 112) showed potential running time savings of approximately 1 min or more. In the morning time period, the results

TABLE 4 Running Time Analysis Summary

	Mean Actual Running Time		Var. Actual Running Time	
TOD	Lower	Higher	Lower	Higher
a.m.	1	1	1	1
Midday	2	2	1	3
p.m.	5	0	1	1
Total	8	3	3	5

TABLE 5 Scheduling Benefits of TSP

		Pre (min)			Post (min)			Sched. Run Time Savings (min)	Recovery Time Savings (min)
TOD	Segment	50th	80th	95th	50th	80th	95th		
a.m.	12-1	19.7	21.4	22.9	20.3	21.7	23.2	0.60	–0.26
	14-1	29.8	31.2	32.8	30.0	31.3	33.3	0.17	0.30
	72-N/W	54.7	58.8	62.1	54.0	56.9	61.1	–0.67	–0.33
	72-E/S	54.8	57.0	60.3	55.2	58.0	61.6	0.42	0.92
	94X-1	21.9	23.9	29.4	22.3	25.2	28.2	0.38	–1.59
	109-1	18.9	20.4	22.4	19.4	21.2	23.1	0.45	0.23
	112-1	25.2	27.0	29.1	25.3	27.8	31.5	0.10	2.27
Midday	12-0	18.9	21.2	23.5	18.6	21.1	23.8	–0.30	0.60
	12-1	17.7	19.3	20.7	17.7	19.1	20.9	0.03	0.11
	14-0	28.4	31.7	35.1	28.4	31.7	36.1	0.05	0.97
	14-1	29.3	31.2	33.4	28.8	30.9	33.8	–0.53	0.87
	72-N/W	58.6	64.5	68.7	59.2	64.3	68.3	0.57	–0.89
	72-E/S	59.8	63.8	68.7	59.9	64.6	69.1	0.07	0.39
	109-0	18.0	20.4	22.4	17.8	19.9	23.0	–0.15	0.72
	109-1	18.2	20.2	22.4	18.3	20.1	22.1	0.17	–0.52
	112-0	22.8	25.1	27.9	22.4	24.7	27.3	–0.40	–0.15
	112-1	22.7	24.5	26.3	23.0	25.0	27.5	0.23	0.90
p.m.	12-0	23.0	30.8	38.1	22.2	24.5	27.7	–0.80	–9.61
	14-0	31.8	33.9	36.7	31.7	34.5	38.6	–0.13	2.02
	72-N/W	62.7	66.0	69.5	62.1	65.3	68.9	–0.53	–0.08
	72-E/S	62.1	66.7	70.8	62.8	67.6	74.5	0.73	3.03
	94X-0	21.4	28.6	42.1	19.7	21.8	26.2	–1.75	–14.19
	109-0	21.3	22.8	25.5	19.8	21.4	24.1	–1.47	0.11
	112-0	25.5	28.2	30.7	24.1	26.2	28.0	–1.43	–1.30
Total	All	.	.	.	.	.	.	–0.09[a]	–0.12[a]

[a] Denotes weighted total (weighted by the number of trips for each segment in time period).

indicate that six of the seven route segments might need running time added to schedules. In contrast, in the afternoon peak time period, six of the seven analysis segments showed that running time may need to be removed from schedules. With respect to savings in recovery-layover time, the largest potential savings were found to be associated with the 12 and 94X segments in the afternoon peak time period in the outbound direction of travel. Within each time period, the results were largely mixed, with certain segments showing potential savings in recovery-layover times and others showing that potential additions are warranted. Overall, when data were weighted by the number of trips, slight potential savings were found in both scheduled running time (5.4 s) and recovery-layover time (7.2 s).

Much of the preceding information can be displayed in a graph of the running time delay distribution. Running time delay is a measure of actual running time minus scheduled running time. Figure 2 illustrates the running time delay distribution for bus trips on the 12 Barbur Blvd. segment in the afternoon peak outbound direction. This route segment was chosen because it is representative of the potential savings in running times that can be expected following TSP implementation. Relative to the baseline time period, the running time delay distribution has narrowed considerably, largely because of reductions in the number of excessive delays.

Passenger Benefits of TSP

The expected benefits to passengers from TSP include improved OTP, reductions in wait time, and shorter in-vehicle times. In this analysis the focus is on the OTP and wait time savings since information on passenger origins and destinations for computing an aggregate measure of in-vehicle time was lacking. TriMet defines a bus as being on time if it departs from a predetermined location between 1 min early and 5 min late. OTP is typically measured at time points. For this analysis, OTP was measured at the terminus of each analysis segment since the benefits of signal priority should be greatest at this location. A comparison of OTP by time of day before and after TSP implementation is presented in Table 6. Over all analysis segments, OTP actually became worse, exhibiting a 5.0% decrease following TSP implementation. This decrease was largely due to the percentage of trips in the on-time category (65.9% before versus 62.6% after) shifting to the early category (22.2% before versus 25.7% after) since the percentage of late departures remained largely unchanged (11.9% before versus 11.7% after). Within each time period, the results were mixed, with some routes exhibiting improved OTP and others becoming worse. The largest percent reductions in OTP were associated with the 94X and 112 inbound in the morning peak, the 14 inbound in the midday time period, and the 12 and 94X outbound during the afternoon peak. The 12 inbound in the morning and afternoon peak periods exhibited the largest improvements in OTP, largely because of a shift in the number of early bus trips to the on-time category. These findings indicate that schedules should be reconsidered following TSP implementation.

An important transit service performance measure of relevance to passengers is excess wait time, which is a stop-level measure that takes into account the mean and variance of headways. As headway variance increases, departure times at stops become less predictable, forcing passengers to compensate by arriving at locations much earlier. In theory, TSP should reduce headway variability since late buses are granted priority and can therefore adhere more closely to schedule. For the current study, headways were measured at the maximum load

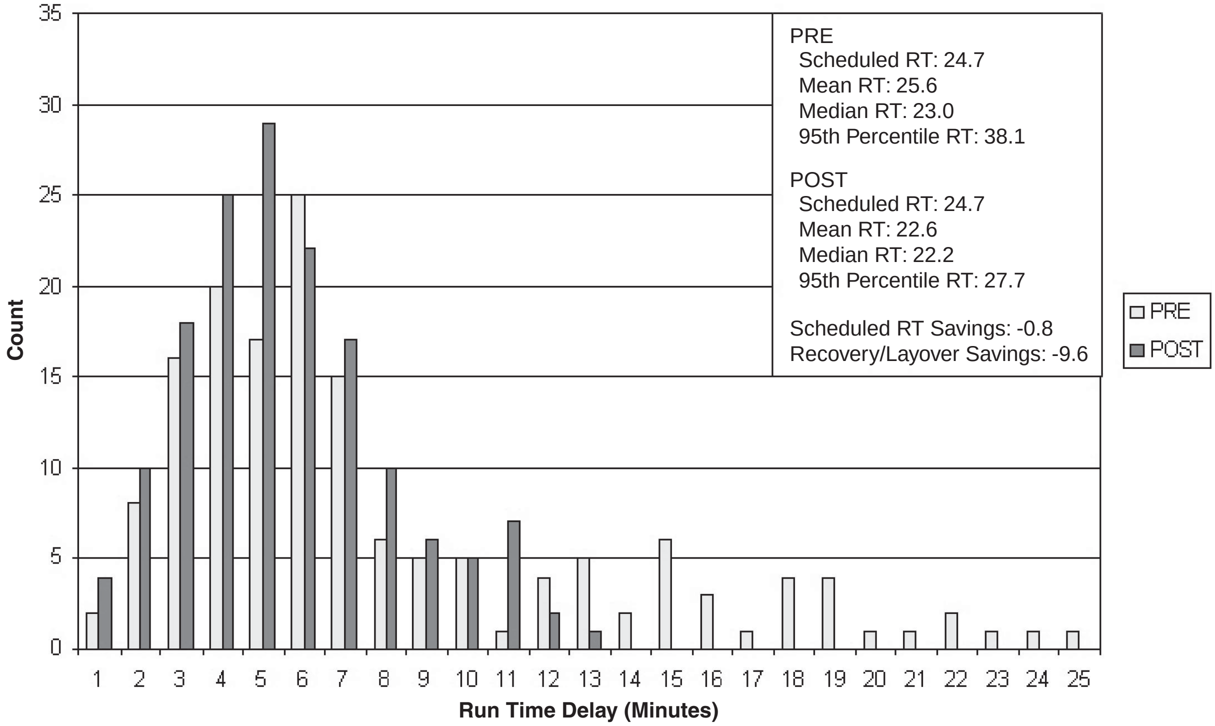

FIGURE 2 Running time delay distribution example: Route 12 outbound, p.m. peak.

TABLE 6 On-Time Performance Analysis

		Pre (% of trips)			Post (% of trips)			% Diff.
TOD	Segment	Early	On Time	Late	Early	On Time	Late	On Time
a.m.	12-1	72.1	25.7	2.2	62.5	36.8	0.7	42.9
	14-1	60.3	39.1	0.6	59.1	40.9	0.0	4.4
	72-N/W	5.9	65.0	29.1	10.8	70.0	19.2	7.6
	72-E/S	20.1	69.6	10.3	19.1	64.9	16.0	–6.7
	94X-1	10.1	79.7	10.1	37.7	58.7	3.6	–26.4
	109-1	15.1	82.1	2.8	9.2	88.1	2.8	7.3
	112-1	18.1	75.7	6.2	37.9	53.7	8.5	–29.1
Midday	12-0	52.0	47.0	0.9	58.7	40.1	1.1	–14.6
	12-1	83.8	16.2	0.0	69.3	30.5	0.2	87.6
	14-0	13.8	74.9	11.2	11.9	74.6	13.5	–0.4
	14-1	23.3	73.9	2.8	45.9	51.2	2.9	–30.8
	72-N/W	6.8	62.1	31.1	6.5	58.9	34.6	–5.2
	72-E/S	11.1	68.6	20.4	10.4	63.8	25.8	–7.0
	109-0	5.0	89.4	5.6	6.1	87.2	6.7	–2.5
	109-1	13.4	81.6	5.0	11.5	84.6	3.9	3.6
	112-0	13.3	76.4	10.3	12.8	80.7	6.6	5.6
	112-1	17.2	79.9	2.9	24.3	71.1	4.5	–10.9
p.m.	12-0	59.0	20.5	20.5	71.8	27.6	0.6	34.4
	14-0	9.7	77.5	12.9	9.1	73.5	17.4	–5.2
	72-N/W	7.0	58.4	34.6	9.1	61.7	29.2	5.6
	72-E/S	2.8	65.9	31.3	10.9	48.8	40.3	–25.9
	94X-0	2.0	68.7	29.3	43.9	49.0	7.1	–28.7
	109-0	11.2	82.5	6.3	12.6	81.1	6.3	–1.7
	112-0	7.6	74.8	17.6	20.5	74.8	4.8	0.0
a.m.	All	31.0	60.9	8.1	34.6	58.5	6.9	–3.8
Midday	All	22.6	67.1	10.3	24.5	63.9	11.6	–4.7
p.m.	All	12.2	66.0	21.8	22.1	61.3	16.6	–7.2
Total	All	22.2	65.9	11.9	25.7	62.6	11.7	–5.0

point in order to be consistent with internal TriMet reporting practices for calculating excess wait time. The analysis used the same matched-pair approach described earlier except that it involved the use of a stop-level data set rather than a trip-level one. It was possible to match 7,348 observations between the before and after time periods, for a success rate of 78.9%. Table 7 shows the results of the headway and wait time analyses. Generally speaking, it was found that both the mean and the variance of headways increased relative to the baseline period. Seventeen of the 24 analysis segments experienced an increase in mean headway compared with the baseline period. Twenty-one of the 24 analysis segments experienced an increase in headway variation. When weighted by the number of trips, the mean and variation of actual headway were found to increase in all time periods relative to the baseline period as well as over all of the analysis segments (34.4% and 3.1%, respectively).

The formula for excess wait time presented in Equation 3 is a modification of an earlier formula presented by Hounsell and McLeod (*16*) and discussed in more detail by Strathman et al. (*13*).

$$EW = \{[HWRV/(2 * HWRX)]/100\} * HWAX \qquad (3)$$

where

EW = excess wait time,
HWRV = variance of headway ratio [(actual HW/scheduled HW) * 100],
HWRX = mean of headway ratio, and
HWAX = average actual headway.

Of the 24 analysis segments, only seven showed a decrease in excess wait time. The largest percentage reductions in excess wait time following TSP implementation were associated with the 94X in the morning peak inbound direction (–55.9%) and the 112 afternoon peak in the outbound direction (–60.4%). The largest percentage increases in excess wait time were associated with the 12 inbound in the morning peak (117.1%) and 12 outbound in the midday time period (93.1%). Over all of the analysis segments, a –2.8% reduction in excess wait time was found for the period following TSP implementation. No clear pattern emerged with respect to changes in excess wait time within each time period. The results were largely segment and time-of-day specific.

Regression Analysis

One objective of the current study was to analyze the determinants of bus running time at the route-segment level of analysis. A regression analysis was included to better understand the determinants of running time and to measure the effect of the data collection period after TSP implementation on bus running time. The data used for the regression model were the same as those used for the running time, OTP, and schedule savings components except that the data for each implementation period were stacked rather than side-by-side. The regression model contains 18,132 observations.

A review of the literature (*13, 15, 17, 18*) finds that running time is related to route characteristics such as distance or the number of stops,

TABLE 7 Headway Analysis

			Mean Headway (min)		Var. Headway (min)		Excess Wait (min)		
TOD	Segment	*N*	Pre	Post	Pre	Post	Pre	Post	% Diff.
a.m.	12-1	83	15.6	16.3	10.4	28.2	0.33	0.72	117.1
	14-1	233	5.1	5.5	5.7	8.6	0.31	0.58	86.1
	72-N/W	193	9.6	11.4	19.2	58.8	0.85	0.86	1.1
	72-E/S	179	9.2	11.4	9.6	55.4	0.42	0.65	54.7
	94X-1	101	10.3	10.1	19.6	20.9	0.71	0.31	–55.9
	109-1	202	9.5	10.0	16.9	17.2	0.48	0.64	33.5
	112-1	160	12.3	10.3	18.4	22.7	0.45	0.58	28.4
Midday	12-0	253	16.2	16.3	27.2	51.6	0.82	1.59	93.1
	12-1	222	15.7	15.4	23.2	27.3	0.41	0.59	44.6
	14-0	556	11.4	11.8	12.5	14.5	0.36	0.40	11.3
	14-1	366	11.7	12.0	12.4	17.3	0.34	0.59	71.4
	72-N/W	767	8.8	10.3	20.1	38.6	0.80	0.90	12.4
	72-E/S	742	8.9	10.1	23.0	31.2	1.15	0.98	–14.8
	109-0	455	13.8	14.3	13.0	30.7	0.36	0.56	53.0
	109-1	509	13.6	14.6	32.3	38.6	1.64	0.99	–39.6
	112-0	436	16.3	14.4	44.8	21.9	0.69	0.43	–37.6
	112-1	446	15.6	14.5	21.5	23.7	0.52	0.62	17.9
p.m.	12-0	109	15.6	15.6	25.2	31.3	0.71	0.77	7.4
	14-0	331	5.4	5.6	8.3	7.0	0.65	0.54	–17.0
	72-N/W	238	8.0	8.9	13.6	22.0	0.77	0.85	10.5
	72-E/S	200	8.0	10.0	25.2	34.4	1.44	1.14	–20.9
	94X-0	251	12.5	12.3	26.3	25.6	0.88	1.03	17.1
	109-0	122	10.2	8.2	15.0	20.2	0.50	0.92	86.2
	112-0	194	11.5	10.5	34.4	16.3	1.36	0.54	–60.4
a.m.	All	1,151	9.5	10.0	13.9[a]	30.3[a]	0.53	0.69	29.1
Midday	All	4,752	12.4	12.7	22.6[a]	29.5[a]	0.83	0.80	–4.0
p.m.	All	1,445	9.4	9.6	20.0[a]	20.7[a]	0.98	0.84	–14.3
Total	All	7,348	11.3	11.7	20.7[a]	27.9[a]	0.82	0.80	–2.8

[a] Denotes weighted total (weighted by the number of trips for each segment in time period).

the amount of scheduled service, passenger demand variation, bus spacing irregularities, operator behavior, nonrecurring delays, time period of operation, and, in the context of this analysis, the effect of the after-implementation period. A description of the variables used in the regression analysis is presented in Table 8.

The dependent variable is actual running time (RTA) in minutes. The number of actual stops (STOPS) was used as a proxy for passenger boarding and alighting activity, which encompasses dwell time and delays associated with acceleration and deceleration. The STOPS variable also proxies for bus interaction effects (headway delay) since late buses tend to stop more often, whereas early buses tend to stop less often. The expected sign on the coefficient for actual stops is positive since actual running time should increase with more stopping activity. Scheduled running time (SRT) is included in the model to control for the effects of distance as well as bus operating conditions such as traffic congestion. The expected sign on the coefficient is positive, with the magnitude of the coefficient expected to be large relative to that of other variables given the authors' past experience with trip-level models of actual running time.

Delay-causing events are addressed through use of a variable representing the actual number of lift operations (LIFT) over the segment. This variable is also expected to contribute to running time. It is posited that the dummy variable for the after-implementation period (PERIOD) will have a negative effect on bus running time. This variable will pick up the effect of TSP along with other exogenous factors that may have changed between the before and after TSP implementation periods. Time period of operation and direction of travel serve as proxies for the effects of traffic. Relative to the midday time period, the morning peak-period dummy variable is expected to have a negative sign and the afternoon peak a positive sign. Operator experience as measured by years of service (EXPER) is posited to be negatively associated with running time since experienced operators should be able to more adequately respond to situational disturbances than inexperienced operators. Operator behavior can adversely affect running time through such actions as departing late from the origin terminal (LTETRM). Bus running times were expected to be positively associated with late departures from trip origins.

Descriptive statistics for the regression data are presented in Table 9. The average running time over all trips is 33.2 min with scheduled running time being 31.9 min. The mean number of actual stops is 26.1 stops per segment per trip with approximately one in five trips being associated with a lift operation. The average number of years of operator experience is 11.8. Buses appear to be departing late from origin terminals by approximately 1.4 min on average. The descriptive statistics also show that roughly 16% of the trips are associated with the morning peak time period in the inbound direction and 17% of the trips are associated with the afternoon peak time period in the outbound direction.

TABLE 8 Regression Analysis: Description of Variables

Variable	Description
RTA	Actual run time (min)-dependent variable
RTS	Scheduled run time (min)
STOPS	Stops made (actual)
LIFTS	Lift operations (actual)
EXPER	Operator years of service (years)
LTETRM	Delay at origin terminal (min)
PERIOD	Period (1 = post TSP implementation, 0 = pre TSP implementation)
TOD2	a.m. peak time period (1 = true, 0 = otherwise)
TOD4	p.m. peak time period (1 = true, 0 = otherwise)

TABLE 9 Regression Analysis: Descriptive Statistics

Variable	Mean	Std. Dev.	Variance	Min.	Max.
RTA	33.15	16.95	287.32	11.67	89.10
RTS	31.85	15.51	240.52	14.62	62.85
STOPS	26.05	15.11	228.41	1.00	85.00
LIFTS	0.18	0.55	0.31	0.00	5.00
EXPER	11.76	8.68	75.42	0.04	31.59
LTETRM	1.36	1.53	2.33	−2.77	17.20
PERIOD	0.50	0.50	0.25	0.00	1.00
TOD2	0.16	0.36	0.13	0.00	1.00
TOD4	0.17	0.37	0.14	0.00	1.00

The results of the regression model are presented in Table 10. Estimates were converted to seconds in the last column for ease of interpretation. The amount of variance explained by the model is 97.1%. In the current model, approximately 53.3 s of each minute of actual running time is controlled for by scheduled running time, holding all other variables at their mean values. The estimated coefficient for the number of actual stops is statistically significant and positive. The magnitude appears reasonable given that each actual stop is shown to contribute 12.1 s to running time. The lift operation variable is statistically significant and positive. The estimated effect is 65.1 s of delay per lift operation. Operator experience is shown to be significant and negatively associated with bus running time, with each year of service attributable to a 1.7-s reduction in running time. The variable for late departure from the terminal is statistically significant and negative but has only a minor effect on actual running time. This finding is perhaps the result of operators' knowing that they can make up a portion of origin delay elsewhere along the route. The variables for time period of operation are consistent with expected trends. The morning peak time period (TOD2) is associated with a 44.4-s reduction in bus running time and the afternoon peak time period (TOD4) is associated with a 70.4-s increase relative to the midday time period. The dummy variable for the period following TSP implementation is statistically significant and negative, with the after implementation

TABLE 10 Regression Analysis: Results

Variable	Coef.	Std. Error	*t*-Ratio	Seconds[a]
RTS	0.89	0.00	292.90	53.26
STOPS	0.20	0.00	64.77	12.10
LIFTS	1.09	0.04	27.24	65.11
EXPER	−0.03	0.00	−10.96	−1.71
LTETRM	−0.05	0.01	−3.52	−2.99
PERIOD	−0.24	0.04	−5.52	−14.20
TOD2	−0.74	0.06	−12.17	−44.35
TOD4	1.17	0.06	19.06	70.43
CONSTANT	−0.14	0.07	−1.99	−8.35
N	18,132	.	.	.
R^2 ADJ.	0.971	.	.	.

Dependent variable is actual run time in minutes.
[a]Seconds = beta coefficient converted to seconds.

period associated with a reduction in running time of 14.2 s per trip, holding all other variables at their mean values. In truth, it cannot be stated that this reduction is solely due to TSP since other factors are at least partially responsible for the decrease.

DISCUSSION OF RESULTS

This study utilizes a large amount of operations data collected from the TriMet Bus Dispatch System. The majority of transit agencies implementing TSP do not have the capability to collect and analyze operations data for each bus in the system at the stop level since their AVL systems tend to be based on poll data. The current study provides a comprehensive analysis of changes in bus performance from the perspective of operators and passengers by analyzing data collected before and after TSP implementation.

One of the most important findings is that the changes in bus performance following TSP implementation are not consistent across time periods, routes, or performance measures. These findings are summarized in Tables 11 through 13. Table 11 provides a summary of the analysis segments according to the various performance measures by time period. A positive sign means that bus performance improved in the ideal direction of a particular measure. For example, an increase in OTP is desirable as well as a decrease in running time variation. For the 12 Barbur Blvd. segment in the outbound direction in the afternoon peak time period, improvements were found in mean running time, running time variation, and potential savings in recovery-layover times. OTP also improved, although the number of early arrivals increased sharply and headway variation and excess wait time became worse. Of the 24 analysis segments, only the 112 Sandy Blvd. outbound in the midday time period exhibits an improvement across all of the performance measures. In looking at the totals, one might conclude that bus transit performance has improved over the majority of the performance measures; however, the results are mixed when individual segments are considered by time of day.

Also of note is the wide variation in bus transit performance when each route segment is aggregated over all time periods, irrespective of the direction of travel. Table 12 shows the percentage of segments exhibiting improvements in performance when data are aggregated by route over all time periods. For example, four analysis segments are summarized for the 12 Barbur Blvd.—the 12 inbound in the morning peak, both directions in the midday time period, and the 12 outbound in the afternoon peak. Of the four segments, two (50%) show improvements in mean actual running time, running time variation, scheduled running time savings, recovery-layover time savings, and mean actual headway. Three of the four segments show an improvement in OTP, and none show an improvement in headway variability and excess wait time. The 94X and the 112 show the greatest improvement over all of the performance measures, and the 14 and the 72 showing the least improvement. It was found that less than 50% of the route segments experience improved performance relative to the baseline period across all of the measures.

Table 13 shows the percentage of segments exhibiting improvements in performance when data are aggregated by time period. Seven analysis segments are represented in the morning peak time period. Only one performance measure, OTP, shows an improvement greater than 50% relative to the baseline period. Of note is that the segments in the afternoon peak time period perform better across each of the performance measures relative to the midday and morning peak time periods with the exception of OTP in the morning peak. In the afternoon peak, 85.7% of the segments show potential scheduled running

TABLE 11 Summary: Performance Measures by Analysis Segment

TOD	Segment	Mean Actual Run Time	Var. Actual Run Time	Sched. Run Time Savings	Recov./Lay. Time Savings	OTP	Mean Actual Hwy.	Var. Actual Hwy.	Excess Wait
a.m.	12-1	−	+	−	+	+	−	−	−
	14-1	+	+	−	−	+	−	−	−
	72-N/W	+	−	+	+	+	−	−	−
	72-E/S	−	−	−	−	−	−	−	−
	94X-1	−	+	−	+	−	+	−	+
	109-1	−	−	−	−	+	−	−	−
	112-1	−	−	−	−	−	+	−	−
Midday	12-0	+	−	+	−	−	−	−	−
	12-1	−	−	−	−	+	+	−	−
	14-0	−	−	−	−	−	−	−	−
	14-1	+	+	+	−	−	−	−	−
	72-N/W	−	+	−	+	−	−	−	−
	72-E/S	−	−	−	−	−	−	−	+
	109-0	+	−	+	−	−	−	−	−
	109-1	−	+	−	+	+	−	−	+
	112-0	+	+	+	+	+	+	+	+
	112-1	−	−	−	−	−	+	−	−
p.m.	12-0	+	+	+	+	+	+	−	−
	14-0	−	−	+	−	−	−	+	+
	72-N/W	+	+	+	+	+	−	−	−
	72-E/S	−	−	−	−	−	−	−	+
	94X-0	+	+	+	+	−	+	+	−
	109-0	+	−	+	−	−	+	−	−
	112-0	+	+	+	+	+	+	+	+
Total	All	+	+	+	+	−	−	−	+

(+) positive (ideal direction of performance measure)
(−) negative (opposite of ideal direction of performance measure)

TABLE 12 Summary: Percentage of Segments Showing Improvements by Route

Segment	No. Segs.	Mean Actual Run Time (%)	Var. Actual Run Time (%)	Sched. Run Time Savings (%)	Recov./Lay. Time Savings (%)	OTP (%)	Mean Hwy. (%)	Var. Hwy. (%)	Excess Wait (%)
12	4	50.0	50.0	50.0	50.0	75.0	50.0	0.0	0.0
14	4	50.0	50.0	50.0	0.0	25.0	0.0	25.0	25.0
72	6	33.3	33.3	33.3	50.0	33.3	0.0	0.0	33.3
94X	2	50.0	100.0	50.0	100.0	0.0	100.0	50.0	50.0
109	4	50.0	25.0	50.0	25.0	50.0	25.0	0.0	25.0
112	4	50.0	50.0	50.0	50.0	50.0	100.0	50.0	50.0
Total	24	45.8	45.8	45.8	41.7	41.7	37.5	16.7	29.2

time savings and 71.4% show savings in mean actual running time. The totals in Table 13 are the same as those for Table 12.

What do these findings mean for traffic engineers and transit professionals? The answer partially depends on how one chooses to interpret the results. The study involves measuring transit performance in select corridors following TSP implementation relative to the before-implementation period. The study does not attempt to ascertain whether changes in bus transit service reliability are the direct result of TSP. Given a complex operating environment, the variables most likely to influence the results include changes in passenger demand, traffic levels, and bus operators; stop relocations and modifications; schedule revisions; signal timing adjustments; and TSP. The authors believe that this study adequately captures real-world conditions since the various parts of the system change over time.

Besides better scheduling and management of operators, a number of potential improvements exist. Since this study was first undertaken, TriMet has since lowered the delay threshold for priority requests to 30 s of schedule delay or greater, the reasoning being that more buses will receive priority with a lower delay threshold. The authors believe that the agency should experiment with altering the delay threshold for priority requests according to the specific corridor, direction, and time of day in order to more adequately respond to spatial and temporal variations in operating conditions. Besides queue jumps, which exist at a few select intersections, other priority treatments such as bus-only phases or elimination of phase skipping could be considered. Discussions are presently under way to add more logic to the existing system by supplementing the AVL information on an intersection-by-intersection basis. For example, priority requests at intersections with nearside bus stops could be deferred until the bus had completed serving a particular stop (i.e., point activation based on AVL distance). It is clear that much work still needs to be done.

TSP projects should be implemented with caution and the following plan of action is recommended:

1. Select candidate bus routes on the basis of identification of operational problems, not scheduling or personnel problems;
2. Perform a baseline analysis so as to have a reference case for comparison following implementation;
3. Undertake regular performance monitoring following TSP implementation to identify problems warranting additional scrutiny; and
4. Be willing to experiment by adjusting schedules, emitter activation thresholds, signal controller and AVL logic, and so on, with the goal of improving the performance of the system over time.

Automatically collected, stop-level data such as those generated by the TriMet Bus Dispatch System can readily provide the kinds of information needed to address each of the foregoing recommendations.

CONCLUSIONS

The effects of TSP implementation were empirically analyzed from the perspective of both the transit operators and the passengers. The study included a statistical analysis of the mean and variance of bus running times. Generally speaking, it was found that the primary benefits of TSP on mean running time are limited to the afternoon peak time period in the primary direction of travel. For the morning peak and afternoon time periods, the results were more ambiguous. Although potential overall savings were found with respect to scheduled running times and recovery-layover times, the results are mixed when one considers individual routes by direction and time of day. The same finding holds true for analysis of excess wait time. The mean and variance of headways became much worse relative to the baseline period. In analyzing OTP, it was found that performance decreased overall since bus trips tended to shift from being either on time or late toward being early. The results of the regression analysis show that there was a

TABLE 13 Summary: Percentage of Segments Showing Improvements by Time of Day

Time Period	No. Segs.	Mean Actual Run Time (%)	Var. Actual Run Time (%)	Sched. Run Time Savings (%)	Recov./Lay. Time Savings (%)	OTP (%)	Mean Hwy. (%)	Var. Hwy. (%)	Excess Wait (%)
a.m.	7	28.6	42.9	14.3	42.9	57.1	28.6	0.0	14.3
Midday	14	28.6	28.6	28.6	21.4	21.4	21.4	7.1	21.4
p.m.	7	71.4	57.1	85.7	57.1	42.9	57.1	42.9	42.9
Total	24	45.8	45.8	45.8	41.7	41.7	37.5	16.7	29.2

statistically significant improvement in bus running times for the period following implementation of TSP. It is believed that a considerable amount of work needs to be done with respect to signal priority programs before the expected benefits of TSP are fully realized.

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