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Automated Bus Dispatching, Operations Control, and Service Reliability: The Initial Tri-Met Experience

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Abstract

This paper presents findings on initial changes in service reliability following Tri-Met's deployment of a new bus dispatching system using automatic vehicle location and automatic passenger counter technology. Changes in on-time performance, headway variation, run time variation, and run times were determined with respect to pre-deployment levels. Changes in headway variation and run times were also used to estimate the initial benefits of the new system with respect to operating costs, passenger waiting, and passenger travel time.

Introduction

Transit providers are increasingly relying on Automatic Vehicle Location (AVL) and Computer-Aided Dispatching (CAD) technology to maintain scheduled service in the face of challenges stemming from worsening congestion on urban roads. Casey (1999), for example, reports 61 transit agencies with operational AVL systems, and another 100 agencies in either the planning or implementation phase. This a near three-fold increase in AVL deployment from his 1995 survey. Transit managers have indicated that improvements in service reliability are a primary reason for acquiring new AVL and CAD systems (Khattak and Hickman, 1998). To date, however, little has been reported on the impact of these technologies on transit operations. This paper presents findings on initial changes in service reliability following the implementation of AVL and CAD technology at Tri-Met, the transit provider for the Portland, Oregon metropolitan area. Changes in key indicators of service reliability - on-time performance, headways and run times - were estimated from data recovered before and after implementation. Analysis of the changes in performance also provided a basis for estimating operating benefits from running time improvements, and waiting and travel time benefits for bus riders.

The authors are engaged in a long-term project to assess the impacts of Tri-Met's new Bus Dispatch System (BDS) on service reliability and transit use. In addition to the

AVL (which is based on use of global positioning satellites) and CAD components, Tri-Met's BDS includes Automatic Passenger Counters (APCs) on all new buses. The framework developed for this assessment focuses on documenting service reliability and passenger activity at three major junctures:

- The pre-operational (baseline) period;

- The initial (passive) period following implementation of the new system, when both drivers and dispatchers have access to schedule adherence information in real time, but before the development and use of operations control practices that actively exploit the information generated by the system;

- Full implementation, when operations control practices are defined and actively employed by dispatchers and field supervisors, and when performance data is used in service planning.

Findings from the baseline period, which occurred in late 1996, have already been reported (Strathman et al., 1999). This paper addresses changes in performance between the baseline and passive implementation stages. It was thought that some improvement in service reliability would be initially observed for several reasons. First, buses are now equipped with control heads that display deviations in schedule in real time to operators. Deviations exceeding a threshold value, which varies between peak and off-peak periods, automatically generate exception reports to dispatchers. Second, communication between operators and dispatchers is enhanced in the new system by a set of pre-programmed messages ("Attention Requests") covering a wide range of operational issues, making it potentially easier for dispatchers and field supervisors to deal with disruptions.

While the BDS is capable of recovering performance data comprehensively over space and time, manual data recovery was required in the baseline survey. Resources available at that time limited the coverage to eight routes that are representative of Tri-Met's service typology. In addition, baseline surveyors were stationed at origin and destination points, which precludes intermediate time point-level performance measures of on-time performance and headways.

The remainder of the paper is organized as follows. The next section presents the service reliability measures and a description of the routes selected for study. The observed changes in performance are then presented and discussed. This is followed by a statistical analysis of running times and calculation of benefits linked to BDS-related changes. The concluding section considers implications of the findings.

Service Reliability Indicators

Three indicators were selected to evaluate changes in service reliability. The first, on-time performance, is the most recognized measure among transit providers. The study uses the convention defined by Bates (1986), which defines on-time service within a window ranging from one minute early to five minutes behind schedule. In practice, on-time performance is probably most relevant in situations of infrequent service, where bus riders tend to time their arrivals in relation to the schedule, or in trips which involve transfers. Headways, the time interval between buses, are the second reliability indicator. With short headways and riders arriving randomly in relation to scheduled service, reliability may be better reflected in the ability to maintain headways rather than adhere to the schedule (Abkowitz and Tozzi, 1987; Hundenski, 1998). The third service reliability measure examines bus run times. Variations in run times reflect the composite effects of disruptions to service associated with traffic, signal timing, on-street parking, passenger activity, and driver behavior (Sterman and Schofer, 1976; Abkowitz and Tozzi, 1987).

Following Hounsell and McLeod (1998), headway variation is also used to derive a measure of excess waiting time that passengers experience as a consequence of unreliable service. This indicator reflects the additional waiting time that service irregularity imposes on the typical passenger.

It was also deemed desirable to standardize the headway and run time indicators so that performance could be more directly compared among the indicators themselves and, for any given indicator, across routes, service frequencies, times of day, and the like. For example, standardization would allow comparing performance on a route with short

headways and long run times to performance on a route with short run times and long headways. Standardization was achieved by relating observed headways and run times to their scheduled values.

The standardized headway indicator is defined as

Headway Ratio (HR) = (Observed Headway / Scheduled Headway) * 100,   (1)

where a value of 100 represents a perfect correspondence between the observed and scheduled headway. The phenomenon of "bus bunching" is represented as the headway ratio value goes to zero for any given bus trip. The existence of bus bunching, in turn, also implies that gaps in service will occur between bunches, producing headway measures for bus trips exceeding 100. Thus, from an operations control standpoint, reducing the variation in headways is an important objective for routes with high service frequencies.

For run times the standardized indicator is defined as

Run Time Ratio (RTR) = (Observed Run Time / Scheduled Run Time) * 100,   (2)

where a value of 100 indicates a perfect correspondence between observed and scheduled run times. In the case of this indicator, the mean value for any given route or time period provides useful information for planning and scheduling. Mean values greater than 100 indicate that scheduled run times are usually insufficient and that bus operators will need to cut into layover times to avoid cumulative departure delays over the scheduled series of bus trips. Run time variation is also important in schedule writing. As this variation increases, schedule writers must build in additional layover time to ensure that trips can begin on schedule.

The coefficient of variation standardizes the variation in headways and run times, allowing comparison across routes, time periods and alternative reliability indicators. For headways, the coefficient of variation is defined as

Coefficient of Variation $(CV)_{HR}$ = (Standard Deviation / Mean)$_{HR}$ (3)

The measure of excess waiting time is derived from headway variability and is defined as

$$\text{Ex. Wait (EW)} = ((\text{Variance}_{HR} / (2 * \text{Mean}_{HR})) / 100) * \text{Mean Observed Headway} \quad (4)$$

Increasing headway variability works against bus riders' desire to time their arrivals at bus stops to coincide with the schedule. As headway variation grows, so too does the likelihood that riders' arrival patterns at stops will become more random. This increases their waiting time and adds to their implicit travel costs. Given that riders find waiting time to be so onerous (Mohring et al., 1987), headway variability has a disproportionately negative impact on the demand for transit compared to other travel time components.

Survey Routes and Data Collection

Eight study routes were selected to represent the typology of routes in Tri-Met's bus system as well as the range of operating conditions the agency faces in providing transit service. These routes are identified in Table 1.

(Table 1 about here)

Seven of the eight routes provide radial service to downtown Portland. Among these, a distinction is made between service that connects the downtown and a single peripheral point (i.e., "Single Spoke"), and service that extends from one peripheral point through the downtown to an opposing peripheral point (i.e., "Inter-Line"). "Cross-town" routes provide lateral service, while "Feeders" provide collector service to transit centers. Route 26 is characterized as both cross-town and a feeder because it runs between the Gresham and Gateway Transit Centers.

A variety of operating challenges are encountered on the selected routes. Route 14 Hawthorne, for example, provides frequent service along a high demand corridor containing many signalized intersections, and non-recurring traffic delays during peak periods. As might be expected, bus bunching is the main problem on this route. The 4

Division / 4 Fessenden, alternatively, provides service over a lengthy and complex route. Passenger loads are relatively high under moderately frequent service. The main challenge on this route is maintaining scheduled service, with reasonable run and layover times, and minimal holding at time points. For the Route 26, timed transfers at transit centers are an important consideration, suggesting that on-time performance is the primary reliability concern.

The data collection process for the baseline and follow-up periods uses a "matched trip" approach. Specific trips for which data are recovered in the baseline period are uniquely matched to their scheduled counterparts in the follow-up period. Thus a panel is effectively created and sampling error is greatly reduced.

For baseline data collection, surveyors were stationed at the route origin and destination points. The surveyors were provided with forms containing train identification numbers, and scheduled arrival and departure times. They were instructed to record bus identification numbers, and actual arrival and departure times. The information was collected over ten weekdays, from November 5 to 15, 1996. Run times were calculated from the recorded departure times at trip origins and arrival times at destinations. Headways were calculated at the destination points as the difference in arrival time of a given bus from the bus preceding it.

There were several instances of missed assignments by surveyors. Surveyors at the other end of the route still recorded arrival and departure times, which allowed calculation of arrival delay and headways, but not run times. Overall, the survey yielded 3,900 arrival, 3,640 headway and 3,152 run time observations.

The BDS recovers data continuously and comprehensively, and thus the choice of follow-up date was less constrained by logistical considerations. The deployment and shake down of the BDS were completed by early 1998, and the research team selected a second group of ten week days, extending from March 9 to March 20, 1998, for comparison. A check of weather records showed similar conditions, and no special events distinguished either period.

Trip records were recovered from the BDS files to match the baseline data. It was not possible to match every baseline trip with its BDS file counterpart. For arrivals, 3,402 (87.2%) were made, while for run times and headways, the number of matches were 2,758 (87.5%) and 3,022 (83.0%), respectively. Several factors were responsible for this attrition. First, changes in scheduled service between the baseline and follow-up periods accounted for about one-fourth of the "missing" trips. Post-processing of the BDS data deleted the remaining trips. Such deletions can occur, for example, when trip records show an arrival time at a destination, but no departure time due to signal interference from tall downtown buildings.

In addition, the run time records were matched to APC trip files containing data on passenger and stop activity. Many of the buses were not APC-equipped, and trip level data capture from those that were was not complete, but 820 valid matches were made. These trips provided a sample for estimating a run time model, which is reported on later in the paper.

Results

Summary statistics for on-time performance, headway, run time and excess wait indicators are reported in Table 2. The results are broken down by route and time period.[1] The time periods are defined as follows: AM peak (6:00-8:59am); Mid-day (9:00am-2:59pm); PM peak (3:00-5:59pm); and Evening (6:00+).

(Table 2 about here)

The summary values at the bottom of Table 2 show the overall levels of reliability for the baseline and follow-up periods. Overall, on-time performance increased from 61.4 to 67.2% of all trips. a 9.4% gain. The greatest improvement occurred in the AM peak period (+129%), while a slight decline (-3%) was observed for the evening period. Routes experiencing the greatest improvement were the 54 Beaverton-Hillsdale (+36%) and 19 Glisan (+34%), while the 4 Fessenden and 14 Hawthorne suffered modest declines (-1% and -6%). Because on-time performance was recorded at route destinations, it is noticeably lower than what would be observed at time points system-wide. This is a result of the

tendency for delay to accumulate over the course of a route. It also reflects the fact that operators are not warned against early arrivals at destinations, while they are admonished for early departures at other time points.

There is a fairly regular pattern of on-time performance over the course of the day in both the baseline and follow-up period data. A deterioration occurs over the AM, mid-day and PM Peak periods, and a recovery finally occurs in the evening. Thus, reliability problems cumulate along routes and over the series of bus trips, suggesting the potential for reliability improvements from early operations control interventions.

Shifting to the headway results, there is a near-5% reduction in the coefficient of variation, indicating an improvement in service regularity. The improvement was largely concentrated in the PM Peak period, where the CV declined by 15%. At the route level, the greatest declines in the headway CV occurred on the 26 Stark and the 20 Burnside (-23% and -18%), while variation increased somewhat on the 4 Fessenden and 54 Beaverton-Hillsdale (+2% and +11%).

There was virtually no change in the mean run time ratio between the baseline and follow-up periods, with observed run times exceeding their scheduled values by about one percent. However, there was an 18% decline in the run time CV, which implies an increase in the percentage of buses that are able to complete their trips within a given time window. Among the routes studied the greatest reduction in the run time CV occurred on the 26 Stark and 54 Beaverton-Hillsdale (-36% and -31%). No route experienced an increase in run time variation.

The final columns in Table 2 report the excess wait estimates. Overall, there was a near-7% reduction between the baseline and follow-up periods (1.65 versus 1.54) minutes. Given that this measure is derived from headway variation, it shows a similar change pattern, with the improvement concentrated in the PM Peak period, and the 26 Stark and 20 Burnside showing the greatest improvement among routes.

Additional insights that can be gained from the delay, headway ratio, and run time ratio frequency distributions, which are shown in Figures 1 to 3. Panel A in each figure

compares the baseline and follow-up period distributions for all trips, while panels B and C focus on AM Peak in-bound and PM Peak out-bound trips respectively.

(Figures 1-3 about here)

As Figure 1 shows, the improvement in on-time performance is largely attributable to a substantial decline (-37%) in early arrivals. The share of trips arriving later than five minutes actually grew by more than 14%. Overall, it is apparent that the distribution has shifted to the right and that average delay has actually increased. Among AM Peak in-bound trips, there was a large decline in both early and late arrivals (-55% and -25%, respectively), while for PM Peak out-bound trips the modest (2%) gain in the share of on-time arrivals occurred as a result of slight reductions in the shares of both early and late arrivals. A note-worthy change in the PM Peak distributions is the substantial decline (25%) in the share of very late (>10 minutes) arrivals. Nevertheless, 40% of all PM Peak out-bound trips in the follow-up period arrived at the destination more than five minutes late.

Moving to the headway ratio distributions in Figure 2, the overall reduction in headway variation is apparent, particularly in the PM Peak out-bound panel. If we define "regular" service to be represented by headways ranging from 70% to 130% of their scheduled values, then, overall, the share of regular trips increased by just over one percent. Bus bunching, which is represented by headways below 70% of their scheduled values, declined by 15%. This phenomenon is most clearly illustrated in panel C, where the spikes in both tails of the distribution reflect the tendency for bunches and gaps to form when initial delays lead to heavier boardings, further delay and fewer boardings for the following bus until it catches the leader. For PM Peak out-bound trips, extreme instances of bus bunching (headway ratios<10% of scheduled values) declined by 37%.

Examining the run time distributions in Figure 3, if we define a corridor of +/-7.5% around the scheduled run time as "maintaining the schedule," the share of trips within this range increased nearly 12% between the baseline and follow-up periods. The improvement was largely concentrated among AM Peak in-bound trips (+23%); the gain

for PM Peak out-bound trips was slight (+1%). Another noticeable change is that the shares of both "hot" and "cold" running trips declined in the AM Peak out-bound distribution, while in the PM Peak out-bound distributions the share of trips running hot increased (+71%) and the share running cold decreased (-14%).

Statistical Analysis of Running Times

For the trips for which it was possible to link reliability data to APC records containing passenger and stop data, we can estimate models of service reliability that more rigorously control for the effects of various disruptions so that BDS-related effects are more clearly identified. In this section we specify and estimate a model for bus running times. This indicator is chosen because it is closely related to the operating costs transit providers incur in providing service.

There is a fairly rich literature on running time models, with excellent reviews and discussion provided by Abkowitz and Tozzi (1987), and Sterman and Schofer (1976). As previously found, running time is affected by departure delays (provided adequate slack exists to make up time during the trip), route length, the number of stops made (reflecting time associated with deceleration, dwell, and acceleration), passenger activity (dwell), traffic conditions and incidents, the number of signalized intersections, and the existence of on-street parking. Time period and direction dummy variables are often used to proxy traffic effects.

With direction from the literature, data from the baseline and follow-up period trips allows us to specify a run time model of the following general form:

Run Time = f(Departure Delay, Stops, Distance, Boardings, Alightings, Sched.
　　　　　　Headway, AMin, PMout, After BDS)
(5)

where

　　　　Run Time =　Run time, in minutes;

Departure Delay =　Observed minus scheduled departure time, in minutes,
　　　　　　at the route origin;

Stops	=	The number of APC-recorded passenger stops made during the trip;
Distance	=	Length of the route (in miles);
Boardings	=	Total passenger boardings made during the trip;
Alightings	=	Total passenger alightings made during the trip;
Sched. Headway	=	Scheduled headway, in minutes;
AMin	=	A dummy variable equaling one if the trip is in-bound during the AM peak period, and zero otherwise;
PMout	=	A dummy variable equaling one if the trip is out-bound during the PM peak period, and zero otherwise;
After BDS	=	A dummy variable equaling one for observations after BDS implementation, and zero otherwise.

Based on previous studies, the following hypotheses can be formed with respect to the variables specified above. Given that a properly designed schedule will allow opportunities for late-departing buses to make up at least some of their initial delay along the course of the route, we would expect that the parameter estimate associated with departure delay would fall in a range from zero (implying that none of the delay is made up) to minus one (implying that all of the delay is made up).

The parameter for the stops variable represents the additional running time associated with deceleration, dwell, and acceleration for each bus stop served along the route. We would expect that this parameter's magnitude will be governed by such characteristics as the attainable speeds along the route, traffic conditions, and stop spacing.

In addition to stops, the model specifies the volume of boardings and alightings. This recognizes that passenger activity can add to running time, particularly when loads are great and riders experience more difficulty moving through congested isles and stairwells. Thus, this parameter is expected to be positive, and its magnitude ought to increase with passenger loads.

Running time is expected to increase with route distance; the parameter associated with this variable should be positive, as it represents the inverse of speed. We have not

found evidence from the literature on the effect of scheduled headways. We posit that they would be inversely related to running times, recognizing that buses running on shorter headways are more subject to the need for control actions (e.g., holding at a stop), which adds to running time.

The parameters for the dummy variables associated with AM Peak in-bound and PM peak out-bound trips are expected to be positive, reflecting the additional running time required to navigate more congested routes. The final variable, After BDS, is a dummy variable distinguishing trips from the follow-up period from those in the baseline. We would expect the parameter for this variable to be negative if the BDS has contributed to improved operations control, albeit in a passive way. It is probably reasonable to conclude that this parameter provides a conservative estimate of the impact of the BDS, given that traffic congestion in Portland clearly worsened between the baseline and follow-up periods.

The run time model was initially estimated as an OLS regression. Diagnostic tests indicated significant heteroskedasticity, and White's (1980) correction procedure was thus employed. Parameter estimates are presented in Table 3.

(Table 3 about here)

Overall, the model fits the data quite well, explaining 86% of the total variance in running time. With respect to the individual parameters, the model estimates that operators are able to make up about a third of their departure delays over the course of the route. Each stop served along the route is estimated to add 20 seconds to the run time, while the effects of boardings and alightings are not significant. The latter finding implies that passenger loads are generally within the vehicles' maximum capacities. Run times are estimated to increase nearly three minutes for each additional mile traversed on a route, indicating an average speed of about 20 mph. The model also estimates that running times decline with increased headways. A shift from 10 to 30 minute headways, for example, is estimated to reduce run times by a little more than 2.5 minutes. Run times are estimated to be 3.7 minutes longer for PM Peak out-bound trips, compared to other trips. Contrary to

expectations, running times for AM Peak in-bound trips are estimated to be nearly a minute and a half quicker than other trips.

The parameter for the BDS dummy variable shows that after controlling for the effects of the other variables in the model, running times are estimated to be 1.45 minutes less for trips in the follow-up period. Given that the nominal average running time actually increased slightly between the baseline and follow-up periods (45.4 to 46.0 minutes), a more reflective interpretation would be that running times would have been nearly one and a half minutes greater in the absence of Tri-Met's new BDS. In short, run time improvement has been masked by such effects as increases in the average number of stops made (30.2 in the baseline v. 33.2 in the follow-up period), increases in scheduled headways (16.3 to 19.2 minutes), and increases in average departure delay (1.0 to 1.8 minutes).

Benefits

Benefits stemming from the initial impacts of the new BDS can be organized into three categories: 1) passenger waiting time reductions; 2) passenger in-vehicle travel time reductions; 3) operator running time improvements.

From Table 2 we note that estimated waiting times declined by .11 minutes. Taking the product of this change and the annual week day boardings (62.2 million), and converting to hours yields an estimate of annual system-wide waiting time savings of about 114,000 hours. Mohring et al. (1987) estimated that median wage riders value wait time at about their wage rate. Given a median wage of $14.10 in the study area (Oregon Employment Department, 1999), this indicates an annual savings in waiting time on the order of $1.6 million.[2]

The run time model results can be used to estimate bus riders' in-vehicle travel time savings. From Section 15 data, we determine that average in-vehicle time is 13.44 minutes per passenger. Applying the same percentage reduction to riders as was estimated over the entire route (-3.15%) yields a time savings of .42 minutes per passenger. Summing over

annual boardings and converting to hours yields an annual savings of nearly 400,000 hours. Mohring et al. (1987) suggest that the value of in-vehicle time savings is in the range of .3-.5 of the median wage. Setting the value at .33 ($4.70) produces an annual savings totaling $1.88 million.

The estimated running time improvement of 1.45 minutes per trip, summed over all week day trips and converted to hours leads to an annual total of 45,400 hours. Valuing this total at the agency's estimated marginal operating cost per revenue hour of $42 yields an annual total of $1.9 million.

(Table 4 about here)

These benefit estimates are summarized in Table 4. We also report present value estimates imposing a 12 year expected life on the BDS and discounting at five percent. The sum total of the annual benefits among the three categories is $5.4 million, while the present value total is $47.8 million.

Tri-Met's initial capital outlay for its BDS was $6.5 million, and it is not presently known how much the costs of operating it differ as compared to the system it replaced. The magnitude of the benefits identified above from the initial experience alone, however, suggest that the deployment of the new BDS has left the agency and its passengers better off.

Conclusion

This paper has examined Tri-Met's initial experience with its new automated bus dispatching system. With the system now fully deployed, there is evidence of initial improvements in reliability, as represented by changes in on-time performance, headway regularity, and running time variation. A more controlled analysis also finds evidence of an improvement in running time. Thus, the general optimism that has been expressed in surveys of the transit industry in regard to the expected effects from this new technology (e.g., Khattak and Hickman, 1998) appears to be well-founded.

Operations control practices have yet to seriously exploit the potential of this new technology. As managers, dispatchers, field supervisors, and service planners become more fully engaged in the use of the BDS, the resulting benefits could well be considerably greater than those reported here.

Acknowledgement

Footnotes

1.   The results were also tabulated by direction and are available by request.

2.   Tri-Met surveys indicate that the median household income of the users of their system is about 6% less than that of non-user households. However, since single person households make up a much larger share of transit user households, it would be incorrect to infer that the median wage for transit users is below the metropolitan-wide median.

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Table 1
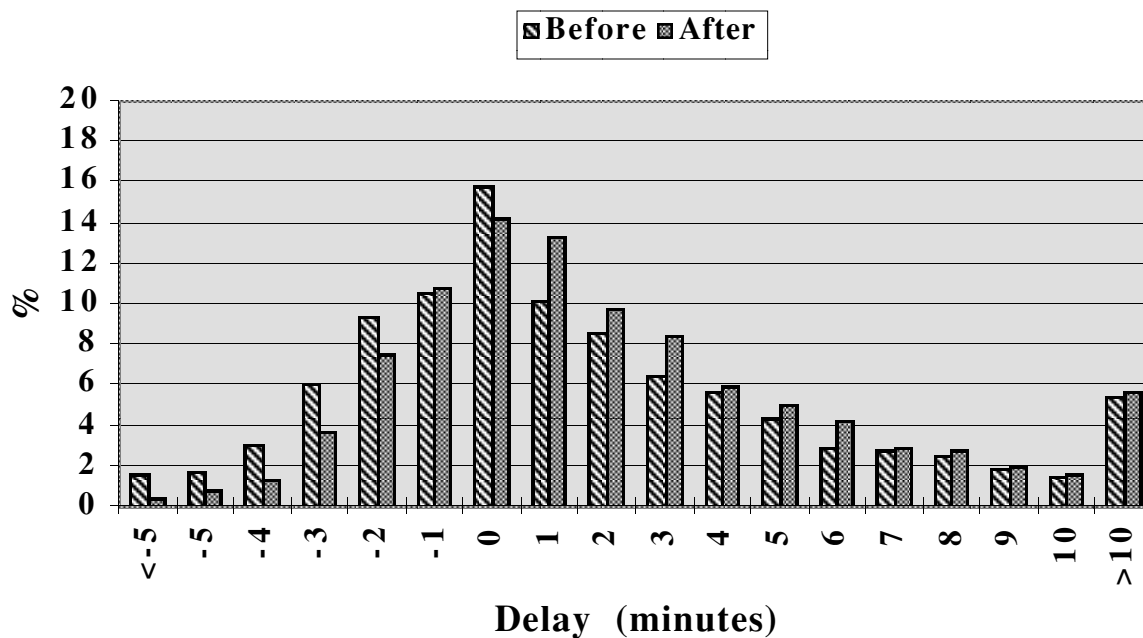**Tri-Met Route Typology and Routes Surveyed**

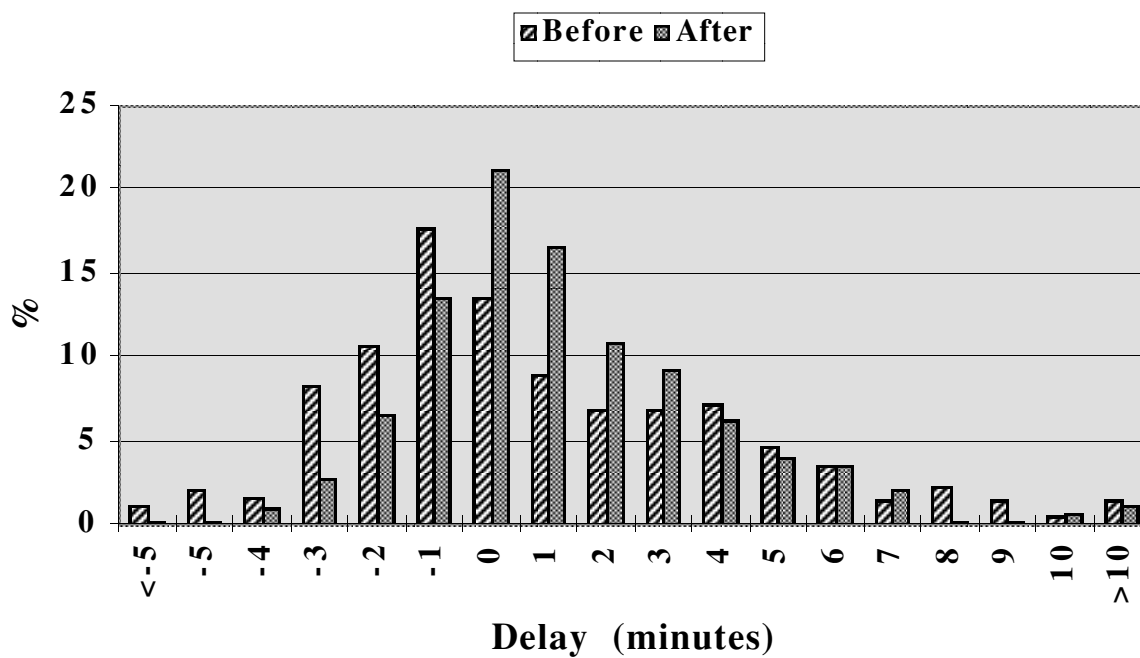| Route Type	Routes Surveyed
Radial • Inter-line	Rt 4 Division / Rt 4 Fessenden Rt 20 Burnside
• Single Spoke	Rt 14 Hawthorne Rt 19 Glisan Rt 54 Beaverton-Hillsdale Rt 59 Cedar Hills
Cross-Town	Rt 26 Stark
Feeder	Rt 26 Stark

Figure 1
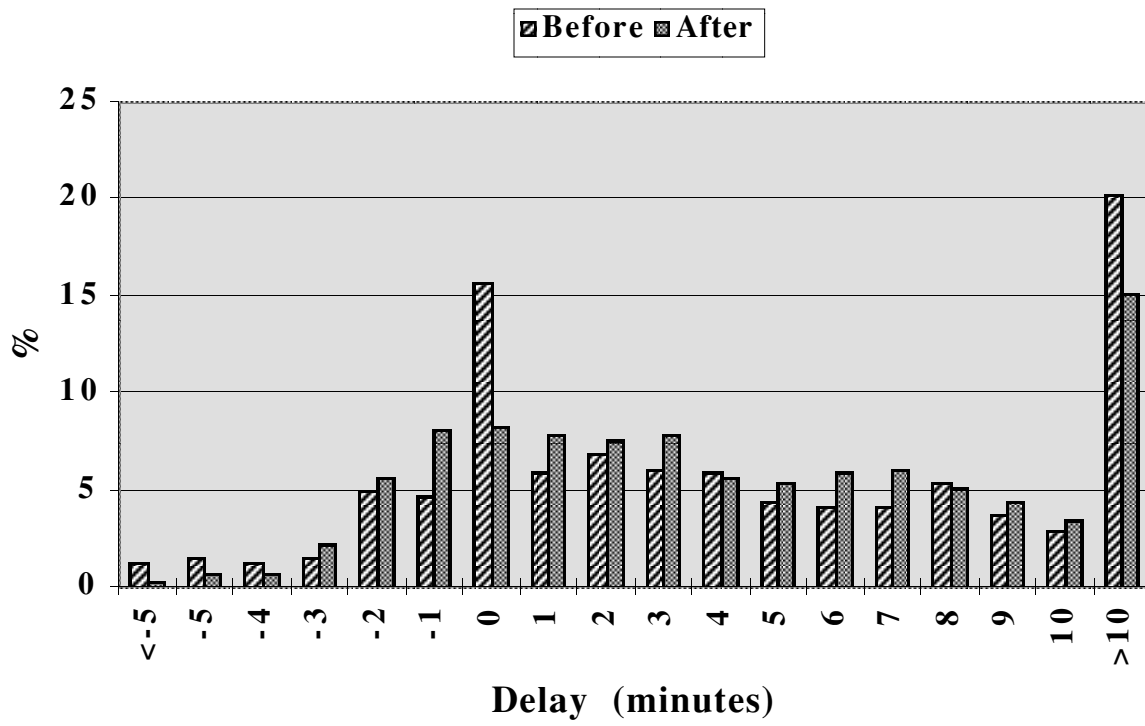# Distribution of Delay Before and After BDS Implementation

A. All Trips
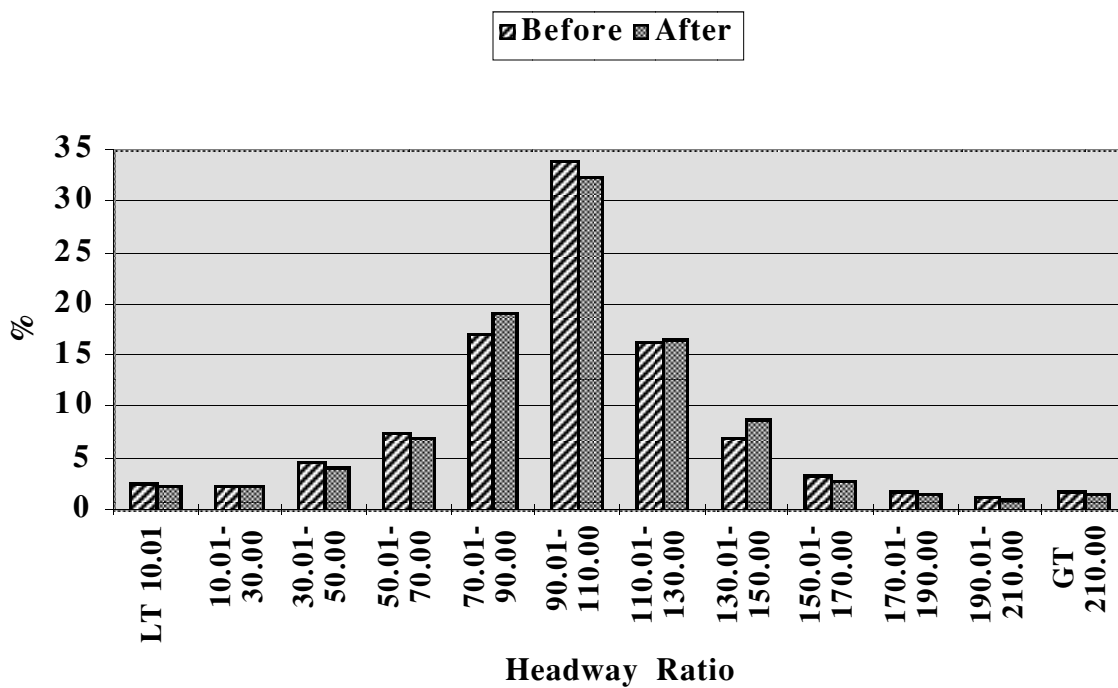

B. AM Peak In-Bound Trips

Figure 1
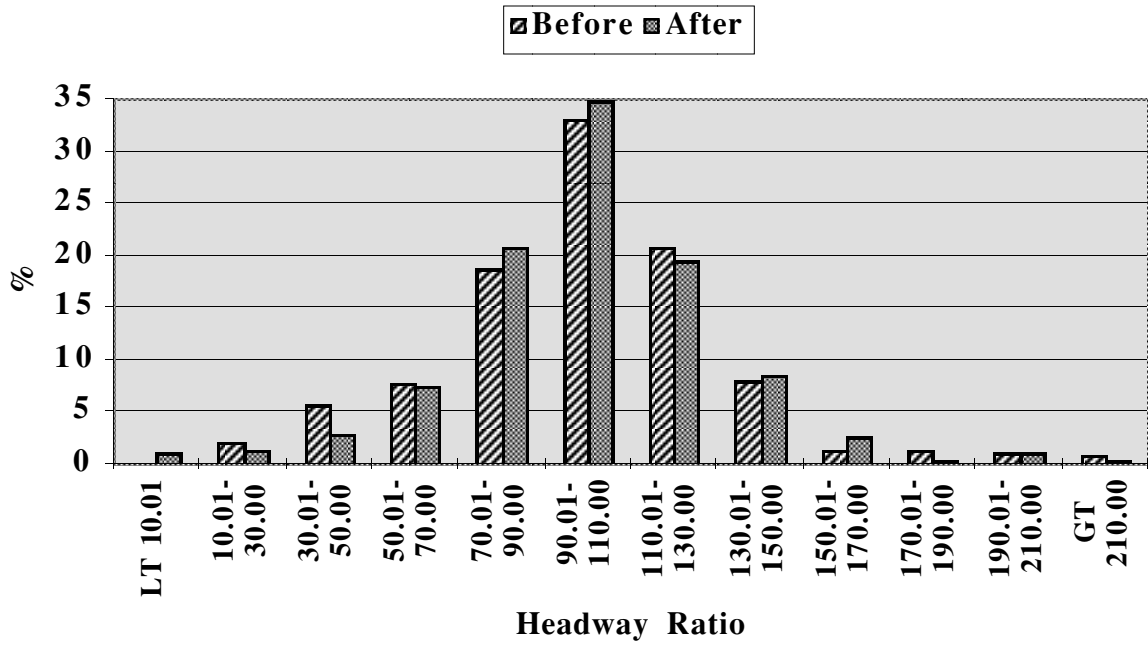## (continued)

C. PM Peak Out-Bound Trips

Figure 2
Headway Ratio Distributions Before and
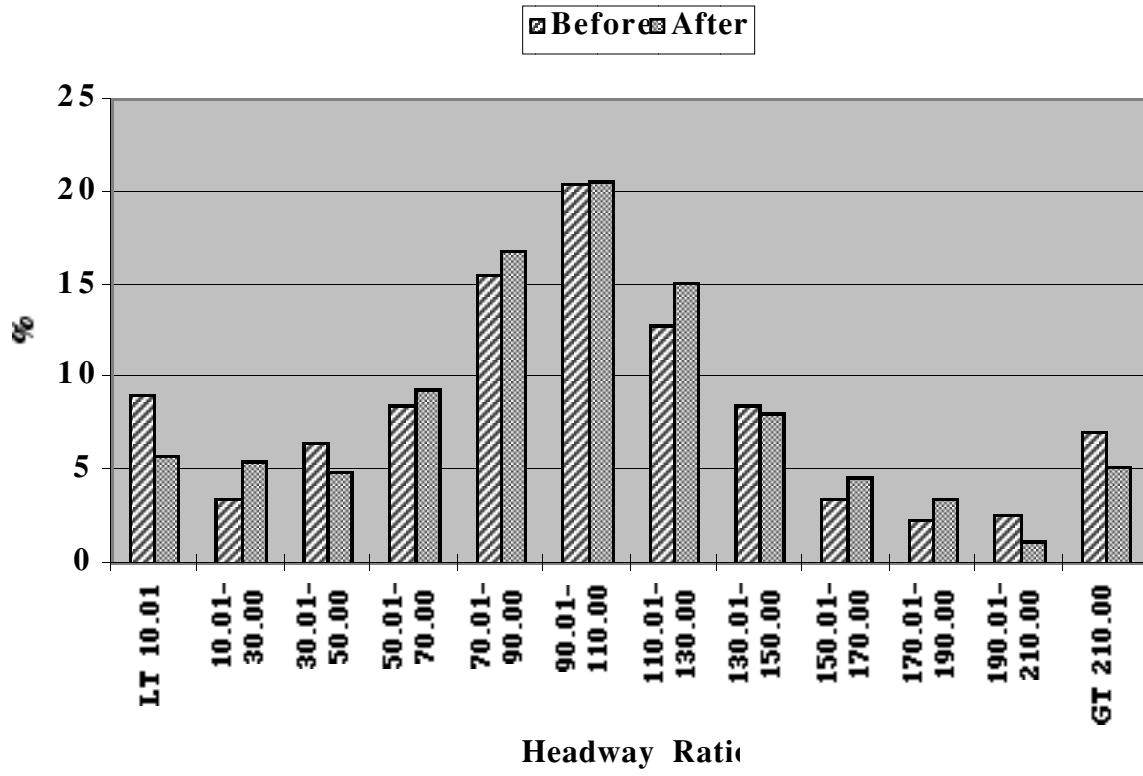**After BDS Implementation**
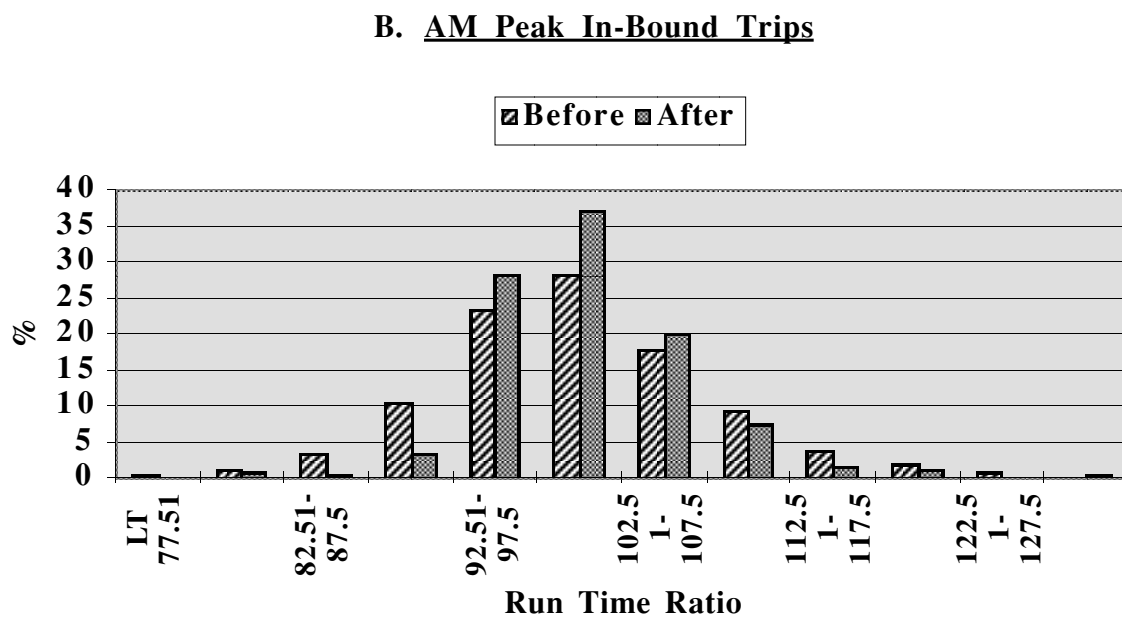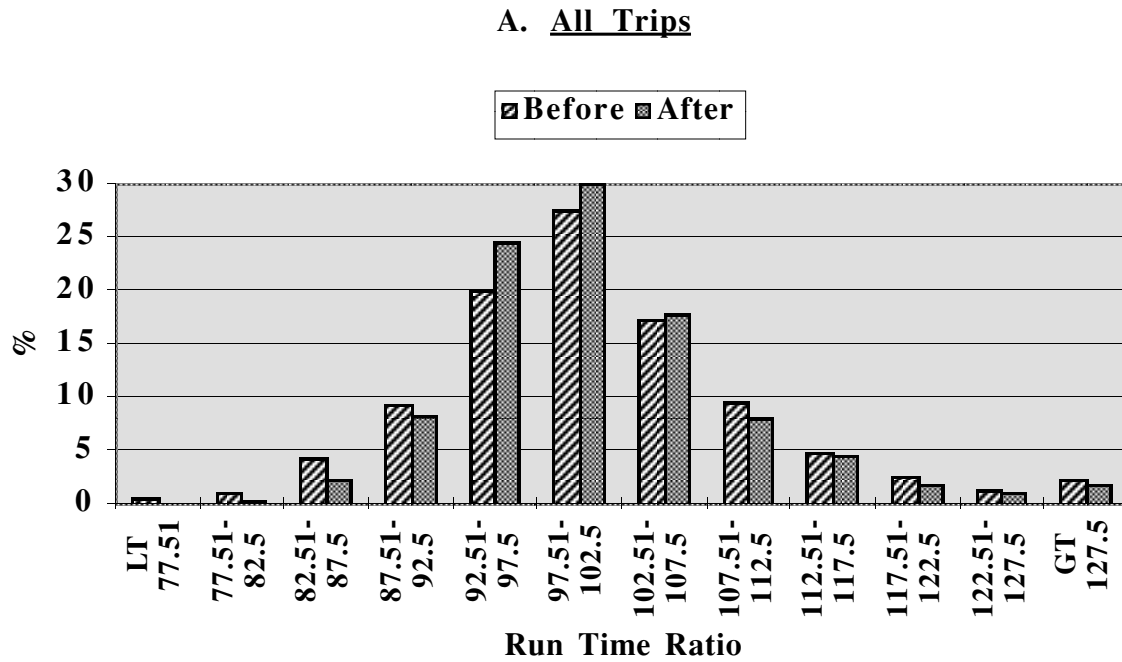
A. All Trips

B. AM Peak In-Bound Trips

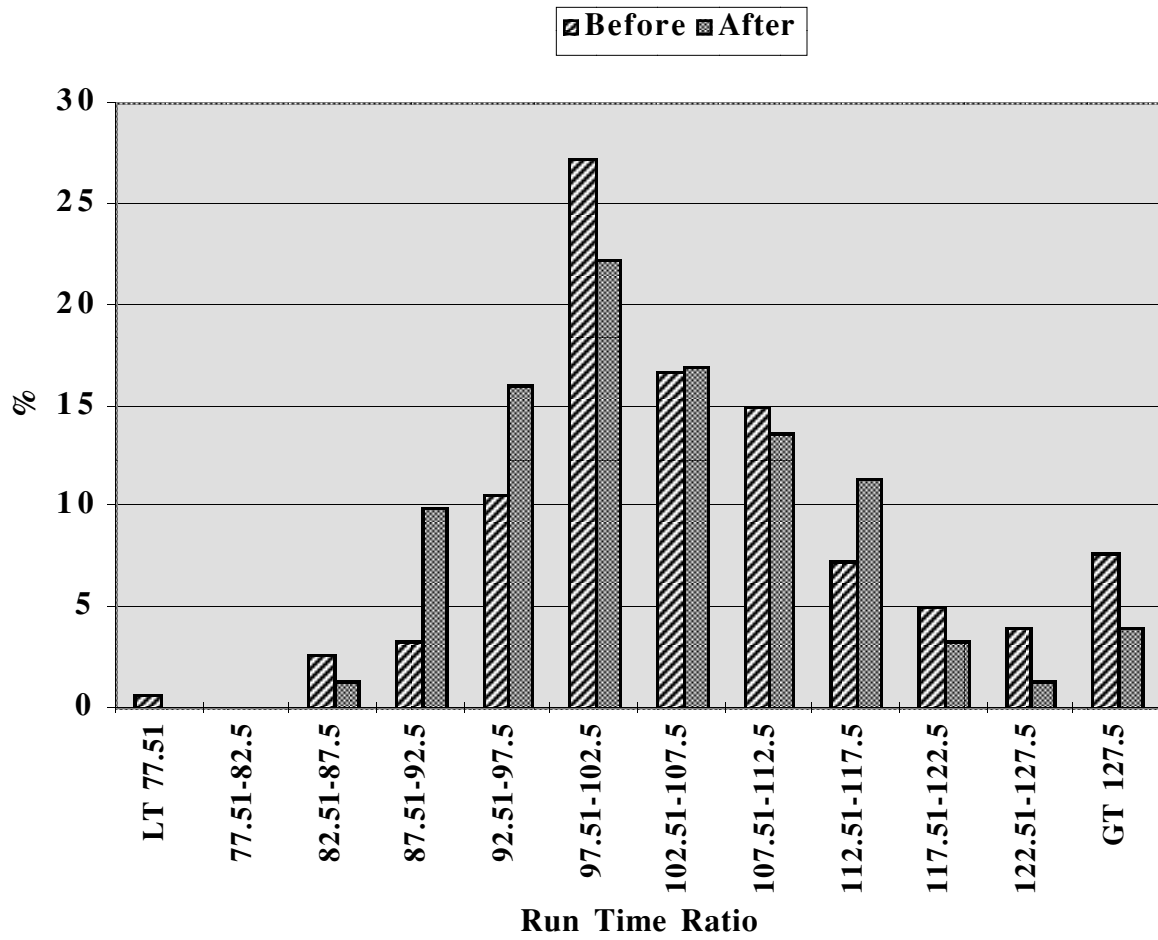**Figure 2**
(continued)

C. PM Peak Out-Bound Trips

Figure 3

Run Time Ratio Distributions Before and After BDS Implementation

A. All Trips

B. AM Peak In-Bound Trips

Figure 3
(continued)

C. PM Out-Bound Trips

Table 3
Parameter Estimates for the Run Time Model*

Variables	Means	Parameter Estimates
Constant	--	5.19
	--	(7.87)*
Departure Delay	1.46	-.30
	(1.91)	(-2.76)*
Distance	10.8	2.90
	(2.8)	(52.71)*
Stops	31.9	.34
	(10.7)	(14.0)*
Boardings	46.2	.01
	(24.2)	(1.24)
Alightings	44.6	.01
	(24.5)	(.88)
Sched. Headway	18.0	-.13
	(8.6)	(-6.95)*
Amin	.12	-1.41
	(.32)	(-3.68)*
Pmout	.13	3.70
	(.34)	(7.09)*
After BDS	.58	-1.45
	(.49)	(-4.65)*
R^2		.86
SEE		4.05
N		830

* The values reported in parentheses under the means and parameter estimates are standard deviations and t-ratios, respectively. The t-ratios denoted by an asterisk are significant at the .05 level.

Table 4

Estimated BDS Benefits
($millions)

Category	Annual Value	Present Value
Bus Operations	1.91	16.89
Bus Riders		
• Waiting	1.61	14.26
• In-Vehicle	1.88	16.66
Totals	5.40	47.80