Arterial Performance Measurement Using Transit Buses as Probe Vehicles

Sutti Tantiyanugulchai and Robert L. Bertini

Abstract—**Developing clear, relevant performance measures for arterials is challenging due to complicated traffic control parameters and users with numerous origins and destinations. With increasing data availability from intelligent transportation systems (ITS) deployments, it is increasingly possible to develop and test new arterial performance measures. Important parameters including average speed, travel time and delay can be obtained both directly and indirectly from sources such as automatic vehicle location (AVL) system. In this paper, we demonstrate how AVL data can be used to characterize the performance of an arterial. Two sources of ITS data were used to assess arterial performance on one corridor in Portland, Oregon. First, we extracted data from the bus dispatch system (BDS) of the transit provider for Portland, Oregon. Performance characteristics as described by bus travel on the arterial were then compared with ground truth data collected by probe vehicles equipped with global positioning systems (GPS) sensors traveling with normal traffic on the same arterial on the same days. Comparisons were made between the two methods and conclusions were drawn regarding the utility of the transit AVL data for real-time advanced traffic management and traveler information systems.**

Index Terms— **global positioning system, intelligent systems, networks, transportation.**

I. INTRODUCTION

THE development of performance measures for freeway systems is a procedure that is well-understood and widely applied. Many freeways are located adjacent to parallel arterials, and in many cities, the arterial roadway network provides major mobility for commuters. As intelligent transportation systems (ITS) continue to be deployed, there has been heightened interest in providing performance measures along arterials, both in the context of advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS). This has been difficult because arterials have complicated traffic control parameters and more origin and destination variables than are associated with freeways.

For site-specific arterial performance measurement, traffic conditions are usually evaluated using test vehicles to collect travel time and delay data [1]. These studies are limited temporally and spatially, and are time consuming and costly. Test vehicles and personnel are usually dispatched to record travel time and delay data for only one peak period on one day.

With ITS, the floating probe vehicle technique can be applied over larger areas (corridors or entire urban areas) and longer time periods (all day, every day). Floating probes respond to changes in traffic flow as they traverse the network and can transmit location and travel time data to a traffic management center at frequent intervals [2]. As with a transit fleet, sometimes these potential floating probes are already in the traffic stream. Most existing transit automatic vehicle location (AVL) systems are used primarily for managing transit operations in real time. Several earlier efforts [3, 4] have used existing transit AVL data to develop possible congestion monitoring and transit information uses. In another case, data from a freeway service patrol AVL system was used to develop freeway performance measures [5].

The Tri-County Metropolitan Transportation District (TriMet) provides transit service in the Portland metropolitan area. During weekdays, more than 600 TriMet buses run along major arterials during peak periods [6]. Each bus is equipped with a bus dispatch system (BDS) including AVL, comprised of differential global positioning systems (GPS), automatic passenger counters, wireless communications, and stop-level data archiving capabilities. Since the buses are already in the traffic stream, they can be used as probe vehicles to collect speed and travel time data. The BDS records bus arrival and departure times at each geo-coded bus stop, as well as recording the maximum instantaneous speed achieved between stops. As a result, TriMet, the Oregon Department of Transportation (ODOT), and the City of Portland are developing plans to use BDS data for ATMS and ATIS purposes [7]. This study is designed to evaluate and validate this potential.

The extent to which bus travel characteristics are related to those of general traffic is not well understood. Therefore, to establish the relationship between actual traffic conditions and bus travel time and speed, a comparison of transit bus data and ground truth data collected by GPS-instrumented passenger vehicles was used in this study. Bus and test vehicle trajectories (plots of vehicle location versus time) were used to measure variations in speed and travel time. To better

Manuscript received March 15, 2003. This work was supported in part by Portland State University Department of Civil & Environmental Engineering.

Sutti Tantiyanugulchai is with Dept. of Civil & Environmental Eng., Portland State University, P.O. Box 751, Portland, OR 97207-0751 USA (phone: 503-725-4285; fax: 503-725-5950; e-mail: hsugush@cecs.pdx.edu).

Robert L. Bertini is with the Dept. of Civil & Environmental Eng., Portland State University, P.O. Box 751, Portland, OR 97207-0751 USA (phone: 503-725-4249; fax: 503-725-5950; e-mail: bertini@ pdx.edu).

Fig. 1. Study corridor

understand the relationship, hypothetical and pseudo bus trajectories were also investigated. Hypothetical buses were defined as buses traveling as if there were no stops and pseudo buses were defined as buses traveling as if they traveled at the maximum speed recorded for each link.

Speed contour plots were also used to observe the spatial and temporal differences in speed for both types of vehicles traveling on the corridor. By estimating speeds over the road segment over time, speed contours were plotted in three-dimensions with time and location as *x*- and *y*- axes respectively. The next section contains a description of the study corridor and the two sources of data used in this study.

II. DATA

The study location is a 4 km (2.5 mi) corridor on Powell Blvd. in Portland, Oregon. The corridor begins at SE 39th Ave. and runs across the Willamette River on the Ross Island Bridge to downtown Portland at SW First Ave., illustrated in Fig. 1. The corridor serves approximately 50,000 vehicles per day [8], with peak travel westbound during the A.M. peak and eastbound during the P.M. peak. This paper focuses on the portion of the study in the westbound direction only using the BDS and test vehicle data obtained on Nov. 7, 2001.

The BDS provides a rich source of transit monitoring information in both real-time and archived formats. For each bus trip and for each geo-coded stop, the BDS records arrival time, departure time, number of boardings and alightings, and location (in NAD83 state plane *X*-*Y* coordinates). In addition, the system stores the maximum instantaneous speed achieved between stops. As shown in Fig. 2, each stop has an imaginary 30 m (100 ft) diameter circle inscribed around it. If the bus does not stop at stop *i*, the BDS records the times that the bus crosses the circle as "arrive time" and "leave time" for stop *i*. If the bus stops at stop *j*, then the BDS records the time that the door opens as the "arrive time," records the "dwell time" (door close time – door open time) and records the "leave time" as the time the bus re-crosses the stop circle. Also at each stop where passengers are served, the BDS records the number of boardings and alightings through both doors [9].

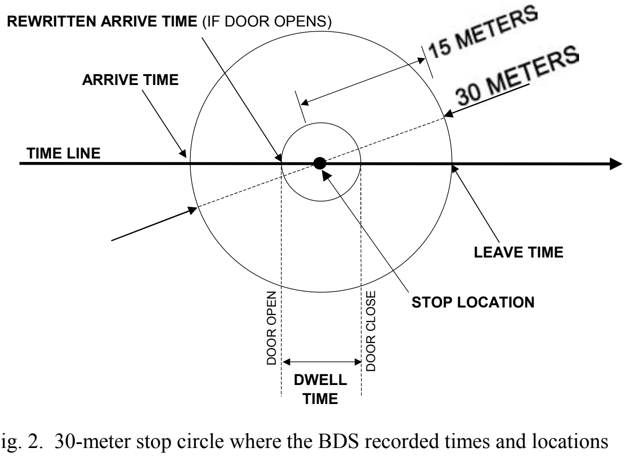

Fig. 2. 30-meter stop circle where the BDS recorded times and locations

Test vehicles equipped with GPS devices were dispatched during several study periods to collect simultaneous corridor time, location and travel time information. The GPS devices were programmed to record each test vehicle's precise location (latitude-longitude) with a time stamp every 3 sec. Two test vehicles were dispatched at approximately 10 min headways on the study corridor between 6:00 A.M. and 9:30 A.M. on Thurs. Nov. 1, 2001 and Wed. Nov. 7, 2001. Further, one test vehicle was dispatched to collect weekend data between 12:00 P.M. and 3:00 P.M. on Sat. Nov. 3, 2001, and Nov. 10, 2001. Travel time data were thus available for 18 runs in each direction (westbound and eastbound) for each weekday, and for 10 runs in each direction for each Saturday. Archived BDS data were also obtained for the same days and times. Note that the transit data are location-based since the BDS system recorded data at preprogrammed geo-coded stop locations, while the test vehicle GPS data are time-based, recorded at a specific frequency. This study demonstrates how fusing the location-based data with the time-based data can reveal important relations between the two sources. The next section describes the analysis of the transit AVL data for determining corridor speed and travel times.

III. BUS PROBE ANALYSIS

For the transit probe investigation, TriMet Route 9 was used for the analysis on Powell Blvd. Route 9 is designated as a "frequent service" route with headways of 15 min or less between the Gresham Transit Center and downtown Portland. Route 9 provides approximately 80 trips per direction per day including several "limited trips," which provide express service during peak periods by skipping specific stops. The study corridor (between a time point at SE Powell Blvd. & SE 39th Ave. and a time point at SW 1st Ave. & SW Arthur St.), is the western end of Route 9, and includes 13 westbound and 12 eastbound stops. In the study corridor, TriMet provides a scheduled mean travel time of 10.7 min, with travel time ranging between 8 min during the off-peak and 13 min during the peak. On Nov. 7, 2001, the mean dwell time was 15.7 sec per stop with an average of 3 passengers boarding and alighting movements per stop served. The buses stopped at an average of 9 stops to serve passengers.

Fig. 3 illustrates a preliminary investigation of the BDS data using vehicle trajectories for a 30-min period. The trajectories were constructed by plotting time on the x-axis and the cumulative distance the bus traveled on the *y*-axis. A trajectory's slope at any time *t* is an estimate of the bus speed at that time on that route segment. Each trajectory shown in Fig. 3 describes an individual bus traveling westbound

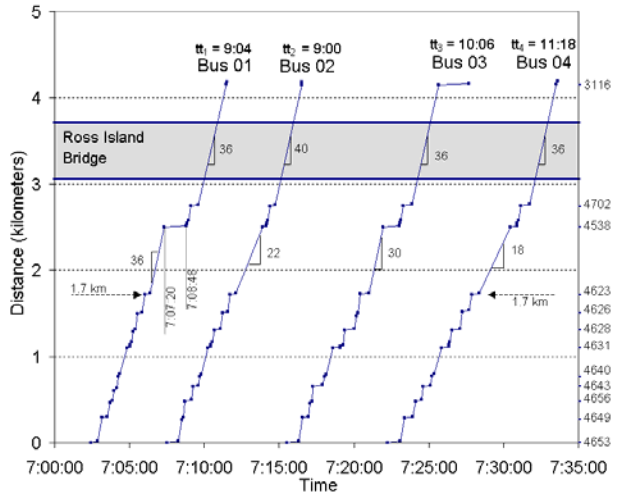

Fig. 3. Bus trajectories

(inbound) and the Ross Island Bridge is illustrated in gray, between 3.1 and 3.7 km (1.9 and 2.3 mi) from the beginning of the corridor. On the secondary (right-hand) y-axis, Fig. 3 shows the stop locations along Powell Blvd., from stop 4653 at SE 39th Ave. to stop 3116 between SW Kelly Ave. and SW Corbett Ave.

To better understand the trajectories' details, Fig. 4 shows sample bus movements in a stop circle. Fig. 4(a) shows a trajectory where the bus enters the stop circle at arrive time t_1, stops for time T to serve passengers, and leaves the circle at leave time t_2. Arrive time is recorded when the bus breaks the stop circle and is overwritten by the time the door opened if passenger activity was present [9]. Leave time is the time recorded when the bus breaks the stop circle while moving away from the stop. Fig. 4(b) presents another trajectory where the bus does not stop to serve passengers. Time T' between arrive and leave time is observed to be shorter than T. The distances traveled inside the stop circles were included in trajectories.

The 4 bus trajectories illustrated in Fig. 3 are sample westbound trips (from total of 16 trips). As shown in Fig. 3, the small horizontal segments reflect bus movement within the stop circles, matching stop locations on the secondary y-axis. The difference between the first location and last location projected on the x-axis is the total travel time (run time). The mean run time was 9:46 min and varied (in the morning peak between 6:00 and 9:30 A.M.) between 8:00 and 11:22 min. In Fig. 3, run times increased from approximately 9 min to 11 min. Fig. 3 also shows the impact of passenger activity, i.e., bus 04 had longer dwell times at almost every stop compared to the other three buses.

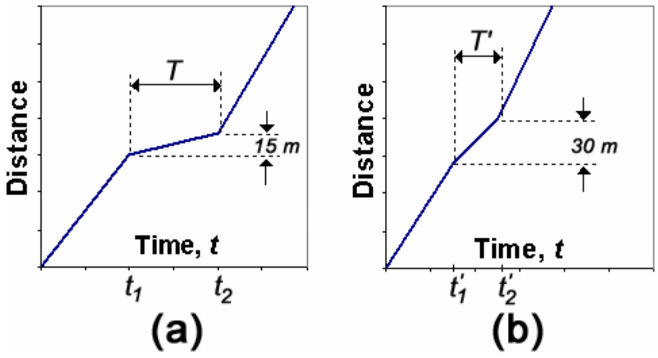

Fig. 4. Sample bus trajectories when a bus stops (a) and when bus does not stop (b)

In Fig. 3, the trajectories show that the buses were traveling at a mean speed of 22 km/h (13.7 mi/h) at the beginning of the route. However, at distance 1.7 km (1.1 mi), bus performance changed. For example, bus 01 was traveling at 36 km/hr (22.4 mi/h) and stopped for a long period (1:28 min at stop 4538). Bus 02 was traveling at a lower speed of 22 km/h (13.7 mi/h) and stopped for a shorter period at the same stop. This can be explained by the nature of this stop location. Since bus stops are usually located near signalized intersections (including stop number 4538, a nearside stop located east of SE 11th Ave.), bus 01 traveled at a higher speed and arrived at stop 4538 at the same time the signal phase changed to red and had to wait until the next cycle before it could leave the stop circle. This resulted in a longer recorded stop time even though the dwell time and number of passengers boarding and alighting were low, e.g., 13 sec dwell time, 2 boardings, and 1 alighting. Bus 02 traveled at a slower speed, stopped, and completed passenger activity when the signal was still green so the bus was able to continue downstream without any additional waiting time.

Recognizing that transit vehicles have different operating characteristics than other vehicles in the traffic stream, it was hypothesized that transit speed could appear similar to other vehicles on the Ross Island Bridge. The bridge has no shoulders and its approaches are bottlenecks, so traffic is usually flowing freely on the bridge. In fact, transit speeds on the bridge were observed to be nearly constant at a mean of 38.9 km/h (24.2 mi/h), while the average overall bus speed on the route was 25.8 km/hr (16.0 mi/h). This indicates that free flow traffic conditions prevailed on the bridge. Toward developing an algorithm to relate the bus data to actual traffic conditions, experiments using the bus data were conducted including hypothetical and pseudo bus scenarios. Non-transit vehicles do not decelerate and accelerate to serve passengers, so the hypothetical bus concept considers a potential non-stop bus trajectory by subtracting the dwell times. The resulting non-stop trajectory is an approximation of how a bus would travel if it did not stop to serve passengers. Buses are large vehicles and their operations are often motivated by schedule adherence and impacted by individual driver characteristics [10]. Thus, even without stopping, their travel characteristics will be different than those of passenger cars.

The BDS system recorded the maximum instantaneous speed achieved between pairs of stops [9]. A pseudo bus trajectory was created by stringing together segments of a trip using the maximum speed between each pair of stops as the slope of the trajectory. This was based on the hypothesis that the maximum speed could approximately reflect the speeds of non-transit vehicles along the route.

Fig. 5 shows a combination of the actual bus trajectories with the hypothetical and pseudo bus trajectories for a 30-min period. As shown, the three trajectories began at the same departure time. For example, bus 01, hypo 01 and pseudo 01 began at 7:02:52 A.M. Pseudo bus trajectories reflect the shortest travel times; for example, pseudo 04 finished its trip

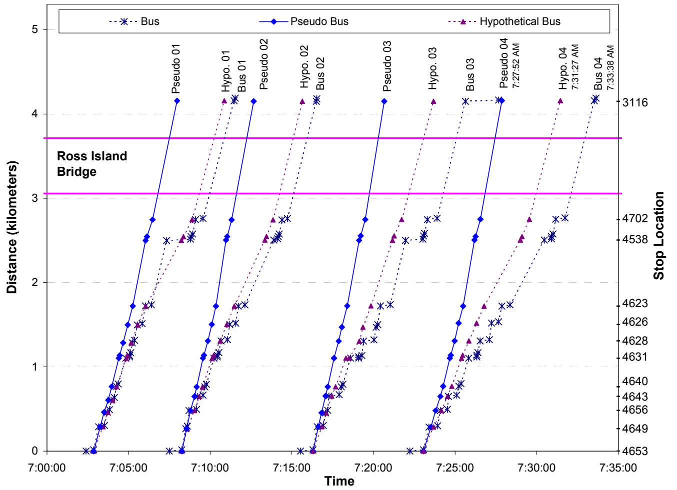

Fig. 5. Comparison of actual, hypothetical and pseudo buses' trajectories

at 7:27:52 A.M., faster than bus 04 and hypo 04 by 3:35 and 4:46 min respectively. The mean pseudo bus speed was 55.3 km/h, twice the actual mean bus speed (25.8 km/h) and about 1.3 times the hypothetical buses speed (33.5 km/h). Since the pseudo buses were created to reflect potential non-transit travel, pseudo buses display more stable speeds along the route. The comparison between the pseudo buses and the test vehicles will be most relevant and will be described later.

IV. TEST VEHICLE ANALYSIS

From the test vehicle data obtained from the GPS devices, the distance between two reported locations was estimated using the spherical geometry method [11]. Test vehicle trajectories were plotted, a sample of which is shown in Fig. 6. The mean test vehicle corridor speed was 44 km/h (27.3 mi/h), ranging between 32.7 km/h and 52.6 km/h. The mean test vehicle travel time was 5:57 min, varying between 5:00 and 7:48 min.

From the trajectory slopes, it is shown that the test vehicles experienced stop-and-go traffic conditions along the corridor. For example, the inset for vehicle 04 shows that it decelerated at distance 2.25 km (1.4 mi), stopped for a short period, and then accelerated to 28.6 km/h (17.8 mi/h). This was also observed at the same location on other test vehicle runs indicating that the location is a signalized intersection. The inset in Fig. 6 also shows that at distance 2.44 km (1.52 mi) at 7:36:45 A.M., vehicle 04 decelerated, traveled at 1.5 km/h (0.9 mi/h) before accelerating at distance 2.46 km (1.53 mi) at 7:37:38 A.M. Test vehicle decelerations occurred at slightly different points, since the queue varied over the morning peak. As indicated in Fig. 6, the mean test vehicle on the bridge was 64 km/hr, varying between 48 and 76 km/hr (29.8 and 46.6 mi/h). This was higher than the average route speed by almost 20 km/hr. Together with the observation of transit speeds on the bridge explained in previous section, this confirms that traffic conditions on the bridge were more stable than the overall conditions along the route.

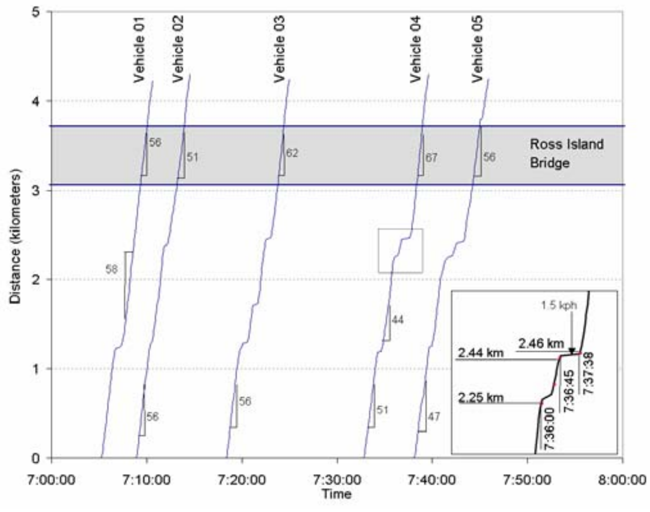

Fig. 6. Test vehicle trajectories

V. COMPARISON

Westbound transit run times were determined using the difference between leave time from the first stop (4653) and the arrive time from the last stop (3116) on the corridor. Test vehicle travel times were calculated by subtracting the time recorded at the beginning of the route from the time at the end. Both times include the time when the vehicles stopped due to traffic control and congestion, e.g., at signalized intersections. Hypothetical (non-stop) travel times were calculated as the net run time minus the time the bus stopped to serve passengers. Pseudo travel times were calculated by applying the recorded maximum speed between stops to each street segment.

Fig. 7 shows one actual bus trajectory, corresponding hypothetical and pseudo trajectories and one test vehicle trajectory. As shown, the actual bus and test vehicle trajectories had similar shapes. By subtracting the effects from the stop-and-go conditions that created the horizontal offsets on the test vehicle trajectory, it is clear that the test vehicle link speeds were substantially higher than those of the actual bus. Instead, the test vehicle's speed appeared similar to the speed of the pseudo bus.

To verify this, test vehicle and pseudo bus travel times and speeds were compared by departure time, as shown in Fig. 8. Travel time trend lines in Fig. 8(a) indicate that all vehicles spent more time traversing the study corridor during the morning peak period (7:00–9:00 A.M.). The speeds of the test vehicles and buses were also plotted against the departure time as shown in Fig. 8(b). Traffic conditions improved after the peak period as shown in Fig. 8(b), at 9:30 A.M. Test vehicles traveled at approximately 50 km/hr (31 mi/hr) and bus speeds were 28 km/hr (17.4 mi/hr). The mean

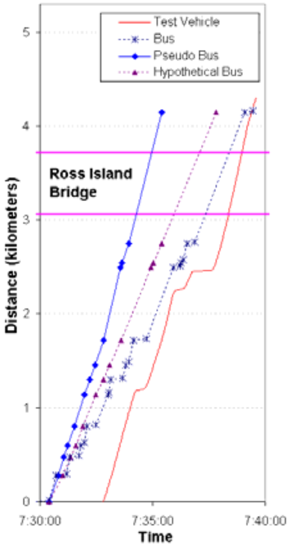

Fig. 7. Comparison of test vehicles, actual buses and conceptual buses' trajectories

TABLE I

AVERAGE RATIO OF TEST VEHICLES SPEEDS COMPARED TO OTHER TYPES

	Actual Bus	Hypothetical Bus	Pseudo Bus
Corridor Speed	1.66	1.03	0.79
Bridge Speed	1.69	1.69	1.01

travel times for all four scenarios are also shown in Fig. 9.

Corridor speeds were derived by dividing the total travel distance, approximately 4 km (2.5 mi), by the net travel time. Fig. 8(b) shows the comparison between test vehicles speeds and pseudo bus speeds. Fig. 10(a) and 10(b) also show a comparison between bridge travel time and speed in detail. Both test vehicle and pseudo bus travel times and speeds were close to one other and their trend lines were similar.

The relationship between test vehicle and bus travel time and speed was analyzed. As shown in Table 1, the mean test vehicle speed was 0.79 times the pseudo bus speed for the entire corridor. However, the test vehicle and pseudo bus travel times and speeds were found to be the same on the bridge. This supports the conclusion stated earlier that the bus maximum speed on the bridge was representative of non-transit traffic speed.

Average U.S. bus travel times were reported as 2.6 min/km (4.2 min/mi) in suburbs, 3.7 min/km (6.0 min/mi) in the city, and 7.1 min/km (11.5 min/mi) in the central business district [12]. Fig. 9 shows a mean travel time of 9:46 min, or 2.4 min/km (3.9 min/mi), faster than the national study. Table 1 also shows that test vehicle speeds were 1.7 times greater than bus speeds. The national average shows that vehicles usually travel 1.4 to 1.6 times faster than buses [12], and the U.S. Department of Transportation reports an average bus speed of 16 km/hr (10 mi/hr) in the city and 23 (14.3 mi/hr) in the suburbs [13].

A three-dimensional speed contour technique was used to assist in visualizing the speed differences between the buses and the test vehicles spatially and temporally. As shown in Fig. 11, speed contour plots for buses and test vehicles were generated using distance and time as the *x*- and *y*-axes respectively with speed plotted on the *z*-axis. The area between each pair of known data points were estimated using a geographic information system (GIS) statistical interpolation method called “kriging” [14].

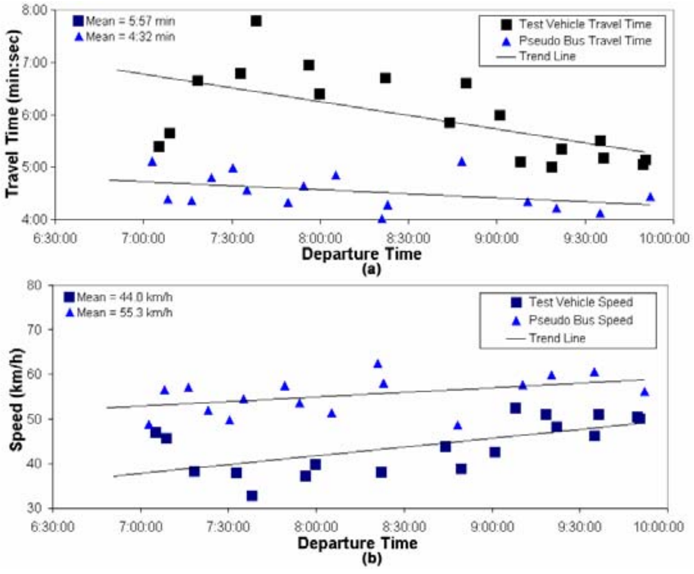

Fig. 8. (a) Travel time and (b) speed of the test vehicle and pseudo bus versus the departure times

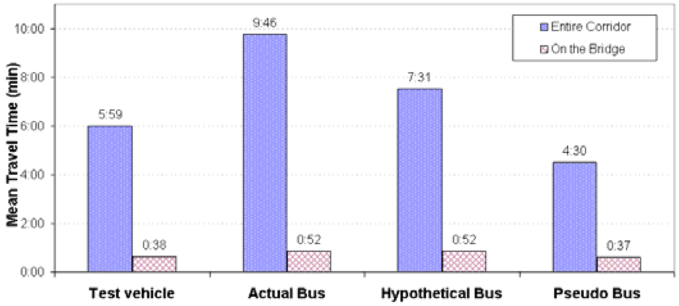

Fig. 9. Mean travel time of the four scenarios both entire corridor and on the bridge.

The speed contour diagram shows that the test vehicle speed changed smoothly on the surface due to the availability of the data every 3 sec while the changes in bus speeds were more coarse since the numbers of bus data points were limited. The concave surface reflects slower traffic conditions compared to other patterns on the surface. As vehicle *i* or bus *j* traverses through distance and time in a diagonal direction on the surface, concave and convex surface features describe the varying traffic conditions resulting in deceleration and acceleration. A concave surface feature, as an example, indicates that a vehicle faced queued traffic downstream and accordingly decelerated. A steep slope on the surface represents a faster change in speed of the vehicle. After the lowest point the surface, traffic conditions began to return to unqueued conditions as the vehicle accelerated.

Finally, Fig. 11 also shows a third surface which is the result of subtracting the bus speed surface from the test vehicles surface. By viewing the differences between the two

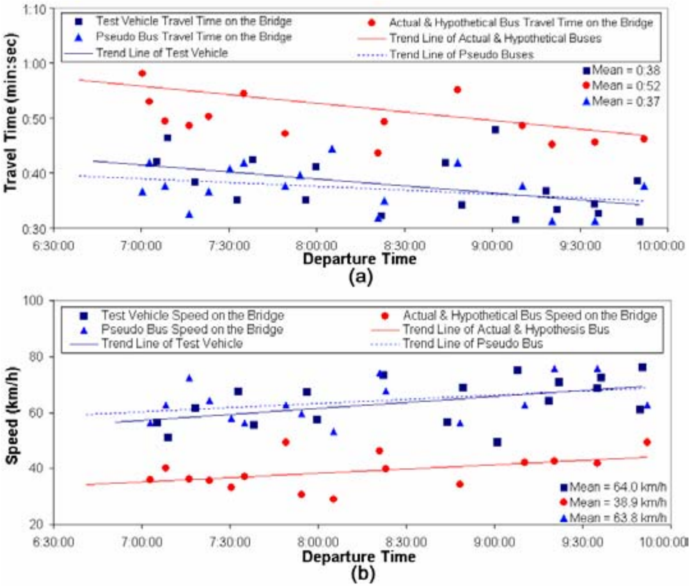

Fig. 10. Test vehicles, actual bus, hypothetical bus and pseudo bus comparison on (a) travel time on the bridge and (b) speed on the bridge

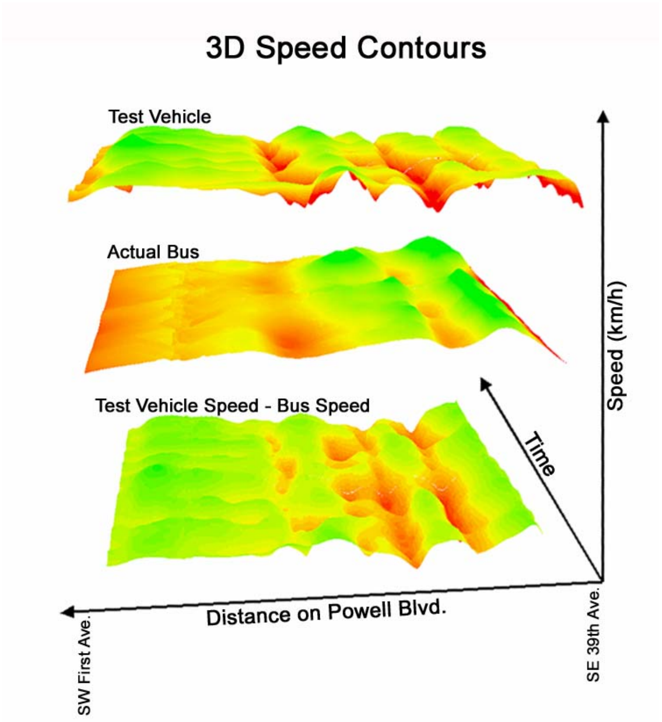

Fig. 11. Speed contour plot

speed surfaces, one can locate specific locations and times that the test vehicles experienced conditions that were different from those experienced by the buses.

VI. CONCLUSION

From this preliminary study, it is shown that actual arterial traffic conditions can be described using transit vehicle AVL information. From the set of transit data used herein, the bus trajectory generated from the maximum instantaneous speed achieved between each stop pair was found to most reliably depict the traffic movement of non-transit vehicles. Key performance measures like travel time and delay should also be described using the relationship established between the test vehicle and the pseudo bus. This study found that the test vehicle corridor travel time was 1.3 times the pseudo bus travel time. Conversely, it was shown that the test vehicle speed was 0.79 times the maximum instantaneous speed achieved by the buses. On the Ross Island Bridge it was found that the test vehicle speed was the same as the pseudo bus speed. While this study focused on only one direction during the morning peak for one day, further analysis on both traffic directions on more numbers of days is ongoing. These results will provide a grater level of confidence to the study results. However, it is possible that this preliminary study could be helpful example toward developing any system assisting transit agencies and traffic engineers to better understand arterial performance assessment.

ACKNOWLEDGMENT

The authors gratefully acknowledge Steve Callas of TriMet, who generously provided the BDS data. Chie Taniguchi, Tung Ly, John Fasana, Lara Downs, Tu Ho, Huy-Thac Tran, Ahmad Qayoumi, Michael Kehano, Renee Summers, Monica Leal and Shazia Malik collected the test vehicle data. Ahmed El-Geneidy assisted with the corridor and contour mapping. Ken Turner, TriMet; Jack Marchant, ODOT; Thomas Kimpel and James Strathman, Center for Urban Studies; Roger Lindgren, Oregon Institute of Technology; and Peter Koonce, Kittelson & Assoc., assisted in developing and completing this study.

REFERENCES

[1] J.C. Oppenlander, “Sample size determination for travel time and delay studies,” *ITE Journal*, vol. 46, pp. 25-28, Aug. 1976.

[2] *Travel Time Data Collection Handbook*. U.S. Department of Transportation, Rep. FHWA-PL-98-035, TTI: Texas, 1998, ch. 5.

[3] D.J. Dailey, “The use of transit vehicles as speed probes for traffic management and traveler information in addition to performance monitoring,” TransNow, Univ. Washington, 2001.

[4] T. Williams, “Use of TriMet computer-aided bus dispatching systems data for traffic congestion monitoring and analysis,” unpublished.

[5] J.E. Moore II, S. Cho, A. Basu and D.B. Mezger, “Use of Los Angeles freeway service patrol vehicles as probe vehicles,” California PATH Res. Program, Berkeley, CA, Rep. UCB-ITS-PRR-2001-5, 2001.

[6] *Meet the Fleet*, TriMet, 2002 [Online]. Available: http://www.trimet.org/factsandphotos/fleet.htm

[7] *Transit Buses as Traffic Probes Project* [Draft Scope of Work]. ODOT Region 1 Transportation Management Operations Center, 2003.

[8] *Oregon State Highway Transportation Volume Tables*, ODOT Transportation Systems Monitoring Unit, 2001.

[9] A. El-Geneidy, “Tri-Met data dictionary,” Great Cities’ University Coalition [Online], Avail: http://www.gcu.pdx.edu/data/dictionary.htm

[10] J.G. Strathman, T.J. Kimpel, K.J. Dueker, R.L. Gerhart and S. Callas, “Evaluation of transit operations: Data applications of Tri-Met’s automated bus dispatching system,” Center for Urban Studies, Portland State Univ., Portland, OR, 2001.

[11] *Distance Calculation*, Meridian World Data, Inc. [Online], Available: http://www.meridianworlddata.com/Distance-Calculation.asp

[12] H.S. Levinson, “Analyzing transit travel time performance,” Transp. Res. Rec. 915, 1983, pp. 1-6.

[13] *Characteristic of Urban Transportation System*, Federal Transit Administration, 1992, Ch. 3 [Online], Avail: http://www.fta.dot.gov/library/reference/CUTS/frchap3.htm

[14] P.A. Longley, M.F. Goodchild, D.J. Maguire and D.W. Rhind, *Geographic Information Systems and Science*, West Sussex, England: John Wiley & Sons, 2001, pp. 297-301.