Analysis of a Transit Bus as Probe Vehicle for Arterial Performance Measurement

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Abstract With increasing data availability due to intelligent transportation systems (ITS) deployments, methods for assessing and reporting traffic characteristics and conditions have begun to shift. While previous Level of Service (LOS) methods were developed for use with limited data, we now have the power to develop and test the use of actual performance measures. Important measures like average speed, travel time, and intersection delay can be used for performance monitoring of the transportation system. On freeways, such performance measures are often estimated directly using data from inductive loop detectors (e.g., speed, occupancy, vehicle counts). For arterials with numerous signalized intersections, performance measures are more challenging due to more complicated traffic control and many origins and destinations. However, within signalized networks, travel time, speed, and other key performance measures can be obtained both directly and indirectly from sources such as automatic vehicle location (AVL) data.

In this paper, we demonstrate how AVL data can be used to characterize the performance of an arterial. First, we extract data from the bus dispatch system (BDS) of the Tri-County Metropolitan Transit District (TriMet), the transit provider for Portland, Oregon. Then, the performance characteristics as described by bus travel on an arterial are compared with ground truth data collected by probe vehicles equipped with global positioning systems (GPS) sensors traveling with normal (non-transit) traffic on the same arterial on the same days. Comparisons are drawn between the two methods and some conclusions are drawn regarding the utility of the transit AVL data.

INTRODUCTION

Throughout the last decade, traffic engineers, planners, researchers, and transportation agencies have expended much effort trying to understand how a freeway system operates. Several key performance measures have been generated, numerous reports published and numerous freeway miles investigated. Even though such performance measures have been successful in describing freeway performance, we still lack solid methods for the analysis of arterials. This is because arterials are characterized by complicated traffic behavior and many more variables than are associated with freeways.

For site-specific arterial performance measurement, of all possible alternatives, traffic conditions are evaluated using test vehicles to collect travel time and delay data [1]. However, the studies of travel time and delay are limited temporally and spatially, time consuming and expensive. Test vehicles and personnel need to be dispatched in order to capture traffic movements and collect travel time data for only one peak period on one day.

With the increasing implementation of ITS, the floating probe vehicle technique can play an important role as an application designed primarily for collecting data in real time. Floating probe vehicles 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 time intervals on the order of minutes or seconds [2]. As in the case of a transit fleet, sometimes these potential floating probe vehicles are already in the traffic stream.

Most existing transit automatic vehicle location (AVL) systems are used primarily for managing transit operations in real time. In earlier efforts, researchers have used existing transit AVL data to develop and explore possible congestion monitoring and transit information uses. Two pilot studies using transit probe vehicles to obtain real-time traffic conditions include the joint Transportation Northwest (TransNow) and Washington State Department of Transportation (WSDOT) project in Washington [3], and an individual traffic congestion monitoring study in Oregon [4]. In another case, data from a California freeway service patrol AVL system were used to develop real-time freeway performance measures in Los Angeles [5].

BACKGROUND

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 system (ATMS) and advanced traveler information system (ATIS).

In Portland, Oregon, the Tri-County Metropolitan Transportation District of Oregon (TriMet) provides transit service in the Portland metropolitan area. During weekdays, more than 600 TriMet buses run along almost every major arterial during the peak periods [6]. Each of these buses is equipped with a Bus Dispatch System (BDS) which includes AVL, comprised of differential global positioning systems (GPS), automatic passenger counters, wireless communications, and stop-level data archiving capabilities. The BDS provides a rich source of accurate time and location information. Since the buses are already in the traffic stream, they can be used for the collection of travel time data as probe vehicles. The BDS records bus arrival and departure times at each geo-coded 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].

The extent to which the travel characteristics of buses are related to those of general traffic is not well understood. Therefore, to establish the relationship between the traffic condition and the bus travel time and speed, a comparison of the transit bus data and ground truth data collected by GPS-instrumented passenger vehicle was used in this study. Vehicle trajectories–graphs plotted with vehicle location versus time–of both buses and test vehicles (non-transit) were produced to measure the differences in travel time and speed. To better understand the relationship, the hypothetical and pseudo bus analyses were also investigated. Hypothetical buses are defined as the buses traveling non-stop and pseudo buses are the buses traveling at the maximum speed recorded for each link.

Speed contour plots were also used to observe the precise differences in speed for both types of vehicles traveling along the study corridor. By estimating speeds throughout the road segment at any particular time, speed contours were plotted on a three-dimensional graph using time and location as the x- and y- axis respectively.

The next section contains a description of the study corridor and the two sources of data used in this study.

DATA

The study location is a 2.5 mi corridor on Powell Blvd. in Portland, Oregon. This corridor begins at SE 39th Ave., runs across the Willamette River on the Ross Island Bridge to downtown Portland at SW First Ave., illustrated in Figure 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. 1, 2001.

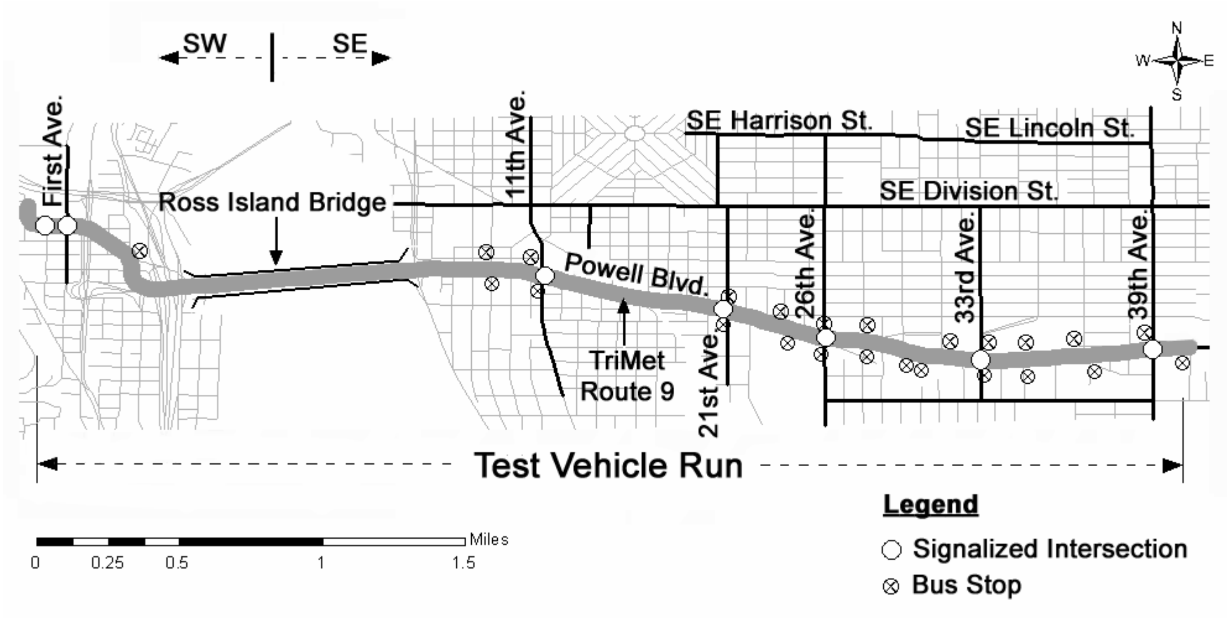

Figure 1. Study corridor

The BDS provides a rich data 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 Figure 2, each stop has an imaginary 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].

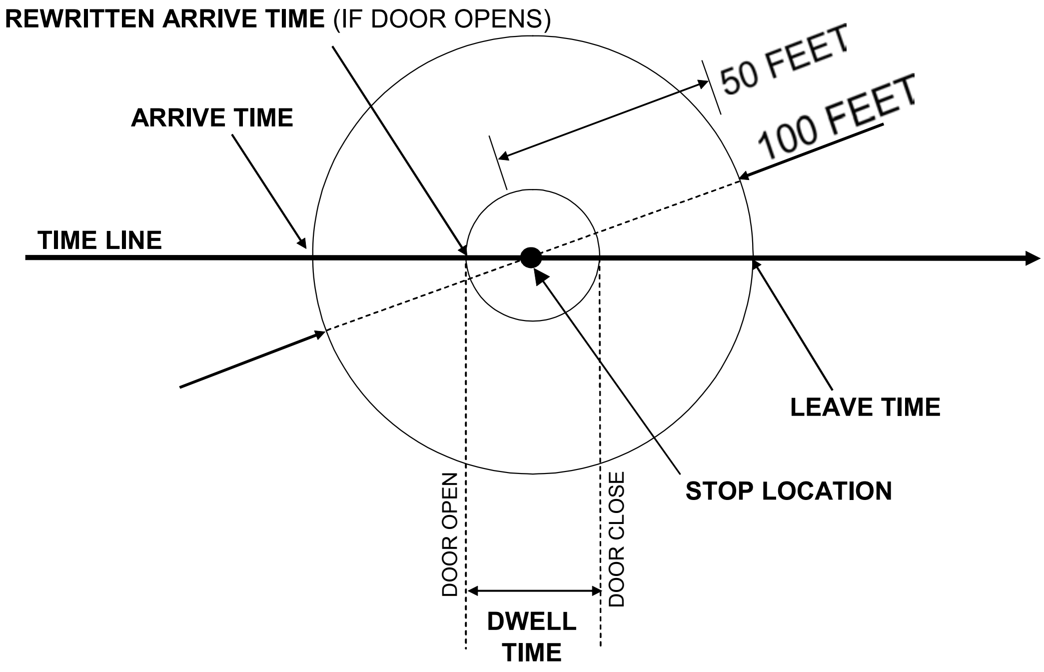

Figure 2. 100-foot stop circle where the BDS recorded times and locations

Test vehicles equipped with GPS devices were dispatched during the study period 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 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. Transit AVL data were also obtained for the same days and times. Note that the transit data is location-based since the BDS system recorded data at preprogrammed geo-coded stop locations, while the test vehicle GPS data is time-based, recorded at specific time intervals. 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 travel times.

BUS PROBE ANALYSIS

For the transit probe investigation, TriMet bus Route 9 was selected for analysis on Powell Blvd. Bus route 9 is designated by TriMet as a “frequent service” route with headways of 15 min or less between the Gresham Transit Center and downtown Portland. Bus Route 9 provides approximately 80 trips per direction per day including several “limited trips,” which provide faster service during peak periods by skipping stops at specific locations. 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., which is the western end of Route 9), includes 13 westbound and 12 eastbound stops. In the study corridor, TriMet provides a scheduled mean trip time of 10.65 min, with trip times ranging between 8 min during the off-peak and 13 min during the peak. On Nov. 1, 2001, the mean observed dwell time was 16.3 sec per stop with an average of 2 passengers boarding and 1 passenger alighting movements per stop served in the study corridor. The buses stopped at an average of 8 stops to serve passengers.

Figure 3 illustrates a preliminary investigation of the BDS data using vehicle trajectories, constructed by plotting the cumulative distance each bus traveled on the *y*-axis and time on the *x*-axis. A trajectory’s slope at any time *t* is the bus speed at that time on that route segment. Each trajectory shown in Figure 3 describes an individual bus traveling westbound (inbound) and the Ross Island Bridge is illustrated in gray, between 1.9 and 2.3 mi from the beginning of the corridor. On the secondary (right-hand) *y*-axis, Figure 3 shows the stop locations along the route, from stop 4653 at the corner of Powell Blvd. and SE 39th Ave. to stop 3116 between SW Kelly Ave. and SW Corbett Ave.

The bus trajectories illustrated in Figure 3 are sample westbound trips (total of 19 trips). As shown in Figure 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 trip time (run time). The mean run time was 9:23 min and varied (in the morning peak between 6:00 and 9:30 A.M.) between 7:26 and 13:12 min. In Figure 3, bus run times were observed to increase from approximately 7 min to 10 min. Figure 3 also shows that passenger activity, i.e., Bus trips 4, 5 and 6 had longer dwell times compared to the other three trips. The mean dwell time for the corridor was 127 sec.

In Figure 3, the trajectories show that the buses were traveling at a mean speed of 13.3 mi/h at the beginning of the corridor (before the bridge). However, when the trajectories are observed in detail, they shows that the buses were traveling with slightly different patterns. Between 7:00:00 and 7:15:00 AM, buses were traveling at a mean speed of 14.5 mi/h with steady movement for Bus trips 1, 2 and 3. Five minutes later, bus movements along the corridor changed. Between 7:20:00 and 7:40:00 AM, the trajectories for Bus trips 3, 4, and 5 were observed to be fuzzy indicating that there were variations in bus speeds. This can be explained by changes in traffic conditions when the morning peak began. As we observed the bus travel times in Figure 3, it also confirms that buses spent more time traversing study corridor. For example, Bus Trip 1 spent 7:26 min to traverse the corridor while Trip 2, 3 and 4 spent 8:22, 8:30 and 8:44 min respectively.

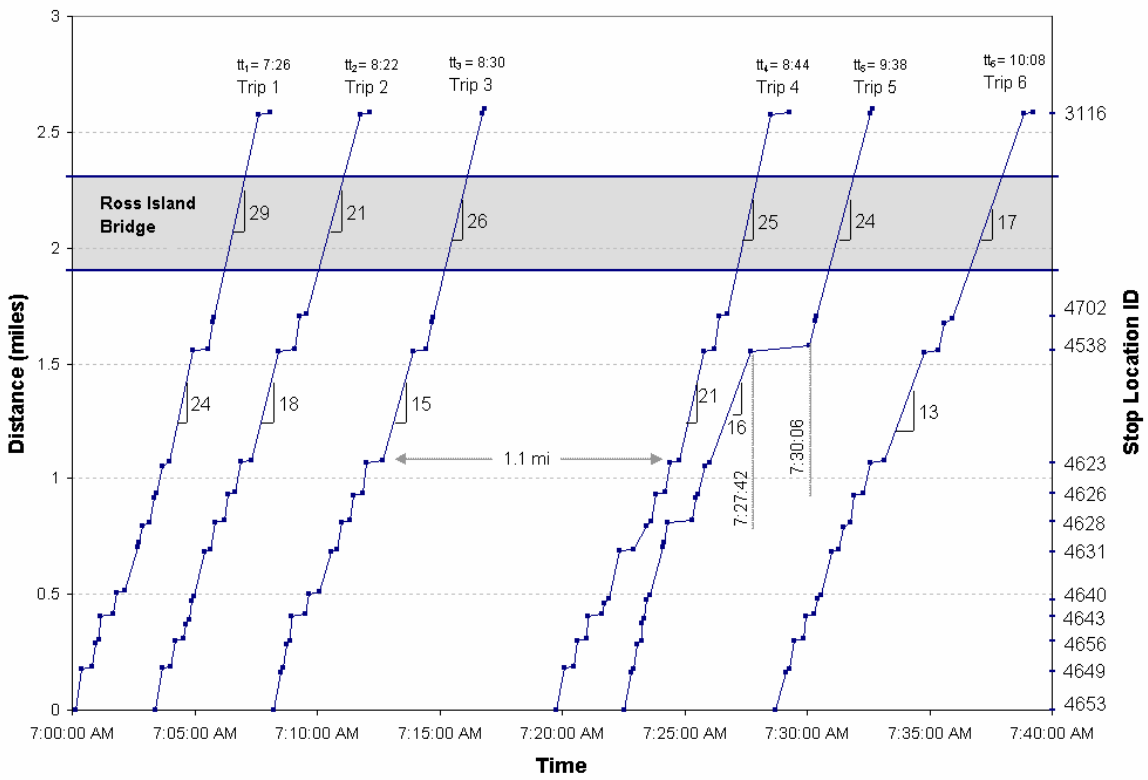

Figure 3. Bus trajectories

One benefit of using vehicle trajectories is the ability to pinpoint specific locations and times that vehicle behavior changes. An example of this benefit is in the case of Bus Trip 5 that we can easily observe a change in the bus's performance graphically. As shown in Figure 3, at distance 1.1 mi, Bus 5 was traveling at 16 mi/h and stopped for a long period (2:24 min at the stop number 4538). At stop 4538, according to TriMet's Bus Route 9 schedule, this stop is a time point with a predefined stop time. In order to keep up with the bus schedule, the operator who arrives at this stop early will stop longer and leave when he/she can get back on schedule. In this case, the bus arrived at stop 4538 at 7:27:42 AM which is earlier than the stop time (time point) at 7:30:00 AM by 2:18 min. We also found a very long dwell time of 1:33 min (from door open to door close) without any passenger movement (zero boarding and alighting). This high stop time is also accompanied with an issue of stop location on this corridor. Since bus stops are usually located near signalized intersections (including stop number 4538, a nearside stop located east of SE 11th Ave.), after bus Trip 5 closed the door and left stop 4538, it reached a signalized intersection 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 an additional-recorded stop time between dwell time (1:33 min) that driver was waiting to keep up with the schedule and a total stop time (2:24 min) before the bus could continue moving downstream.

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. This 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 21.4 mi/h, while the average overall bus speed on the route was 16.9 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 where the pseudo bus traveled at its maximum speed between each pair of stops. This was based on the hypothesis that the maximum speed could approximately reflect the speeds of non-transit vehicles along the route.

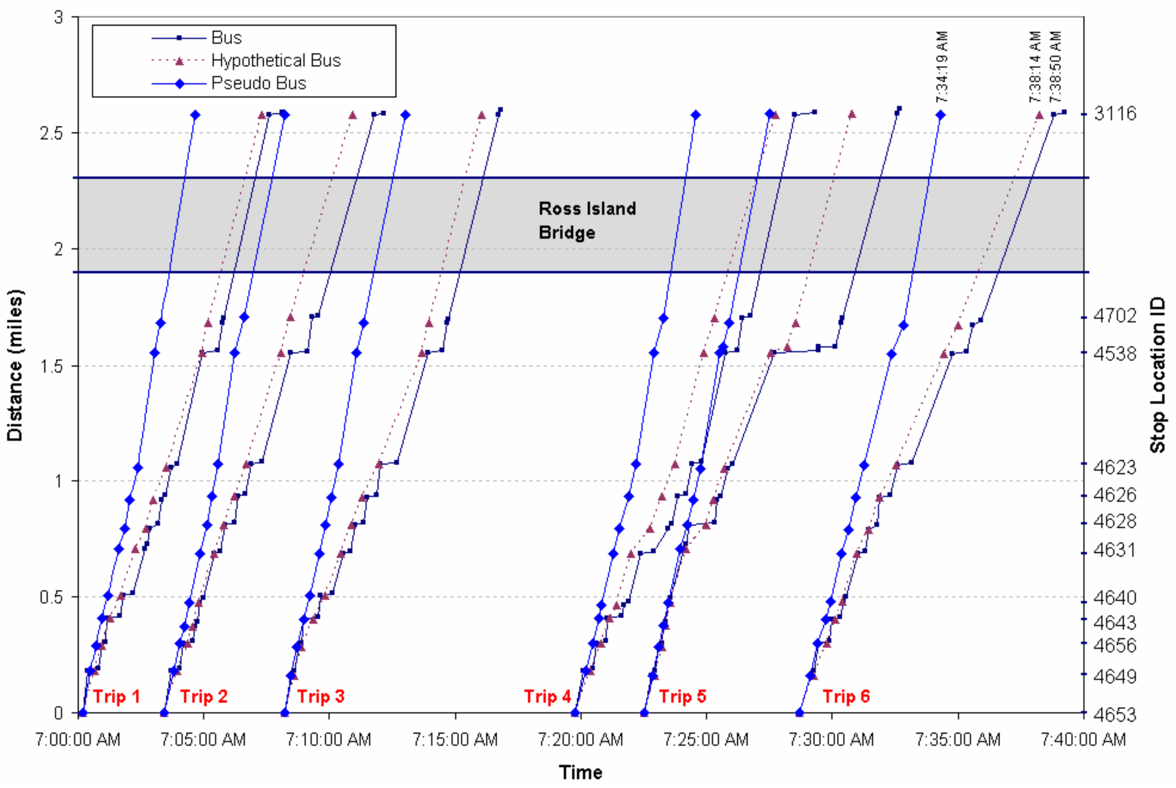

Figure 4. Comparison of actual buses and conceptual buses' trajectories

Figure 4 shows the combination of the bus trajectories with these two conceptual bus trajectories. As shown, the three trajectories began at the same departure time. For example, Bus Trip 1, Hypothetical Bus Trip 1 and Pseudo Bus Trip 1 began at 7:00:10 A.M. Pseudo bus trajectories reflect the shortest travel times; for example, Pseudo Bus Trip 4 finished its trip at 7:34:19 A.M., faster than Hypothetical Bus Trip 4 and Bus Trip 4 by 3:55 and 4:31 min respectively. The mean pseudo bus speed was 32.3 mi/h, twice the actual mean bus speed (16.9 km/h) and the mean hypothetical buses speed was 20.1 mi/h, about 1.3 times the mean actual bus speed. Since both the hypothetical and pseudo buses were created to reflect potential non-transit travel, pseudo buses maintain 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.

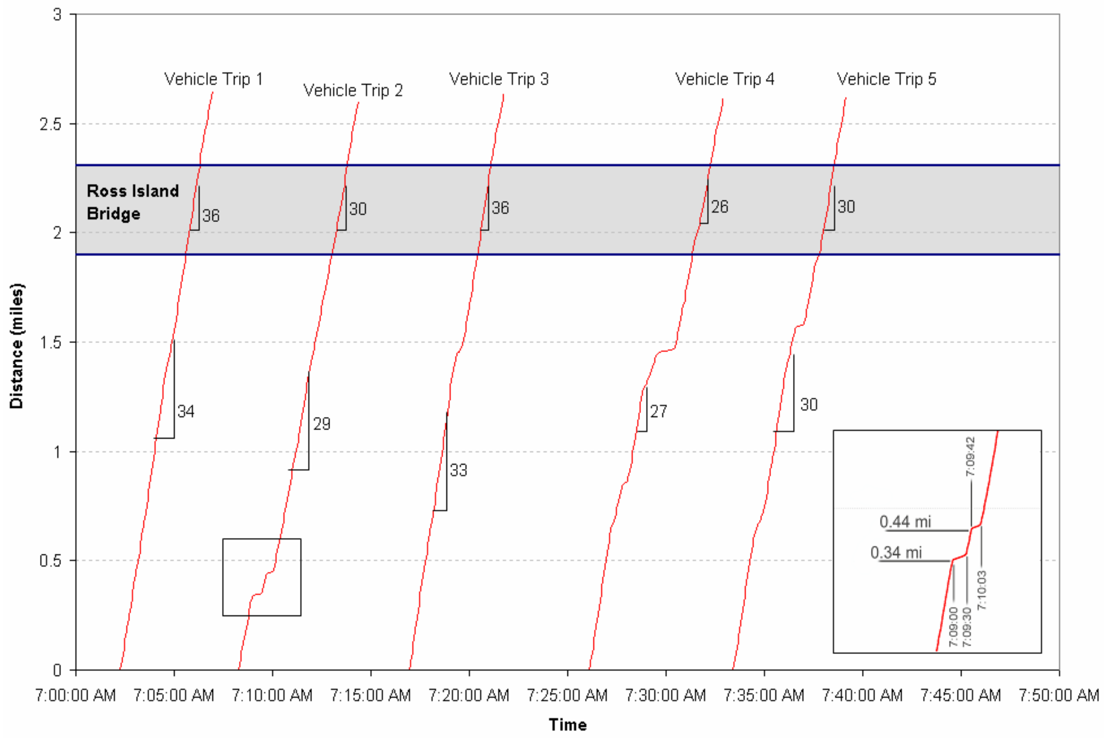

Figure 5. Test vehicle trajectories

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 as shown in Figure 5. The mean test vehicle corridor speed was 27.2 mi/h, ranging between 20.7 mi/h and 33.8 mi/h. The mean test vehicle travel time was 5:57 min, varying between 4:39 and 7:33 min.

Figure 6. Geo-coded vehicle locations

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 Trip 2 shows that the test vehicle decelerated at distance 0.34 mi, stopped for a short period, and then accelerated to the vehicle's desired speed of 22.6 mi/h. The inset in Figure 5 also shows that at distance 0.44 mi at 7:09:42 A.M., Vehicle 2 decelerated, traveled at 1.9 mi/h before accelerating to the previous speed at distance 0.46 km mi at 7:10:03 A.M. This was observed where the vehicle arrived at a signalized intersection. As shown in Figure 6, at 7:09:00 AM, the test vehicle arrived at a signalized intersection between Powell Blvd. and SE 33rd Ave. at the end of queue. The vehicle waited and then accelerated at 7:09:30 AM when the queue diminished after the signal phase turned green. This behavior was repeated again at the next signalized intersection between Powell Blvd. and SE 31st Ave. Test vehicle decelerations occurred at slightly different locations, since each vehicle reached the end of the queue formed at that intersection (a different queue length resulted in a slight difference in location). Refering back to Figure 6, the mean test vehicle speed on the bridge was 31 mi/h, varying between 22.6 and 42.4 mi/h. This was higher than the average route speed by almost 4 mi/h. Together with the observation of transit speeds on the bridge explained in previous section, this confirms that traffic conditions on the bridge were better than the overall conditions along the route.

SAMPLE SIZE ANALYSIS

For a travel time study, a minimum sample size is desired to minimize the data collection cost in order the fit with the budgetary constraints. However, output from this sample size determination is also a valuable resource to statistically ensure the level of confidence and reliability of such data. Therefore, it is important to execute a number of travel time collection runs to determine a statistically permitted level of error from the sample size.

In general, the statistical estimation for the sample size n is based on specifying the probability statements about level of confidence that the error is most acceptable. The permitted error E is expressed as

$$E = Z_{\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}$$

Where n = minimum sample size
$Z_{\alpha/2}$ = standard normal curve area to its right equals $\alpha/2$ for a confidence level of $1 - \alpha$
σ = standard deviation of population
E = maximum error of the estimation

Often the estimation is done based on prior information or an initial sample which led to a random variable having a t-distribution with $n - 1$ degrees of freedom [11]. At the same level of confidence of $(1 - \alpha)100\%$, the new equation is written upon solving for n as

$$n = \left[\frac{t_\alpha \cdot s}{E}\right]^2$$

Where s = estimate standard deviation of random samples
t_α = t distribution statistic (used instead of $Z_{\alpha/2}$ when dealing with random samples or small sample size) [12]
E = maximum error of the estimation

For this study, both bus data and test vehicle data were used in determining the minimum number of runs:

Bus mean speed = 16.9 mi/h
Standard Deviation = 4.66 mi/h
$\alpha = 0.05$ (corresponds to 95% level of confidence)
E = ± 3 mi/h
Number of bus data = 19 runs
Since the statistic t_α is a function of n, an iterative procedure is needed to solve for n.
As a result, $n \approx 12$ runs.

Test vehicle mean speed = 27.15 mi/h
Standard Deviation = 2.49 mi/h
$\alpha = 0.05$ (corresponds to 95% level of confidence)
E = ± 3 mi/h
Number of test vehicle data = 14 runs
With the same iterative procedure, n was estimated to be ≈ 7 runs

This ensures that the availability of data exceed the minimum level of confidence of 95%.

COMPARISON

Westbound bus run times were estimated using the difference between leave time from the first stop (stop 4653) and the arrive time at the last stop (stop 3116) on the corridor. Test vehicle travel times were estimated by subtracting the time recorded at the end of the route from the time at the beginning. Both include the time when the vehicles stopped due to traffic control and congestion, e.g., at the end of the queues at signalized intersections.

In order to use the bus data to represent actual traffic conditions, experiments using the bus data were conducted including the “pseudo” and “hypothetical” bus scenarios. 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. Figure 7 shows bus trajectories, corresponding hypothetical and pseudo trajectories and test vehicle trajectories for three trips. 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.

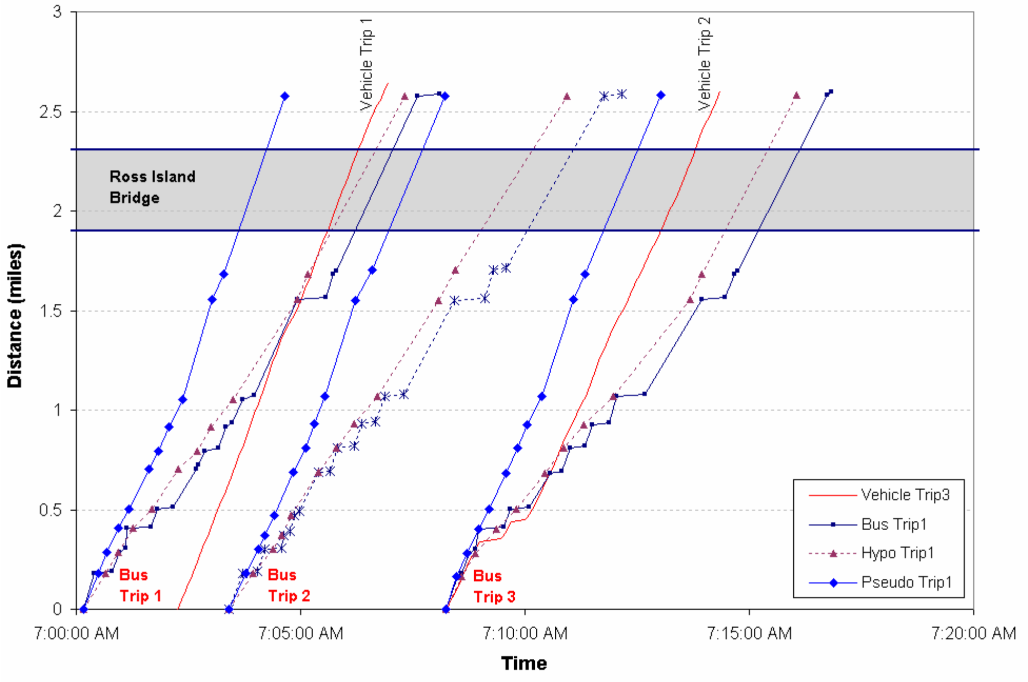

Figure 7. Comparison of test vehicles, actual buses and conceptual buses’ trajectories

To verify this, test vehicle and pseudo bus travel times and speeds were compared by departure time. Test vehicle and pseudo bus travel times were plotted versus departure time in Figure 8(a). Travel time trend lines 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 pseudo buses were also plotted against the departure time as shown in Figure 8(b). The speed scatter plots show that vehicles traveled at lower speeds during the morning peak period as well. Traffic conditions improved after the peak period as shown in Figure 8(b), at 9:30 A.M. Test vehicles were traveling at approximately 33 mi/h. The mean travel times for all four scenarios are also shown in Figure 9.

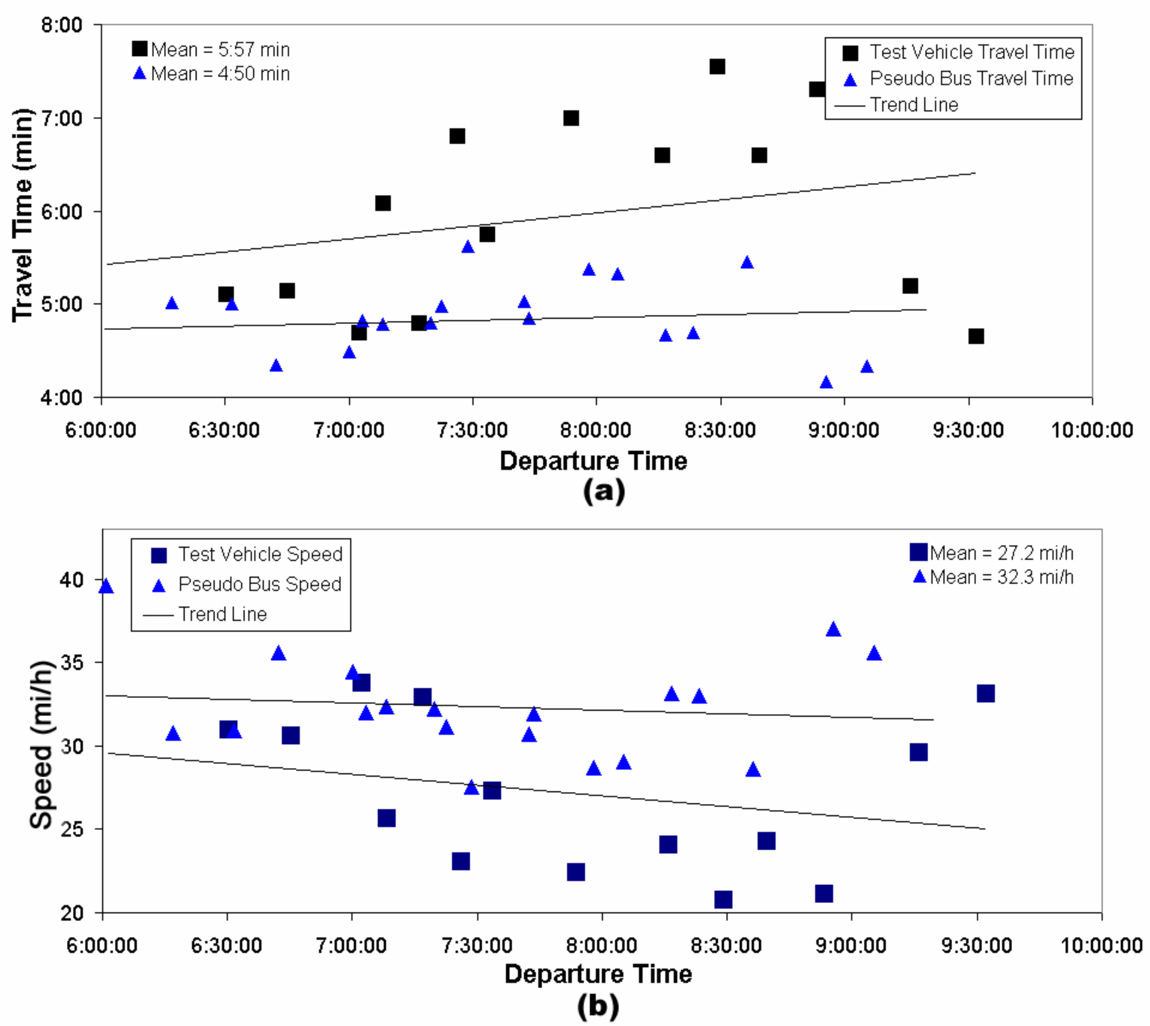

Figure 8. (a) Travel time and (b) speed of the test vehicle and pseudo bus versus the departure times

The relationship between travel time and speed of the test vehicles and the three bus scenarios was analyzed. It was determined that the mean test vehicle corridor travel time was 1.23 times the pseudo bus travel time. However, the test vehicle and pseudo bus travel times were found to be closer on the bridge. As shown in Figure 9, test vehicle mean travel time was lower than pseudo bus mean travel time on the bridge while it was higher than the pseudo bus when compared their mean corridor travel time. This supports the conclusion stated earlier that the traffic conditions on the bridge were nearly free flow that allowed test vehicle to achieve higher speeds than the buses.

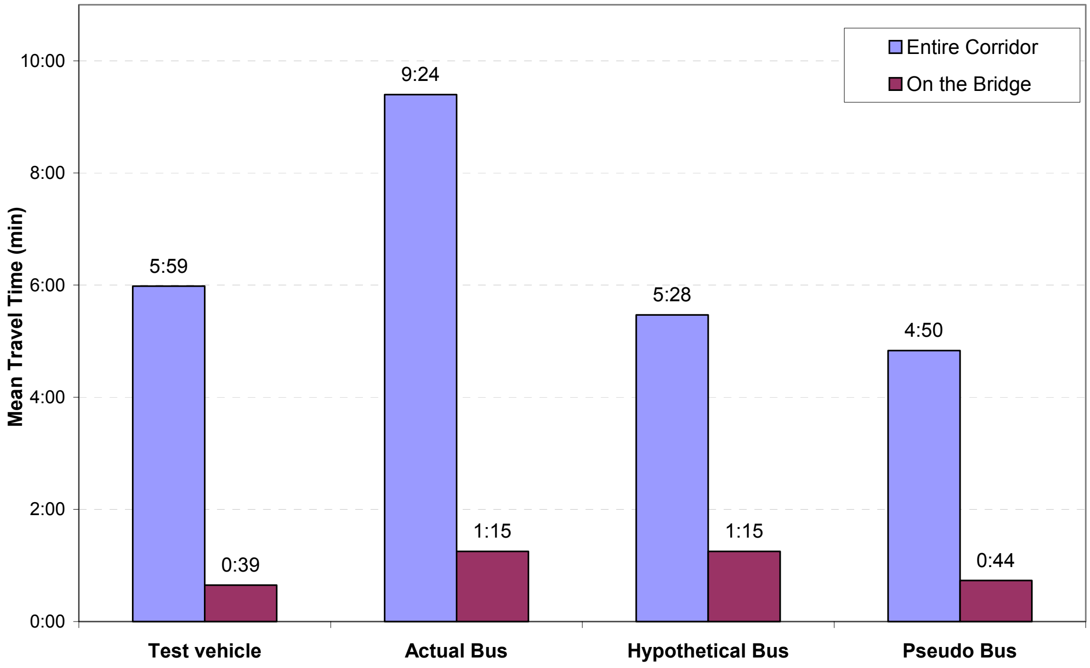

Figure 9. Mean travel time of the four scenario both entire corridor and on the bridge.

	Actual Bus	Hypothetical Bus	Pseudo Bus
Corridor Speed	1.63	1.35	0.84
Bridge Speed	1.45	1.45	0.90

Table 1 – Average Ratio of Test Vehicles Speeds Compared to Other Types

Corridor speeds were derived by dividing the total travel distance, approximately 2.5 mi, by the net travel time. Figure 8(b) shows the comparison between test vehicles speeds and pseudo bus speeds. As shown in Table 1, the test vehicle speed was 0.84 and 0.90 times the pseudo bus speed for the entire corridor and on the bridge respectively. Figure 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 scattered close to one other and their trend lines were close and partially overlapping.

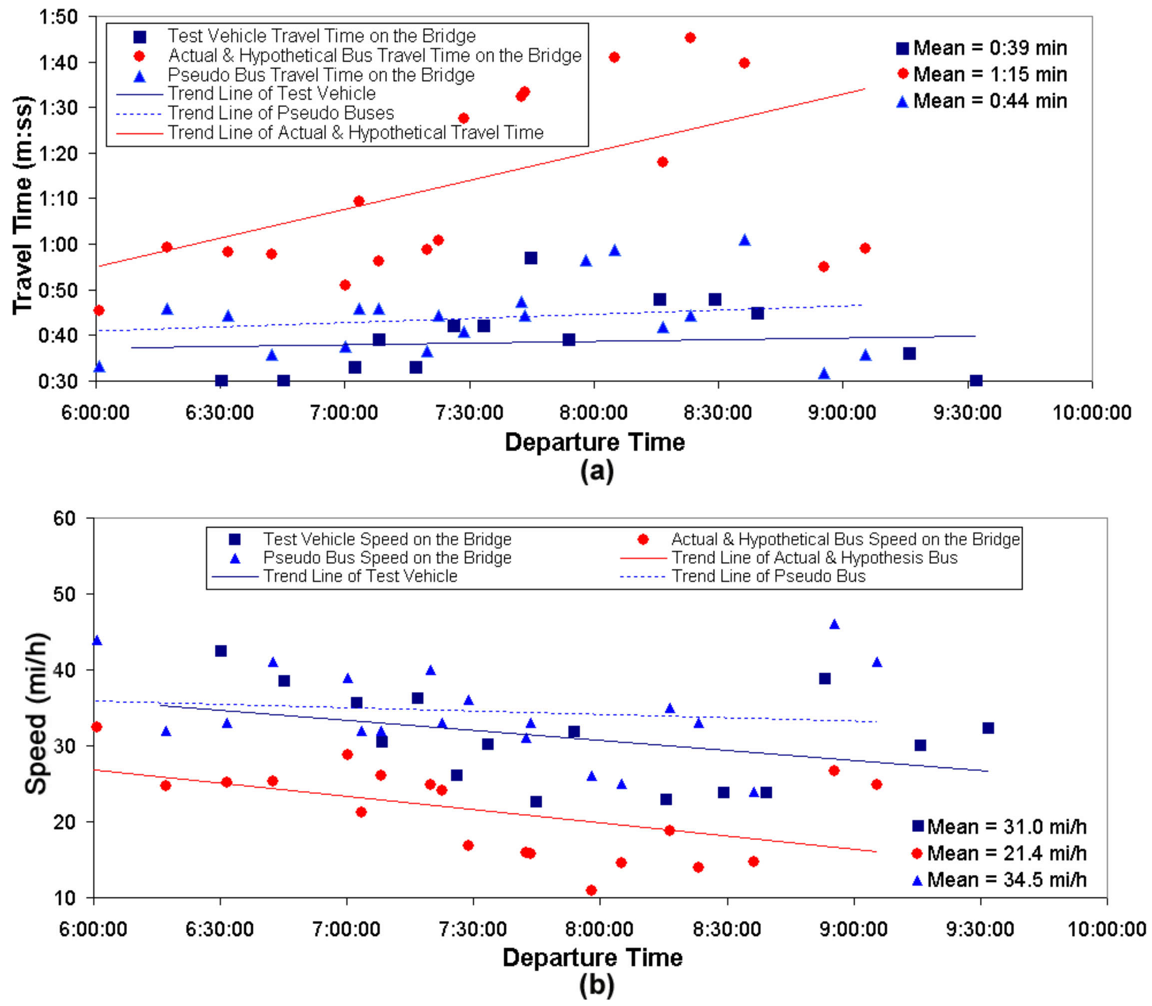

Figure 10. Test vehicles, actual bus, hypothetical bus and pseudo bus comparison on (a) travel time on the bridge and (b) speed on the bridge

Average U.S. bus travel times were reported as 4.2 min/mi in suburbs, 6.0 min/mi in the city, and 11.5 min/mi in the central business district [14]. Fig. 9 shows a mean travel time of 9:24 min, or 3.8 min/mi, faster than the national study. Table 1 also shows a comparison of test vehicle and bus speeds, showing that test vehicle speeds were 1.63 times greater. The national average shows that vehicles usually travel 1.4 to 1.6 times faster than buses [14], and the U.S. Department of Transportation reports an average bus speed of 10 mi/h in the city and 14.3 mi/h in the suburbs [15].

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

Figure 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" [16].

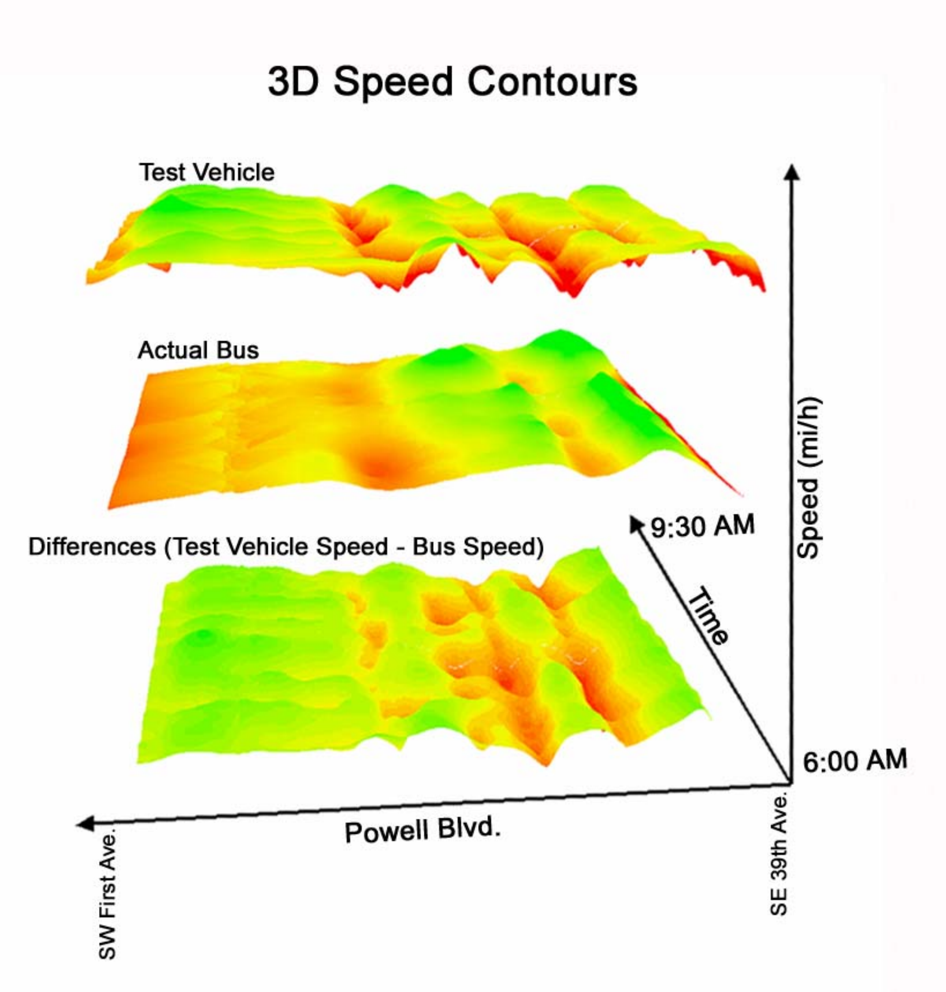

Figure 11. Speed contour plot

The speed contour diagram shows that the test vehicle speed changed smoothly on the surface due to the availability of 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. By viewing the differences between the two speed surfaces, one can locate specific locations and times that the test vehicles experienced conditions that were different from those experienced by the buses.

CONCLUSION

From this preliminary study, it is shown that there is a possibility to explain actual arterial traffic conditions using transit vehicle AVL information. From the set of transit data used herein, the bus movement 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 speed should also be described using the relationship established between the test vehicle and the pseudo bus. This study found that the test vehicle travel time was 1.23 times the pseudo bus travel time. Conversely, it was shown that the test vehicle speed was 0.84 times the maximum instantaneous speed achieved by the buses. 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 greater 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.

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