Using Signal System Data and Buses as Probe Vehicles to Define the Congested Regime on Arterials

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ABSTRACT
Currently, many municipalities offer information about current conditions on local freeway facilities via the Internet or some other media. However, as important as freeways may be for many travelers, it is clearly desirable to collect and disseminate traveler information about arterials since nearly forty percent of the nation’s vehicle miles traveled (VMT) occur on the arterial roadway network. Surveillance using loop detectors (or other point-based data collection systems) associated with traffic signals can be one way to develop an arterial monitoring system. In addition, with the prevalence of transit buses operating on arterials, and the development of more advanced bus dispatch systems that include global positioning systems and real-time communications capabilities, attention is turning to the possible use of buses as probe vehicles along arterials. This paper describes research to extract arterial performance measures combining both traffic signal system detectors and from buses acting as probe vehicles using a case-study approach in the Portland, Oregon metropolitan region. Graphical techniques are developed for constructing the shape of the congested regime in time and space along a key arterial corridor. The paper includes recommendations for expanding the techniques to other corridors, the use of higher resolution, real-time transit AVL data, and on-line implementation of an arterial travel time information system.

INTRODUCTION
Currently, many municipalities offer information about current conditions on local freeway facilities via the Internet or some other media. However, as important as freeways may be for many travelers, it is clearly desirable to collect and disseminate traveler information about arterials since nearly forty percent of the nation’s vehicle miles traveled (VMT) occur on the arterial roadway network. Travelers would benefit by gaining information about the current traffic conditions on all facilities so that potential alternate routes (particularly for short trips) could be evaluated. If performance of arterials were measured over time, transportation managers and operators would better be able to evaluate the effectiveness of signal timing plans and other operational improvements. In the long run, planning agencies would be able to better monitor the arterial network and understand the effects of changing land uses. However, estimation of travel time or performance on interrupted flow facilities is more challenging than uninterrupted flow facilities such as freeways. Travel time along an arterial essentially includes two distinct components: the travel time along links between the influence areas of traffic signals and the travel time through the signalized intersection itself. The traffic flow between signals (nodes) generally behaves like an uninterrupted flow facility and methods to extrapolate measured speed at a point (from system loop detectors) to estimate link travel time would likely produce results comparable to freeway experience. Estimating travel times through the signals (nodes) requires detailed knowledge about queues and signal settings. Accordingly, an increasing amount of research has been directed toward improving techniques to monitor arterial performance (1-11). Several authors have proposed methods for estimating travel time that take into account these two components of travel on signalized arterials. Such research has either attempted to measure each component directly (3-5) or used traffic flow theory to model relationships between traffic flow and signal control settings (6,7). Skabardonis and Geroliminis (9) have formulated a model that addresses the problem of collecting data by predicting travel time on corridors based on count and occupancy data from signal loop detectors, green times, cycle lengths, and offsets for the signals in the corridor. The use of high resolution data (i.e. individual vehicle activations) for performance measurement at isolated signals was explored in (10) and the effect of blending these data with more dynamic information about signal timing was explored by Liu and Ma (11). While promising approaches, high resolution data are not available from most signal systems.

There are other methods to measure link travel times such as license plate matching, transponder matching, and cell phone tracking. In addition, there have been efforts to use buses as probe vehicles to aid in providing real time condition monitoring and travel time estimates along arterials (12-14). Transit providers are increasingly equipping their bus fleets with automatic vehicle location (AVL) technology. Global positioning systems (GPS) units located onboard enable the buses to be smart—“knowing” information such as their exact location, their schedule, whether they are late or early and how many passengers they are serving, among other important performance parameters. If made available in real-time, these data could potentially be extrapolated to provide a snapshot of arterial speed conditions as shown in Figure 1. This figure was generated using archived speed data from five bus routes in Portland, Oregon as a sample. However, there are clear limitations to using buses for the purpose of predicting passenger vehicle travel times. Buses lose time when they stop to serve passengers, including time spent accelerating and decelerating. Furthermore, even when not stopping to load and unload passengers, a bus is larger with different performance characteristics and thus generally travels slower than a passenger vehicle. Because of these factors, buses can also tend to lose the ability to take advantage of traffic signal timing progression.
strategies on arterials. Finally, the frequency of information provided by buses is dependent on bus headway which may be insufficient for providing up-to-date traveler information.

Though both buses and signal system data sources suffer from being insufficient separately, it is possible that together they can be used to provide a more complete and accurate picture of the conditions on the arterial roadway system. Therefore, the objective of this paper is to examine the potential of using bus AVL data to improve arterial condition monitoring that is better than can be achieved using signal system loop detector data alone; ultimately the techniques developed here could be extended to real-time traffic management and traffic information applications. The paper first describes the data available for the corridor then presents a prototype graphical exploration of combining these data sources. Next, a more automated method is described based on results of the prototype exploration. A summary and recommendations for future work conclude the paper.

STUDY AREA AND DATA

To explore the feasibility of combining signal system data with bus AVL data to improve estimates of arterial performance, a case study corridor was selected. A 4.5-mile section of the four-lane arterial Barbur Blvd. between Sheridan Street and the Barbur Blvd. Transit Center (a regional park & ride facility) was chosen. A schematic of the corridor (including the locations of signalized intersections) is shown in Figure 2. Data were collected from both the signal and bus systems for the week of February 12, 2007. These data are described in the following sections.
FIGURE 2 Map and schematic of Barbur Blvd.

Signal System Detector Data

The corridor is equipped with five detector stations configured as system detectors (count stations) in the City of Portland’s central signal system. The detectors are located between 100 and 780 feet upstream of each traffic signal stop bar. Each count station recorded average values for its constituent detectors, as well as data for the detector that saw the most activity for a given 5 minute period (the “critical” detector as determined by the TransCore central software). The arterial signal system detector data was collected for the one week period from February 12–20, 2007. Critical lane, critical volume, critical occupancy, critical stops, critical speed, total volume, average occupancy, total stops, and average speed were collected for each 5 minute period over the 7 day sample. Note that occupancy in this context refers to the percentage of time that the sensor detects a vehicle. While it would be desirable to have high-resolution vehicle actuation data (or even measurements on a cycle-by-cycle basis with cycle status) due to data management and communications issues 5-minute intervals is the highest resolution available.

Archived Bus AVL Data

In addition to several other routes, TriMet’s Route 12 travels along Barbur Blvd. (see Figure 2). TriMet has AVL equipment installed on all of its buses and has an extensive bus dispatch system (BDS) which collects performance metrics about each vehicle’s daily activities. At each bus stop (whether the vehicle stops or not) or when a bus opens its doors, the BDS records 26 data elements. The information recorded by the bus includes the time it arrived at the stop, the time it departed the stop, the number of passengers that boarded and alighted, and how long the door was open (15,16). Finally, the bus records a maximum speed, which is the maximum speed that the bus attained in the interval between the current entry and the previous one. As part of earlier research, a statistically valid relationship (model) linking the bus trajectory data to passenger vehicle speeds and travel times along one particular corridor. (14). As an extension of that earlier work, this research creates bus vehicle trajectories by plotting the location of the bus at consecutive time points (on average, less than 0.25 miles apart). In this study, the TriMet stop-level AVL data was collected for the same days as the signal system data.

ANALYSIS

In order to characterize traffic flow dynamics on northbound Barbur Blvd. during the study period, Route 12 bus travel times were analyzed for the 4.5-mile corridor. Figure 3 shows individual trip times in minutes arranged by
departure time for the entire week. It is clear from this figure that travel times fall in the 12 to 16 minute range, with shorter travel times in the early morning and late evening periods. Most important for the purposes of this study are the two spikes in travel times that are found during the 7:00 to 9:00 am morning peak and the 4:00 to 6:00 pm afternoon peak period. Travel time estimation and condition reporting during free flow conditions is important but relatively trivial if conditions are homogeneous. Because estimating travel times is most difficult and also most necessary during transitions to and from congested periods, it was important to identify the congested periods that occurred during this week.

![Travel Time Per Bus Run](image)

**FIGURE 3** Bus travel time by time of day for week of February 12, 2007.

Given that the system detector and bus AVL data are available for simultaneous days and locations, it is possible to reconstruct a “map” of traffic conditions by producing a color contour plot of speed as measured by the detectors, overlaid with trajectories of the buses as constructed from the archived AVL data. Using a time-space plane, a trajectory is a convenient way to view any vehicle’s progress over time and space, such that the slope of the trajectory is the speed at any point. Figure 4 shows a preliminary analysis for viewing the bus and loop detector data on a combined time-space plane, where the x-axis is time and the y-axis is the distance along Barbur Blvd. The detector location names are labeled on the left-hand y-axis and mileposts are labeled along the right-hand y-axis. As shown in the figure, the loop detector measurements are color coded to indicate levels of congestion. Green is free flow conditions (0-7.5% occupancy), while yellow (7.5-22.5%), red (22.5-45%), and black (45-100%) represent increasing levels of congestion. The selection of these thresholds was made based on an analysis of speed, flow and occupancy data along the corridor. A sample of these data is shown in Figure 5 for the northbound approach of one intersection. The overall shape of the relationship between flow and density is a truncated version of the expected “wedge” shape, due to the influence of the downstream traffic signal. Nonetheless, several distinct stages are apparent. Free-flow conditions break down at around 7-10% occupancy. Peak flow is appears to be reached at around 23% occupancy. And after remaining constant from 23-50%, flow begins to decline at occupancies above around 50% (though data is understandably sparse for regimes above 35% occupancy; more data should be collected to robustly model the precise shape of the curve.) These occupancy values are typical for the system detectors in the corridor. Also in Figure 4, the bus trajectories are added to the loop detector readings, with each point on the trajectory indicating the time that the bus passed (or served) a particular stop. Each point on the bus trajectory is also color-coded, where the color of the circle indicates the maximum speed achieved on the previous segment. As a first exploratory step toward combining the two sources of data, it does appear that the slower bus speeds (which in this case appear in red) do appear more frequently in the sections where the detectors indicate congestion. Further refinements on this concept will now be described.
Buses as Probes

Past research has investigated the prospect of using data from buses to generate travel time estimates for passenger vehicles (12-14). In one comprehensive case study using data from a Portland arterial, several statistically valid methods were explored in depth for generating travel time estimates using AVL data from TriMet buses (14). Several algorithms for computing arterial travel time from the AVL data were compared with actual probe vehicle (non-bus) travel times along Powell Blvd. The first method tested was one where the dwell time was “subtracted” from the trajectories, in order to reduce the travel time by the total amount of time that the bus is stopped serving passengers. Since TriMet’s measurement of dwell time is from the time the door opens until the time the door closes, this method cannot account for the lost time due to deceleration and acceleration. Another method tested in (14) was a “max speed” method, which used the maximum speed achieved by the bus between stops (this value is recorded in the TriMet database). As a proxy for knowing the speed of other adjacent vehicular traffic, this method extrapolates the bus’ maximum speed over the entire segment between two stops in order to estimate the vehicular travel time for each segment. These estimates are summed to create a travel time estimate for the travel area in question. This method effectively excludes stops as well as time lost accelerating and decelerating. Because
passenger cars do stop, accelerate, and decelerate as a part of normal travel, this method underestimates travel times. However, of all the methods considered in (14), the maximum speed model was confirmed to most reliably approximate actual vehicle travel times, which were found to be 125% of the travel times determined using the maximum segment speed. A statistically valid model for arterial speed and travel time was developed using this relation. Since ground truth data are not available we are using the AVL data, in particular the “max speed” method as our ground truth for this project.

Signal System Measurements

Turning now to the signal system data, Figure 6 illustrates the challenges inherent in using these data for estimating arterial travel times over a sample two-hour period on February 15, 2007. On this time-space diagram, the 12 vertical lines indicate the five minute intervals at which the detectors report congestion information. The names of the five loop detector locations are indicated on the y-axis. Each square represents a loop detector data point. There is one data point per detector at each five minute interval. The squares each have a color associated with them, a fact that is obscured because the measurements and associated colors are then interpolated over a much larger region in the time-space plane. Each detector speed measurement is extrapolated in time over the subsequent five-minute interval, and in space halfway to the upstream detector and halfway to the downstream detector (referred to as the midpoint method). Green sections indicate periods with free-flow conditions (0–7.5% occupancy), yellow represents higher occupancies and slower speeds (7.5–22.5% occupancy), followed by red for congested (22.5–45% occupancy). Black would be very congested (> 45% occupancy).

FIGURE 6 Time space diagram showing bus trajectories and occupancy values on Barbur Blvd.

Clearly, interpolating the measured occupancy at each signalized intersection to represent link conditions will not accurately represent actual travel conditions. For example, when the Bertha detectors indicate congested conditions, where does the congestion actually begin, how far does it propagate, and how long does it last? This question has important implications for condition monitoring and travel time estimation. For example, using the mid-point method, congested conditions are reported between mileposts 1 and 3. If in reality the congested conditions are only present over a ½-mile segment (rather than the entire 2-mile segment), the conditions would be misreported, and travel time estimates would be substantially over-predicted. An analogous situation would occur which would be more troublesome for travel time information if the congested regime is underestimated, resulting in an under-prediction of travel times.

Using Archived Bus Data to Define the Congested Regime

The question of determining the shape of the congestion regime around each signal is an instance where the bus AVL data can inform and improve the condition and travel time estimates. The dashed lines on Figure 6 are the actual bus trajectories for the same day and time period. Further inspection of the figure reveals that it is clear from
the slope of the trajectories that the buses are all experiencing a speed reduction inside the congested regime (red) in the figure. It is also clear, however, that the duration of the bus speed reduction does not match the interpolated conditions derived from the detector-based mid-point method.

In an initial prototype effort to improve the defined areas of congestion, manual adjustments are made to the time and space boundaries generated by the signal system data to accurately represent travel conditions. Figure 7A reveals the use of actual bus trajectories to improve the estimate of the shape of the congested regime as measured by signal system detectors and extrapolated using the midpoint method. In the figure, the interpolation of the conditions measured by the Bertha detectors has been adjusted manually to match the congested interval revealed by the bus trajectories. In this figure, the red section indicating congestion corresponds more closely with the flatter (slower) portions of the bus trajectories and the hinge points on the trajectories where the bus speeds change notably match more closely with the edges of the congested regime shown in the figure.

While this represents an improvement in defining the shape of the congestion regime around the two Bertha signals, Figure 7B illustrates how we are now left with large segments of the arterial for which loop detector readings will not provide accurate measures of travel conditions. This is another instance in which the bus AVL data can provide a more accurate picture. Figure 7C adds the maximum speed information for each stop along the bus trajectories. For each 5 minute interval indicated by the vertical lines, we can use the bus data to locate the last bus that passed through each unknown segment and use the maximum speed data to fill in the color contour plot, as is done in Figure 7D. While there are several maximum speed readings on each trajectory within these segments, it makes the most sense to select the highest value, which eliminates distortions resulting from low speeds associated with unusual bus operations (such as a bus traveling a short distance before stopping to accommodate a passenger that forgot to get off at the previous stop). To ensure this, our algorithm only locates buses that have traveled a sufficient distance into the unknown segment, which avoids a bus trajectory with only one or two maximum speed data points from being interpolated over a fifteen minute interval, which is the approximate headway of buses along this route.

Finally, Figure 7D thus represents a color contour plot based upon both AVL bus and system signal loop detector data. The congestion regime around the Bertha signals was redefined based upon the shape of the bus trajectories and maximum speed bus readings were used to define the segments where loop detector data would not provide a meaningful representation of traffic conditions.

B. Identification of segments of the study area where loop detector readings do provide useful information.

C. Maximum speed readings from buses represent a complimentary source of data.

D. A color contour plot derived from a combination of signal system and archived AVL bus data.

FIGURE 7 A set of contour plots illustrating the method for combining bus and signal data.
Creating an Algorithm for Identifying the Shape of Congestion from Archived Bus Data

While the congestion regime around the Bertha signals was redefined manually by comparing the bus trajectories with the interpolated color contour plot derived from loop detectors, it would be useful to develop an algorithm that could identify the shape of congestion based upon the bus trajectories automatically. Figure 8 illustrates the results of an algorithm developed for this purpose. The difficulty with using bus data to identify traffic conditions is that, as mentioned earlier, buses behave differently than passenger vehicles. The flatter slopes of a bus trajectory, such as the ones highlighted in this analysis to identify the shape of the congestion regime, can indicate congestion, but can also result from stopping to serve passengers, a layover, or even from a bus waiting at a stop to avoid operating ahead of schedule. In order to distinguish “bus” behavior from actual congestion, we developed an algorithm that counts each time a trajectory between two bus stops indicates slower conditions.

We began by flagging each record in which two segments in a row had a slope of less than 10 miles per hour. For any two segments we would be flagging three data points: the stops at either end as well as the stop in the middle. Finally, we aggregated these flagged records by stop location in order to identify the stops that were most frequently part of a segment of slower conditions. The idea is that while “bus” type behavior can be expected to occur somewhat randomly along the route, a congested regime will express itself in the bus data more regularly.

In Figure 8, the stop locations that were most frequently a part of a bus trajectory of less than 10 miles per hour are surrounded by a blue diamond. As can be clearly seen, this algorithm correctly identifies the congestion interval around the Barbur signals. It also identifies a stop between mileposts 0 and 1. This stop was identified on all of the days that we analyzed, which suggests that there may be a congested regime in between signals. This highlights another potential application of the bus data. By identifying congested regimes that are not at signalized intersections, the bus data could be used to help a city strategically place loop detectors to more accurately measure and diagnose arterial conditions.

We performed this analysis on a day-by-day basis, highlighting those stops that experienced slower conditions on at least 15% of the daily runs. With more data in ongoing research, it would be useful to perform a separate analysis of peak hour and off-peak conditions. As the next section suggests, it is likely that different methods will need to be employed to describe peak and off-peak arterial conditions.

![Algorithm identifies congested areas, confirming the manual adjustment of the congestion regime around the Bertha signals](image)
Comparison of Travel Time Estimates by Methods

Using the signal system measurements directly to calculate travel time estimates is a reasonably reliable method during periods of free flow conditions. Figure 9A shows hypothetical vehicle (non-bus) travel time estimates calculated from the signal system data (blue) as well as estimates based on the maximum speed method (green), which we will use as a proxy for passenger vehicles. Figure 9A shows travel time estimates between 12:00-7:00 pm. It is clear from the figure that using estimates based on extrapolating point-based speed measurements does not correspond well with the bus probe measurements, particularly during the congested period which results in significant overprediction. The reason for this relates back to our findings shown in Figure 6. The detector travel time estimates are based on the midpoint method and as a result, the very slow speed estimates reported by the sensors at Bertha are being extrapolated over the 2 mile segment between mileposts 1 and 3.

Figure 9B illustrates revised loop detector travel estimates that make use of the bus data to redefine the congested regime around the Barbur signals as well as employing the maximum speed from the bus data for estimating the unknown intervals. As can be seen in the figure, the peak hour travel time predictions are greatly improved. Here we benefit from the previously developed statistical relation showing that the vehicular travel times are 125% of the travel times estimated using the maximum speed method. The relationship is not as perfect during the earlier off-peak periods. It is also possible that a different model will be needed for peak and off-peak conditions. While this paper has developed a theoretical model for using signal system data in conjunction with bus data to evaluate arterial performance, refinement of the model is needed before precise travel time estimations can be made. This is planned as part of ongoing research.

FIGURE 9 Comparison of travel time estimates from unrefined and refined methods

SUMMARY AND NEXT STEPS

Using graphical tools, statistically valid algorithms, and a rich source of archived data from two sources, this paper has demonstrated the potential for using bus AVL data to construct the shape of the congested regime on an arterial street. It has been shown that it is possible compare the evolution of bus trajectories over an arterial segment with hypothetical trajectories generated from loop detector data. An algorithm for identifying congestion intervals has also been demonstrated.

This analysis has focused on the uses of archived TriMet AVL data. However, AVL data is also available in real time. We have recently begun working with data from C-TRAN, the transit provider for Clark County, Washington (part of the Portland-Vancouver metropolitan region). C-TRAN has installed AVL system more recently than TriMet, and C-TRAN buses report their position back to central dispatch every 10 seconds. TriMet’s communication interval is closer to a 60–90 second timeframe. One of the next extensions of the analysis presented in this paper will be the use of real-time bus data to identify the time-space dimensions of congested regimes on key regional arterials. While the loop detectors used in this study only provide data every five minutes, a bus that passes through the
arterial corridor at a relatively high speed could signal that the congestion has ended minutes before the next
detector measurement. A threshold speed could be set, and once a bus reports passing through the arterial exceeds
this speed, the travel time estimates can be adjusted accordingly to indicate shorter travel times.

Combining bus and signal data could have other uses as well. The City of Bellevue, Washington has
instituted a real time travel time map using an extensive network of loop detectors (8). Once installed, traffic
engineers spent time viewing live video footage of the roadway and comparing it with the loop detector
measurements. In this way, they gradually were able to calibrate their algorithms to accurately represent the current
traffic conditions. Similarly, a city without sufficient loop detectors but with a network of buses could perform an
analysis similar to that presented in this paper in order to calibrate a model for travel time estimation of its arterial
streets.

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