Using High-Resolution Bus GPS Data to Visualize and Identify Congestion Hot Spots in Urban Arterials

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Congestion and travel delay on urban roadways can influence the roadways' operating costs and service attractiveness. This research used high-resolution bus data to examine sources of delay on urban arterials. A set of tools was created to help visualize trends in bus behavior and movement; these tools allowed larger traffic trends to be visualized along urban corridors and streets. With buses as probes and examining aggregated bus behavior, contoured speed plots were used to understand the behavior of roadways outside the zone of influence of bus stops. Speed plots were used to discover trends and travel patterns with only a few days' data. Congestion and speed variation were viewed by time of day, and plots helped to indicate delays caused by intersections, crosswalks, or bus stops. This type of information is important to transit authorities looking to improve bus running times and reliability. Congested areas were detected and ranked. Speed plots were used to reevaluate bus stop locations (e.g., near side versus far side) and to identify locations where improvement are needed (e.g., queue jump lanes). Transportation agencies can also benefit from this type of information because arterial performance measures are difficult to estimate.

Arterial corridors are one of the most important elements of any transportation network. Despite their relative significance, however, arterial performance measures are relatively underdeveloped. While this situation results in part because arterials are difficult to monitor and analyze, it also results from nationwide focus being placed on the creation of performance measures, data collection efforts, and research developments for freeway operations. Arterials are difficult to study because of the number of intersections, both signalized and unsignalized, and their wide variability in composition. Given the number of interactions and factors affecting performance, intersections are often the weakest link in arterial performance and safety. Understanding where delays occur and which intersections are underperforming can improve transit service, increase overall ridership, and reduce passenger delay. Being able to recognize and understand where inefficiencies are occurring is the first step in solving arterial congestion problems, and having performance metrics that assess these conditions can be used by transit agencies and operators to identify these specific problem areas along urban arterials and then to implement solutions (*1*).

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Using data collected from buses in Portland, Oregon, this study—building on prior research—examined arterial traffic performance and used high-resolution bus data to examine portions of arterial roadways between bus stops. Examining this inter-bus-stop area is useful for understanding general traffic conditions on arterials and for identifying potential issues. Furthermore, using this high-resolution bus data provides the opportunity to explore the potential of using buses as probes to examine general traffic trends.

BACKGROUND

Traffic performance along arterials or corridors is a growing area of research in traffic operations, and it has been examined through sampling travel times, applying models of traffic flow theory, and looking directly at delays caused by signals (*2, 3*). Because of the importance of arterials, a growing body of research is dedicated to improving these techniques to understand performance better. Some research predicts travel times by using aggregated data from signal loop detectors, green times, cycle lengths, and offsets for the signals in a corridor (*4*). In addition, researchers have analyzed archived bus data to examine travel time delay, deviation, and coefficient of variation (*5–9*). Others studies have examined readily available bus data to understand whether they are a viable metric for arterial traffic performance.

Since 1997, the Tri-County Metropolitan Transportation District of Oregon (TriMet) has been archiving stop-level automatic vehicle location (AVL) and automatic passenger counts as part of their computer-aided dispatch system. Past research has included attempts to use these AVL bus data at the stop level alongside vehicle detector data to estimate trajectories and detect congestion (*10*). Researchers have also used these data to help study factors that affect bus travel time and service reliability at the point-segment level (*5, 11, 12*), the stop-to-stop segment level (*13*), and the route level (*14, 15*).

Only recently did researchers begin using high-resolution time and position bus data to estimate bus travel speeds between bus stops; categorize speed breakdowns; and identify signal delays, queuing delays, or both (*16*). Until the recent introduction of high-resolution data, researchers were mostly able to examine behavior at the bus stop level and stop-to-stop performance metrics on urban arterials. The introduction of higher-resolution data has removed much of the guesswork involved in understanding bus performance between bus stops and allowed for improvements in the application of using buses as probes to assess arterial traffic performance.

The use of buses as probes to estimate travel times has been attempted in the past but with coarser data (*17, 18*). In particular, TriMet buses have been used as probe vehicles to evaluate arterial

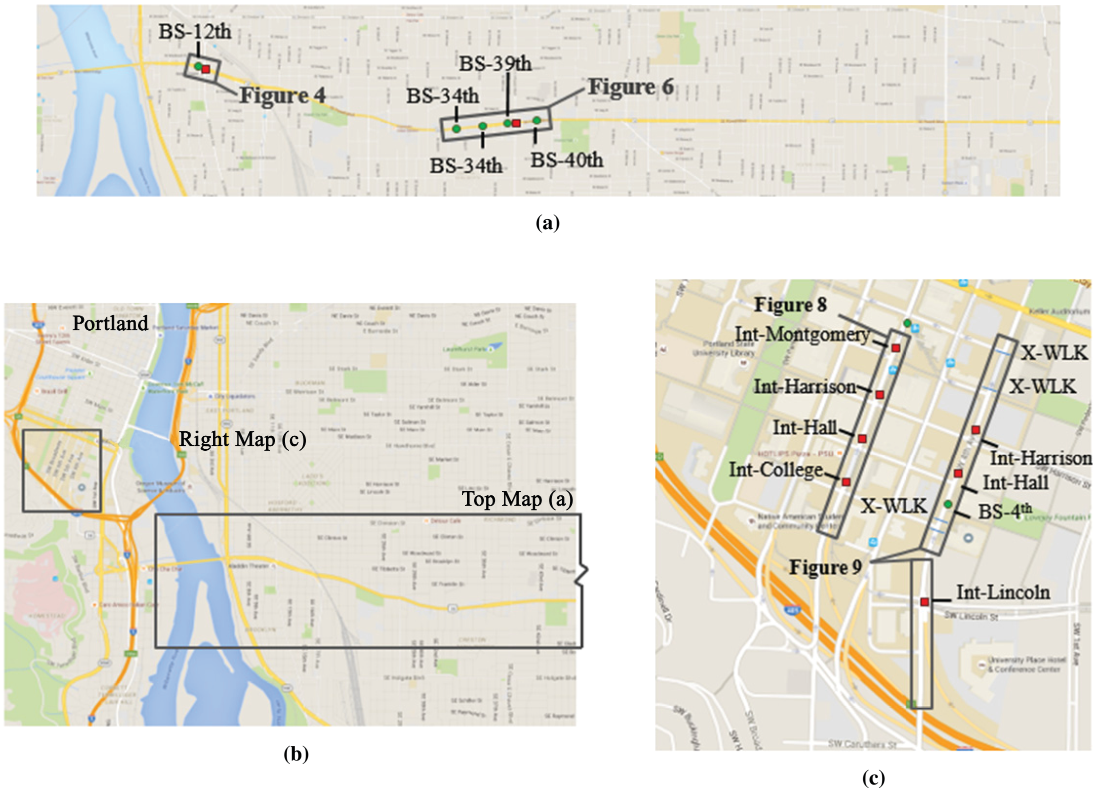


FIGURE 1 City of Portland: (*a*) map of Powell Boulevard, inset from (*b*) general map showing relationship between (*a*) and (*c*) inset of map of downtown Portland (BS = bus stop; int = intersection; X-wlk = cross walk).

and transit performance (*19–21*). However, these studies were confined to first-generation stop-level AVL data that had time records only for bus arrivals and departures from a bus stop.

Recent research projects have focused on the proposed study area, Southeast Powell Boulevard, to study the performance of an adaptive traffic signal system (*22*), the impact of transit signal priority on transit performance (*13*), air quality at bus stops (*23*), sidewalks at intersections (*24*), and sidewalks at midblock locations (*25*). In addition, recent papers have successfully integrated detailed signal timing and first-generation AVL data to estimate simultaneously the impact of traffic volumes and intersections on bus travel times (*1*) and have examined arterial travel speeds by using the newly available high-resolution bus data (*16*). This paper adds to the existing knowledge of arterial performance by illustrating tools that can be used to examine travel behavior and delay along urban streets and urban corridors and to show that high-resolution bus data provide helpful insights into arterial road performance. To do this, the authors proposed a simple method of visualizing high-resolution bus data to quickly identify congestion and potential problem areas along arterial roadways. This method combines both first-generation AVL data and high-resolution data. The sites of the different analyses are shown in Figure 1.

DATA

In late 2013, TriMet second-generation AVL data became available. The second-generation data have finer granularity at 5-s intervals [5-s resolution (5-SR)]: bus identification, position (meters), time, and other information are recorded (See Table 1).

These new AVL data were integrated with first-generation stop-level data to provide passenger boarding and alighting as well as arrival and departure data at bus stops. The AVL and stop-level data were merged by using bus identification, location, train mileage, and trip ID fields. The merged data made possible acquisition of information about the traffic conditions in which buses operate, passenger movements, and dwell times at bus stops. While the 5-SR data generally recorded time and location information every 5 s, often referred to as "bread crumbs," they failed to do so when (*a*) the bus was stopped or (*b*) the bus entered an administrator-defined area. For the latter case, the 5-SR data set did not contain records at a bus stop; the bus stop area or bus zone was usually 10 m upstream and

TABLE 1 Sample of 5-SR Data Set

Vehicle ID	Distance (m)[a]	Actual Time (s)[b]	GPS Latitude	GPS Longitude
2004	55,559	28,773	45.50291	122.42633
2004	55,579	28,778	45.50277	122.42618
2004	55,614	28,783	45.50247	122.42616
2004	55,655	28,788	45.50213	122.42595
2004	55,696	28,793	45.50174	122.42588
2004	55,741	28,798	45.50133	122.42591
2004	55,765	28,803	45.50109	122.42593

NOTE: Service date of November 1, 2014.
[a]Distance = total distance traveled by vehicle.
[b]Actual time = number of seconds after midnight on given day.

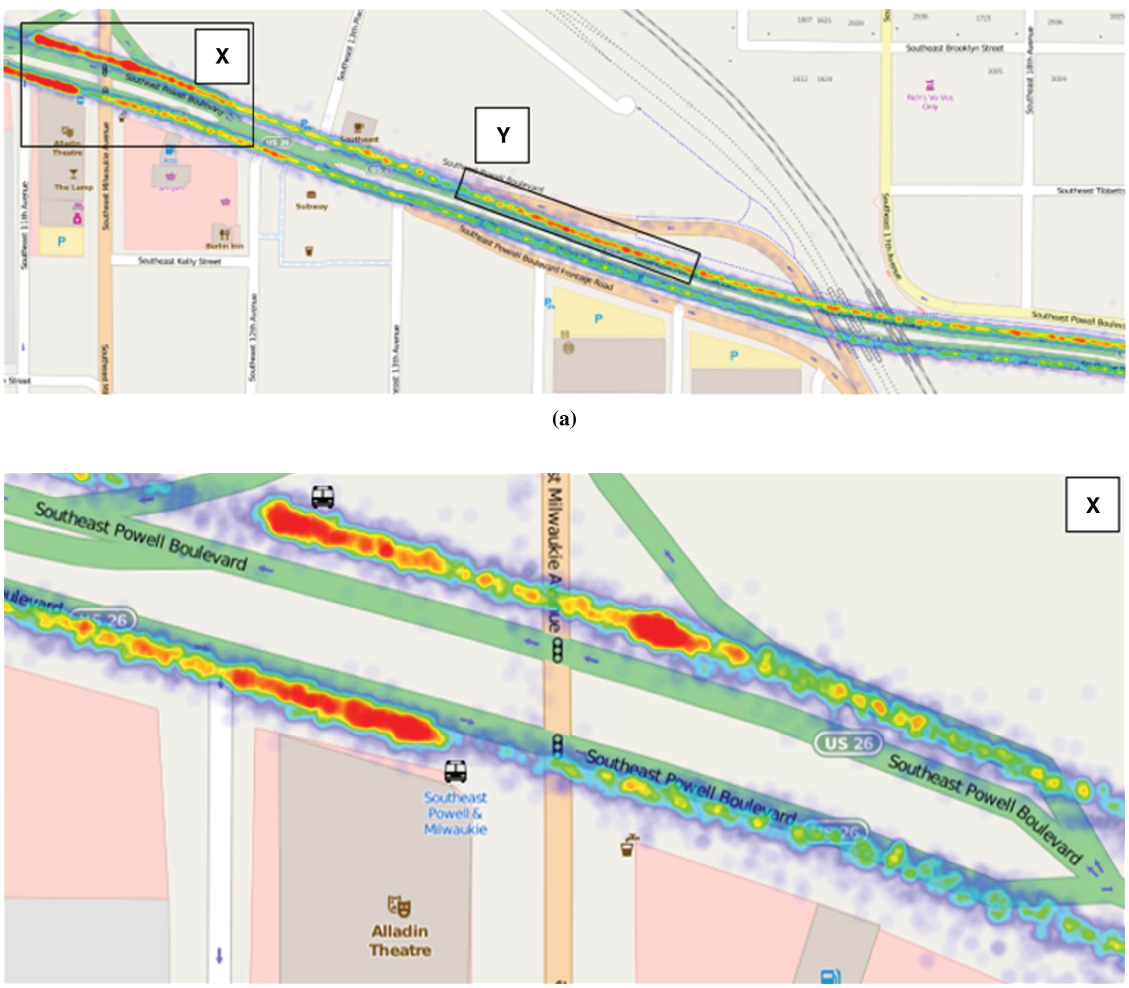
15 m downstream from the bus stop pole. The bus identified bus zones by using train mileages before and after the bus stop. Data at the bus stop level included vehicle arrival, dwell, and departure times; hence, the two data sets were complementary.

DATA VISUALIZATION: HEAT MAP

A series of tools was developed to analyze the November 2014 high-resolution data. By using time and location coordinates of the entire 5-SR data set as inputs, an interactive heat map was created to display concentrations of GPS points. Because data were generally recorded every 5 s, locations where buses stop or move slowly, as indicated by speed, left higher levels of bread crumbs and thus had denser collections of GPS points. The heat map tool assigned a color value to different densities, with high concentrations visible as red and lower concentrations as blue. Because of the density of points, locations where buses stopped, like bus stops and traffic intersections, and stretches of road where buses are moving slowly became easily visible. Several features were built into the heat map to allow for customizability when these data were being examined, and by interacting with the heat map—either by zooming in on specific segments of road or by changing scale and blur attributes—the user could observe general trends in bus behavior.

Figure 2 shows the usefulness of this type of visualization. Figure 2*a* includes Insets X and Y. Inset X, enlarged in Figure 2*b*, shows two bus stops—one for westbound and one for eastbound traffic—and the intersection of Milwaukie Avenue and Southeast Powell Boulevard. Even with the close proximity of the intersection to the westbound bus stop, the figure clearly shows the trend for many buses to stop at the intersection before reaching the stop. Conversely, the bus stop for eastbound traffic is slightly upstream of the intersection, and the buses that stop at the bus stop and at the intersection cannot be easily distinguished from the visualization alone. For both bus stops, the gap in bread-crumb recordings as a result of the bus being within a bus zone, described above, is visible as a gap in the cloud. This gap can be seen slightly upstream of each bus stop, where the distance between the zone edge and the bus stop pole is greatest.

Inset Y, enlarged in Figure 2*c,* illustrates another useful application of the heat map: finding locations of congestion. Because the maps

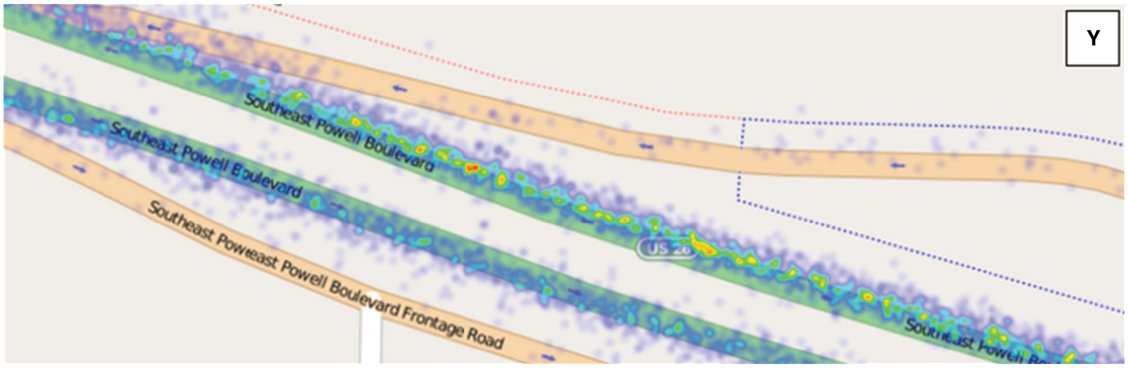


(a)

(b)

FIGURE 2 Example of heat map output: (*a*) analysis segment along Southeast Powell Boulevard from 14th Avenue to 11th Avenue and (*b*) enlargement of Inset X to show bus stop at Milwaukie Avenue.

(continued)



(c)

FIGURE 2 *(continued)* **Example of heat map output: (c) enlargement of Inset Y to show merger of 17th Avenue and Powell Boulevard.**

show concentration of points, extended areas of high concentration indicate frequent points generated from slow-moving traffic. This stretch of road along Powell Boulevard from 14th to 11th Avenues is notoriously congested in the morning peak. The congestion can also be triggered by right-lane merges from Southeast 17th Avenue and continues through the right edge of the figure. Differences in color and intensity between the different parts of Figure 2 are results of different blur factors and the extent of zooms.

This tool was used to examine general behavior of buses and to select areas that necessitated further exploration. From this initial data exploration, four distinct segments were chosen for further numerical analysis.

DATA VISUALIZATION: NUMERICAL METHOD

The heat map visualized a data set that included all buses for the month of November 2014. The data set used in the numerical analysis, in contrast, included only weekdays of the first three weeks. The fourth week was omitted from the analysis because of the Thanksgiving holiday and the altered holiday bus schedule then in effect. That week was omitted so that average workday travel trends could be analyzed. To examine bus behavior at the four selected segments in more detail, a method to filter, analyze, and visualize speeds from 5-SR was created. Filters were also made to select subsets of data that were based on day, time of day, and direction of travel.

First, the length of time (s) and distance (ft) was calculated between each pair of consecutive GPS points. By defining pairs of GPS points nearest to a point of interest (POI) for a selected direction of travel, researchers could then determine speeds for buses passing that POI. Any point along the route could be a POI. In this research, bus stops and intersections were always POIs; in addition, POIs were added so that segments between consecutive POIs always had a length less than 30 ft (9.15 m). Knowing the direction of travel also allowed for the ability to determine points upstream and downstream of the POI. Once speed was determined, the process of examining a specific point, location, or segment could begin. All defined points were compared with the POI to find buses that were one GPS point upstream and one GPS point downstream of the POI. For a typical weekday on the segments analyzed, 70 point pairs (one point upstream and one point downstream of the POI) on average surrounded any given POI. Inclusion of 15 weekdays resulted in more than 1,000 point pairs for estimating travel times and speeds. Figure 3 shows the westbound bus stop at Milwaukie Avenue and Southeast Powell Boulevard (same as that in Figure 2). In the 5-SR data set, the locations of the GPS points had more variability (longer tail) after the bus stop than before it.

Starting with a specific POI, average speed around that point could be calculated. The same process that was applied to individual POIs could also be applied to a range of POIs occurring over a specified segment. For this paper, four segment-level analyses were completed, with the average distance between consecutive POIs ranging from 25 to 30 ft.

APPLICATION 1. CONGESTED URBAN CORRIDOR

The first type of roadway to which this numerical approach was applied was Southeast Powell Boulevard, which runs from the nearby city of Gresham, Oregon, and enters the downtown core of Portland from the southeast. Powell Boulevard is a major arterial in the Portland metropolitan area and carries between 30,000 and 45,000 vehicles a day (more traffic closer to downtown Portland). It is a popular commuter route during the morning hours, bringing people from neighboring suburbs into downtown. The posted speed limit along Powell is 35 mph. TriMet Bus Route 9 runs directly along the corridor. Bus stops are located in varying proximity to intersections and thereby offer a variety of unique situations to investigate. Three segments along Powell were chosen to be examined in more detail.

Westbound Southeast Powell Boulevard Between Southeast 11th and Southeast 17th Avenues

Figure 4 shows the same segment as in Figure 2. For this illustration, color represents speed, with green indicating faster speeds. Because of the 35-mph speed limit on Powell Boulevard, all buses with speeds greater than 35 mph are represented by the highest-level green. The *y*-axis was created by ordering all bus observations by time of day. By doing so, behavior during morning peak (6:30 to 9:30 a.m.), midday off-peak (9:30 a.m. to 4:30 p.m.), and evening peak (4:30 to 7:30 p.m.) can be more easily examined. Horizontal lines are included in these

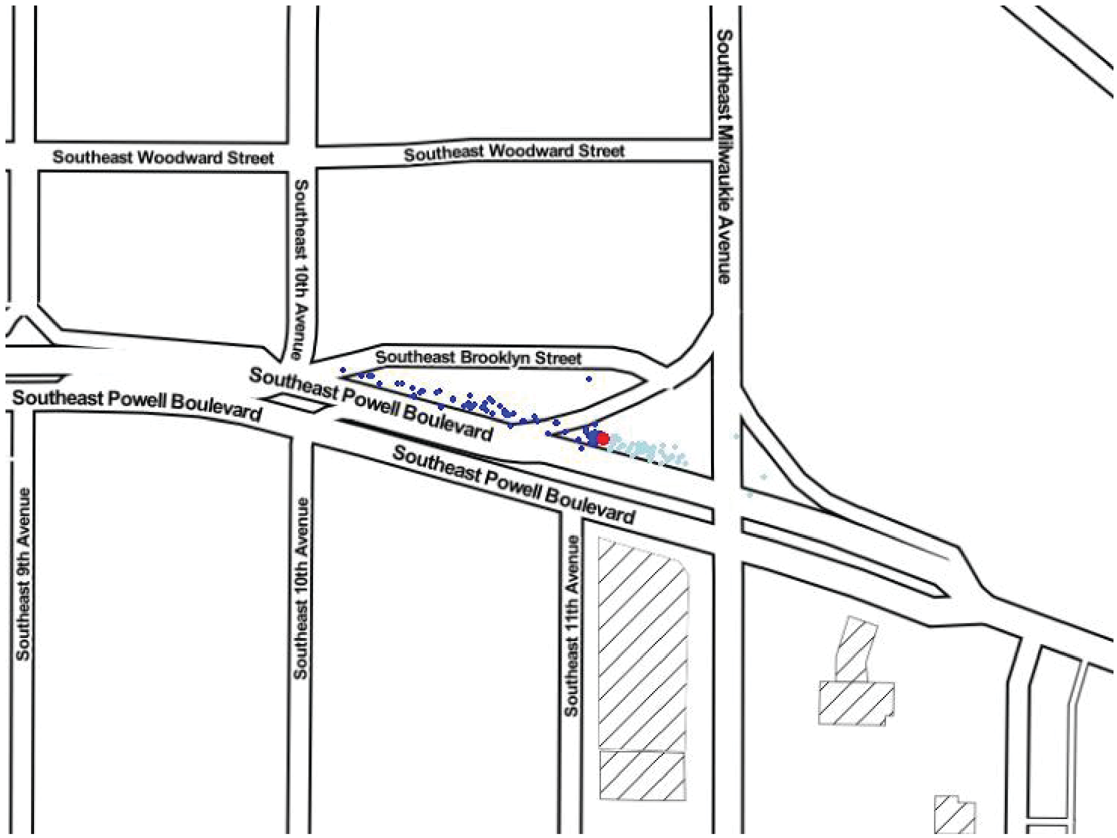


FIGURE 3 Example of POI: red dot at westbound bus stop at Milwaukie Avenue and Southeast Powell Boulevard.

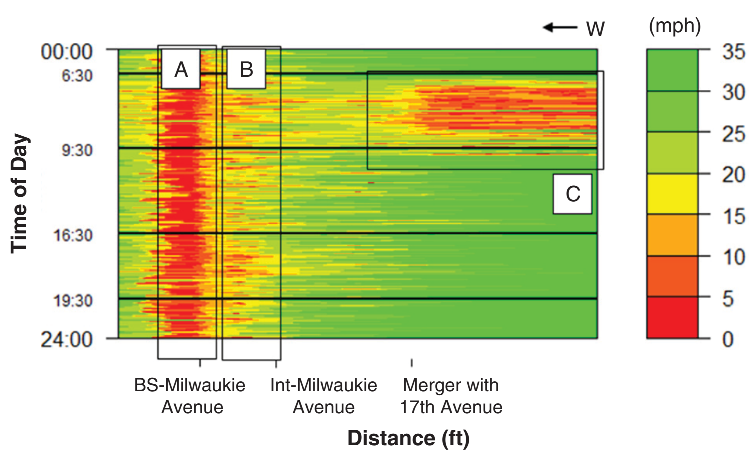


FIGURE 4 Application of numerical method applied to 5 days of bus speeds on a 2,000-ft segment of Southeast Powell Boulevard: (*a*) bus stop at Milwaukie Avenue, (*b*) intersection of Southeast Powell Boulevard and Milwaukie Avenue, and (*c*) merger of 17th Avenue with Southeast Powell Boulevard.

FIGURE 5 Satellite view of merger of 17th Avenue with Southeast Powell Boulevard.

plots to distinguish the different periods clearly. The *x*-axis here represents distance in feet from the starting POI to the final POI and is equivalent to the length of the segment. Direction of travel is given along the top border of each plot. Geometry of the segment, including intersection locations, bus stops, and other design features, is ordered across the bottom of the plots. Keeping with previous examples, the stretch of Southeast Powell Boulevard from 14th to 11th Avenues is included in Figure 4, with a satellite image of the segment in Figure 5.

The bus stop at Southeast Powell Boulevard and Milwaukie Avenue is clearly visible as a vertical band of low speeds that stretches through the entire day (highlighted in Box A in Figure 4). Slower speeds caused by congestion and delay at the intersection of Southeast Powell [average daily traffic (ADT) ≈ 45,000 vehicles/day] and Milwaukie (ADT ≈ 21,000 vehicles/day) are also clearly visible (Box B in Figure 4). During the morning peak, traffic experiences delays that extend backward and toward Box C. Low speeds begin at the merger of 17th Avenue and Southeast Powell Boulevard; 17th Avenue (ADT ≈ 8,500 vehicles/day) creates severe congestion during morning rush hours. This delay dissipates as the day progresses and typically disappears by 10:00 a.m.

Westbound Southeast Powell Boulevard Between Southeast 33rd and Southeast 42nd Avenues

The segment of Southeast Powell Boulevard between Southeast 33rd and Southeast 42nd Avenues stretches nearly a half mile; within the segment are four bus stops and one signalized intersection: Southeast Powell Boulevard and Southeast Cesar E. Chavez Boulevard. The bus stops are clearly visible as vertical red bands that last throughout most of the day (Figure 6). The percentage of buses that stop at Chavez Boulevard is compared with percentages of several other nearby bus stops in Figure 7.

During the morning peak there are also thin horizontal bands of slow speeds that stretch the width of the segment (Figure 6, Box A). On some days, delays and queuing that start at Powell Boulevard and 17th Avenue extend all the way to Powell and Southeast Chavez Boulevards and beyond. Between the morning peak and midday off peak, intersection delay is also noticeable at Southeast Chavez Boulevard (Figure 6, Box B) and between the 40th Street bus stop and the Chavez Boulevard bus stop.

A correlation can be seen between the number of buses stopping by time of day and the intensity of the red in Figure 6. While almost

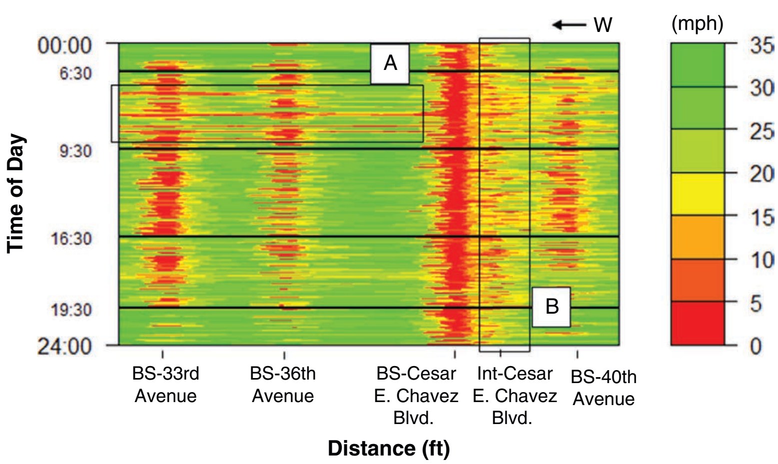


FIGURE 6 Five-day speed plot along westbound Southeast Powell Boulevard between Southeast 42nd and Southeast 33rd Avenues.

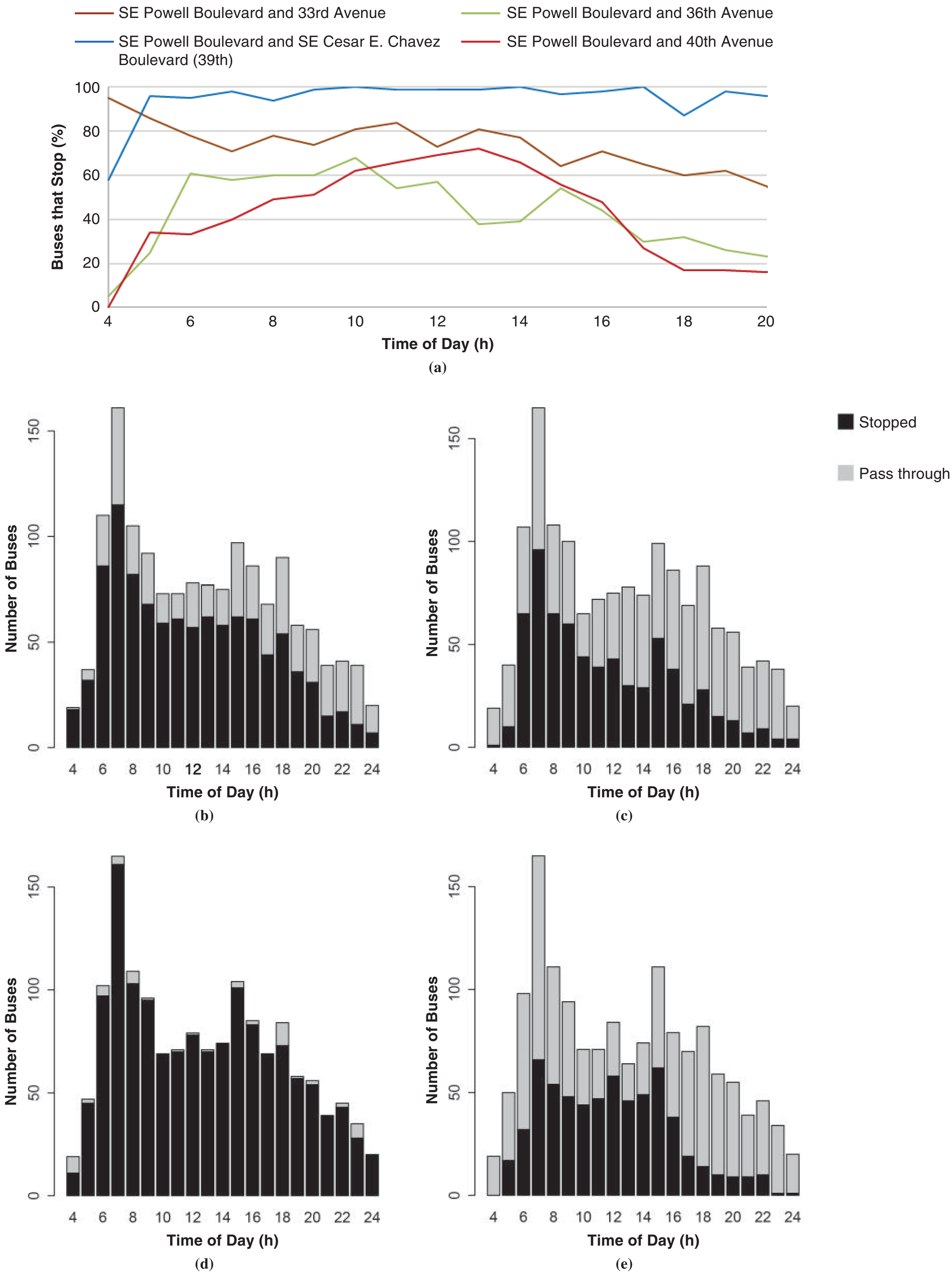


FIGURE 7 Percentages and numbers of buses stopping near Southeast Cesar E. Chavez (39th) Boulevard at four locations: (*a*) line graph for all locations, (*b*) Southeast Powell Boulevard and 33rd Avenue, (*c*) Southeast Powell Boulevard and 36th Avenue, (*d*) Southeast Powell Boulevard and Southeast Cesar E. Chavez (39th) Boulevard and (*e*) Southeast Powell Boulevard and 40th Avenue.

100% of buses stop at Chavez Boulevard during the day, the same cannot be said for the 36th or 40th Avenue bus stops. The sporadic vertical red bands that appear at 36th and 40th Avenues in Figure 6 for the morning hours dissipate by the middle of the evening peak.

The Chavez Boulevard bus stop is the most used bus stop in this segment. This stop has the highest number of boardings and alightings, and some transit riders use this stop to transfer to or from buses running along 39th Avenue (Chavez Boulevard).

APPLICATION 2. URBAN STREET

Urban streets behave differently from arterial corridors. They are characterized by lower speeds and sometimes increased stop-and-go traffic as a result of a more densely laid-out grid, pedestrian crosswalks, and traffic signals. Both the heat map and the numerical methods were applied along two urban streets. Bus Route 9 enters Portland from the southeast and heads north along Southwest 6th Avenue (ADT ≈12,000 vehicles/day). The 5-SR data set from November 2014 was used to examine this urban street. A second street, Southwest 4th Avenue (ADT ≈ 11,000 vehicles/day), was also chosen because it contains highly trafficked pedestrian crosswalks, bus stops, and intersections. A different set of 5-SR data was used for this street, from February 4th, 2015, and included all buses that traveled along this segment (TriMet Routes 12, 43, and 44). To supplement analysis along 4th Avenue, footage of bus movements was also recorded and analyzed. This video footage more accurately portrayed when a bus was stopping, for how long it was stopped, and when it started moving again. The video data showed that 5-SR data were accurate. In plots of downtown speeds, a 25-mph cap on speeds was used for the upper speed limit. Signal timing progression in the downtown core of Portland is set to a speed of 15 to 18 mph.

Southwest 6th Avenue Between Jackson and Southwest Montgomery Streets

The 1,100-ft segment of Southwest 6th Avenue (an urban street) between Jackson and Southwest Montgomery Streets spans several intersections with no bus stops, allowing observation of how buses interact solely with closely spaced intersections. Figure 8 shows the four intersections covered by this segment. The intersections at College Street and Montgomery Street caused the most delay. Time of day was seen as unimportant in determining traffic performance on this stretch of this urban street. This segment along Southwest 6th Avenue is part of a transit corridor, and buses have a dedicated travel lane. Hence, traffic levels are not affecting the performance of bus travel times. Because intersections are more closely spaced and the segment has no bus stops, the benefits of a dedicated bus lane and signal timing progression can be seen in Figure 8 in the various green horizontal bands that stretch the width of the segment.

Southwest 4th Avenue Between Southwest Caruthers Street and Southwest Mill Street

The second urban street segment selected, Southwest 4th Avenue between Southwest Caruthers and Southwest Mill Streets, is a stretch of arterial road that feeds into the southwest corner of downtown Portland. This segment includes one bus stop. Directly upstream from this stop are two marked crosswalks with heavy pedestrian traffic (Southwest 4th Avenue and College Street), two signalized intersections (Hall and Harrison Streets), and a marked crosswalk (Southwest 4th Avenue and Montgomery Street) with significant pedestrian traffic. The 5-SR data for this segment are from February 4, 2015.

The visualizations from this stretch of arterial roadway capture delay caused by crosswalk activity at Southwest 4th Avenue and College Street and at Southwest 4th Avenue and Montgomery Street (Figure 9, Boxes A and C, respectively). Heavy pedestrian traffic (students) goes to and from Portland State University buildings along 4th Avenue, and office workers and students access food carts and restaurants along Southwest 4th Avenue for lunch. Figure 9 shows crosswalk activity during the morning peak, at midday, and in the early evening. Satellite views of the crosswalks are shown in Figure 10.

Thin bands of higher speeds can be seen upstream and downstream. These, however, are interrupted occasionally by the signalized intersection at Southwest Harrison Street. The Portland Streetcar uses the Southwest 4th Avenue and Harrison Street intersection. Because of the streetcar's preemption of traffic signals and relatively low

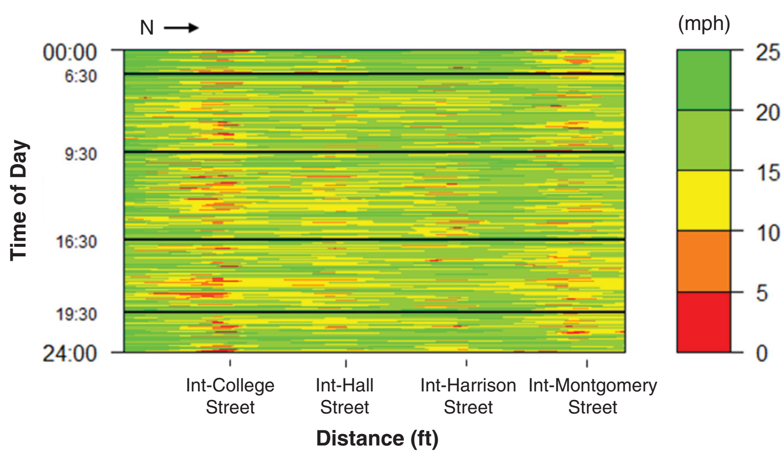


FIGURE 8 Five-day speed plot along northbound Southwest 6th Avenue from Southwest Jackson Street to Southwest Montgomery Street (int. = start of intersection).

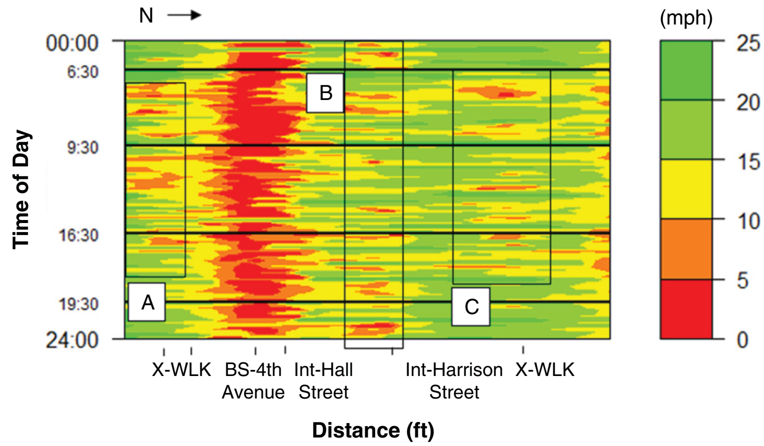


FIGURE 9 One-day speed plot for 4th Avenue.

speed, coordination of signal timing cannot be effectively achieved in this segment along Southwest 4th Avenue. Figure 9 should be contrasted against Figure 8; Southwest 4th Avenue has no dedicated bus lane, and signal progression cannot be implemented because of the streetcar and the heavily used marked pedestrian crosswalks.

DISCUSSION AND CONCLUSION

Arterial corridors and urban streets are important components of any transportation network, yet few studies have examined their performance. The authors used new high-resolution bus location data, to develop tools that can help to quickly locate and examine sources of delay along these streets. By using buses as probes and examining aggregated bus behavior, contoured speed plots can be used to understand the behavior of roadways outside the zone of influence of bus stops. The analysis here shows that speed plots can be used successfully to discover trends and travel patterns with only a few days' data. Congestion and speed variation can be viewed by time of day, and with knowledge of a transportation network, Google Maps street or satellite views, or both, researchers can use these plots to help indicate congestion caused by intersections, crosswalks, or bus stops.

Transportation agencies can detect and rank congested segments or locations. Speed plots can also be used to reevaluate bus stop locations (e.g., near side versus far side) and to identify locations where improvement are needed (e.g., queue jump lanes). This research focused on segments outside bus stops' area of influence. Future research efforts can analyze speeds around bus stops.

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(a) (b)

FIGURE 10 Satellite views of crosswalks at (*a*) College Street and (*b*) Montgomery Street.

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The analysis, interpretation, and any errors are those of the authors.

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