Exploring Applications of Second-Generation Archived Transit Data for Estimating Performance Measures and Arterial Travel Speeds

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Travel time and operating speed influence the attractiveness, operating cost, and system efficiency of transit service. As part of its bus dispatch system, the Tri-County Metropolitan Transportation District of Oregon has been archiving automatic vehicle location (AVL) and automatic passenger count data for all bus trips at the stop level since 1997. In 2013, a new and higher-resolution bus AVL data collection system was implemented. This new system provides stop-level data as well as 5-s resolution (5-SR) bus position data between stops. The objective of this paper is to explore potential applications of the new data for assessing transit performance and for estimating transportation system performance measures for urban arterials. Results suggest that the 5-SR data provide high-resolution information on time and position that can be used to determine bus travel speeds between bus stops, identify speed breakdowns, and estimate intersection signal and queuing delays.

Analysis and modeling of bus travel time and operating speed are integral for the transportation planning process (*1*), operations management, route planning and scheduling, and continued performance measurement and evaluation (*2*). This study uses two sets of archived transit data provided by the Tri-County Metropolitan Transportation District of Oregon (TriMet) for their bus dispatch system (BDS): stop-level metrics including automatic passenger count (APC) data and new 5-s resolution (5-SR) automatic vehicle location (AVL) data between stops. The objective of this paper is to explore the new 5-SR data for a particular bus route in Portland, Oregon, and to analyze more detailed bus trip time and speed information that are not visible with previously available, lower-resolution AVL and APC data. This paper examines finer-resolution bus travel speed as a means to examine speed changes, queuing, and delay at signalized intersections and other locations along the route.

The use of buses as probes to estimate travel times has been studied in the past (*3, 4*). In particular, TriMet buses have been used as probe vehicles (*5*) to evaluate arterial and transit performance (*6*). However, these studies used TriMet stop-level data, which were the only data available at the time. To estimate travel times and trajectories between stops, researchers had to use proxies, such as removing the estimated stop time, which does not account for bus accelerations or decelerations, or estimating travel time using the recorded or reported maximum speed in a segment between stops. Signal delay is also a key source of variability for bus travel time (*7*) and is of interest to transit operators and researchers.

The route chosen for this study was a 14.8-mi segment that ran from Northeast Kelly Avenue and 5th Street to Northwest 6th Avenue and Flanders Street in Portland. Route 9 is shown in Figure 1. Because of some missing data, the first westbound stop, Gresham Transit Center, was not included in the analysis. Route 9 included 71 westbound trips on May 1, 2013. A total of 22 trips traversed Powell Boulevard between 6:00 and 10:00 a.m.: 15 trips began at Northeast Kelly Avenue and 5th Street, six trips began at Southeast Powell Boulevard and 92nd Avenue, and one began at West Powell Boulevard and Northwest Birdsdale Avenue. All 22 buses ended their westbound trips at Northwest 6th Avenue and Flanders Street. Data for all 22 trips were extracted from both the AVL-APC and 5-SR systems.

DATA

TriMet has implemented a BDS as a part of its operation and monitoring control system (*8–10*). The BDS postprocesses and archives detailed stop-level data from buses during all trips. These data include scheduled departure time, dwell time, actual arrival and departure times, and the number of boarding and alighting passengers at every stop. The BDS also logs data for every stop in the system, whether or not the bus stops to serve passengers. Table 1 contains a sample list of archived BDS data. The calendar date, vehicle, badge, train, trip, and route number are all listed for identification. In the far-right column, a location identification number is listed. Each stop location has GPS coordinates associated with it. These coordinates are the basis by which arrival, departure, and dwell time are recorded. Times are not given as shown, but are presented in seconds past midnight, which is then converted into a standard clock format.

Additionally, each location has a predefined 45-ft stop circle surrounding the stop. The arrival times and departure times are recorded as the time the bus enters and exits the stop circle, respectively. Dwell is recorded when the doors of the bus open. If dwell occurs, arrival time is recorded as the time the doors open; arrival time plus

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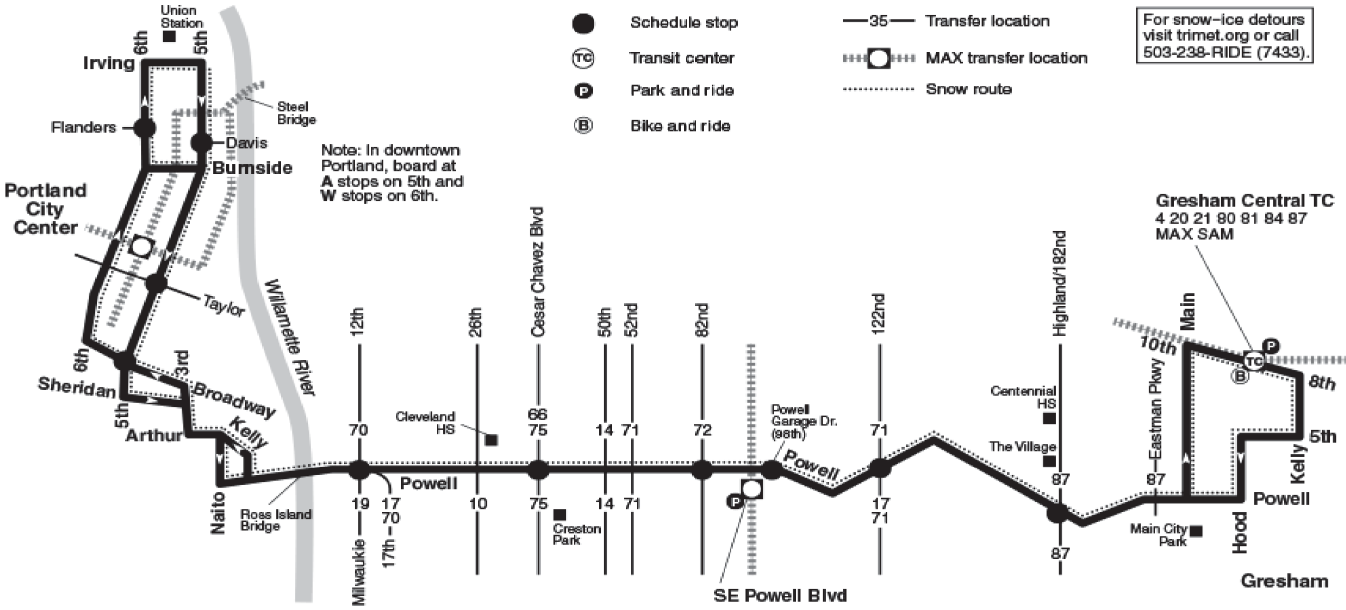

(a)

(b)

FIGURE 1 TriMet Route 9 overview: (*a*) Route 9 schematic (Source: TriMet website) and (*b*) Route 9 (westbound) trip plotted onto Google Maps (HS = high school; pkwy = parkway; dr =drive; SE = southeast; blvd = boulevard; NW = northwest; ave. = avenue; NE = northeast).

the number of seconds of dwell gives the departure time. Figure 2 shows this setup.

When passenger activity occurs, the total number of boarding and alighting passengers is recorded in two separate fields by APCs installed on the front and rear doors. APCs use infrared light to detect passenger movement and are only activated if the doors open. The use of a lift to assist passengers with disabilities is indicated in the lift field of the BDS data. Additionally, two distance measurements are recorded: pattern distance and train mileage. Pattern distance is an estimate of the linear distance, in feet, from the beginning of a route's pattern to the vehicle's current location. Scheduled trips for a single vehicle are grouped together into blocks called "trains" for assignment. Train mileage is the cumulative distance, in miles, from the start of the "train's" recorded service (*11*).

The vehicle identifiers included in the BDS data are not available for the 5-SR data, which records a time stamp and GPS location of each bus between stops every 5 s if the bus is moving. Using the BDS data as a guide, 5-SR data can be extracted by comparing the times recorded on each. 5-SR data do not start and stop at the beginning and end of a trip; by determining the start and end times for any specific bus and day, that information can be used to define a complete trip of the 5-SR data. Table 2 contains sample 5-SR data and additional calculated values. The fourth and fifth columns in the table were calculated. When the bus is not moving, data points do not record every 5 s and Table 2 contains three gap intervals greater than 5 s. Hence, the resolution of the 5-SR data is up to 5 s.

TRAJECTORY ANALYSIS

The trajectories of 22 westbound Route 9 buses are plotted in Figure 3 using a time–space diagram, where the slope of each trajectory is the average speed of a bus. The figure shows cumulative distances versus time for all 22 trips between 6:00 and 10:00 a.m. for Route 9 created using BDS data. The first number (e.g., 2544) is the bus number and the second number (e.g., 1040) is the trip number.

TABLE 1 Sample TriMet Data: BDS Data Table

Service Date	Vehicle Number	Badge	Train	Trip Number	Stop Time	Arrival Time	Dwell
May 1, 2013	2,260	1,892	934	1,140	6:54:30	6:54:58	0
May 1, 2013	2,260	1,892	934	1,140	6:54:53	6:55:32	0
May 1, 2013	2,260	1,892	934	1,140	6:55:31	6:56:23	10
May 1, 2013	2,260	1,892	934	1,140	6:56:19	6:57:02	0
May 1, 2013	2,260	1,892	934	1,140	6:56:36	6:57:12	0
May 1, 2013	2,260	1,892	934	1,140	6:56:59	6:57:28	0
May 1, 2013	2,260	1,892	934	1,140	6:57:38	6:57:56	16
May 1, 2013	2,260	1,892	934	1,140	6:58:09	6:58:31	0
May 1, 2013	2,260	1,892	934	1,140	6:58:39	6:58:49	0
May 1, 2013	2,260	1,892	934	1,140	6:59:10	6:59:20	15
May 1, 2013	2,260	1,892	934	1,140	6:59:49	6:59:44	0
May 1, 2013	2,260	1,892	934	1,140	7:00:31	7:00:09	0

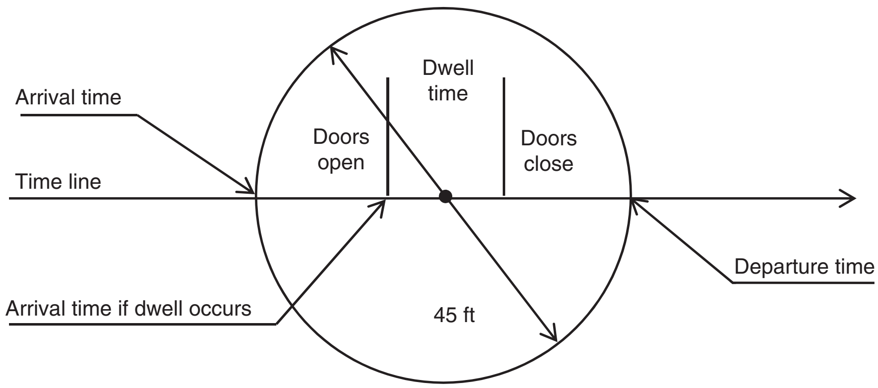

FIGURE 2 BDS data: stop circle definition.

TABLE 2 Sample TriMet Data: 5-SR Data with Calculated Values

Vehicle Number	Operation Date	Actual Time	Time[a]	Gap Interval	GPS Latitude	GPS Longitude	Δ in Distance[a]	Cumulative Distance
2,205	May 1, 2013	23,334	6:28:54	0:00:05	45.496690	−122.458707	0.0000	0.0000
2,205	May 1, 2013	23,339	6:28:59	0:00:05	45.496295	−122.459357	0.0417	0.0417
2,205	May 1, 2013	23,349	6:29:09	**0:00:10**	45.495643	−122.460055	0.0563	0.0980
2,205	May 1, 2013	23,419	6:30:19	**0:01:10**	45.495472	−122.460537	0.0262	0.1242
2,205	May 1, 2013	23,424	6:30:24	0:00:05	45.495165	−122.461137	0.0360	0.1601
2,205	May 1, 2013	23,429	6:30:29	0:00:05	45.494790	−122.461758	0.0397	0.1998
2,205	May 1, 2013	23,434	6:30:34	0:00:05	45.494400	−122.462355	0.0395	0.2394
2,205	May 1, 2013	23,439	6:30:39	0:00:05	45.494037	−122.463117	0.0446	0.2840
2,205	May 1, 2013	23,444	6:30:44	0:00:05	45.493823	−122.463692	0.0315	0.3155
2,205	May 1, 2013	23,464	6:31:04	**0:00:20**	45.493585	−122.464338	0.0354	0.3509
2,205	May 1, 2013	23,469	6:31:09	0:00:05	45.493212	−122.465003	0.0413	0.3921

NOTE: Items in boldface indicate gaps larger than 5 s.
[a]Data were calculated.

Departure Time	Door	Lift	Ons	Offs	Train Mileage	Pattern Distance (ft)	Location ID
6:54:58	2	0	3	2	26.63	0	3,123
6:55:32	0	0	0	0	26.74	568	7,605
6:56:23	0	0	0	0	26.92	1,496	13,033
6:57:02	0	0	0	0	27.12	2,671	12,862
6:57:12	0	0	0	0	27.19	3,097	9,347
6:57:28	0	0	0	0	27.30	3,668	4,558
6:58:12	2	0	1	0	27.49	4,606	12,868
6:58:31	0	0	0	0	27.63	5,377	12,863
6:58:49	0	0	0	0	27.77	6,122	4,556
6:59:20	0	0	0	0	27.91	6,870	4,553
6:59:44	0	0	0	0	28.10	7,835	12,864
7:00:09	0	0	0	0	28.29	8,871	4,516

Figure 3 shows how the bus speeds vary over time (scheduled stop times are not shown for clarity). This westbound route carries buses past 84 scheduled stops. On average, the buses stopped at 46 stops, but as few as 33 and as many as 54 stops were serviced by any one bus. Similar trends can be seen across all bus routes. For example, a sudden decrease in average speed is observed just before Mile 4 when the buses reach Southeast 162nd Avenue on Powell Boulevard; further, a constant average speed is observed at Mile 12 when buses begin to travel across the Ross Island Bridge.

Previous research has examined methods for analyzing bus trip time and for producing transit performance measures with archived stop-level AVL-APC data for Route 14 in Portland (*12, 13*). Building on this and other previous research in the literature, this paper aims to test and modify or improve the previous methods that relied on the stop-level data using the higher-resolution bus AVL data now available. To ensure this comparison is justified, Bus 2231/Trip 1170 was analyzed in depth using both data sets. A time–space diagram (Figure 4*a*) and an oblique curve (Figure 4*b*) were created. This comparison highlights the small amount of deviation between the two data sets (*14*). This result was constant across different buses and trips. Moving forward it can be assumed that the two data sets are close enough to compare directly. Additionally, the similarities between the trajectory analyses imply little benefit to using 5-SR data over stop-level data when conducting a trajectory analysis. The previous body of research (*12, 13*) is sufficient to compare differences between scheduled and actual arrival times at stop locations, which are the only locations where scheduled times are available.

CUMULATIVE ANALYSIS

GPS coordinates can be used to calculate distances between two points. Since GPS coordinates were recorded where $-180° <$ longitude $< 180°$ and $-90° <$ latitude $< 90°$, Equation 1 was used to calculate

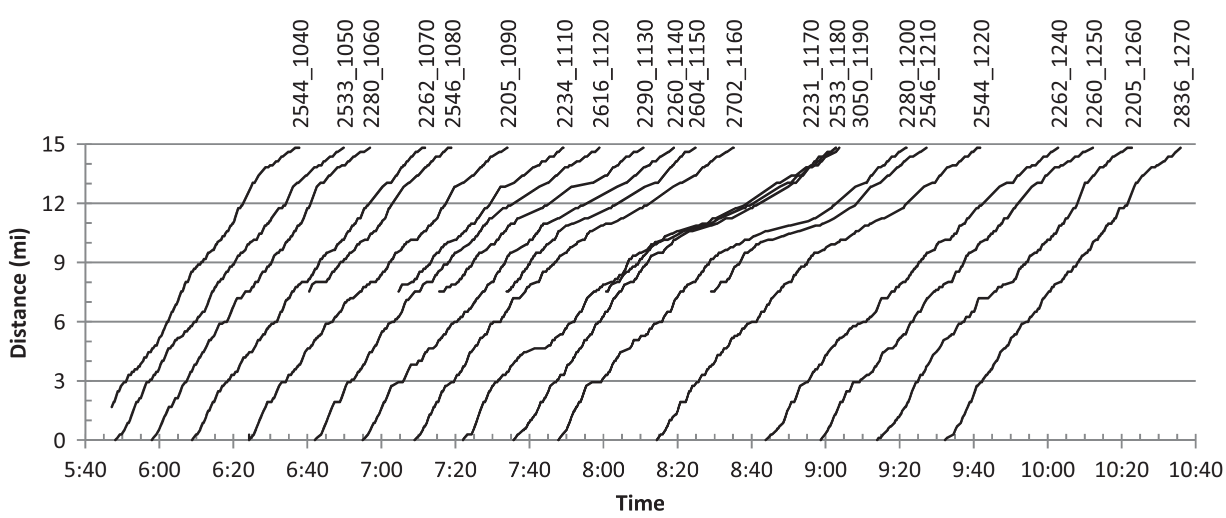

FIGURE 3 Westbound Route 9 time–space diagram.

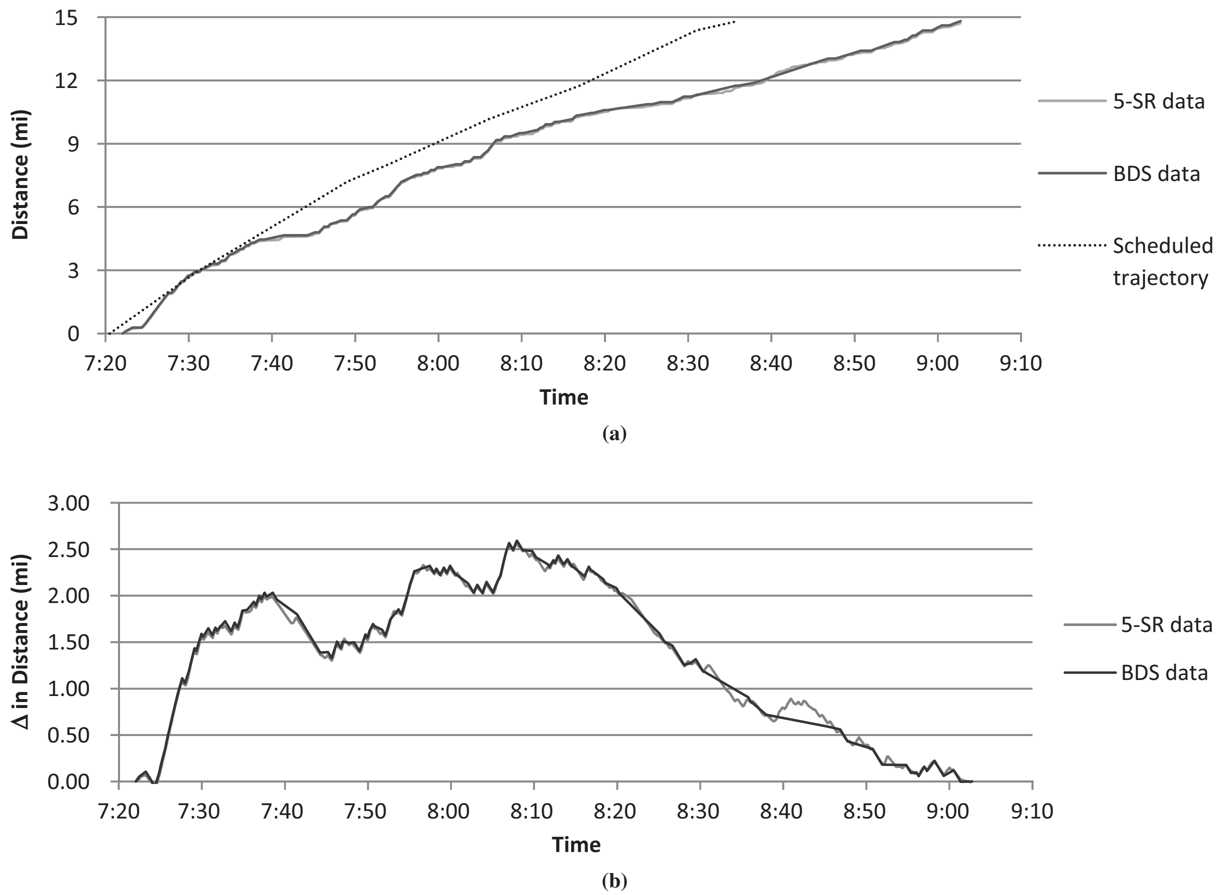

FIGURE 4 Bus 2231/Trip 1170: (*a*) time–space diagram created using BDS and 5-SR data and (*b*) oblique curve.

distances between two points. These differences were then added together for a cumulative distance value. The average radius of Earth, 3,959 mi, was used in the calculation:

$$\cos^{-1}\left(\sin\left(\frac{\text{lat}_1^\circ \cdot \pi}{180^\circ}\right)\cdot\sin\left(\frac{\text{lat}_2^\circ \cdot \pi}{180^\circ}\right)+\cos\left(\frac{\text{lat}_1^\circ \cdot \pi}{180^\circ}\right)\cdot\cos\left(\frac{\text{lat}_2^\circ \cdot \pi}{180^\circ}\right)\cdot\cos\left(\frac{\text{long}_2^\circ \cdot \pi}{180^\circ}-\frac{\text{long}_1^\circ \cdot \pi}{180^\circ}\right)\right) * 3{,}959 \text{ mi} \quad (1)$$

When attempting to compare the AVL-APC data with 5-SR positioning data, only the bus number and time stamps can be used to cross-reference the data. Once equivalent time stamps have been established, cumulative distance could be calculated for both data sets. The stop-level AVL-APC data allow for distance to be calculated three different ways. Train mileage, pattern distance, and stop location GPS data result in average cumulative distances of 14.614, 14.814, and 14.487 mi, respectively, for Route 9 westbound. When 5-SR is used, the average cumulative distance is 14.738 mi. It can be assumed that the 5-SR distance calculation is the most accurate estimation of actual bus travel distance; the distance calculated using Google Maps was 14.74 mi. Therefore, the train-, pattern-, and stop-based distance errors are –0.85%, 0.52%, and –1.7%, respectively. From the AVL-APC data set, pattern distance is most accurate and was used as the cumulative distance to calculate other related metrics on the AVL-APC data.

Dwell time is a directly recorded metric included in the archived AVL-APC data. At each stop, the number of seconds of dwell is recorded as the time that the door was open. 5-SR data are not directly recorded. However, stop time information can still be gleaned from the data. Within this data set, time stamps and GPS are not always recorded every 5 s; gaps of greater than 5 s are seen when the bus either stops or is moving slowly. Unfortunately, the data do not indicate which of these scenarios initiates gaps in the data recorded, since speeds of zero rarely appear in the data. Therefore, the assumption must be made that gaps with calculated speeds of 5 mph indicate a stop. One way to estimate bus stop time is to calculate the change in time between each successive entry to determine the gap time. If the value is 5 s or less, no stopping time is indicated. When the change in time is greater than 5 s, that time minus 5 s indicates the time spent stopped or in slow motion (gap-stop time). The average cumulative gap time indicated by the 5-SR data was 29.5 min, while the BDS data gave an average dwell time of 20.6 min. These two times indicate that the average bus spent almost 9 min stopped at locations not associated with passengers boarding or alighting.

TRIP SPEED ANALYSIS

While the amount of gap-stop time spent at 0 mph remains unclear, a histogram of bus speed could be created. The speeds of the buses were counted by grouping all reported values into 2-mph bins. The

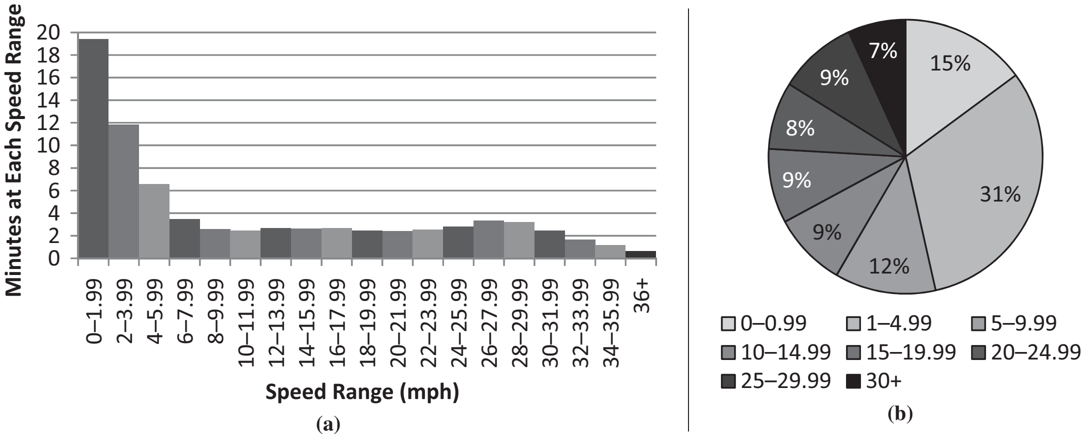

FIGURE 5 Analysis of time spent moving in speed ranges: (*a*) minutes and (*b*) percentage.

calculated speed was an average over the time period and did not take into account acceleration or deceleration. From the grouping of speed data, it was determined that a majority of the buses' time was spent moving at less than 10 mph with a quarter of that time traveling less than 1 mph. Figure 5 shows the breakdown of speeds in 2-mph bins for the average complete trip ($n = 15$) and for all trips between 6:00 and 10:00 a.m. ($n = 22$). The average trip length was 1 h 17 min.

This analysis reveals a trend for the buses to be moving less than 5 mph for more than 45% of the time. To identify where these low speeds occur along the route, an analysis of trip speed plotted against cumulative distance was conducted. More details about bus travel speeds between stops are not readily available from AVL-APC data because speeds can only be determined between recorded stops. For 5-SR data, the average distance between data points was about 1⁄40 mi (132 ft) rather than the 910-ft average stop spacing from the AVL-APC system. This 132-ft interval was used to define a cumulative distance and the function needed to create an average.

From data observation, it is clear that in almost all cases there is only one reported speed per bus per interval. When a bus speed was reported for a cumulative distance within each 1⁄40-mi grouping [e.g., (7.900 to 7.925 mi), (7.925 to 7.950 mi), etc.], the value was added to a table. If a particular trip did not have a report within the given range, the cell was left blank. When a value was added to the table, a weight for that value was calculated and then also added to the table. The values of the weights are equal to the number of seconds that a speed was maintained within a given cumulative distance interval. For example, if three buses report speeds for the same 1⁄40-mi segment of 22.5, 9.0, and 1.4 mph maintained for 4, 10, and 64 s, respectively, a weight of 4, 10, and 64 is assigned to each, respectively. The weighted average speed for that segment would be 3.46 mph. Table 3 shows a sample of how average speed was calculated. S1, S2, and so forth are speeds for each bus while W1, W2, and so forth are weights for those speeds.

While only six columns of speeds and six columns of weights are shown in Table 3, 22 bus trips were used to create Figure 6, which shows the calculated speed versus distance created from both data sets with major intersection locations noted. The solid black line is the weighted average speed created using 5-SR data of 22 trips. The dashed gray line is the average speed created by using the AVL-APC data for the 15 complete trips. The mean number of bus speeds recorded per segment was 14.4 with a standard deviation of 4.6. Figure 6, *a* to *c*, shows speeds for Mile 0 to Mile 5.5, Mile 5.0 to Mile 10.5, and Mile 10.0 to end, respectively.

The speed between stops was also calculated from the AVL-APC data by dividing the distance between two successive stops by the difference between arrival time at the second stop and the departure time at the first stop. Even though the buses had dwell time where their speed would be 0 mph, this time was not shown in Figure 6.

TABLE 3 Sample of Average Speed Analysis

Distance (mi)	Weighted Avg. Speed (mph)	Speed Count	Weight Count	Miles per Hour by Speed											
				S1	S2	S3	S4	S5	S6	W1	W2	W3	W4	W5	W6
7.900	17.9	6	30	13.5	15.1	18.2	17.3	23.0	20.5	5	5	5	5	5	5
7.925	4.6	6	74	17.0	13.3	7.7	14.9	0.5	10.2	5	5	5	5	49	5
7.950	7.0	4	30	13.3	na	13.4	1.0	12.1	na	5	na	5	15	5	na
7.975	2.8	5	191	na	2.1	9.4	14.6	10.1	2.0	na	81	5	5	5	95
8.000	3.2	4	119	na	30.8	2.0	10.9	1.7	na	na	4	45	5	65	na
8.025	5.3	5	139	2.5	na	23.5	4.0	28.0	24.8	94	na	5	30	5	5
8.050	28.9	4	20	28.1	31.5	25.9	na	na	30.2	5	5	5	na	na	5
8.075	29.1	2	10	na	na	na	29.3	28.9	na	na	na	na	5	5	na
8.100	20.4	6	31	30.2	12.8	13.0	30.3	27.7	9.9	5	6	5	5	5	5

NOTE: Avg. = average; na = not applicable.

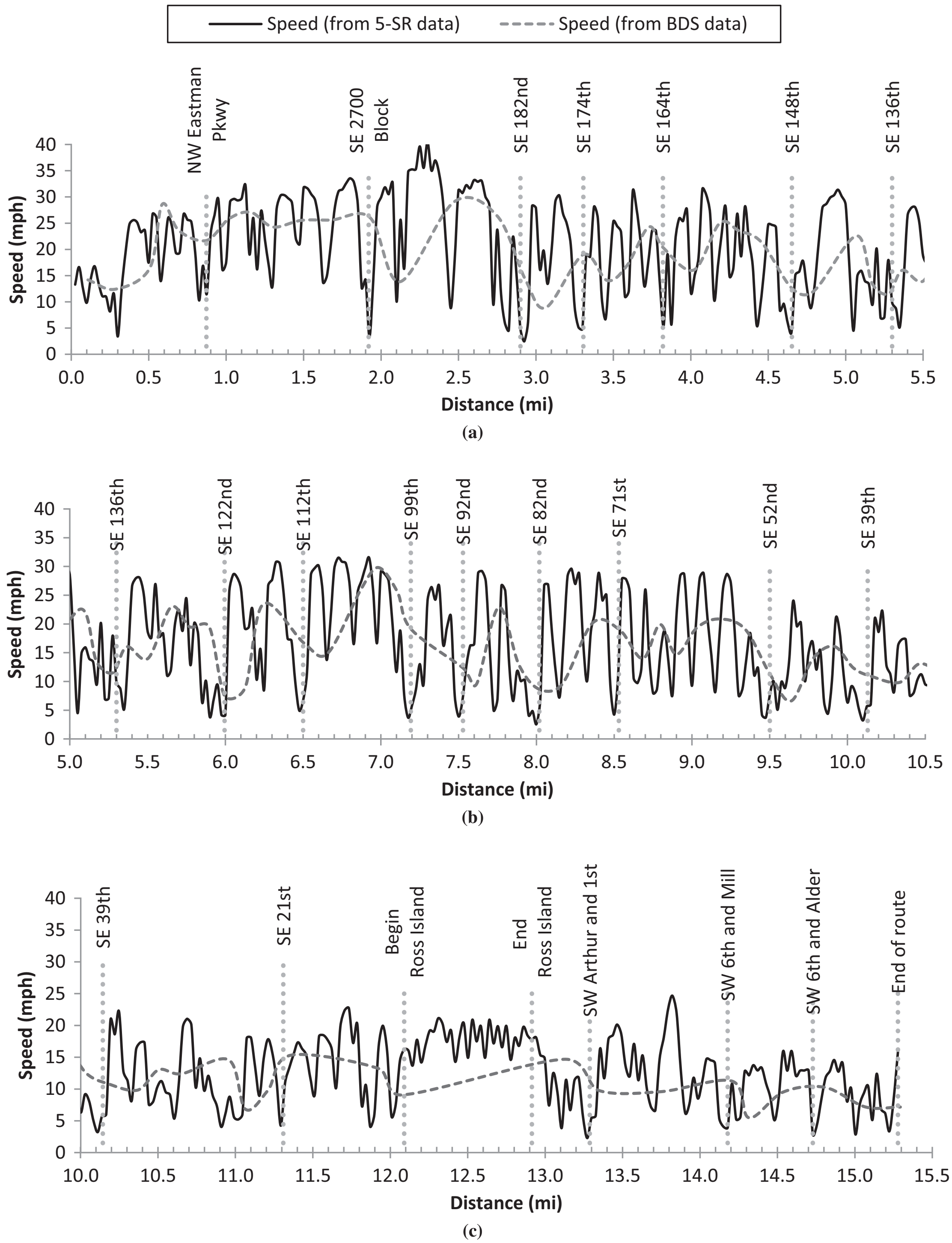

FIGURE 6 Average speed versus cumulative westbound trip distance (n = 22): (*a*) start 5.5 mi, (*b*) 5 to 10.5 mi, and (*c*) 10 mi to end (SW = southwest).

The distance between locations with AVL-APC data creates uncertainty in speeds calculated from those data alone. Because of the higher number of reports at positions between stops locations of AVL-APC, speeds calculated from 5-SR data have a higher resolution and can be used to examine trip characteristics previously obscured by the lower-resolution AVL-APC data. The new 5-SR data allow a better detection of congestion or delays at intersections. The analysis also reveals a trend that congestion is prevalent before and after crossing the Ross Island Bridge, but traffic still runs smoothly on the bridge itself.

The two data series in Figure 6 do not contain all the same information at different resolutions. Since distance is used for the x-axis, only nonzero speeds permit the function to continue; the AVL-APC data lack stop time consideration, while the 5-SR plot does not,

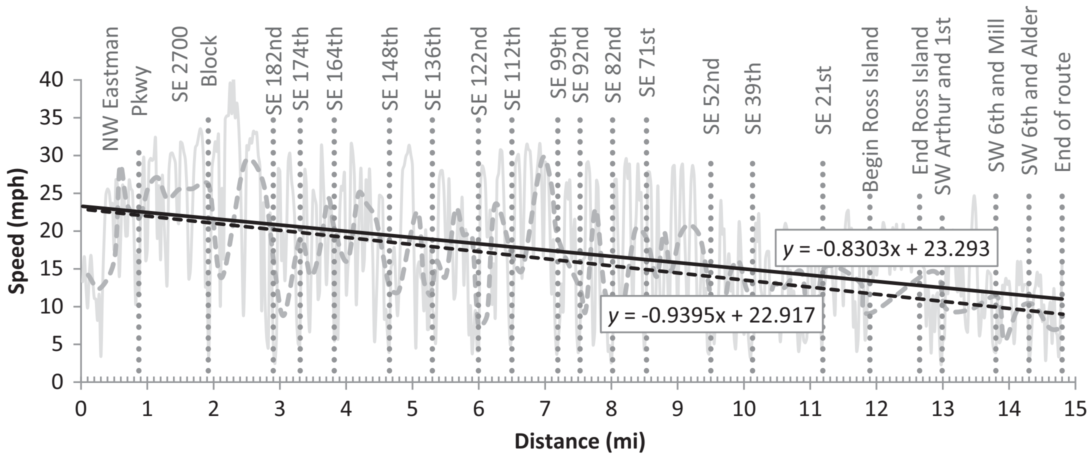

FIGURE 7 Average speed versus cumulative distance trend line (n = 22).

since slow speeds associated with long gap time are taken into account. For example, at distance 7.900 in Table 3, all six speeds are similar and have equal weight because each speed was recorded for a 5-s interval, while at 8.000 the largest speed has a weight of 0.8 while the slowest speed has a weight of 13, indicating speed duration of 4 and 65 s, respectively. Distance 8.000 marks the crossing of Southeast 82nd Avenue on Powell Boulevard; while all the buses stopped at this location, zero speeds tend not to appear when 5-SR data are used. However, it can be assumed that distances where the average speed falls below 5 mph likely included stopped buses even if the exact stop time is unknown.

As shown in Figure 7, the analysis of average speed allowed for two linear trend lines to be created: one for the stop-level AVL-APC data and one for 5-SR data. These trend lines indicate that the speed of buses decreases as they move westward during the morning commute. An average speed estimate can be calculated by integrating the linear regression lines over the distance and dividing by total distance traveled. This average speed divided by total distance gives an average trip time estimate. The AVL-APC and 5-SR data sets resulted in calculated average trip times of 1 h 4.7 min and 1 h 9.5 min, respectively. Since it is known that the mean trip time was 1 h 17 min, an error of >10% is associated with each estimate.

Despite this error, the trip speed versus distance graph allows for the locations of unscheduled stops to be observed. For example, the quarter-mile running up to Mile SE 82nd (Mile 8.0) runs slowly preceding the stop location. This finding is likely caused by buses waiting in queues before crossing Southeast 82nd Avenue to reach the stop on its farside.

TRIP TIME ANALYSIS

Figure 8 was created using similar methodology employed in the creation of Figure 6. The x-axis is the actual time and the y-axis represents an average speed created from all bus trips operating over all positions along the route at the same time. The gray line is an average speed at 5-s intervals. The black line is 1-min moving average speed with ±30 s of accuracy. The white line is a polynomic trend line that highlights the overall shape of the plot. A dip in the speeds between 7:00 and 9:00 a.m. coincides with the morning congestion and represents a decrease in average speed of about 9 mph.

A trip time analysis using 5-SR data has some limitations created by the lack of information about passenger movement (i.e., passenger boarding and alighting), specified dwell time, use of a lift, traffic signal indications, activation of transit signal priority, and so forth. Without more independent information, a trip time model using 5-SR data will be of limited utility. The observed decrease in speed serves to confirm the effects of morning congestion on Route 9 buses.

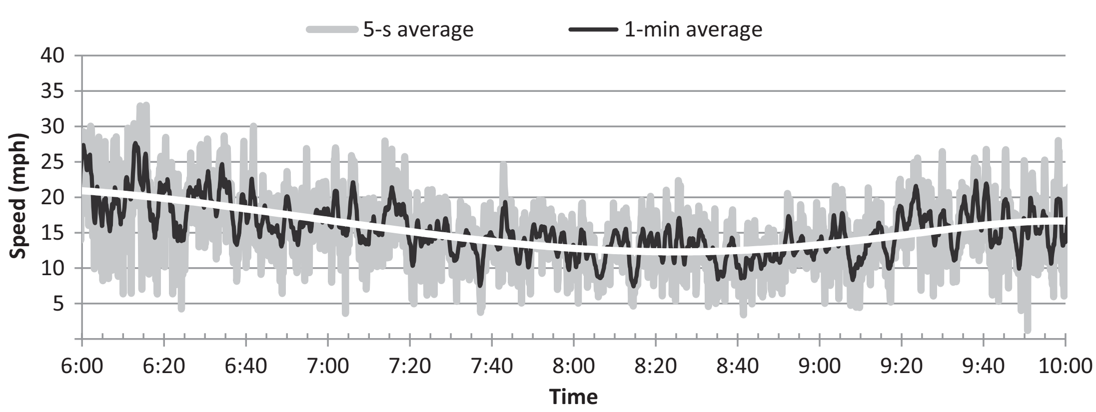

FIGURE 8 Average bus speed versus time ($2 \leq n \leq 6$).

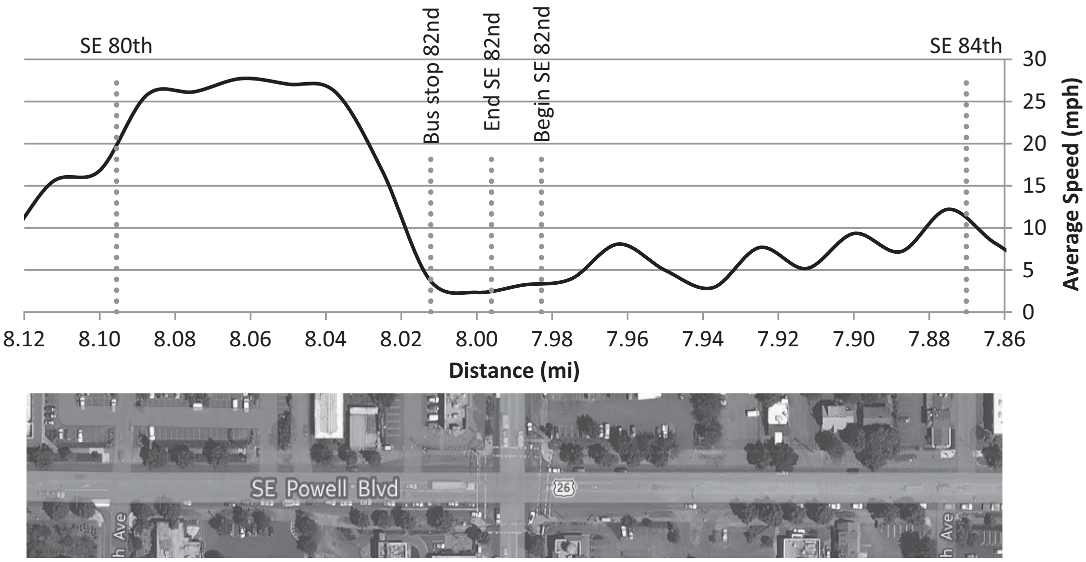

FIGURE 9 Speed analyses of Southeast Powell Boulevard and 82nd Avenue.

INTERSECTION LEVEL ANALYSIS

In the previous section, it was noted that around Southeast 82nd Avenue and Powell Boulevard, buses have lower speeds; Southeast 82nd Avenue is also Oregon Route 213 and has higher traffic signal coordination priority than Powell Boulevard. The area from Southeast 84th Avenue to Southeast 80th Avenue was examined in detail and is shown in Figure 9; average bus speed is decreasing as the buses approach Southeast 82nd Avenue. Bus speed increases after the bus has passed its scheduled stop on the farside of the intersection (most buses stop at 82nd Avenue). The speed of the buses is steady around 27 mph until the buses pass Southeast 80th Avenue and approach the bus stop at Southeast 79th Avenue. This example shows that it is now possible to zoom in on specific intersections and detect areas with significant queuing.

CONCLUSIONS

The results of this study suggest that the new generation of higher-resolution bus trajectory data can be successfully employed to identify congestion along urban arterials. The analysis conducted shows that 5-SR data can be used to observe metrics about operating speed in more detail than could previously be seen using stop-level AVL-APC data. This study found that the average travel speed decreased as buses moved eastward on Route 9 with an overall average of 17.1 mph. Additionally, while it is to be expected that slow average bus speeds should occur at scheduled bus stops, slow speeds were reported on approaches to many bus stops. This finding indicates congestion before buses were able to reach their stop destinations, especially for bus stops shortly following signalized intersections, such as Southeast 82nd Avenue and Southeast 39th Avenue. An analysis of average speed created with 5-SR data at each intersection can indicate where buses are stopping and highlight whether those locations are intended to be slow moving or a stop.

Dwell time accounted for 27% of the average trip time of 1 h 17 min. Gap-stop time accounted for 38% of this average trip. The speed breakdown shows that 46% of the time was spent moving <5 mph; therefore, it can be concluded that 27% to 38% of the time was spent stopped. However, the exact stop time remains uncertain.

The next step is to validate this model by examining specific intersections for all buses for a complete day. This step will help to determine more specifically where problems are occurring and allow for solutions to be presented. This analysis calls for a recommendation for a change in TriMet's 5-SR data. It is recommended that reports should be made every 5 s regardless of bus motion. This change will allow for accurate stop times and the locations of these stops to be directly analyzed. Currently, only assumption of slow speed can be used and actual stopping time is uncertain. In addition, without a few additional pieces of information, 5-SR data are not accessible on their own. BDS data must be used to compare and extract the data. This situation could be resolved by including additional fields in the data about train and trip number. Wheel sensor movement data could be another complementary data set to overcome the limitations in this paper.

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REFERENCES

1. Levinson, H. S. Analyzing Transit Travel Time Performance. In *Transportation Research Record 915,* TRB, National Research Council, Washington, D.C., 1983, pp. 1–6.
2. Cambridge Systematics. *Multimodal Transportation: Development of a Performance-Based Planning Process.* NCHRP Project 8–32(2). TRB, National Research Council, Washington, D.C., 1999.
3. Hall, R. W., and N. Vyas. Buses as a Traffic Probe: Demonstration Project. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1731,* TRB, National Research Council, Washington, D.C., 2000, pp. 96–103.

4. Chakroborty, P., and S. Kikuchi. Using Bus Travel Time Data to Estimate Travel Times on Urban Corridors. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1870,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 18–25.
5. Bertini, R. L., and S. Tantiyanugulchai. Transit Buses as Traffic Probes: Use of Geolocation Data for Empirical Evaluation. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1870,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 35–45.
6. Berkow, M., M. Wolfe, C. M. Monsere, and R. L. Bertini. Using Signal System Data and Buses as Probe Vehicles to Define the Congested Regime on Arterials. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.
7. Feng, W. *Analyses of Bus Travel Time Reliability and Transit Signal Priority at the Stop-to-Stop Segment Level.* PhD dissertation. Portland State University, Portland, Ore., 2014.
8. Strathman, J. G., K. J. Dueker, T. Kimpel, R. L. Gerhart, K. Turner, P. Taylor, S. Callas, and D. Griffin. Service Reliability Impacts of Computer-Aided Dispatching and Automatic Vehicle Location Technology: A TriMet Case Study. *Transportation Quarterly,* Vol. 54, No. 3, 2000, pp. 85–102.
9. Strathman, J. G., 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. *Transportation,* Vol. 29, 2002, pp. 321–345.
10. Strathman, J. G., K. J. Dueker, T. Kimpel, R. Gerhart, K. Turner, P. Taylor, S. Callas, D. Griffin, and J. Hopper. Automated Bus Dispatching, Operations Control, and Service Reliability: Baseline Analysis. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1666,* TRB, National Research Council, Washington, D.C., 1999, pp. 28–36.
11. Data Resources Derived from BDS Card Data. *Stop Event Data Dictionary, 2003.*
12. Bertini, R. L., and A. M. El-Geneidy. Modeling Transit Trip Time Using Archived Bus Dispatch System Data. *Journal of Transportation Engineering,* Vol. 130, No. 1, 2004, pp. 56–67.
13. Bertini, R. L., and A. El-Geneidy. Generating Transit Performance Measures with Archived Data. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1841,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 109–119.
14. Li, H., and R. L. Bertini. Comparison of Algorithms for Systematic Tracking of Patterns of Traffic Congestion on Freeways in Portland, Oregon. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2178,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 101–110.

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