Traffic and Transit Travel Time Reliability Indexes and Confidence Intervals

Novel Methodologies for the Corridor and Segment Levels

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As congestion worsens, the importance of rigorous methodologies to estimate travel time reliability increases. Exploiting fine-granularity transit GPS data, this research proposes a novel method to estimate travel time percentiles and confidence intervals. Novel transit reliability measures based on travel time percentiles are proposed to identify and rank low-performance hot spots; the proposed reliability measures can be utilized to distinguish peak-hour low performance from whole-day low performance. As a case study, the methodology is applied to a bus transit corridor in Portland, Oregon. Time–space speed profiles, heat maps, and visualizations are employed to highlight sections and intersections with high travel time variability and low transit performance. Segment and intersection travel time reliability are contrasted against analytical delay formulas at intersections—with positive results. If bus stop delays are removed, this methodology can also be applied to estimate regular traffic travel time variability.

Travel time and travel time variability are of major importance to travelers and transportation agencies. Travel time reliability is a fundamental factor in travel behavior that gains importance as congestion worsens (*1*).

Travel time reliability measures have been widely applied to analyze freeways and regional travel (*2*). These analyses often used Bluetooth data, which are collected by matching media access control addresses from numerous different vehicles passing by relatively few fixed locations along a route. Bus GPS data are intrinsically different. Stop-level and high-resolution data sets are collected by buses without matching; the high-resolution data do not occur at specific locations; relatively few vehicles (buses) collect numerous GPS time stamps along the route. Hence, the procedures developed to analyze Bluetooth data cannot be transferred to high-resolution bus GPS data. The advent of GPS in transit vehicles generated several research efforts to model and understand transit travel time variability. However, until recently, researchers and transit analysts were only able to examine GPS data recorded at or near bus stops. The availability of bus stop–level data was a great improvement but limited the analysis to route or segment levels. For example, it is not possible to readily study the impact of traffic signals on bus travel times with stop-level GPS data.

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This study takes advantage of the recent availability of fine-granularity data (FGD), which collects 5-s intervals of GPS bus travel data between bus stops. The availability of FGD allows the estimation of transit travel time reliability measures at arbitrary segments; that is, the analysis is not limited to the study of stop-to-stop segments or complete routes. It is proposed to utilize the FGD method to estimate travel time percentiles and confidence intervals.

The proposed new transit reliability measures can be utilized to distinguish peak-hour low performance from whole-day low performance. The method is applied to a bus transit corridor in Portland, Oregon. Speed and travel time percentiles are estimated and utilized to create visualizations that clearly highlight sections and intersections with high travel time variability. Intersection travel time reliability is contrasted against analytical delay formulas at intersections with positive results. If bus stop delays are removed, this methodology can also be applied to estimate regular traffic travel time variability.

LITERATURE REVIEW

The *Transit Capacity and Quality of Service Manual* provides a comprehensive list of factors that influence travel time variability and indicates that dwell time and signalized intersections are the largest sources of bus delay (*3*). Researchers have attempted to quantify transit travel time variability, but in the past the lack of widespread data sets hindered these efforts. The advent of GPS data allowed researchers to study large numbers of accurate travel time observations. At the route level, researchers studied day-to-day variability in public transport travel time using a GPS data set for a bus route in Melbourne, Australia (*4*); linear regression models showed that land use, route length, number of traffic signals, number of bus stops, and departure delay contributed to travel time variability. Other research efforts showed how traffic volume, traffic signals, traffic signal priority, and bus stop type can affect travel times and travel time variability (*5*).

Several research efforts have focused on estimating travel times and using public buses as probe vehicles (*6–9*). These early research efforts revealed that when automobiles experience long delays, buses on the same facility are also likely to be delayed but the reverse relationship is not always true, as in the case when buses dwell at stops because they are ahead of schedule. Previous research efforts in the Portland region have utilized stop-to-stop bus travel data to assess arterial performance and transit performance (*9*). However, all these studies were severely limited by the lack of GPS coordinates between bus stops (*4–9*). The recent availability of 5-s GPS data for buses has removed much of the guesswork involved in estimating bus travel speed profiles between bus stops; it is now possible to measure relative changes in bus speed at intersections, ramps, crosswalks, and other features (*10*). Unlike previous studies, the current effort focuses on the estimation of travel time variability and confidence intervals in arbitrary segments or locations along a transit route. In addition, the proposed transit reliability measures can be used to contrast peak-hour performance against whole-day performance at corridor intersections and segments.

METHODOLOGY

The proposed methodology partitions any route or section of a route s_i into a set of nonoverlapping segments denoted S; the midpoint of each segment forms the set of points P. The subindex i is utilized to denote any segment s_i and corresponding midpoint p_i. The total number of segments is denoted n_I.

If there is a set of J bus trips passing segment s_i, it is possible to find for each bus trip j, $\forall j \in J_i$, $J_i = \{1, 2, 3, \ldots, n_{Ji}\}$, the pair of consecutive GPS coordinates immediately before and after p_i (i.e., located closest to p_i); these pairs of GPS coordinates are denoted p_{ij}. For each pair denoted p_{ij}, it is possible to estimate the velocity or speed v_{ij} of bus j in segment i. With each speed v_{ij} it is possible to form the set of speeds V_i for segment s_i. The number p, $0 < p \leq 100$, denotes a percentile; $v_{i,p}$ is the pth percentile of travel speeds obtained from V_i in segment i. A pair of GPS points produces a point speed estimate at a midpoint p_i; the (harmonic) mean speed is used to provide segment-level speed estimates because it properly weighs the impact of slower vehicles that spend a longer time traveling a segment.

$$\bar{v}_i = \frac{n_{Ji}}{\sum_{J_i}\left(\frac{1}{v_{ij}}\right)} \tag{1}$$

Given the large sample sizes utilized in this study ($n_{Ji} > 50\ \forall i$), it is possible to estimate confidence intervals for the percentiles assuming that the estimated percentile is normally distributed; for $n_{Ji} < 30$ a binomial distribution must be employed. To estimate the confidence interval for any estimated $v_{i,p}$, it is necessary to know the number of observations $n = n_{Ji}$, the confidence level α, and the $z(\alpha)$ score by which the interval is determined (*11*):

$$\sigma_{ip}^2 = n_{Ji}\,p(1-p) \tag{2}$$

$$\left[pn_{Ji} - \sigma_{ip}z(\alpha),\ pn_{Ji} + \sigma_{ip}z(\alpha)\right] \tag{3}$$

This interval provides the indexes that can be used to estimate the interval of speeds in S_i; the interval is denoted $[v_{i,p'}, v_{i,p''}]$, where p' and p'' denote the extremes of the confidence interval around $v_{i,p}$. Similarly, it is possible to estimate a time t_{ij} associated with speed v_{ij} to travel segment i. After a set of travel times for a given segment is obtained, it is possible to estimate mean $\bar{t}_i$ (standard mean, not harmonic in this case), percentiles $t_{i,p}$, and confidence intervals for percentiles $[t_{i,p'}, t_{i,p''}]$, as already explained for travel speeds. To calculate the cumulative mean travel time or the cumulative percentile travel it is necessary to sum from $i = 1$ to $i = k > 1$; to obtain the whole section cumulative mean or percentile travel time it is necessary to sum from $i = 1$ to $i = n_I$.

$$\bar{T} = \sum_{i=1}^{n_I}\left(\bar{t}_i\right) \tag{4}$$

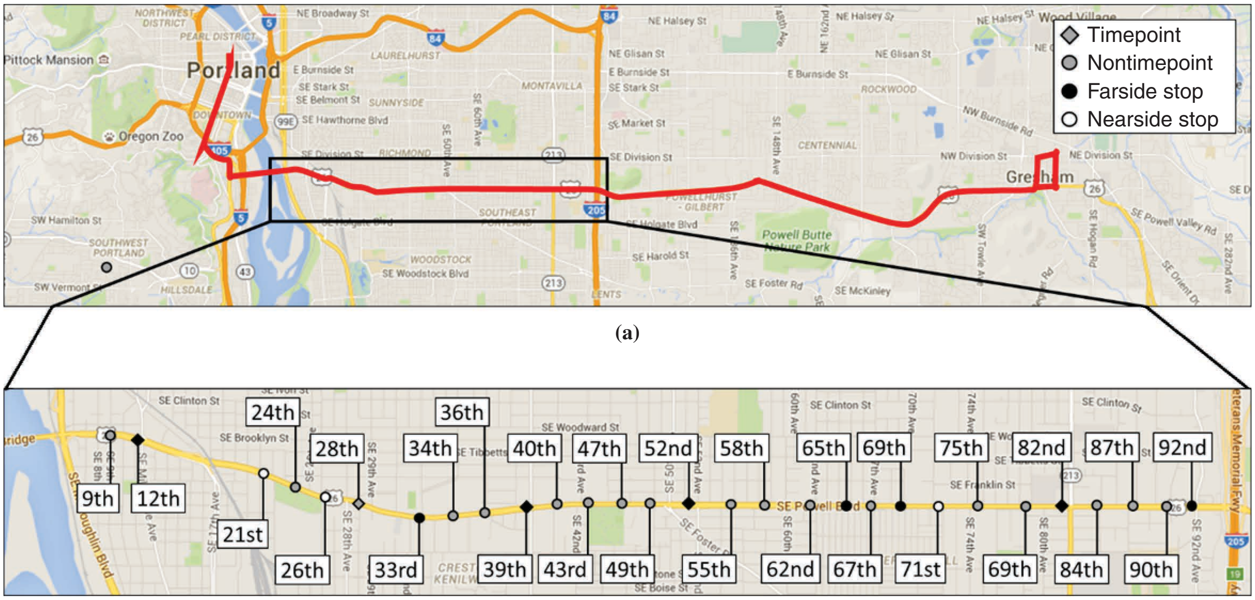
$$T_p = \sum_{i=1}^{n_I}\left(v_{i,p}\right) \tag{5}$$

With an algorithm that matches GPS points from the high-resolution data to individual stop events by using day, bus number, and time, two points preceding and two points following each stop event are removed. These clean, high-resolution data are used when stop events are not wanted in the FGD data.

CASE STUDY LOCATION AND DATA

The route chosen for this study, TriMet Route 9, runs from the intersection of northeast Kelly and 5th Avenues to the intersection of northwest 6th Avenue and Flanders Street in Portland. Route 9 was chosen because the researchers had excellent knowledge from previous studies of traffic patterns, bus operations, and the geometry of the roadways and bus stops. The current analysis will focus on a westbound and eastbound segment of Powell Boulevard between I-205 and the Willamette River. In this 4.83-mi [25,500-ft (7,772-m)] segment there are 15 signalized intersections and 29 stops. Powell Boulevard, a major urban arterial in the Portland metropolitan area, connects the city of Gresham, Oregon, to downtown Portland and carries more than 40,000 vehicles daily. The west side of the study section ends at the Ross Island Bridge, which connects downtown Portland and East Portland over the Willamette River. The study segment and bus stop locations are shown in Figure 1.

In 2013, Portland's metropolitan region transit agency, TriMet, implemented a new system to collect 5-s bus GPS data. The accuracy of the archived data has been validated by both TriMet and researchers using Wavetronix sensors (*12*). There is a high level of correlation between traffic speeds and speeds estimated with bus GPS data, especially if the speeds are not estimated within ±200 ft (61 m) from a frequently served bus stop. The new GPS data were intended to augment the existing stop-level data sets. Unlike the stop-level data, the new GPS data set collects information between bus stops; these data allow the estimation of bus trajectories and speeds between stops. However, unlike the stop-level data, GPS data do not provide information about passenger movements, doors, or other factors that occur at the stops themselves; this type of information is only found in the original stop-level data. The GPS data were designed to be recorded only when the bus is not stationary. When a bus stops for more than 5 s the GPS data are not collected; that is, there are no consecutive points that display different time stamps and the same GPS coordinates. When a bus stops, the interval between consecutive points can be longer than 5 s. It is possible to augment the original stop-level data set by matching the time and location of the GPS coordinates before and after a bus stop; this matching can be done for each stop, bus, and trip. The merging of data sets was used to create the data set used for this analysis. Three weeks of weekday bus data are utilized in this case study, the first three weeks of November. The fourth week of November, Thanksgiving



(a)

(b)

FIGURE 1 (*a*) Map of study area in Portland and (*b*) bus stops for westbound buses.

week, was excluded from the analysis because of changes in holiday bus scheduling and passenger activity. GPS and stop-level data may occasionally contain errors associated with the estimation of coordinates or the passenger counting equipment aboard the buses. The data were carefully parsed and analyzed to remove obvious outliers.

TRAVEL TIME AND SPEED PROFILES

The section of Route 9 under study was divided into equal-length segments of 25 ft (7.6 m). The shortest time period between GPS time stamps is 5 s; a bus traveling at 3.4 mph (almost walking speed) covers 25 ft (7.6 m) in 5 s, and this speed lower bound is useful to identify locations with severe congestion. Bus travel speeds at the 15th, 50th (median), and 85th percentiles with their corresponding confidence intervals for the percentiles at $\alpha = 0.01$ are shown in Figure 2. Bus stops are shown above each graph; the speed profiles show dramatic changes in travel speeds at and near popular bus stops.

The 15th percentile speed profile clearly shows the impact of delays at bus stops. In contrast, the 85th percentile speed profile shows major speed reductions only around the popular stops, that is, where buses tend to stop more than 85% of the time (e.g., see the 12th, 39th, and 82nd Avenue bus stops). The influence of many of the bus stops appears to decrease for the 50th and 85th percentile buses as compared with the 15th percentile buses. Many of these stops are passed for the majority of the time because of the lack of passengers waiting at the stop, onboard passengers wishing to alight, or both. This effect is also seen for signalized intersections, where the 85th-fastest buses reach the signals when they are green.

Figure 3 shows calculated speeds and their confidence intervals after stop events have been removed from the data set, that is, after the GPS coordinates around bus stops are removed when a bus serves a stop. The locations of the intersections are shown above the graphs. Figure 4 shows how the speed histogram changes after the GPS data for buses that have served a bus stop are removed.

The 85th percentile speed profile can be utilized to identify problematic bus stops, intersections, or segments of a route that have low performance throughout the day, for example, areas around 12th, 39th, and 82nd Avenue bus stops or intersections in Figures 2 and 3.

The speed data that include dwell time speed have a bimodal distribution, whereas the data without dwell times are unimodal (see Figure 4). Because of the decrease in the number of data points available for analysis, the confidence interval can be wider in some sections of Figure 3 than it is in Figure 2; however, many of the dips associated with bus stops no longer make an appearance. In Figure 3, the remaining dips in travel speed correspond to a combination of signalized intersections, time-point bus stops, and bus stops with bays. At bus bays, buses are required to exit from and return to the regular flow of traffic to serve the stop; even when the bus does not serve passengers, it must wait to reenter the travel lane.

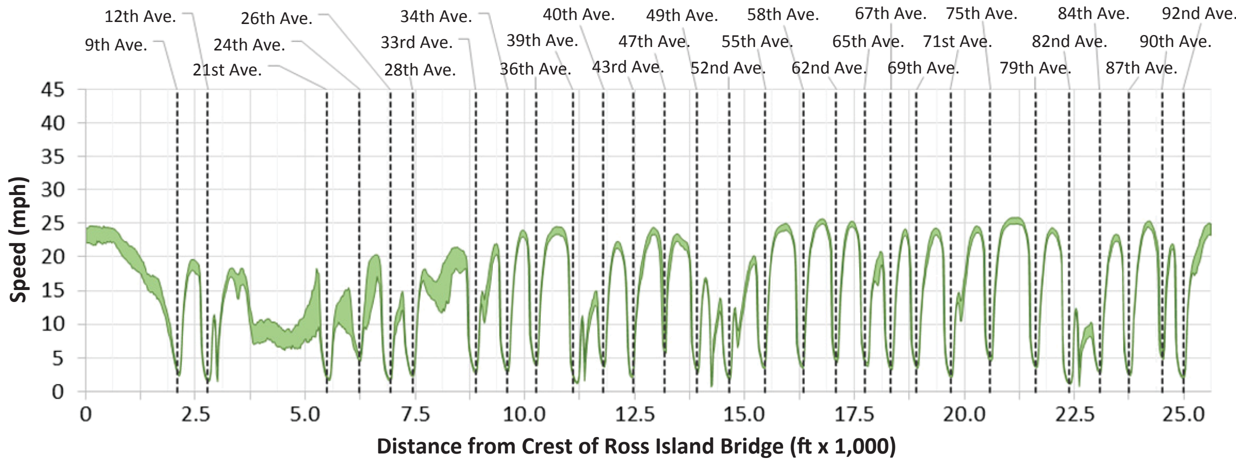
The speed profiles shown in Figures 2 and 3 seem to properly capture delays at bus stops and intersections. In the next section the findings are validated by comparing the dips in speed profiles against estimated traffic signal data delays.

COMPARING SIGNALIZED INTERSECTION DELAYS

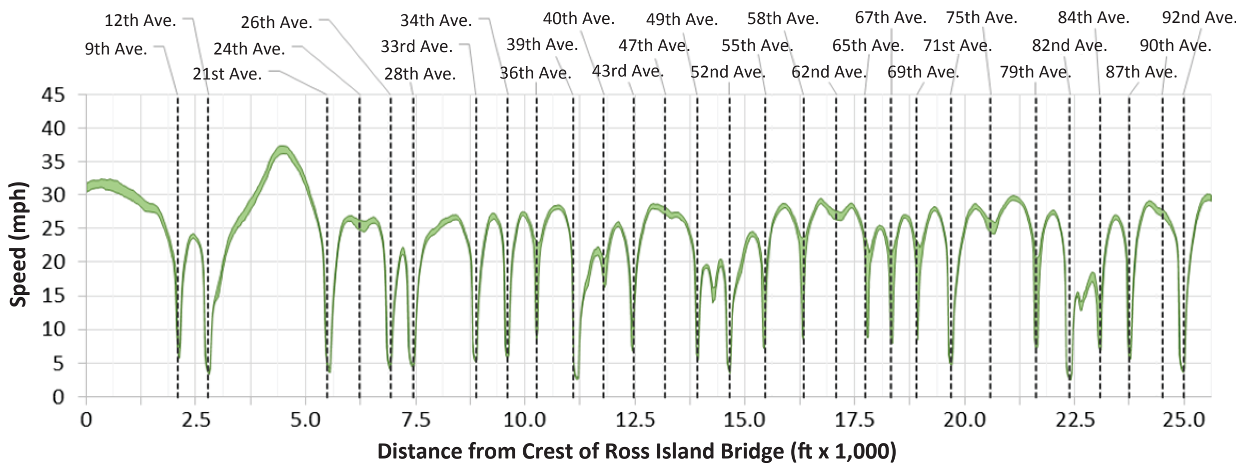
Traffic signal uniform delay and variability were calculated for all intersections in the study area. The intersections in the analysis will be denoted by the following indexes:

- u = signalized intersection, $\forall u \in U = \{1, 2, 3, \ldots, n_U\}$, and
- n_U = number of signalized intersections

The variance of uniform delay has been studied previously (*13*). The current study utilizes the equations developed by Fu and Hellinga (*13*)



(a)



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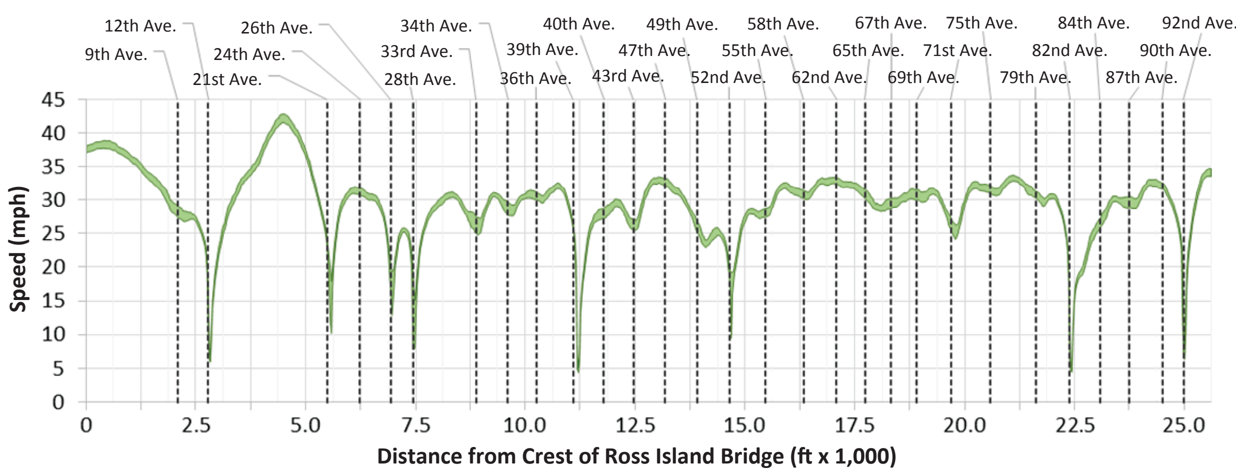


(c)

FIGURE 2 Westbound bus speeds with $\alpha = 0.01$ (direction of travel is from right to left, bus stop locations are labeled): (*a*) 15th percentile, (*b*) 50th percentile, and (*c*) 85th percentile.

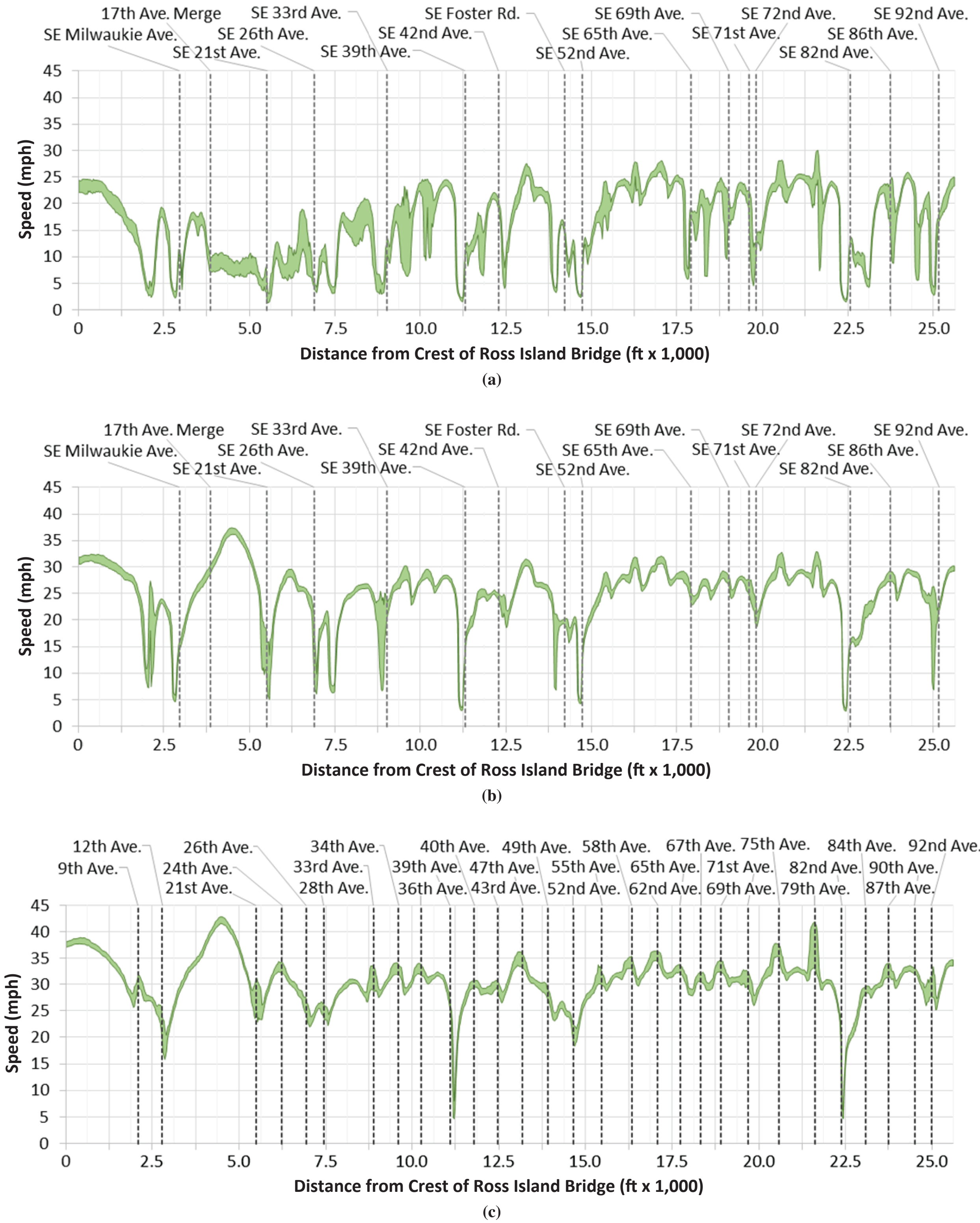


FIGURE 3 Westbound bus speeds without dwell times with $\alpha = 0.01$ (direction of travel is from right to left, bus stop locations are labeled): (*a*) 15th percentile, (*b*) 50th percentile, and (*c*) 85th percentile.

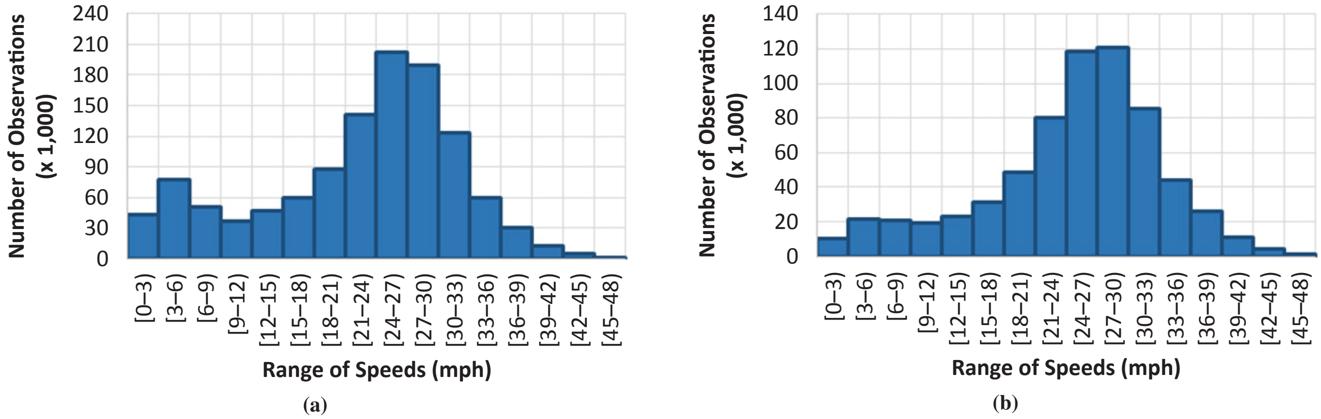


FIGURE 4 Westbound speed histogram: (*a*) with dwell times and (*b*) without dwell times.

to predict the standard deviation of signal delay with the following formulas:

$$D_u = \frac{0.5 \cdot C\left(1-\frac{g}{C}\right)^2}{1-\left[\min\left(1,\frac{v}{c_a}\right)\cdot\frac{g}{C}\right]} \tag{6}$$

$$\operatorname{var}[D_u] = \frac{C^2 \cdot \left(1-\frac{g}{C}\right)^3 \cdot \left(1+3\cdot\frac{g}{C}-4\cdot\min\left(1,\frac{v}{c_a}\right)\cdot\frac{g}{C}\right)}{12\cdot\left(1-\min\left(1,\frac{v}{c_a}\right)\cdot\frac{g}{C}\right)^2} \tag{7}$$

where

- g = effective green time,
- r = effective red time (Table 1),
- C = cycle length,
- s = saturation flow rate (Table 1),
- $c_a = s\ g/\mathrm{C}$ = lane group capacity, and
- v = traffic volume.

D_u and var[D_u] are the mean and variability of the uniform delay for signalized intersection u. Green, red, and cycle times vary significantly along the corridor, as shown in Table 1. By applying the formulas for D_u and var[D_u], it is possible to approximately estimate uniform red delay distributions. Because of the long tails of the normal distribution, there are negative delay values that are associated with zero delay or green-light events; that is, the bus reached the signalized intersection during its green phase. The distribution for 82nd Avenue is shown in Figure 5; according to Fu and Hellinga, only 7.9% of vehicles will experience no delay at this intersection (*13*). Delays for the 15th and 85th percentile of vehicles can be estimated on the basis of the 15% cumulative delay and the 85% cumulative delay.

Table 2 shows that only the intersections at SE Powell Boulevard and Cesar Chavez Boulevard (39th Avenue) and SE Powell Boulevard and 82nd Avenue present significant delays for more than 85% of the vehicles. These values validate the 85th percentile speed drop that buses show at SE Powell Boulevard and Cesar Chavez Boulevard (39th Avenue) and SE Powell Boulevard and 82nd Avenue; other intersections do not show a major speed drop (see Figures 2*c* and 3*c*).

TIME-OF-DAY SPEED HEAT MAPS

Speed data can also be viewed by time of day by applying a moving average within a range of times across an entire day. The time-of-day plots shown in Figures 6 and 7 are produced by using the harmonic mean for westbound buses from the first scheduled trips at 4:00 a.m. until midnight with averages calculated over the 15-day study period.

The diagrams for speed by time of day in the westbound direction (Figure 6) show some unique features of this travel direction. For example, both the morning and evening peaks affect buses on Powell Boulevard up to the Ross Island Bridge. In the morning peak, buses are traveling less than 10 mph (16 km/h) for almost 2 mi (1.6 km). Congestion is highly correlated with slow speeds, and as such, low

TABLE 1 Effective Green Time, Red Time, Cycle Length, Traffic Volume, and Saturation Flow Used for Analysis

	Westbound			Eastbound		
Intersection	*g*	*r*	*C*	*g*	*r*	*C*
SE Powell Blvd. and Milwaukie (12th Ave.)	69	46	115	60	55	115
SE Powell Blvd. and 21st Ave.	101	29	130	101	29	130
SE Powell Blvd. and 26th Ave.	85	38	123	85	38	123
SE Powell Blvd. and 33rd Ave.	115	17	132	115	17	132
SE Powell Blvd. and Cesar Chavez Blvd. (39th Ave.)	50	65	115	50	65	115
SE Powell Blvd. and 42nd Ave.	104	27	131	104	27	131
SE Powell Blvd. and 50th Ave.	64	54	118	72	46	118
SE Powell Blvd. and 52nd Ave.	92	34	126	82	44	126
SE Powell Blvd. and 65th Ave.	86	14	100	86	14	100
SE Powell Blvd. and 69th Ave.	189	11	200	188	12	200
SE Powell Blvd. and 71st Ave.	81	19	100	85	15	100
SE Powell Blvd. and 72nd Ave.	84	16	100	83	17	100
SE Powell Blvd. and 82nd Ave.	60	110	170	60	110	170
SE Powell Blvd. and 86th Ave.	110	15	125	110	15	125
SE Powell Blvd. and 90th Ave.	45	80	125	45	80	125

NOTE: On the basis of annual average daily traffic on Powell Blvd., v (vph) westbound = 787; v (vph) eastbound = 923; saturation flow rate = 1,900.

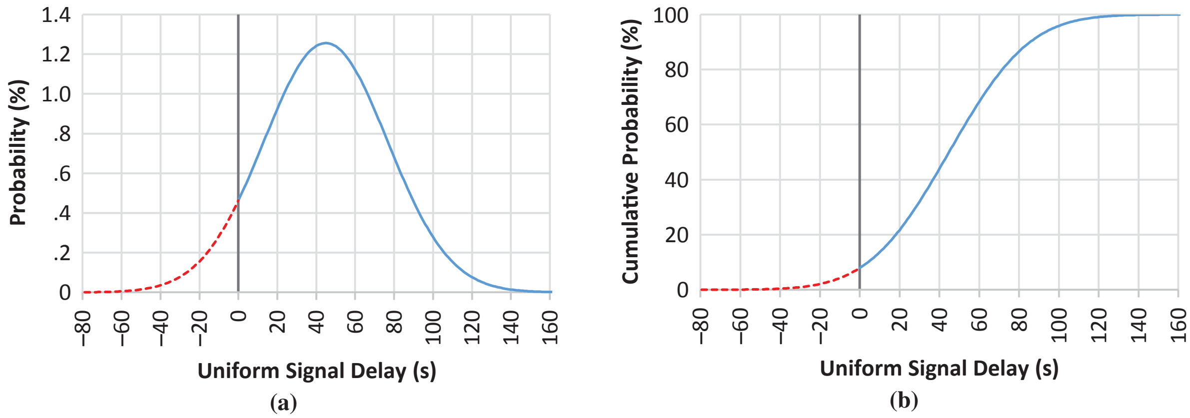


FIGURE 5 Estimated delay at SE Powell Boulevard and 82nd Avenue: (*a*) probability density function and (*b*) cumulative function.

speeds can be used as a proxy for congestion. Following the merge of 17th Avenue, buses can travel along a short, bus-only lane. This facility accounts for the sudden speed increase following the merge. In addition, these plots illustrate how some intersections, such as 82nd, 50th (SE Foster), and 39th Avenues, show slow speeds throughout the day rather than just in the morning or evening peak. In contrast, eastbound travel (Figure 7) does not show the same decrease in speed. There are lower speeds during the evening peak travel period, mainly between 4:00 p.m. and 6:30 p.m.; likely the congestion and queuing are not as severe as is shown in Figure 6.

PEAK-HOUR VERSUS WHOLE-DAY TRANSIT PERFORMANCE MEASURES

The previous analyses have been useful to identify bus stops with long dwell times and (after dwell times are removed) segments or intersections with low performance. However, the speed heat maps shown in Figures 6 and 7 indicate that not all the stops or segments have long travel times throughout the day. Hence, whole-day speed profiles like Figures 2 and 3 may conceal low-performance conditions that may occur only for a few hours in the morning or evening.

To identify segments or locations where low performance only takes place during peak hours, the following performance measure is proposed: the speed difference (Δv_i) between the high and low travel speed percentiles. When this difference is divided by the median travel time, the speed variability index (μ_i) is obtained. With the 85th percentile and the 15th percentile speed, respectively, as a reference for high and low travel speeds, the formulas to obtain the speed difference and the variability index for each segment are the following:

$$\Delta v_i = v_{i,85} - v_{i,15} \tag{8}$$

$$\mu_i = \frac{v_{i,85} - v_{i,15}}{v_{i,50}} \tag{9}$$

TABLE 2 Intersection Delay Along Study Corridor

Intersection	Westbound Percentage—No Delay	Westbound Delay (s) 15th	Westbound Delay (s) Median	Westbound Delay (s) 85th	Eastbound Percentage—No Delay	Eastbound Delay (s) 15th	Eastbound Delay (s) Median	Eastbound Delay (s) 85th
SE Powell Blvd. and Milwaukie (12th Ave.)	22.5	0.0	11.6	27.5	15.1	0.0	17.4	34.8
SE Powell Blvd. and 21st Ave.	32.0	0.0	4.1	13.1	31.9	0.0	4.3	13.7
SE Powell Blvd. and 26th Ave.	27.5	0.0	7.4	20.2	26.9	0.0	7.8	20.8
SE Powell Blvd. and 33rd Ave.	37.1	0.0	1.4	5.7	37.2	0.0	1.4	6.0
SE Powell Blvd. and 39th Ave.	11.6	3.1	23.2	43.3	9.8	4.8	24.3	43.7
SE Powell Blvd. and 42nd Ave.	32.9	0.0	3.5	11.7	32.8	0.0	3.7	12.2
SE Powell Blvd. and 50th Ave.	19.0	0.0	15.6	34.0	21.8	0.0	11.8	27.6
SE Powell Blvd. and 52nd Ave.	29.6	0.0	5.8	17.0	24.4	0.0	10.1	25.3
SE Powell Blvd. and 65th Ave.	36.5	0.0	1.2	4.9	36.5	0.0	1.3	5.2
SE Powell Blvd. and 69th Ave.	41.9	0.0	0.4	2.3	41.7	0.0	0.5	2.8
SE Powell Blvd. and 71st Ave.	33.8	0.0	2.3	7.9	36.0	0.0	1.5	5.8
SE Powell Blvd. and 72nd Ave.	35.4	0.0	1.6	6.1	34.8	0.0	1.9	7.0
SE Powell Blvd. and 82nd Ave.	7.9	12.0	44.9	77.8	6.9	14.1	47.0	79.9
SE Powell Blvd. and 86th Ave.	37.6	0.0	1.1	4.9	37.7	0.0	1.2	5.1
SE Powell Blvd. and 90th Ave.	8.1	8.4	32.3	56.2	7.2	9.9	33.8	57.7

NOTE: Total intersection delay (TID), in seconds: westbound 15th = 23.5, median = 156, 85th = 333; eastbound 15th = 28.8, median = 168, 85th = 348.

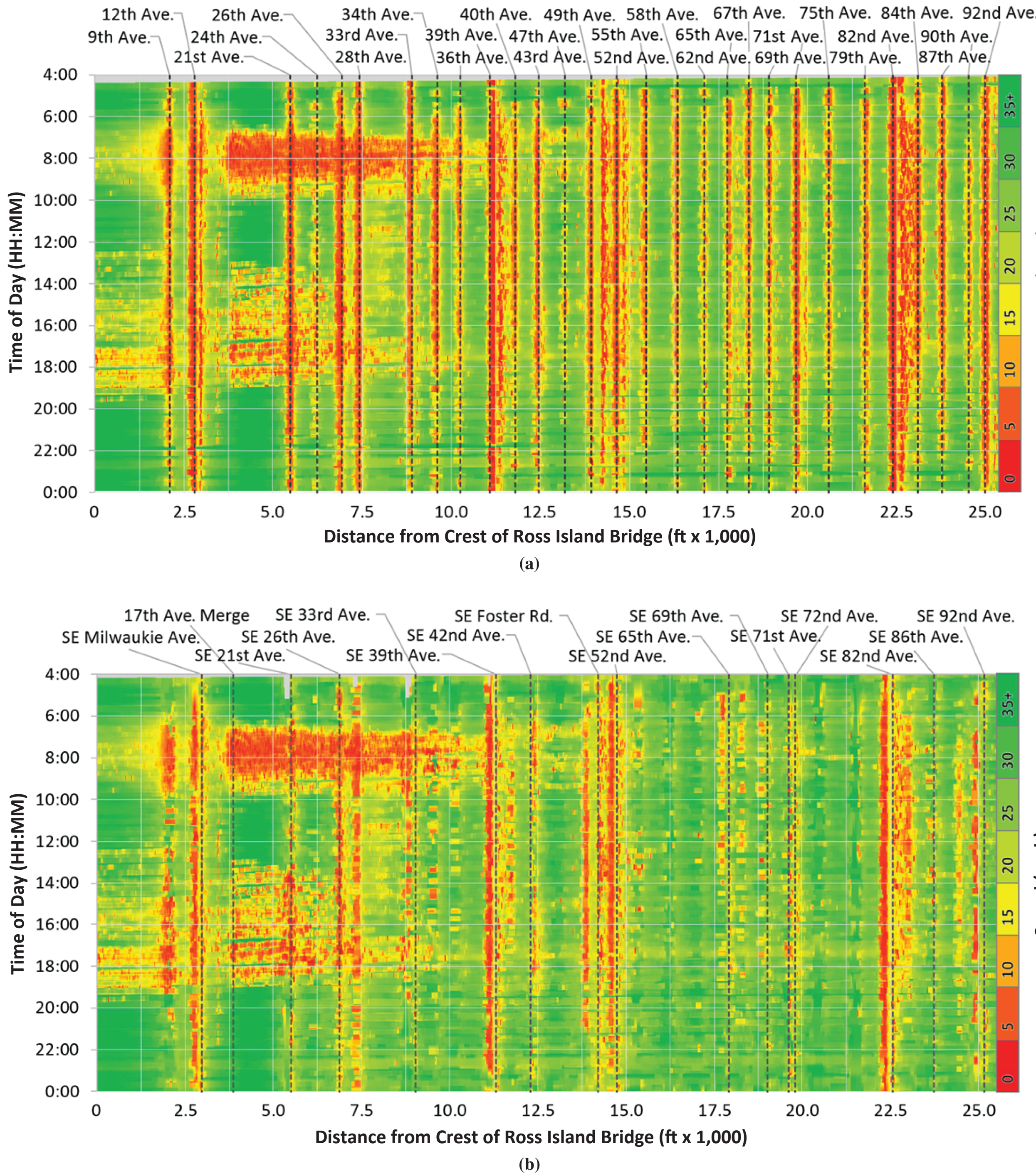


FIGURE 6 Westbound space–time speed diagram (direction of travel from right to left; bus stops and signalized intersections labeled): (*a*) with dwell times and (*b*) without dwell times [HH = hours (2-digit); MM = minutes (2-digit)].

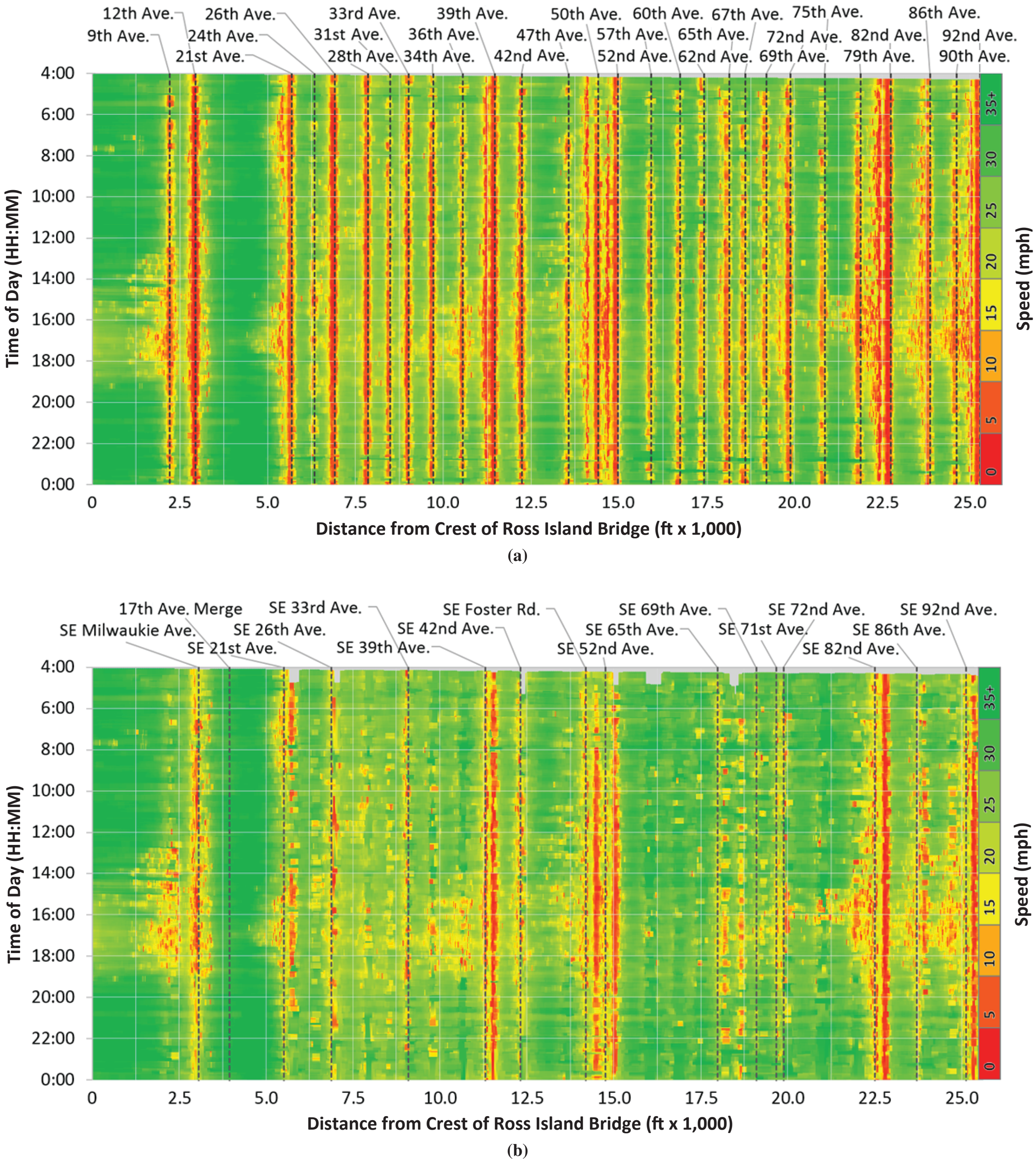


FIGURE 7 Eastbound space–time speed diagram (direction of travel from left to right; bus stops and signalized intersections labeled): (a) with dwell times and (b) without dwell times.

The value of Δv_i provides a direct reference to the speed difference between high- and low-performance periods in segment *i*. The value of $0 \leq \mu_i$ provides a direct reference to the speed difference in relation to the median travel speed in a segment. A value of $\mu_i = 0$ indicates no speed variability (an ideal value); realistic values of low-speed variability are in this interval $0.25 \leq \mu_i \leq 0.50$. A value of $\mu_i \geq 1.0$ indicates severe speed variability in segment *i*. For example, if the median travel speed is 15 mph (25 km/h), the 15th percentile speed is 10 mph (16 km/h), and the 85th percentile is 25 mph (40 km/h), the speed variability index is equal to 1, $\mu_i = 1.0$.

Figure 8 shows graphs for westbound speed differences. In Figure 8*a* it is possible to see that the area around the 17th Avenue ramp merge shows a speed difference that dwarfs the differences at the bus stops. Bus stops that are busy throughout the day, such as 82nd and 39th Avenues, show the lowest values. When dwell times are removed (Figure 8*b*), it is possible to more clearly distinguish segments with low performance at peak hours, such as nearby SE 33rd or 65th Avenues; this performance matches the changes observed in Figure 6*b*.

Figure 9 shows graphs for the westbound variability index (μ_i). It is possible to observe variability index values of up to 5 and that the segments near SE 82nd and SE 39th Avenues have the highest variability index with (Figure 9*a*) and without (Figure 9*b*) dwell times. Removing the dwell times clearly highlights the delays that take place at the other major intersections, SE Milwaukie (SE 12th) and SE 50th to 52nd Avenues; this finding is congruent with the values presented in Table 2. Also, several blocks of congestion around SE 50th to 52nd Avenues can be seen in the heat map presented in Figure 6.

Figure 10 presents graphs for the eastbound variability index (μ_i). There are some clear differences when westbound and eastbound values are compared; for example, the intersection at SE 92nd Avenue has significantly higher speed variability for eastbound trips. After dwell times are removed, it is possible to observe many segments with a low variability index ($\mu_i < 0.5$). It is possible to observe variability index values higher than 5 around SE 50th to 52nd Avenues; this finding is congruent with the values presented in Table 2 and the speed heat map shown in Figure 7.

The proposed performance measures can be estimated for daily speed distributions or at hourly intervals to examine how transit performance changes hourly. Figure 11*a* shows the speed difference (Δv_i) by hour of the day for westbound travel. Again, speed changes at the 17th Avenue on-ramp merge are clearly displayed

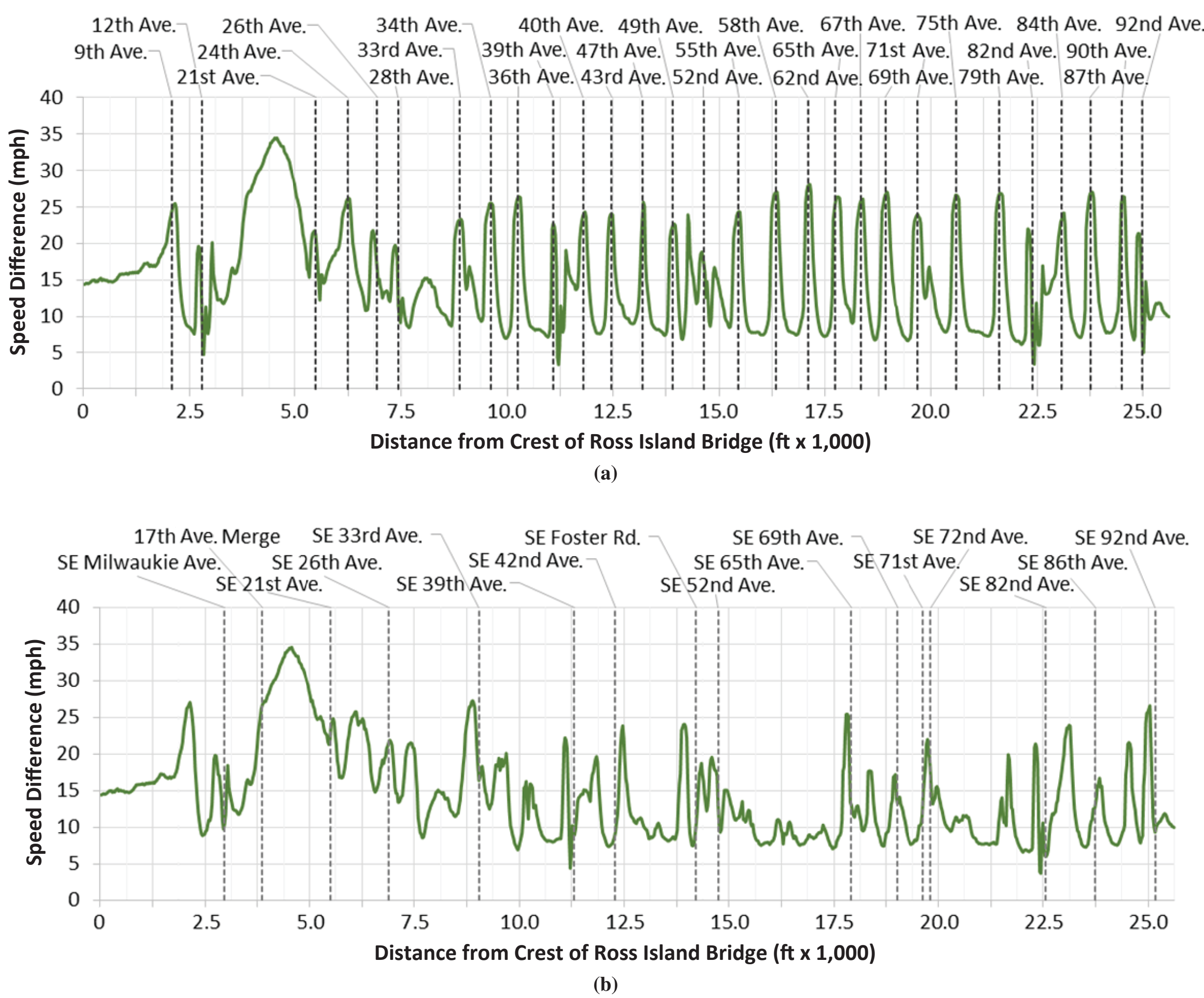
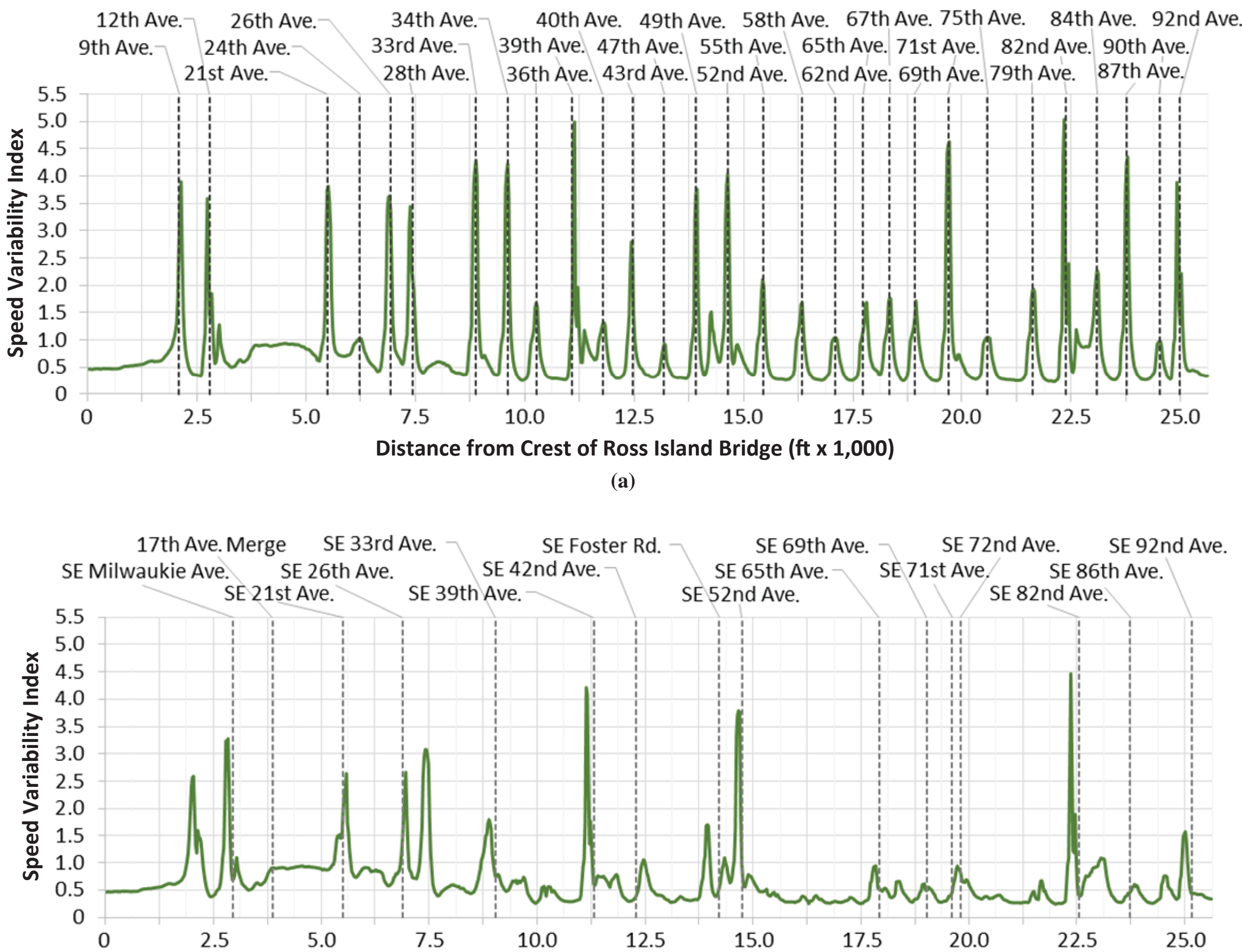


FIGURE 8 Westbound $\Delta v_i = v_{i,85} - v_{i,15}$ (direction of travel from right to left; bus stops and signalized intersections labeled): (*a*) with dwell times and (*b*) without dwell times.



(a)

(b)

FIGURE 9 Westbound speed variability index μ_i (direction of travel from right to left; bus stops and signalized intersections labeled): (*a*) with dwell times and (*b*) without dwell times.

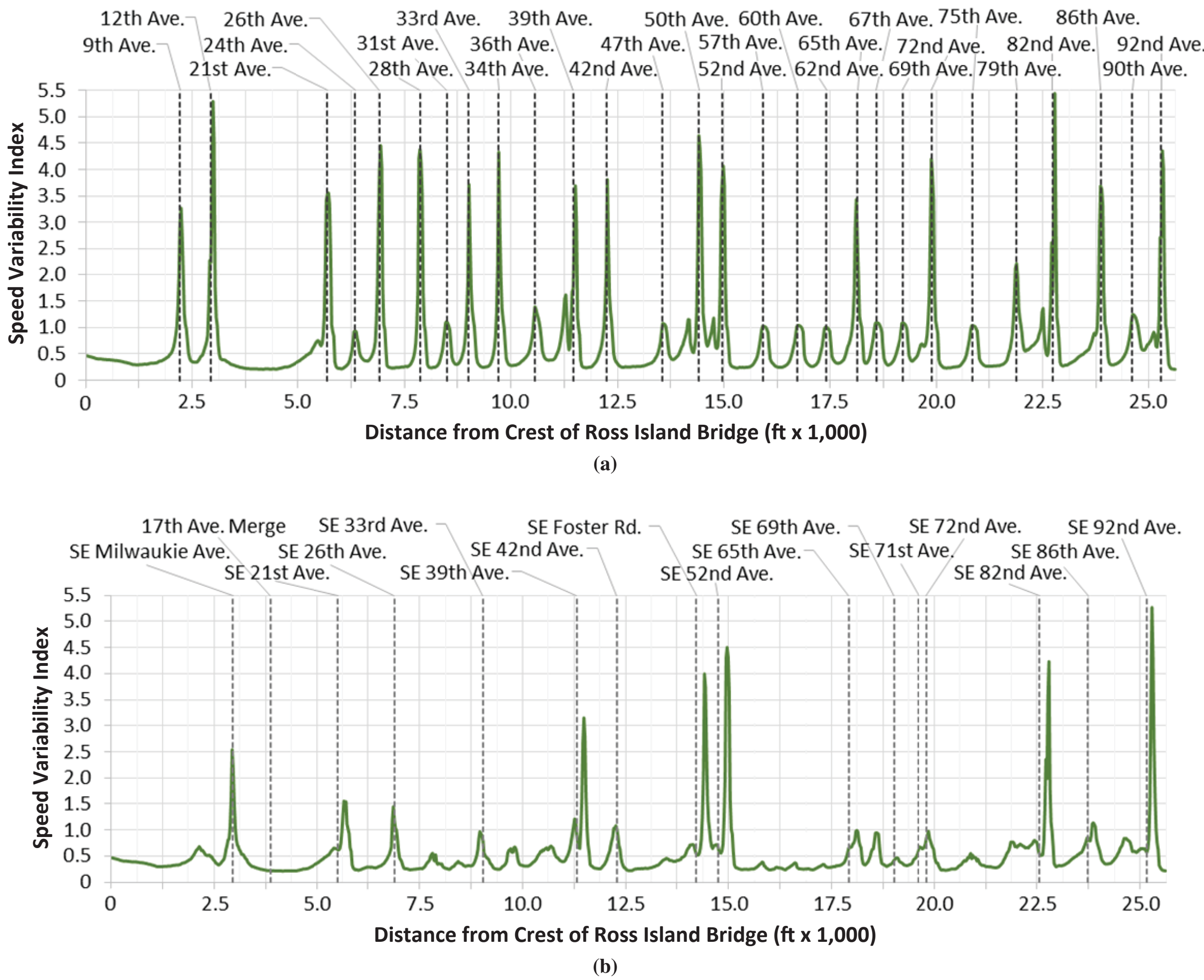
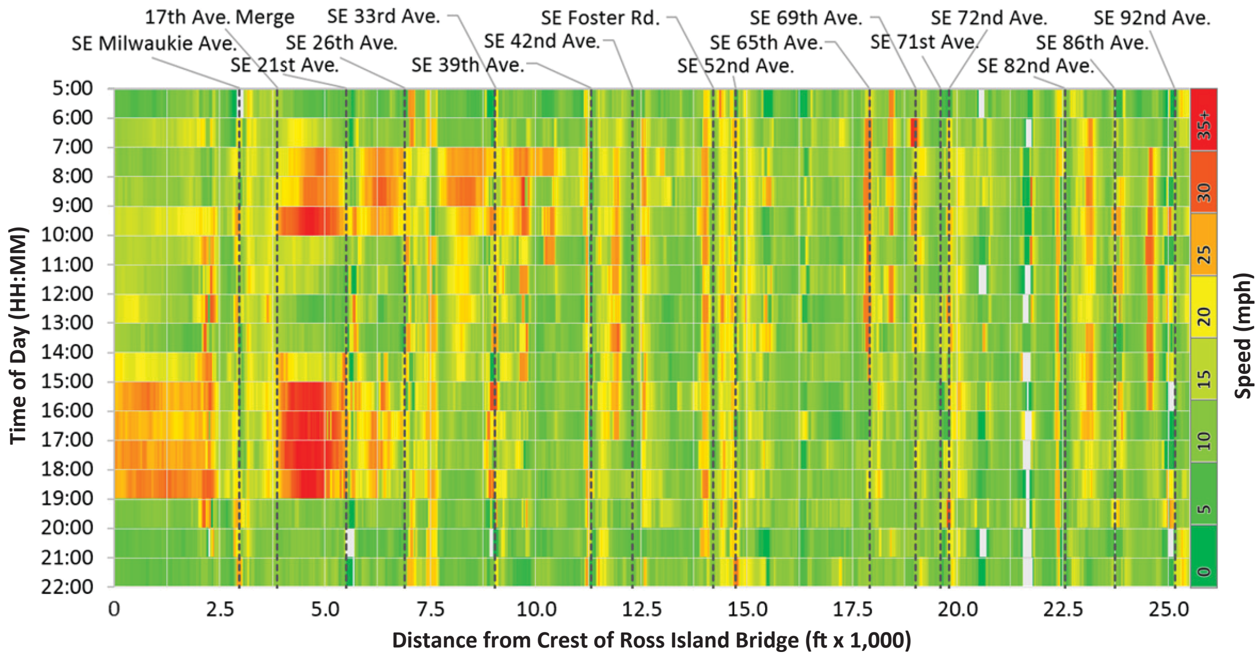
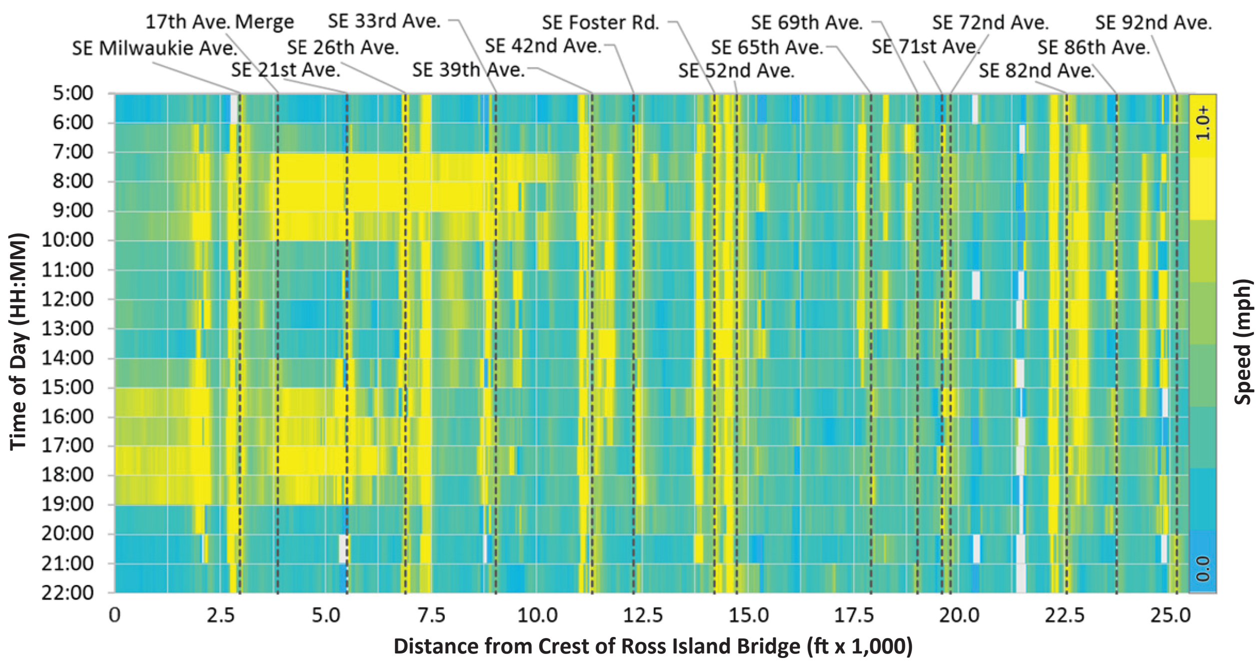


FIGURE 10 Eastbound speed variability index μ_i (direction of travel from left to right; bus stops and signalized intersections labeled): (*a*) with dwell times and (*b*) without dwell times.



(a)



(b)

FIGURE 11 Performance by hour: (*a*) westbound $\Delta v_i = v_{i,85} - v_{i,15}$ with dwell time data (travel from right to left) and (*b*) westbound speed variability index μ_i with dwell time data.

during the morning and evening peak hours. Even without removal of dwell time data, speed changes due to traffic congestion are readily observable. Figure 11*b* shows the speed variability index (μ_i) by hour of the day for westbound travel. The heat map shows yellow areas with high speed variability. In Figure 11 it is possible to easily rank segments and times of day with high speed variability and traffic congestion, even when the dwell time data are not removed.

CONCLUSIONS

This study proposes novel reliability measures that exploit recently available, fine-granularity transit GPS data. Formulas are provided to estimate travel speed percentiles and associated confidence intervals.

Novel performance indexes are proposed to identify corridor sections or intersections with low performance throughout the day, that is, by utilizing the 85th-speed percentiles. To identify sections with low performance during peak hours or throughout the day, or both, the speed difference (Δv_i) and speed variability index (μ_i) are proposed. The new methodology was successfully applied to understand causes of delay along a transit corridor; problematic segments and intersections were readily identified and visualized. The comparison of daily and hourly performance measures is also useful to localize, visualize, and rank congested segments and problematic intersections.

The results of this research are valuable for both transit operators and city or state transportation agencies. The methodology of this study provides a novel framework to study transit routes and diagrams that can deliver clear insights regarding when and where transit transportation infrastructure improvements are needed.

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Any errors or omissions are the sole responsibility of the authors.

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