Novel Methodology to Estimate Traffic and Transit Travel Time Reliability Indices and Confidence Intervals at a Corridor and Segment Level

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Paper # **17-06136**

Submitted: 29 July 2016
Revisions Submitted: 15 November 2016
Final Paper Submitted: 12 March 2017

Submitted for presentation at the 96th Annual Meeting of the Transportation Research Board (8–12 January 2017) and for publication in *Transportation Research Record*.

Word count: 4217 + (2 tables and 11 figures) * 250 = 7467 total words (including references)

ABSTRACT
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 hotspots; 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, heatmaps, and visualizations are employed to highlight sections and intersections with high travel-time variability and transit low 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.

KEYWORDS
Transit, Travel Time, Performance Measures, Reliability, Percentile, Confidence Interval

INTRODUCTION

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 collects data by matching MAC addresses from *numerous different* vehicles passing by *relatively few fixed* locations along a route. Bus GPS data is intrinsically different. Stop level and high-resolution data sets are collected by buses without matching; the location of the high-resolution data does not take place at specific locations; relatively *few vehicles* (buses) collect *numerous* GPS timestamps 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 nearby bus stops. The availability of bus stop-level data was a great improvement but limited the analysis to route or segment levels. For example, with stop-level GPS data it is not possible to readily study the impact of traffic signals on bus travel times.

This study takes advantage of the recent availability of fine-granularity data (FGD), which collects five-second 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; i.e. the analysis is not limited to the study of stop-to-stop segments or complete routes. Utilizing FGD method to estimate travel-time percentiles and confidence intervals is proposed.

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*). Researches have attempted to quantify transit travel-time variability, but in the past the lack of widespread datasets 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 effects showed how traffic volumes, 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, 7, 8, 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 is 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 (*4*-*9*) were severely limited by the lack of GPS coordinates between bus stops. The recent availability of five-second 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, etc. (*10*). Unlike previous studies, this 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 performances 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 non-overlapping segments denoted by the capital letter S; the midpoint of each segment forms the set of points P. The sub-index i is utilized to denote any segment s_i and corresponding midpoint p_i. The total number of segments is denoted as 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, then $v_{i,p}$ is the p^{th} percentile of travel speeds obtained from V_i in segment i. A pair of GPS points produce 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.

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

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*):

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

$$[p\, n_{Ji} - \sigma_{ip}\, z(\alpha),\, p\, n_{Ji} + \sigma_{ip}\, z(\alpha)]$$

This interval provides the indices 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 to speed v_{ij} to travel segment i. After obtaining a set of travel times for a given segment, 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 $i = n_I$.

$$\bar{T} = \sum_{i=1}^{n_I} (\bar{t}_i)$$
$$T_p = \sum_{i=1}^{n_I} (v_{i,p})$$

By using an algorithm that matches GPS points from the high-resolution data to individual stop events using day, bus number, and time, two points preceding and two point following each stop event are removed. This clean high resolution data is 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 (NE) Kelly & 5th to the intersection of northwest (NW) 6th & Flanders in Portland, Oregon. Route 9 was chosen because the researchers have an excellent knowledge, from previous studies, of traffic patterns, bus operations, and the geometry of the roadways and bus stops. This analysis will focus on a westbound and eastbound segment of Powell between I-205 and the Willamette River, in this 4.83 mile (25,500 ft. (7772 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 to downtown Portland and carries more than 40,000 vehicles daily. The left 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 five-second bus GPS data. The accuracy of the archived data has been validated both by TriMet and researchers using Wavetronix sensors *(12)*. There is a high level of correlation between traffic speeds and speeds estimated utilizing bus GPS data, especially if the speeds are not estimated within +/-200 feet (61 m.) from a frequently served bus stop. The new GPS data was intended to augment the existing stop-level data sets. Unlike the stop-level data, the new GPS data set collects information between bus stops, allowing the estimation of bus trajectory and speeds between stops. However, unlike the stop-level data, GPS data does not provide information about passenger movements, doors, or other factors that occur at stops themselves; this type of information is only found in the original stop-level data. The GPS data was designed to be recorded only when the bus is not stationary. When a bus stops for more than five seconds the GPS data is not collected, i.e. there are no consecutive points that display different timestamps and the same GPS coordinates. When this happens (i.e. a bus stopping), the interval between consecutive points can be longer than five seconds. It is possible to augment the original stop-level dataset 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. This 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 data. The fourth week of November, Thanksgiving week, was excluded from the analysis due to 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 was 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 feet (7.6 m.). The shortest time period between GPS timestamps is 5 seconds; a bus traveling at 3.4 mph (almost walking speed) covers 25 feet (7.6 m.) in 5 seconds 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 displayed in FIGURE 2. Bus stops are displayed on top, the speed profiles show dramatic changes in travel speeds at and nearby popular bus stops.

The 15th-percentile speed profile clearly shows the impact of delays at bus stops. On the other hand, the 85th-percentile speed profile shows major speed reductions only around the popular stops, i.e. where buses tend to stop more than 85% of the time; see for example 12th-, 39th-, and 82nd-street bus stops. The influence of many of the bus stops appears to fall away for the 50th and 85th percentile buses as compared to the 15th percentile buses. Many of these stops are passed by the majority of the time due to the lack of passengers waiting at the stop and/or onboard passengers wishing to alight. This effect is also seen for signalized intersections where the 85th fastest buses are reaching the lights when they are green.

FIGURE 3 shows calculated speeds and their confidence intervals after stop events have been removed from the dataset, i.e. after removing the GPS coordinates around bus stops when a bus services a stop. The location of intersections is displayed on top. FIGURE 4 shows how the speed histogram changes after removing GPS data of buses that have served a bus stop.

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

The speed data that includes dwell-time speed has a bimodal distribution whereas the data without dwell times is unimodal (see FIGURE 4). Due to 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. The next section validates the findings 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 index:

$u =$ signalized intersection $\quad \forall u \in U = \{1,2,3,\dots,n_U\}$
$n_U =$ number of signalized intersections.

The variance of uniform delay has been previously studied (*13*). This study utilizes the equations developed in (*13*) to predict the standard deviation of signal delay with the following notation and formulas:

$g =$ effective green time
$r =$ effective red time
$C =$ cycle length
$s =$ saturation flow rate
$c_a = s\frac{g}{C} =$ lane group capcity
$v =$ traffic volume

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

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

D_u and $\mathrm{Var}[D_u]$ are the mean and variability of the uniform delay for signalized intersection u. Green, red, and cycle times do vary significantly along the corridor as shown in TABLE 1. Applying the formulae for D_u and $\mathrm{Var}[D_u]$ it is possible to approximately estimate uniform red delay distributions. Due to the long tails of the normal distribution, there are negative delay values that are associated to zero delay or green-light events, i.e. the bus reached the signalized intersection during its green phase. The distribution for 82nd street is shown in FIGURE 5; according to (*13*) only 7.9% of vehicles will experience no delay at this intersection. Delays for the 15th and 85th percentile of vehicles can be estimated based on the 15% cumulative delay and the 85% cumulative delay.

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

TIME OF DAY SPEED HEATMAPS

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 showed in FIGURE 6 and 7 are produced using the harmonic mean for westbound buses, from the first scheduled trips at 4:00 a.m. until midnight using averages calculated over the 15-day study period.

The visuals 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 peak affect buses on Powell up to the Ross Island Bridge. In the morning peak, buses are traveling less than 10 mph (16 kph) for almost two miles (1.6 km). Congestion is highly correlated with slow speeds, as such, low 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 accounts for the sudden speed increase following the merge. Additionally, these plots also illustrate how some intersections, such as 82nd, 50th (SE Foster), and 39th show slow speeds throughout the day rather than just at the morning or evening peak. On the other hand, eastbound travel (FIGURE 7) does not show the same decrease in speeds. 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 is not as severe as 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 removing dwell times) segments or intersections with low performance. However, the speed heatmaps 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 take only for a few hours in the morning or evening.

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

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

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

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 between in relation to the median travel speed in a segment. A value $\mu_i = 0$ 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 $\mu_i \geq 1.0$ indicates severe speed variability in segment i. For example, if the median travel speed is 15 mph (25 kph), the 15th percentile 10 mph (16 kph) and the 85th percentile 25 mph (40 kph) the speed variability index is equal to one, $\mu_i = 1.0$.

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

FIGURE 9 presents a graph 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 have the highest variability index with, see FIGURE 9 (a), and without dwell times, see FIGURE 9 (b). Removing the dwell times though clearly highlight the delays that take place at the other major intersections, SE Milwaukee (SE 12th) and SE 50th-52nd, which is congruent with the values presented in TABLE 2. Also, several blocks of congestion around SE 50th-52nd Avenues can be seen in the heatmap presented in FIGURE 6.

FIGURE 10 presents a graph for the Eastbound variability index (μ_i). There are some clear differences when comparing Westbound and Eastbound values, for example the intersection at SE 92nd has significantly higher speed variability for Eastbound trips. After removing dwell times it is possible to observe many segments with low variability index ($\mu_i < 0.5$). It is possible to observe variability index values higher than 5 around SE 50th-52nd which is congruent with the values presented in TABLE 2 and the speed heatmap 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 11a shows the speed difference (Δv_i) by hour of the day for westbound travel. Again, speed changes at the 17th street on-ramp merge are clearly displayed during the morning and evening peak hours. Even without removing dwell time data, speed changes due to traffic congestion are readily observable. FIGURE 11b shows the speed variability index (μ_i) by hour of the day for westbound travel. The heatmap shows yellow areas with high speed variability. In this figure it is possible to easily rank segments and times of day with high speed variability and traffic congestion, even when the dwell time data is not removed.

CONCLUSIONS

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

Novel performance indices are proposed to identify corridor sections or intersections with low-performance throughout the day, i.e. utilizing the 85th speed percentiles. To identify sections with low-performance during peak-hours and/or throughout the day, 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 are 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/state transportation agencies. The methodology of this study provide a novel framework to study transit routes and visuals that can deliver clear insights regarding when and where transit transportation infrastructure improvements are needed.

ACKNOWLEDGEMENTS

The authors would like to thank TriMet staff members Steve Callas and Miles J. Crumley for graciously providing the data sets used in this analysis and for their support in understanding the intricacies of how the data is structured. The authors would like to thank Jacoba Lawson and Ellen Bradley for carefully editing and proofreading the paper. The authors would also like to acknowledge the support of NITC (National Institute for Transportation and Communities) transportation center for funding this research effort. Any errors or omissions are the sole responsibility of the authors.

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LIST OF TABLES

LIST OF FIGURES

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

	Westbound			Eastbound		
	g	**r**	**C**	**g**	**r**	**C**
SE Powell & Milwaukie (12th)	69	46	115	60	55	115
SE Powell & 21st	101	29	130	101	29	130
SE Powell & 26th	85	38	123	85	38	123
SE Powell & 33rd	115	17	132	115	17	132
SE Powell & Cesar Chavez Blvd (39th)	50	65	115	50	65	115
SE Powell & 42nd	104	27	131	104	27	131
SE Powell & 50th	64	54	118	72	46	118
SE Powell & 52nd	92	34	126	82	44	126
SE Powell & 65th	86	14	100	86	14	100
SE Powell & 69th	189	11	200	188	12	200
SE Powell & 71st	81	19	100	85	15	100
SE Powell & 72nd	84	16	100	83	17	100
SE Powell & 82nd	60	110	170	60	110	170
SE Powell & 86th	110	15	125	110	15	125
SE Powell & 90th	45	80	125	45	80	125
v [veh/h]*	787			923		
s [veh/h]	1900					

** Based on AADT of Powell BLVD*

TABLE 2 Intersection Delay along the Study Corridor

		Westbound Delay [sec]				**Eastbound Delay [sec]**		
	Westbound Percent No Delay	**15th**	**Median**	**85th**	**Eastbound Percent No Delay**	**15th**	**Median**	**85th**
SE Powell & Milwaukie (12th)	22.5%	0.0	11.6	27.5	15.1%	0.0	17.4	34.8
SE Powell & 21st	32.0%	0.0	4.1	13.1	31.9%	0.0	4.3	13.7
SE Powell & 26th	27.5%	0.0	7.4	20.2	26.9%	0.0	7.8	20.8
SE Powell & 33rd	37.1%	0.0	1.4	5.7	37.2%	0.0	1.4	6.0
SE Powell & 39th	11.6%	3.1	23.2	43.3	9.8%	4.8	24.3	43.7
SE Powell & 42nd	32.9%	0.0	3.5	11.7	32.8%	0.0	3.7	12.2
SE Powell & 50th	19.0%	0.0	15.6	34.0	21.8%	0.0	11.8	27.6
SE Powell & 52nd	29.6%	0.0	5.8	17.0	24.4%	0.0	10.1	25.3
SE Powell & 65th	36.5%	0.0	1.2	4.9	36.5%	0.0	1.3	5.2
SE Powell & 69th	41.9%	0.0	0.4	2.3	41.7%	0.0	0.5	2.8
SE Powell & 71st	33.8%	0.0	2.3	7.9	36.0%	0.0	1.5	5.8
SE Powell & 72nd	35.4%	0.0	1.6	6.1	34.8%	0.0	1.9	7.0
SE Powell & 82nd	7.9%	12.0	44.9	77.8	6.9%	14.1	47.0	79.9
SE Powell & 86th	37.6%	0.0	1.1	4.9	37.7%	0.0	1.2	5.1
SE Powell & 90th	8.1%	8.4	32.3	56.2	7.2%	9.9	33.8	57.7
Total Intersection Delay (TID) [sec]		23.5	156	333	**(TID) [sec]**	28.8	168	348

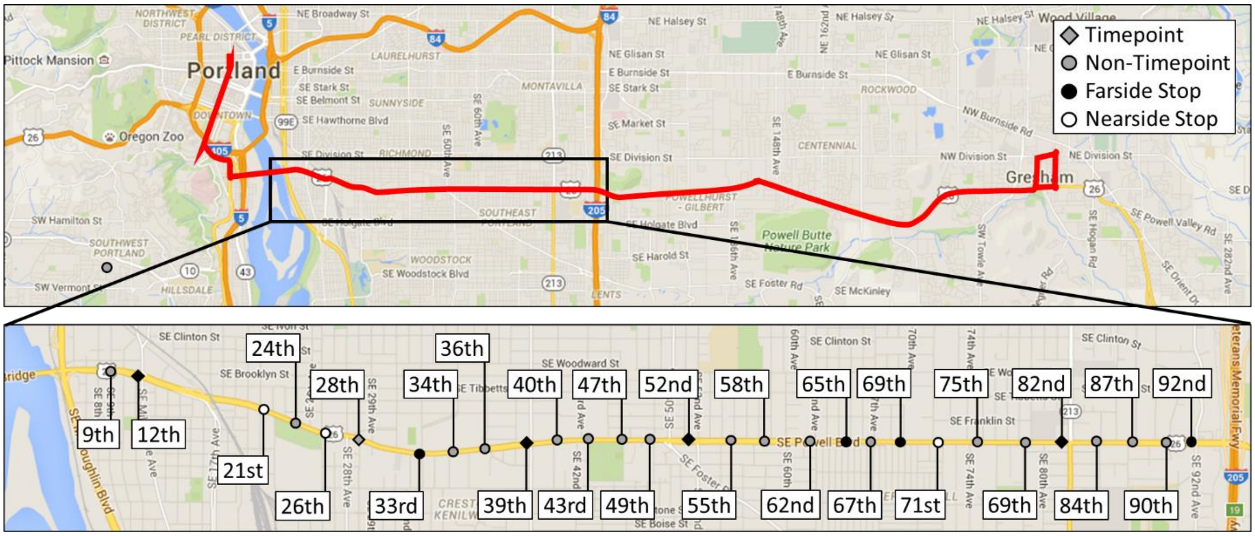
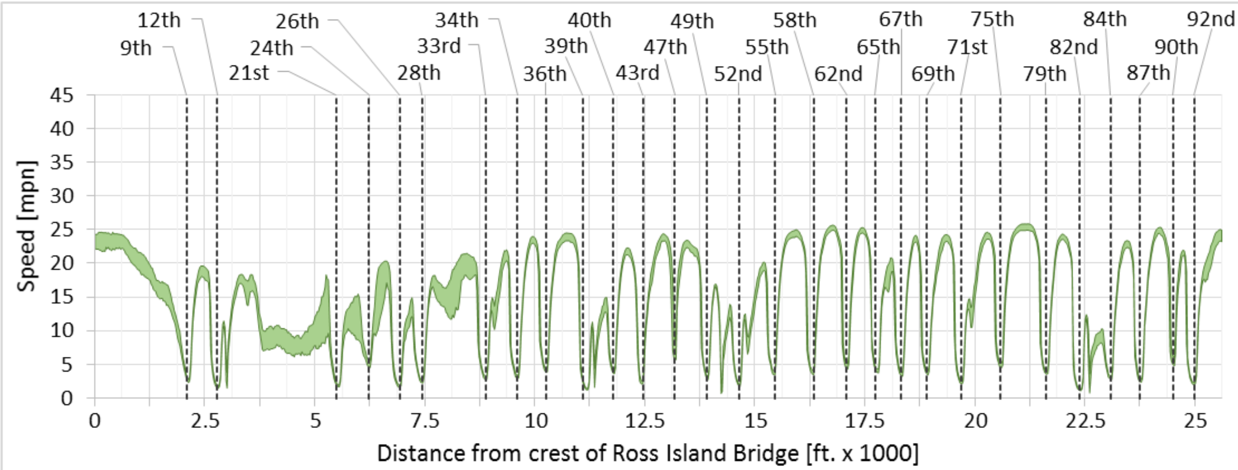
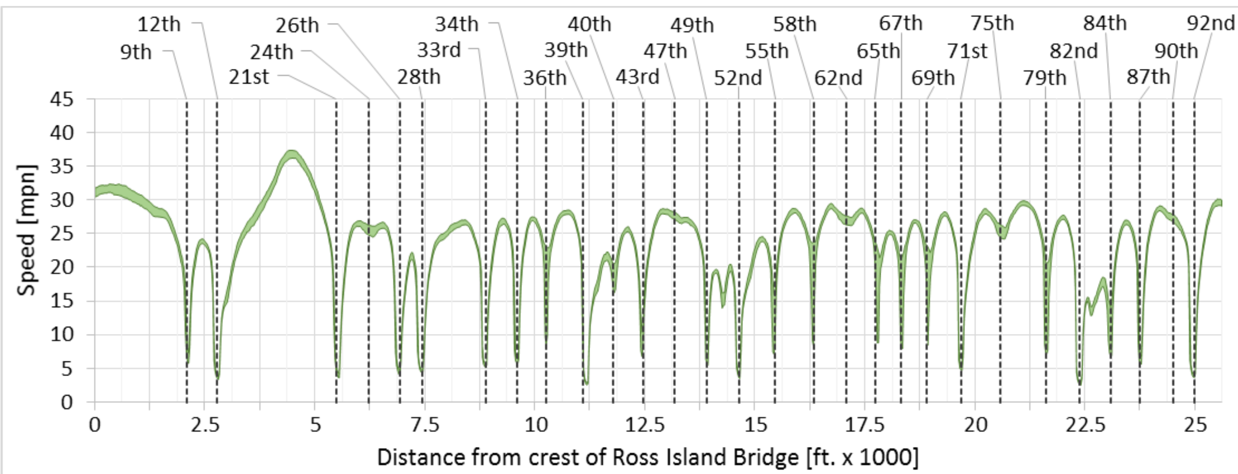


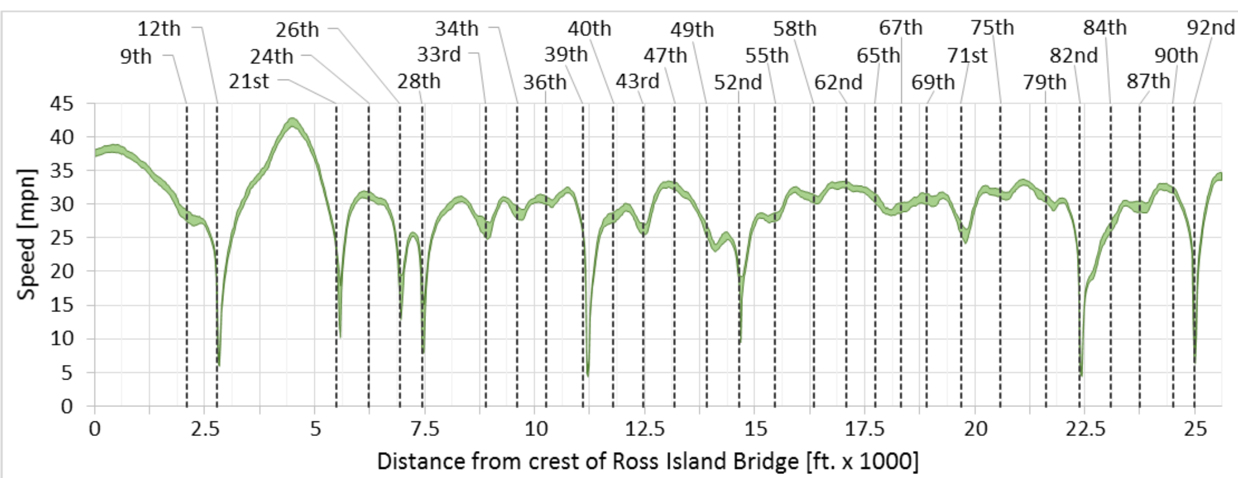
FIGURE 2 Map of study area in Portland, OR. The bus stops shown for westbound buses.



(a) 15th Percentile (bus stop locations are labeled)

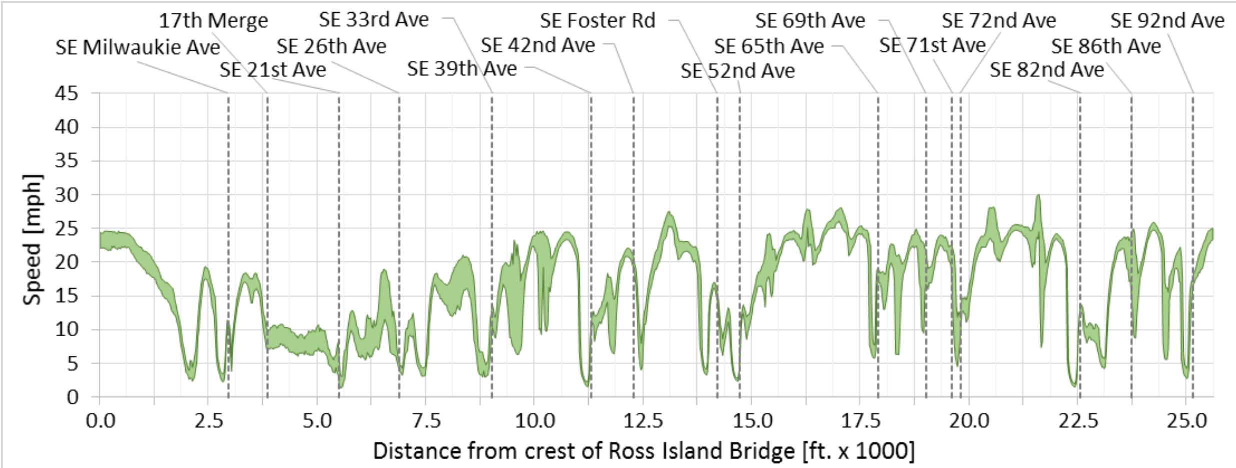


(b) 50th Percentile (bus stop locations are labeled)

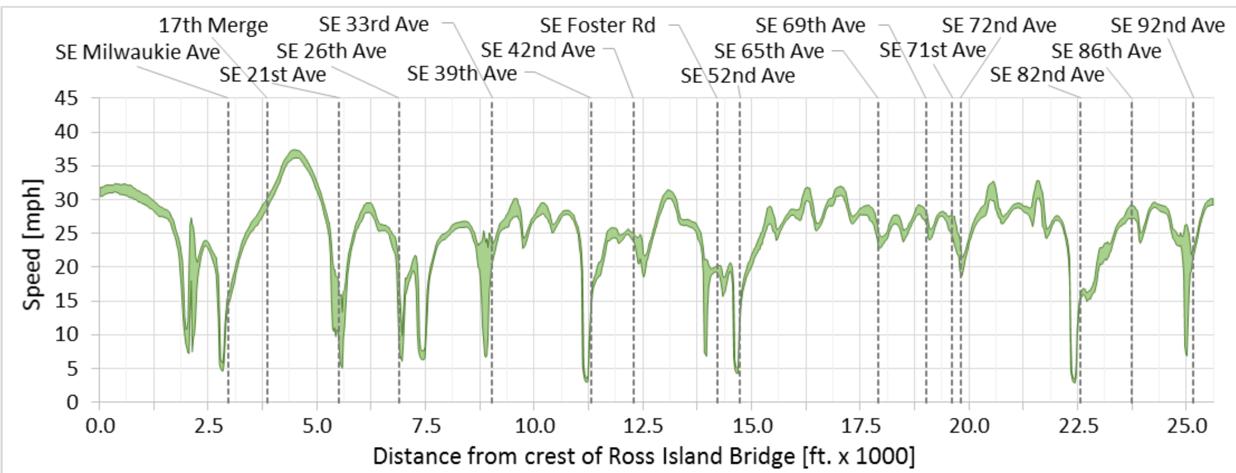


(c) 85th Percentile (bus stop locations are labeled)

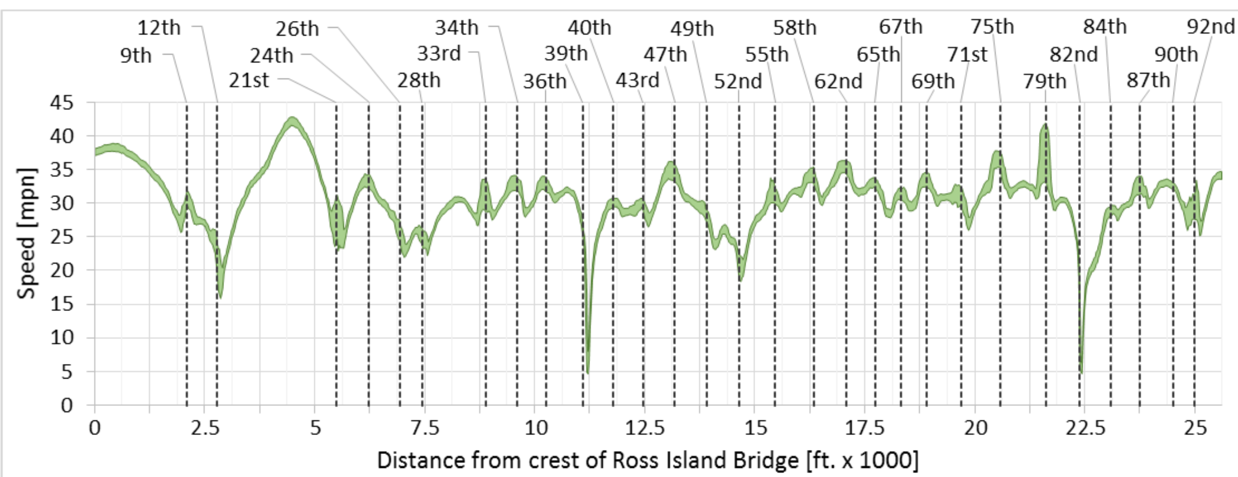
FIGURE 3 Westbound bus speeds with $\alpha = 0.01$. (a) 15th percentile. (b) 50th percentile. (c) 85th percentile (direction of travel is from right to left).



(a) 15th Percentile (Signalized Intersections are labeled)

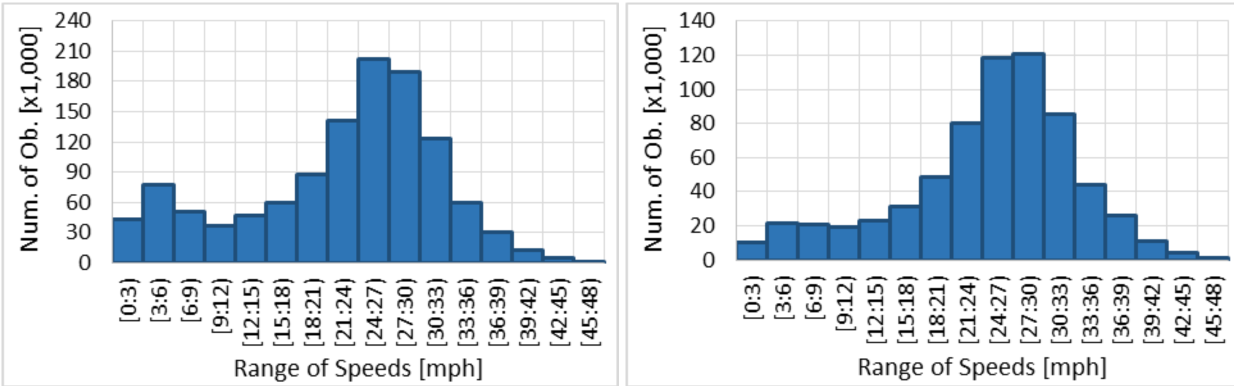


(b) 50th Percentile (Signalized Intersections are labeled)



(c) 85th Percentile (Bus stop locations are labeled)

FIGURE 4 Westbound bus speeds without dwell times with α = 0.01. (a) 15th percentile. (b) 50th percentile. (c) 85th percentile (direction of travel is from right to left).



(a) *(b)*

FIGURE 5 Westbound speed histogram: (a) with dwell and (b) without dwell.

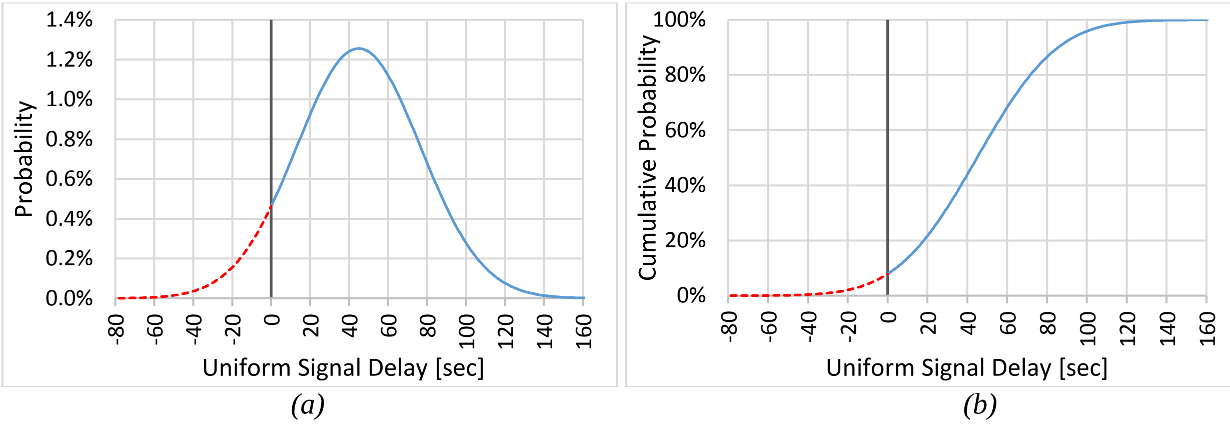
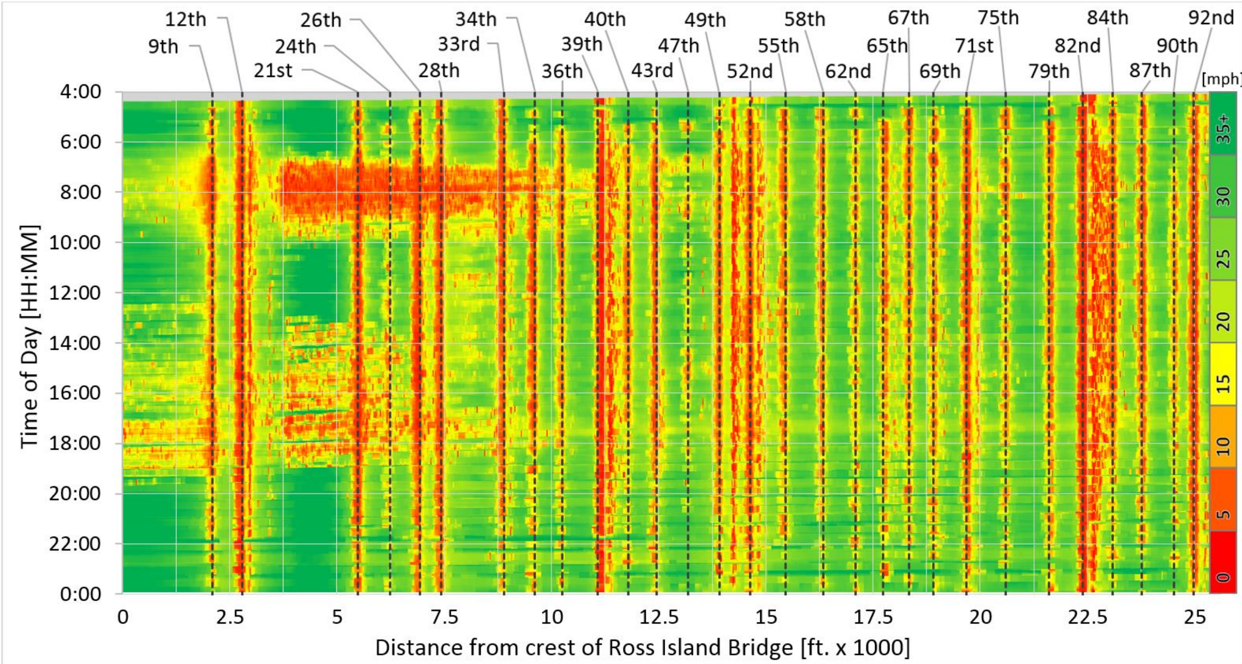
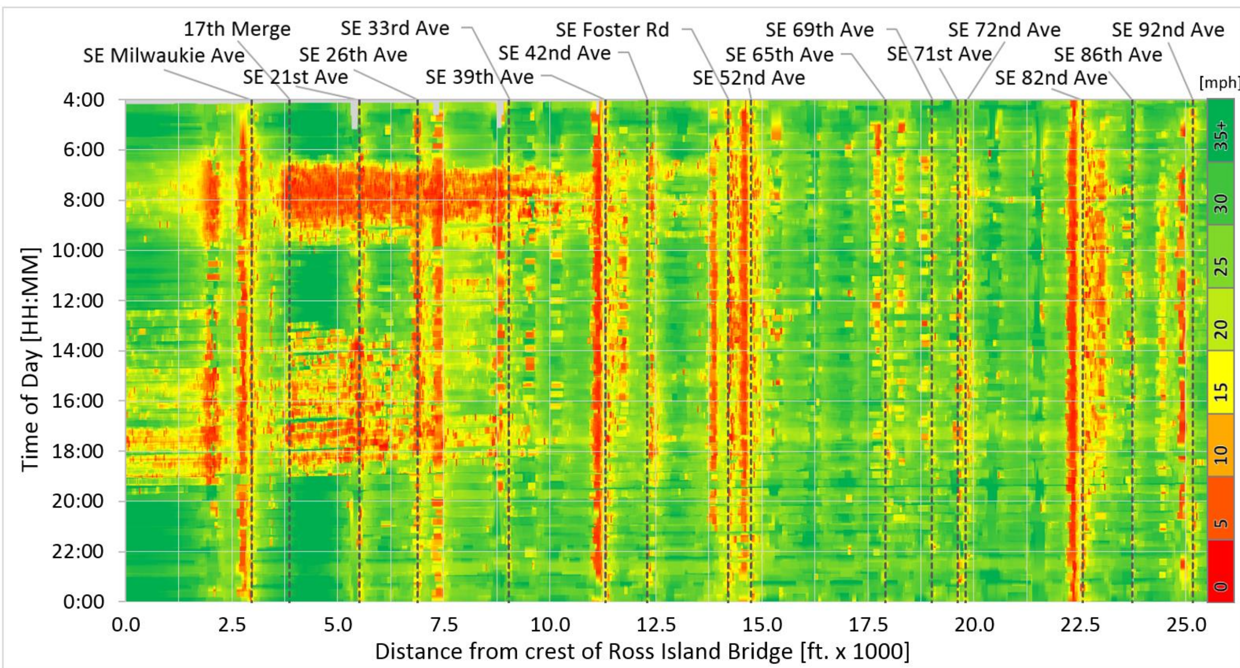


FIGURE 6 Estimated delay probability density function (a) and cumulative function (b) at SE Powell and 82nd.

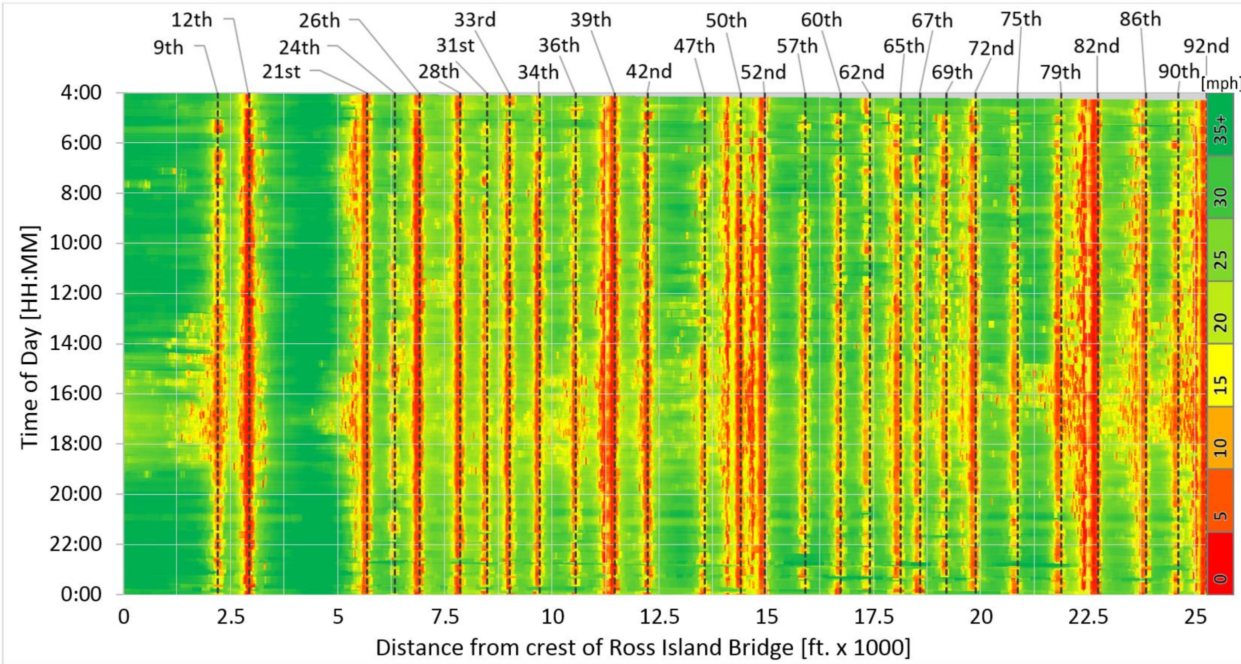


(a) Time-Space Speed Diagram (bus stop locations are labeled)

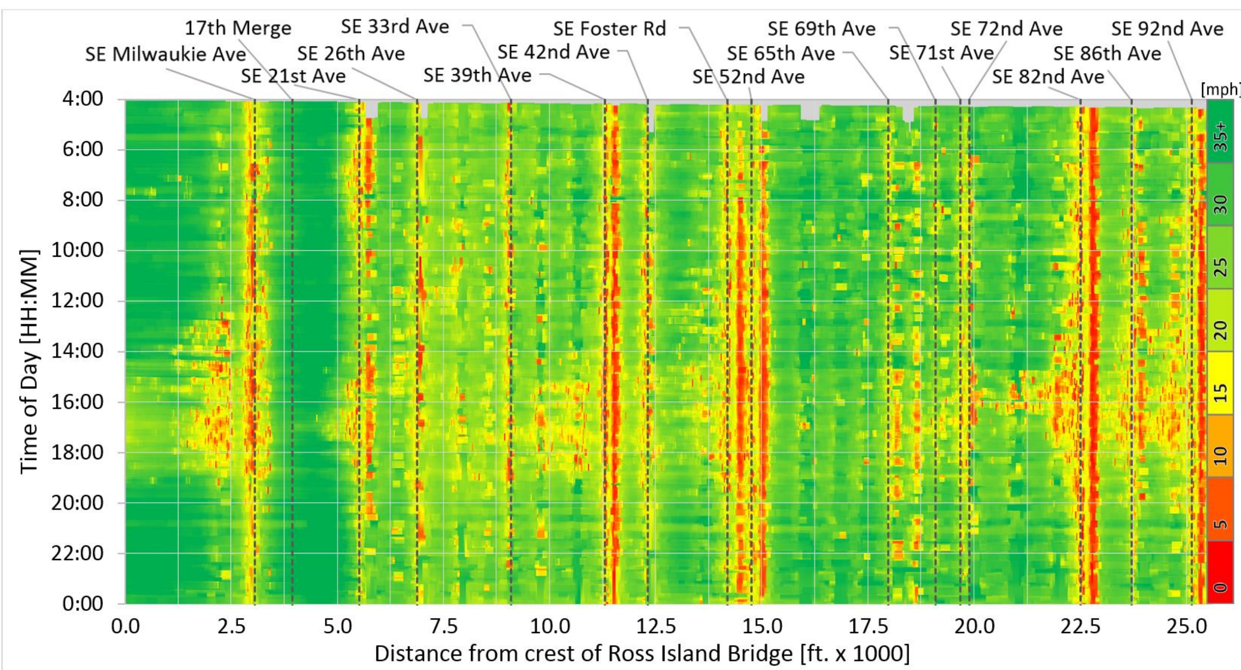


(b) Time-Space Speed Diagram (Signalized Intersections are labeled)

FIGURE 7 Westbound space-time speed diagram: (a) with dwell times (b) without dwell times – direction of travel from right to left.

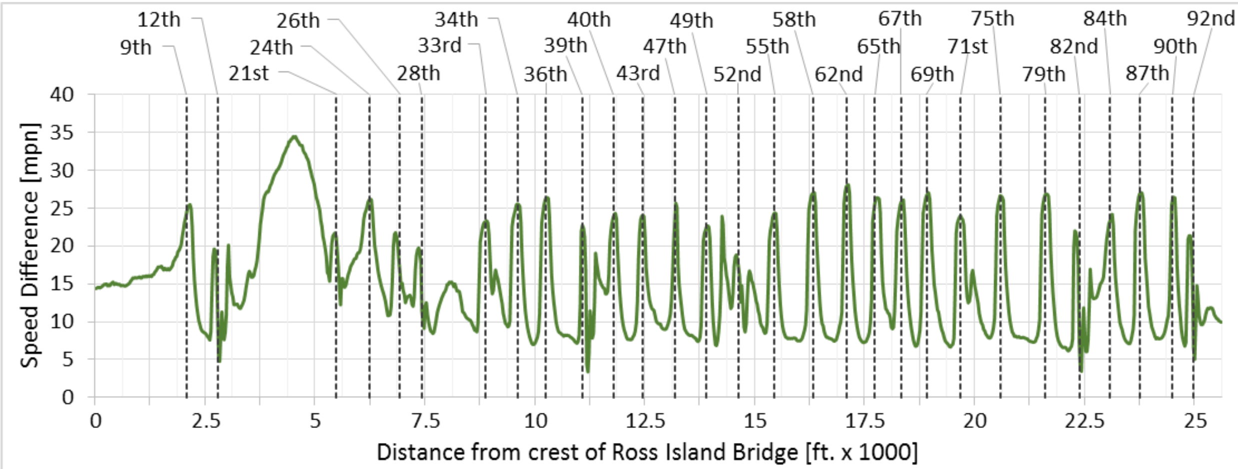


(a) Time-Space Speed Diagram (bus stop locations are labeled)

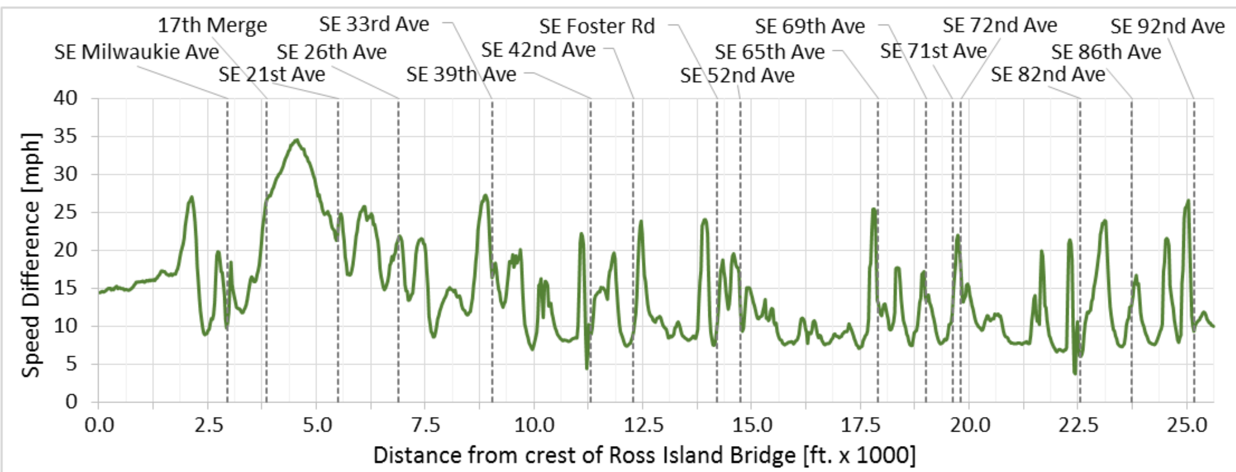


(b) Time-Space Speed Diagram (Signalized Intersections are labeled)

FIGURE 8 Eastbound space-time speed diagram: (a) with dwell times (b) without dwell times – direction of travel from left to right.

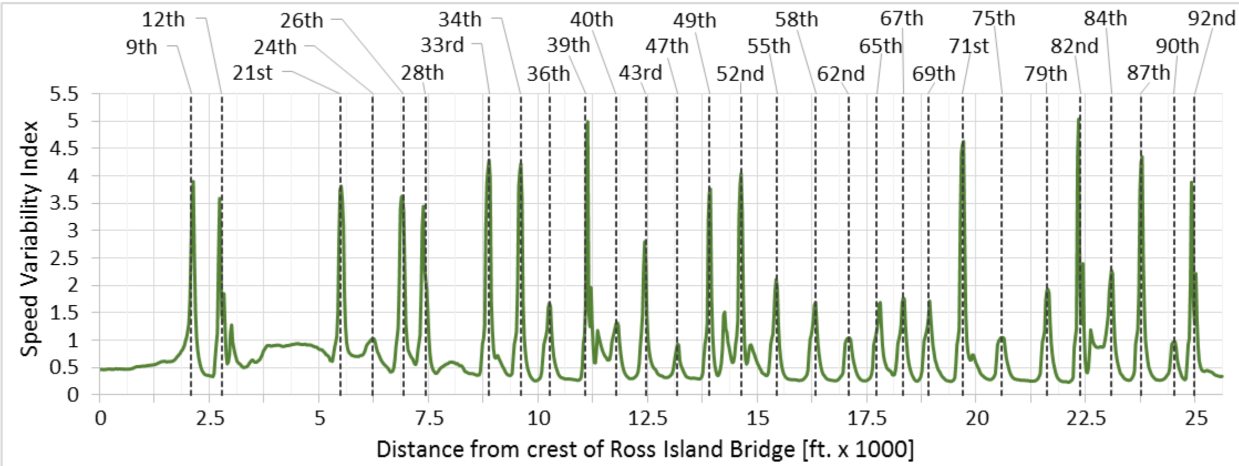


(a) (Bus stop locations are labeled)

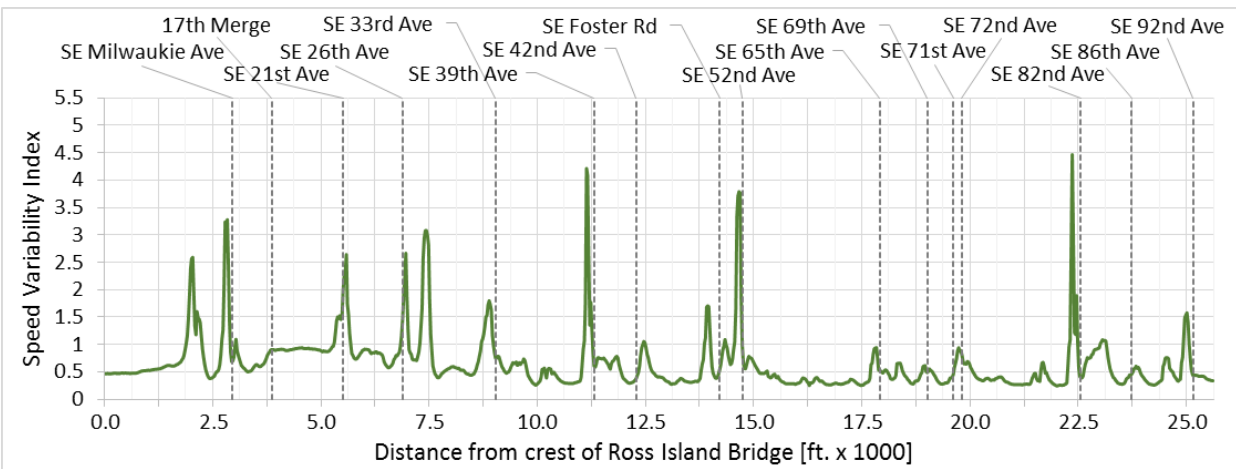


(b) (Signalized intersections are labeled)

FIGURE 9 Westbound $\Delta v_i = v_{i,85} - v_{i,15}$: (a) with dwell times (b) without dwell times – direction of travel from right to left.

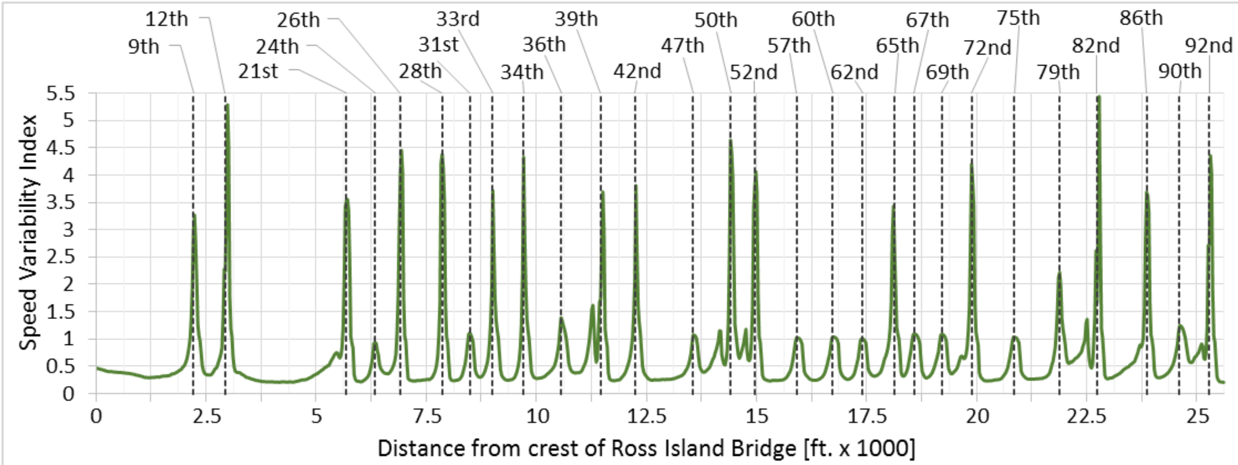


(a) *(bus stop locations are labeled)*

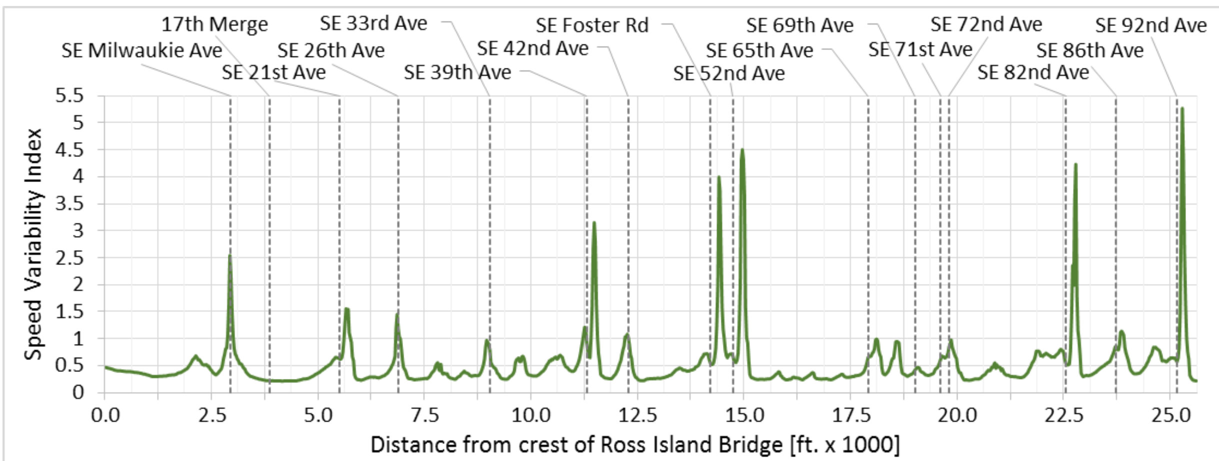


(c) *(signalized intersections are labeled)*

FIGURE 10 Westbound speed variability index μ_i: (a) with dwell times (b) without dwell times – direction of travel from right to left.

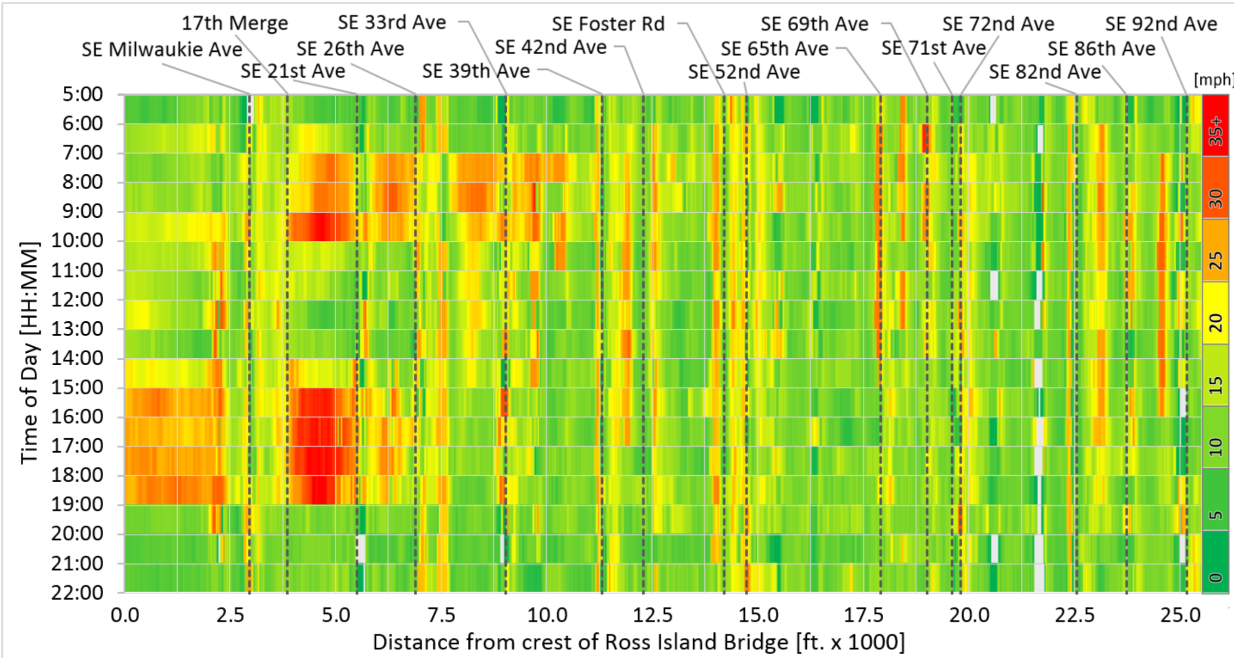


(a) (bus stop locations are labeled)

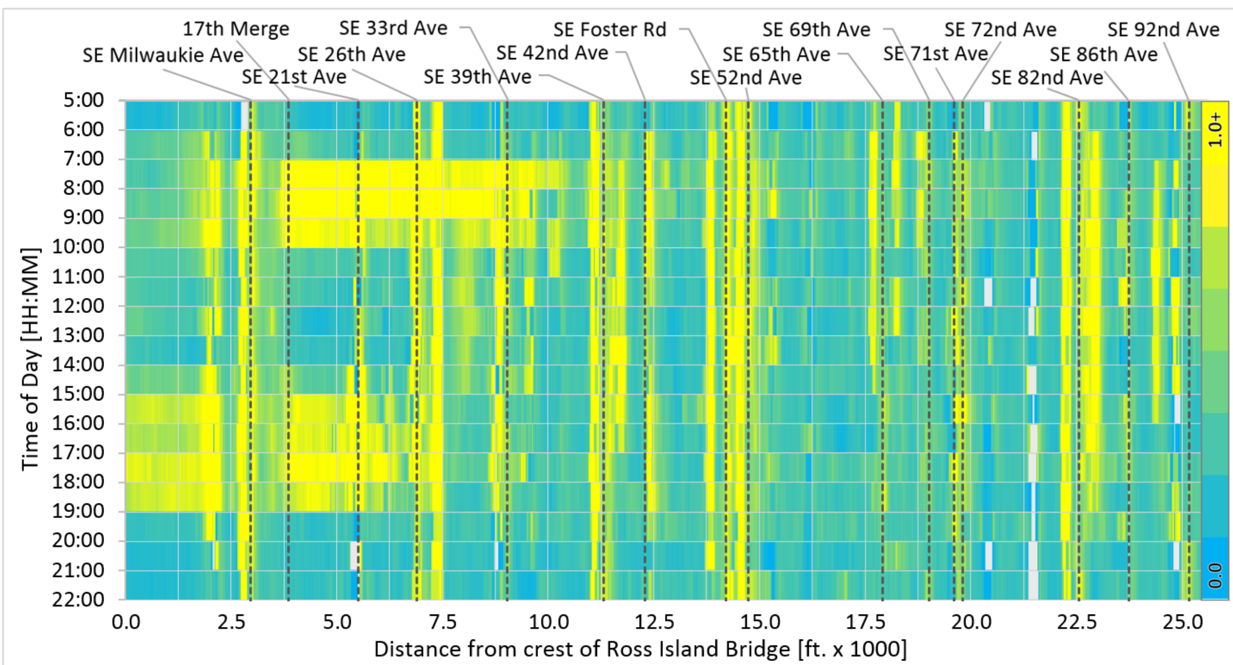


(b) (signalized intersections are labeled)

FIGURE 11 Eastbound speed variability index μ_i: (a) with dwell times (b) without dwell times – direction of travel from left to right.



(a)



(b)

FIGURE 12 a) Westbound $\Delta v_i = v_{i,85} - v_{i,15}$ with dwell time data – travel from right to left b) Westbound speed variability index μ_i with dwell time data