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FINAL REPORT

Exploiting New Data Sources to Quantify Arterial Congestion and Performance Measures

NITC-RR-770 January 2017

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Transportation Insight for Vibrant Communities

EXPLOITING NEW DATA SOURCES TO QUANTIFY ARTERIAL CONGESTION AND PERFORMANCE MEASURES

Final Report

NITC-RR-770

by

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DISCLAIMER

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EXECUTIVE SUMMARY

Transit travel time, operating speed and reliability all influence service attractiveness, operating cost and system efficiency. These metrics have a long-term impact on system effectiveness through a change in ridership. As part of its bus dispatch system (BDS), the Tri-County Metropolitan Transportation District of Oregon (TriMet) has been archiving automatic vehicle location (AVL) and automatic passenger count (APC) data for all bus trips at the stop level since 1997. In 2014, a new and higher-resolution bus AVL data collection system was fully implemented.

This new AVL system provides stop-level data as well as five-second resolution (5-SR) bus position data between stops. Rather than relying on interpolation tools to estimate bus trajectories (including stops and delays) between stops, the higher-resolution data shows more precise bus positions along each trip. Bus travel speeds and intersection signal/queuing delays may be determined using this newer information of several variables on transit travel time.

This research project explored potential applications of the new data for assessing transit performance, and for estimating transportation system performance measures for urban streets and arterials. Results suggest that the 5-SR data provides high-resolution time and position information which can be used to determine bus travel speeds between stops, identify speed breakdowns, and estimate intersection signal/queuing delays. Additionally, high-resolution achieved bus data can be used to visualize sources of congestion and delay on urban arterials.

A new inter-stop trip time model was developed using the five-second resolution data. This newly developed model resulted in statistically significant and improved results over previous models. The models for overall travel time indicated that dwell time and average speed between stops were the major factors influencing transit travel time. Hence, it was concluded that estimation of average speed between stops is a critical component of the transit trip time models. Using this 5-SR data in the trip time model led to more precise and statistically valid trip time models.

The research provides conclusions that can be used by transit agencies to improve operations through improvements such as transit signal priority. More importantly, for transit agencies looking for ways to archive data the research provides recommendations on formatting the data that can be most useful for future analysis.

1.0 PROBLEM/BACKGROUND

1.1 LITERATURE REVIEW

Traffic performance along arterials or corridors is a growing area of research in traffic operations and has been examined through sampling travel times, examining traffic flow theory relationships, or looking directly at delays caused by signals (Cheu et al., 2002; Zhang, 1999). Due to the increasing importance of arterials, a growing body of research is dedicated to improving these techniques to better understand performance. Some research predicts travel times by using aggregated data from signal loop detectors, green times, cycle lengths and offsets for the signals in the corridor (Skabardonis, 2005). Additionally, researchers have analyzed archived bus data to examine travel time delay, deviations and coefficients of variation (El-Geneidy et al., 2009, 2011; Diab and El-Geneidy, 2012; Strathman et al., 1999; Bertini and El-Geneidy, 2003). Others studies have examined readily available bus data to show that it is a viable metric for analyzing arterial traffic performance.

Since 1997, TriMet has been archiving stop-level automatic vehicle location (AVL) and automatic passenger count (APC) as part of its Bus Dispatch System (BDS). Past research has included attempts to use this AVL bus data at the stop level alongside vehicle detector data to estimate trajectories and detect congestion (Berkow et al., 2009). Researchers have also used this data to help study factors which affect bus travel time and service reliability at the point-segment level (El-Geneidy et al., 2011; Bertini and El-Geneidy, 2004; Feng and Figliozzi, n.d.), the stop-to-stop segment level (Albright and Figliozzi, 2013), and the route level (Abkowitz and Engelstein, 1984; Strathman et al., 2000).

It was not until recently that researchers began using high-resolution time and position bus information to determine bus travel speeds between stops, categorize speed breakdowns, and identify signal/queuing delays (Glick et al., 2014). Until the recent introduction of high-resolution data, researchers were only able to examine bus stop-level behavior and performance metrics on urban arterials. This introduction of higher-resolution data has removed much of the guesswork involved in understanding bus performance in between bus stops, and allowed for improvements in the application of using buses as probes to assess arterial traffic performance.

The use of buses as probes to estimate travel times has been studied in the past (Hall and Vayas, 2000; Chakroborty and Kikuchi, 2004). In particular, TriMet buses have been used as probe vehicles to evaluate arterial performance and transit performance (Bertini and Tantiyanugulchai, 2004; Berkow et al., 2008; Bertini and El-Geneidy, 2003). However, these studies were confined to first-generation, stop-level AVL data, and were constrained in having only time records for bus arrival, pass-bys, or departure from a bus stop. To estimate travel times and trajectories, researchers had to use proxies.

Recent research projects have focused on SE Powell Boulevard to study the performance of the adaptive traffic signal system (SCATS) (Slavin et al., 2012); the impact of transit signal priority (TSP) on transit performance (Albright and Figliozzi, 2013); air quality at bus stops (Moore et al., 2012); sidewalks at intersections (Slavin and Figliozzi, 2011)*;* and sidewalks at mid-block locations (Moore et al., 2014). In addition, recent papers have successfully integrated detailed signal timing and first generation AVL data to simultaneously estimate the impact of traffic volumes and intersections on bus travel times (Feng, 2014), and have examined arterial travel speeds using the newly available high-resolution bus data (Glick et al., 2014).

2.0 DATA

2.1 OVERVIEW

The data sets used for the two published papers were the same but the number of observations used in each changed from the first paper to the second. The use of R programming over Microsoft Excel allowed for larger data sets and more complex analysis.

TriMet implemented a Bus Dispatch System (BDS) as a part of its overall operation and monitoring control system (Strathman et al., 2000; Strathman et al., 1999). The BDS archives detailed stop-level data from the bus during all trips that are post-processed. This includes 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**a is 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 ID number is listed. Each stop location has GPS coordinates associated with it. These coordinates are the basis by which arrival, leave 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-foot stop circle surrounding the stop. The "arrive times" and "leave 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, arrive time is recorded as the time the doors open; arrive time plus the number of seconds of dwell gives the leave time. Figure 1 shows this setup.

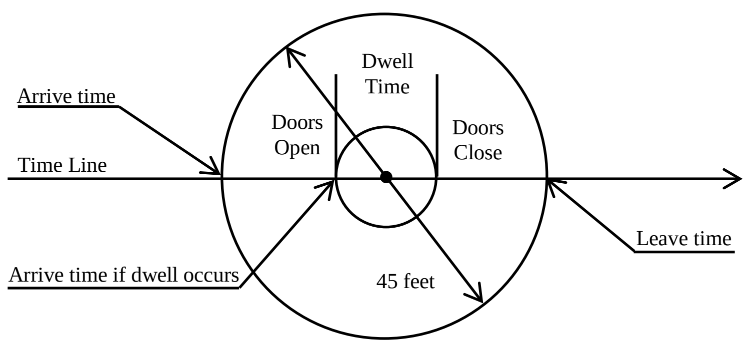


Figure 1: BDS Data – Stop circle definition.

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. Train mileage is the cumulative distance, in miles, from the start of the train's recorded service.

Table 1: Sample TriMet Data
(a) BDS Data Table

Service Date	Vehicle Number	Badge	Train	Trip Number	Stop Time	Arrive Time	Dwell	Leave Time	Door	Lift	Ons	Offs	Train Mileage	Pattern Dist. (ft.)	Location ID
1-May-13	2260	1892	934	1140	6:54:30	6:54:58	0	6:54:58	2	0	3	2	26.63	0	3123
1-May-13	2260	1892	934	1140	6:54:53	6:55:32	0	6:55:32	0	0	0	0	26.74	568	7605
1-May-13	2260	1892	934	1140	6:55:31	6:56:23	10	6:56:23	0	0	0	0	26.92	1,496	13033
1-May-13	2260	1892	934	1140	6:56:19	6:57:02	0	6:57:02	0	0	0	0	27.12	2,671	12862
1-May-13	2260	1892	934	1140	6:56:36	6:57:12	0	6:57:12	0	0	0	0	27.19	3,097	9347
1-May-13	2260	1892	934	1140	6:56:59	6:57:28	0	6:57:28	0	0	0	0	27.30	3,668	4558
1-May-13	2260	1892	934	1140	6:57:38	6:57:56	16	6:58:12	2	0	1	0	27.49	4,606	12868
1-May-13	2260	1892	934	1140	6:58:09	6:58:31	0	6:58:31	0	0	0	0	27.63	5,377	12863
1-May-13	2260	1892	934	1140	6:58:39	6:58:49	0	6:58:49	0	0	0	0	27.77	6,122	4556
1-May-13	2260	1892	934	1140	6:59:10	6:59:20	15	6:59:20	0	0	0	0	27.91	6,870	4553
1-May-13	2260	1892	934	1140	6:59:49	6:59:44	0	6:59:44	0	0	0	0	28.10	7,835	12864
1-May-13	2260	1892	934	1140	7:00:31	7:00:09	0	7:00:09	0	0	0	0	28.29	8,871	4516

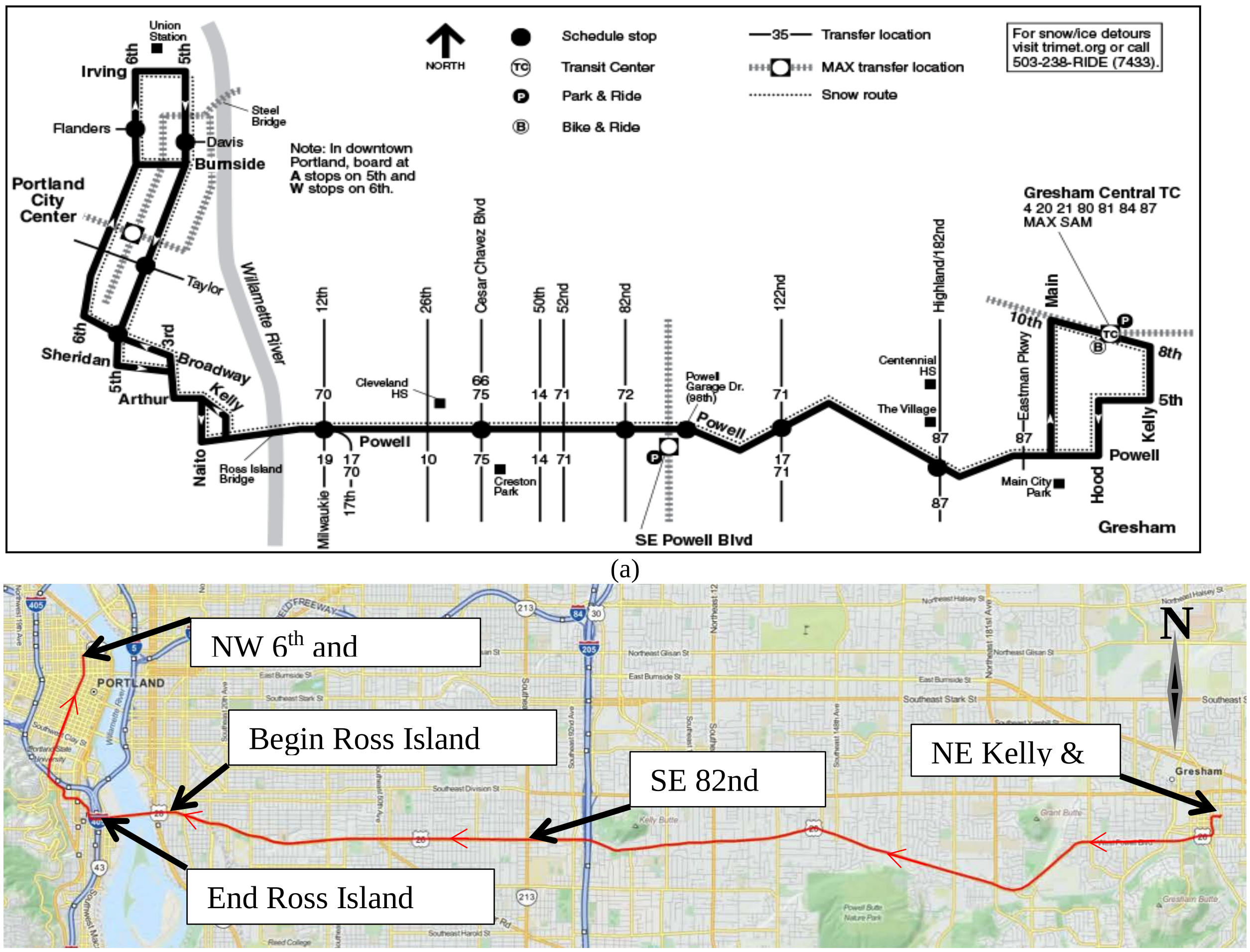
(b) Five-Second Resolution Data with Calculated Values

Vehicle ID	Opd Date	Act Time	**Time*	**Gap Interval*	GPS Latitude	GPS Longitude	**Δ Distance*	**Cum. Distance*
2205	1-May-13	23334	*6:28:54*	*0:00:05*	45.496690	-122.458707	*0.0000*	*0.0000*
2205	1-May-13	23339	*6:28:59*	*0:00:05*	45.496295	-122.459357	*0.0417*	*0.0417*
2205	1-May-13	23349	*6:29:09*	***0:00:10***	45.495643	-122.460055	*0.0563*	*0.0980*
2205	1-May-13	23419	*6:30:19*	***0:01:10***	45.495472	-122.460537	*0.0262*	*0.1242*
2205	1-May-13	23424	*6:30:24*	*0:00:05*	45.495165	-122.461137	*0.0360*	*0.1601*
2205	1-May-13	23429	*6:30:29*	*0:00:05*	45.494790	-122.461758	*0.0397*	*0.1998*
2205	1-May-13	23434	*6:30:34*	*0:00:05*	45.494400	-122.462355	*0.0395*	*0.2394*
2205	1-May-13	23439	*6:30:39*	*0:00:05*	45.494037	-122.463117	*0.0446*	*0.2840*
2205	1-May-13	23444	*6:30:44*	*0:00:05*	45.493823	-122.463692	*0.0315*	*0.3155*
2205	1-May-13	23464	*6:31:04*	***0:00:20***	45.493585	-122.464338	*0.0354*	*0.3509*
2205	1-May-13	23469	*6:31:09*	*0:00:05*	45.493212	-122.465003	*0.0413*	*0.3921*

The vehicle identifiers included in the BDS data are not available for the five-second resolution data, which records a timestamp and GPS location of each bus between stops every five seconds 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. Five-second resolution data does 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 1**b contains sample 5-SR data and additional calculated values. Columns marked with an asterisk in the table were calculated. When the bus is not moving data points do not record every five seconds, and **Table 1**b contains three gap intervals greater than five seconds. Hence, the resolution of the 5-SR data is up to five seconds.

3.0 SPEED AND CONGESTION ANALYSIS

This section utilizes high-resolution data to examine travel behavior and delay along urban streets and arterials, as well as provide supporting evidence that high-resolution bus data offers the potential to have buses serve as probes for measuring performance. To do this, we proposed a simple method of visualizing high-resolution bus data to quickly identify congestion and potential problem areas along arterial roadways. These methods combine both data sets, first generation AVL data and high-resolution data. The location of the route is shown in Figure 2. Different areas along the route used for specific analysis are shown in Figure 3.



(b)

Figure 2: TriMet Route 9.

(a) Schematic (source: TriMet Website): (b) Westbound trip plotted onto Google Maps.

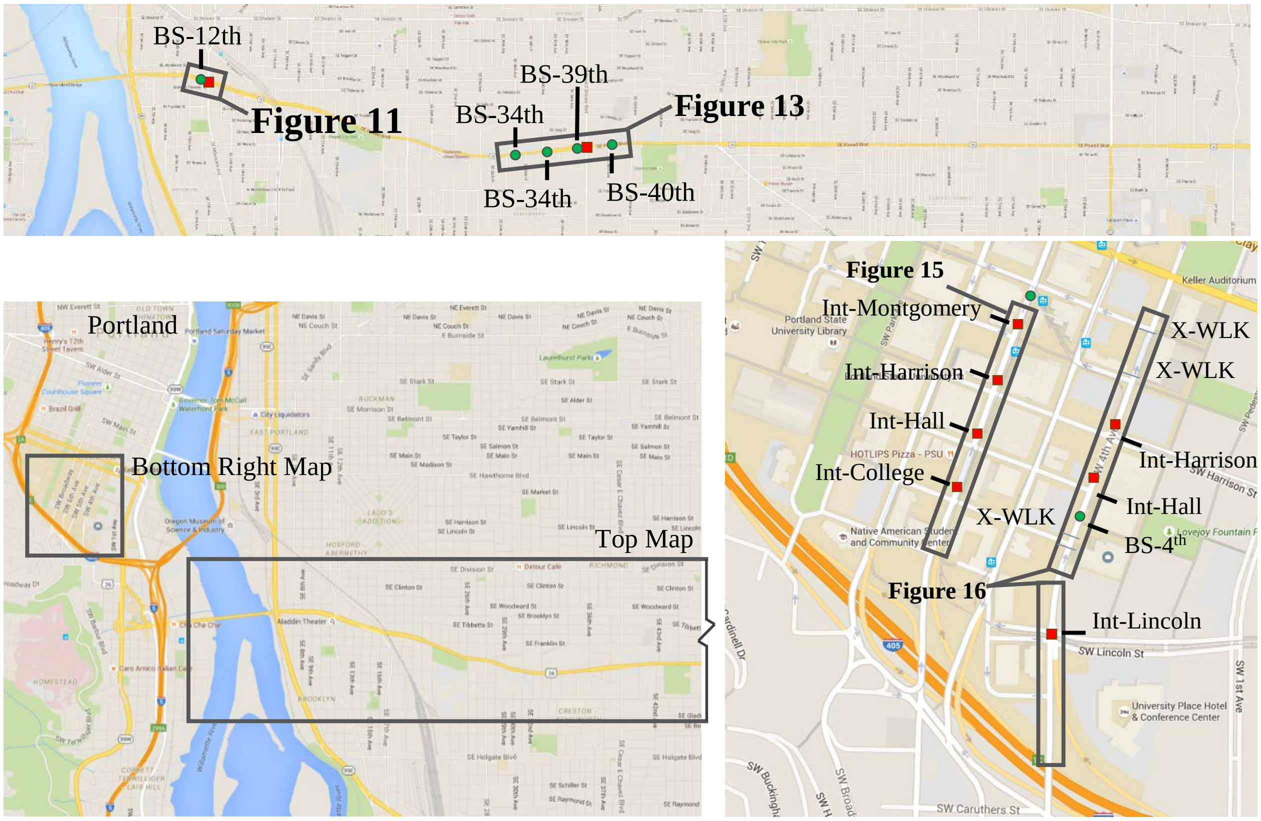


Figure 1: Map of Portland and segments analyzed.
(Bottom-Left) Map of Portland showing the relationship between (Top) Map of Powell Boulevard. Each of the bus stops used in the analysis are shown by green dots and labeled. Signalized intersections included in analysis are shown with red squares. (Bottom-Right) Map of downtown Portland.

3.1 TRAJECTORY AND SPEED ANALYSIS

3.1.1 TRAJECTORIES

The trajectories of 22 westbound Route 9 buses are plotted in Figure 2 utilizing 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 6-10 a.m. for Route 9 created using BDS data. The first and second groupings of four numbers in ####_#### are the bus number and the trip number, respectively.

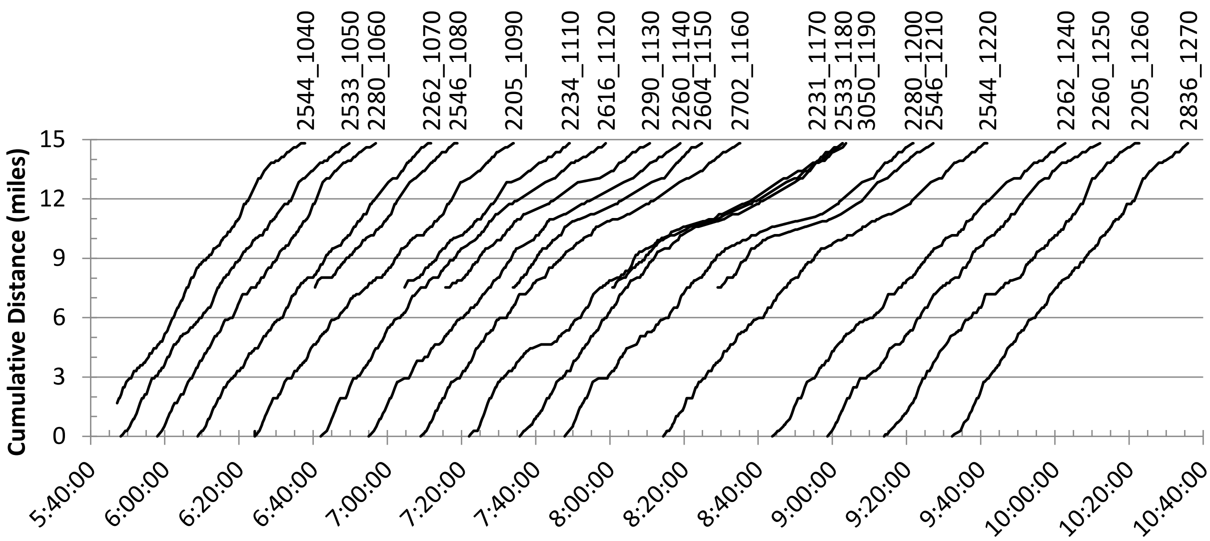
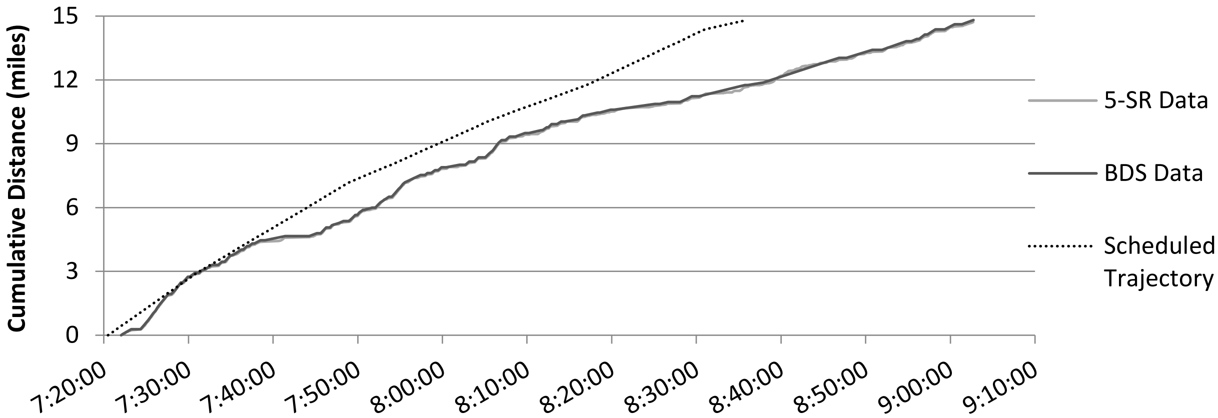


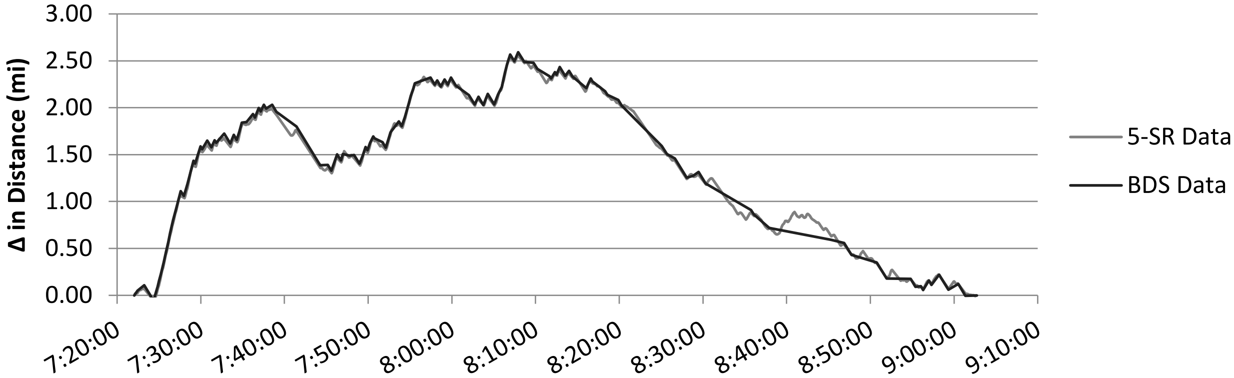
Figure 2: Westbound Route 9 time-space diagram.

Figure 2 shows how the buses' 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 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 SE 162nd 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 using archived stop-level AVL/APC data for Route 14 in Portland (Bertini and El-Geneidy, 2003, 2004). Building on this and other previous research in the literature, this paper aims to test, 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_1170 was analyzed in depth using both data sets. A time-space diagram (Figure 3a) and an oblique curve (Figure 3b) were created. This comparison highlights the small amount of deviation between the two data sets. 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.



(a)



(b)

Figure 3: Bus 2231 Trip 1170.
(a) Time-space diagram created using BDS and 5-SR data (b) Oblique Curve

3.1.2 CUMULATIVE ANALYSIS

Global Positioning System (GPS) coordinates can be used to calculate distances between two points. Since GPS coordinates were recorded where $-180° < longitude < 180°$ and $-90° < latitude < 90°$, was used to calculate distances between two points. These differences were then added together for a cumulative distance value. We used 3,959 miles as it is the average radius of the Earth in miles.

$$\cos^{-1}\left(\sin\left(\frac{lat_1° \cdot \pi}{180°}\right) \cdot \sin\left(\frac{lat_2° \cdot \pi}{180°}\right) + \cos\left(\frac{lat_1° \cdot \pi}{180°}\right) \cdot \cos\left(\frac{lat_2° \cdot \pi}{180°}\right) \cdot \cos\left(\frac{long_2° \cdot \pi}{180°} - \frac{long_1° \cdot \pi}{180°}\right)\right) * 3959\ miles$$

When attempting to compare the AVL/APC data to 5-SR positioning data, only the bus number and timestamps can be used to cross reference the data. Once equivalent timestamps have been established, cumulative distance could be calculated for both data sets. The stop-level AVL/APC data allows for distance to be calculated three different ways. Train mileage, pattern distance and stop-location GPS data result in average cumulative distances of 14.61 miles, 14.81 miles, and 14.49 miles, respectively, for Route 9 westbound. When 5-SR is used, the average cumulative distance is 14.74 miles. 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 miles. 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.

Dwell time is a directly recorded metric included in the archived AVL/APC data. This is not the case with 5-SR data. However, stop-time information can still be gleaned from the data. Within this data set, timestamps and GPS are not always recorded every five seconds; gaps of greater than five seconds are seen when the bus either stops or is moving slowly. Unfortunately, the data does 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 five seconds or less, no stopping time is indicated. When the change in time is greater than five seconds, that time minus five seconds 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 minutes while the BDS data gave an average dwell time of 20.6 minutes. These two times indicate that the average bus spent almost nine minutes stopped at locations not associated with passengers boarding or alighting.

3.1.3 TRIP SPEED ANALYSIS

While the amount of gap-stop time spent at zero 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 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 4 shows the breakdown of speeds in 2 mph bins for the average complete trip (n=15) and for all trips between 6-10 a.m. (n=22). Note that the average trip length was one hour 17 minutes.

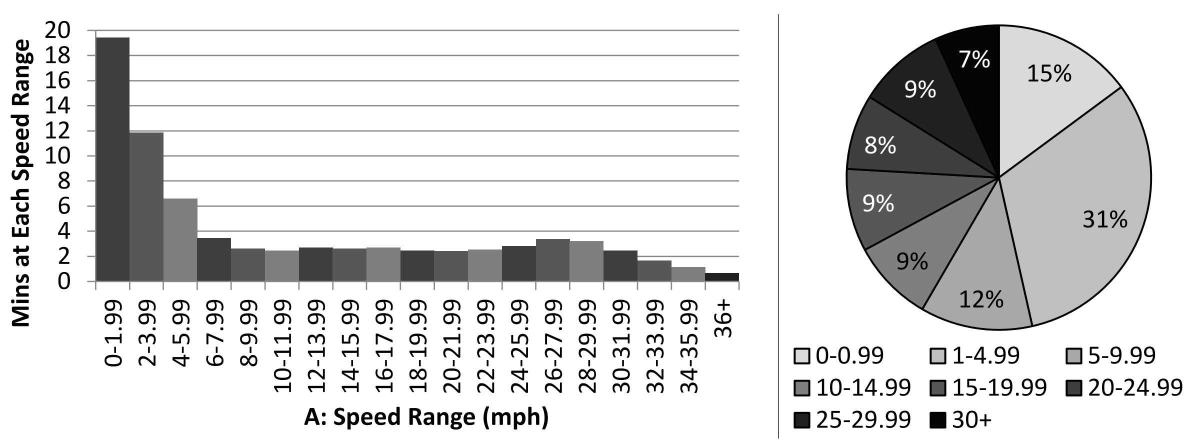


Figure 4: Analysis of time spent moving in speed ranges.

This analysis reveals a trend for the buses to be moving less than 5 mph for greater than 45% of the time. In order 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 as speeds can only be determined between recorded stops. For 5-SR data, the average distance between data points was about $^{1}/_{40}$ mile (132 feet) rather than the 910-foot average stop spacing from the AVL/APC system. This 132-foot 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 $^{1}/_{40}$-mile grouping (e.g., 7.900 mile-7.925 mile, 7.925 mile-7.950 mile, 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 one-fifth 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 $^{1}/_{40}$-mile segment of 22.5 mph, 9.0 mph, and 1.4 mph maintained for four seconds, 10 seconds, and 64 seconds, respectively, a weight of 0.8, 2.0, and 12.8 is assigned to each, respectively. The weighted average speed for that segment would be 3.46 mph. Table 2 shows a sample of how average speed was calculated. S1, S2, etc. are speeds for each bus while W1, W2, etc. are weights for those speeds. While only six columns of speeds and six columns weights are shown in **Table 2**, 22 bus trips were used to create Figure 5, 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 grey 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 5a, dtk7b, and dtk7c show speeds for mile 0-mile 5.5, mile 5.0-mile 10.5, and mile 10.0-end, respectively.

Table 2: Sample of Average Speed Analysis

Distance	Weighted Avg. Speed	Speed Count	Weight Count	S1	S2	S3	S4	S5	S6	W1	W2	W3	W4	W5	W6
7.900	17.9	6	6.0	13.5	15.1	18.2	17.3	23.0	20.5	1.0	1.0	1.0	1.0	1.0	1.0
7.925	4.6	6	14.8	17.0	13.3	7.7	14.9	0.5	10.2	1.0	1.0	1.0	1.0	9.8	1.0
7.950	7.0	4	6.0	13.3	---	13.4	1.0	12.1	---	1.0	---	1.0	3.0	1.0	---
7.975	2.8	5	38.2	---	2.1	9.4	14.6	10.1	2.0	---	16.2	1.0	1.0	1.0	19.0
8.000	3.2	4	23.8	---	30.8	2.0	10.9	1.7	---	---	0.8	9.0	1.0	13.0	---
8.025	5.3	5	27.8	2.5	---	23.5	4.0	28.0	24.8	18.8	---	1.0	6.0	1.0	1.0
8.050	28.9	4	4.0	28.1	31.5	25.9	---	---	30.2	1.0	1.0	1.0	---	---	1.0
8.075	29.1	2	2.0	---	---	---	29.3	28.9	---	---	---	---	1.0	1.0	---
8.100	20.4	6	6.2	30.2	12.8	13.0	30.3	27.7	9.9	1.0	1.2	1.0	1.0	1.0	1.0

The speed between stops was also calculated from the AVL/APC data by dividing the distance between two successive stops by the difference between arrive time at the second stop and the departure time at the first stop. It should be noted that even though the buses had dwell time where their speed would be zero mph, this was not shown in Figure 5. The distance between locations with AVL/APC data creates uncertainty in speeds calculated from that data alone. Due to 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 allows 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.

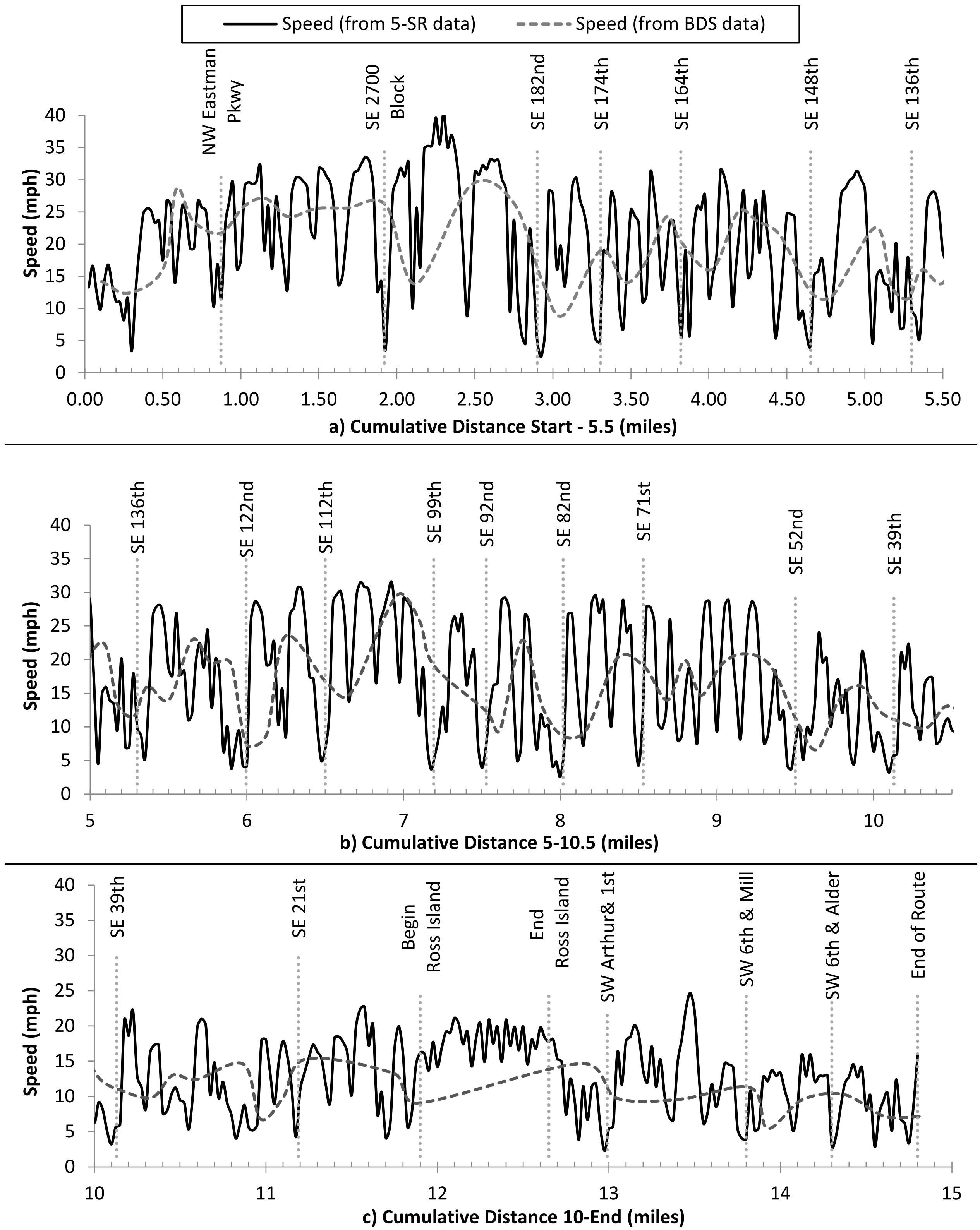


Figure 5: Speed versus cumulative westbound trip distance.

The two data series in Figure 5 do not contain all of the same information at different resolutions. Since distance is used for the *x*-axis only non-zero speeds permit the function to continue, and the AVL/APC data lacks stop time consideration while the 5-SR plot does not since slow speeds associated with long gap time are taken into account. For example, at distance 7.900 in Table 2, all six speeds are similar and have equal weight because each speed was recorded for a five-second interval; 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 four seconds and 65 seconds, respectively. Distance 8.000 marks the crossing of SE 82nd on Powell; while all the buses stopped at this location, zero speeds tend not to appear while using 5-SR data. 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.

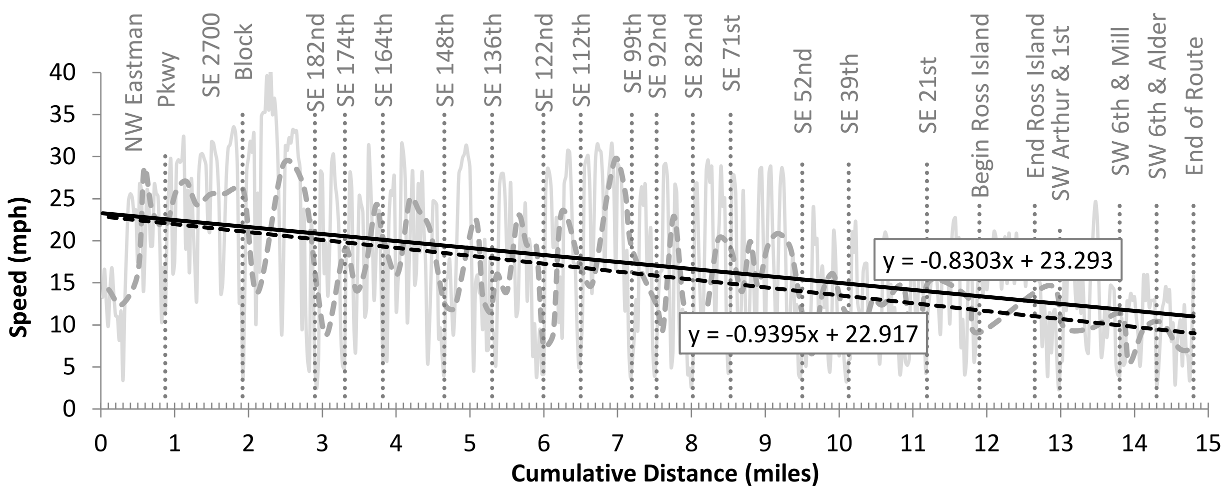


Figure 6: Speed trend line.

As shown in Figure 6, 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. 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 one hour 4.7 minutes and one hour 9.5 minutes, respectively. Since it is known that the mean trip time was one hour 17 minutes, 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 slow preceding the stop location. This is likely caused by buses waiting in queues before crossing SE 82nd to reach the stop on its far side.

3.1.4. TRIP TIME ANALYSIS

Figure 7 was created using similar methodology employed in the creation of Figure 5. 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 grey line is an average speed at five-second intervals. The black line is one-minute moving average speed with ±30 seconds of accuracy. The white line is a polynomic trend line that highlights the overall shape of the plot. A dip in the speeds between 7-9 a.m. coincides with the morning congestion and represents a decrease in average speed of about 9 mph.

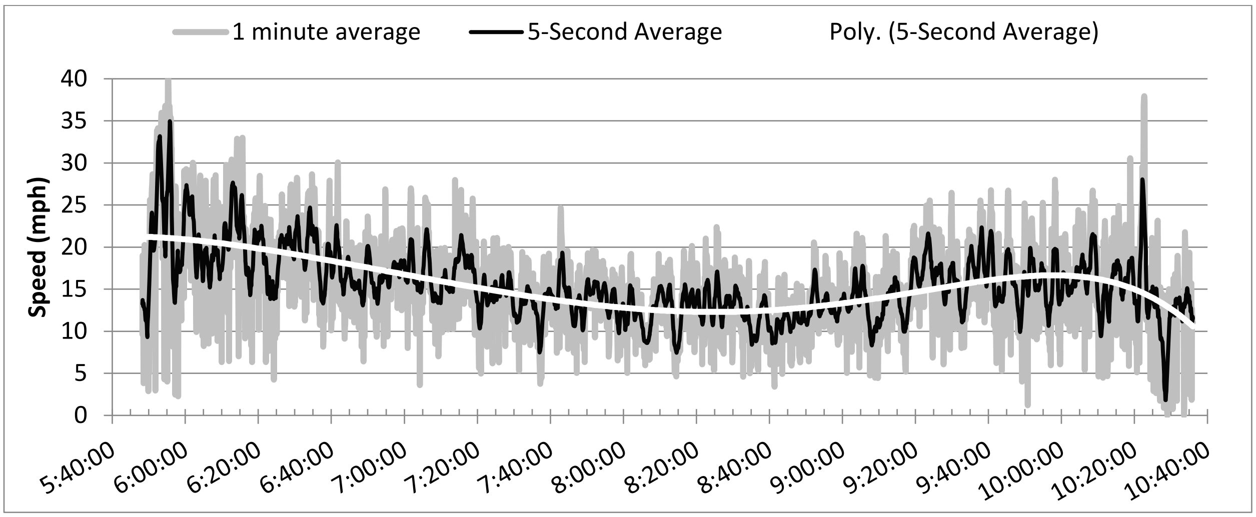


Figure 7: Speed versus time.

A trip time analysis using 5-SR data has some limitations created by the lack of information regarding passenger movement (i.e., passenger boarding and alighting), specified dwell time, use of a lift, traffic signal indications, activation of transit signal priority, etc. 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.

3.1.5. INTERSECTION-LEVEL ANALYSIS

In the previous section, it was noted that around SE 82nd and Powell Boulevard, buses have lower speeds; SE 82nd is also Oregon Route 213 and has higher traffic signal coordination priority than Powell. The area from SE 84th-SE 80th was examined in detail and is shown in Figure 8; average bus speed is decreasing as they approach SE 82nd. Bus speed increases after the bus has passed its scheduled stop on the far side of the intersection (most buses stop at 82nd). The speed of the buses is steady around 27 mph until the buses pass SE 80th Avenue and approaches the bus stop at SE 79th Avenue. This example shows that it is now possible to zoom in on specific intersections and detect areas with significant queuing.

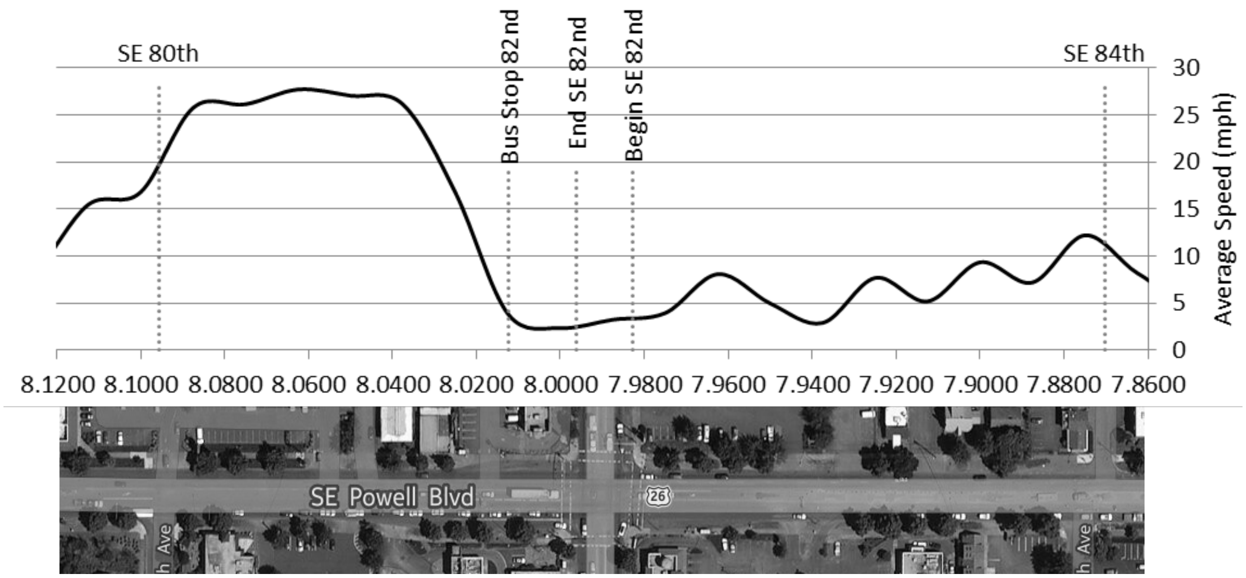


Figure 8: Speed analyses of SE Powell & 82nd.

3.2 HEAT MAPS

3.2.1 Data Visualization

A series of tools were developed to analyze the November 2014 high-resolution data. Using time and location coordinates of the entire 5-SR data set as inputs, an interactive heat map was created to display concentrations of GPS points. Because data is generally recorded every five seconds, locations where buses stop or move slowly, as indicated by speed, will leave higher levels of "breadcrumbs," and thus have denser collections of GPS points. The heat map tool assigns a color value to different densities, with high concentrations visible as red and lower concentrations in blue. Due to the density of points, locations where buses stop, like bus stops and traffic intersections, as well as stretches of road where buses are moving slowly become easily visible. Several features have been built into the heat map to allow for customizability when examining the data. By interacting with the heat map – either by zooming in on specific segments of road or by changing scale and blur attributes – the user can observe general trends in bus behavior.

Figure 9 illustrates the usefulness of this type of visualization. Within Box A are two bus stops – one for westbound traffic and one for eastbound traffic – and the intersection of Milwaukie and SE Powell. Even with the close proximity of the intersection to the westbound bus stop, clear trends about where buses are stopping can be seen, showing that many buses are stopping at the intersection before reaching the bus stop. Conversely, the bus stop for eastbound traffic is slightly upstream of the intersection, and the buses that stop at the bus stop and at the intersection cannot be easily distinguished from the visualization alone. For both bus stops, the gap in "breadcrumb" recordings as a result of the bus being within a bus zone, described above, is visible as a gap in the cloud. This gap can be seen slightly upstream of each bus stop, where the distance between zone edge and the bus stop pole is greatest.

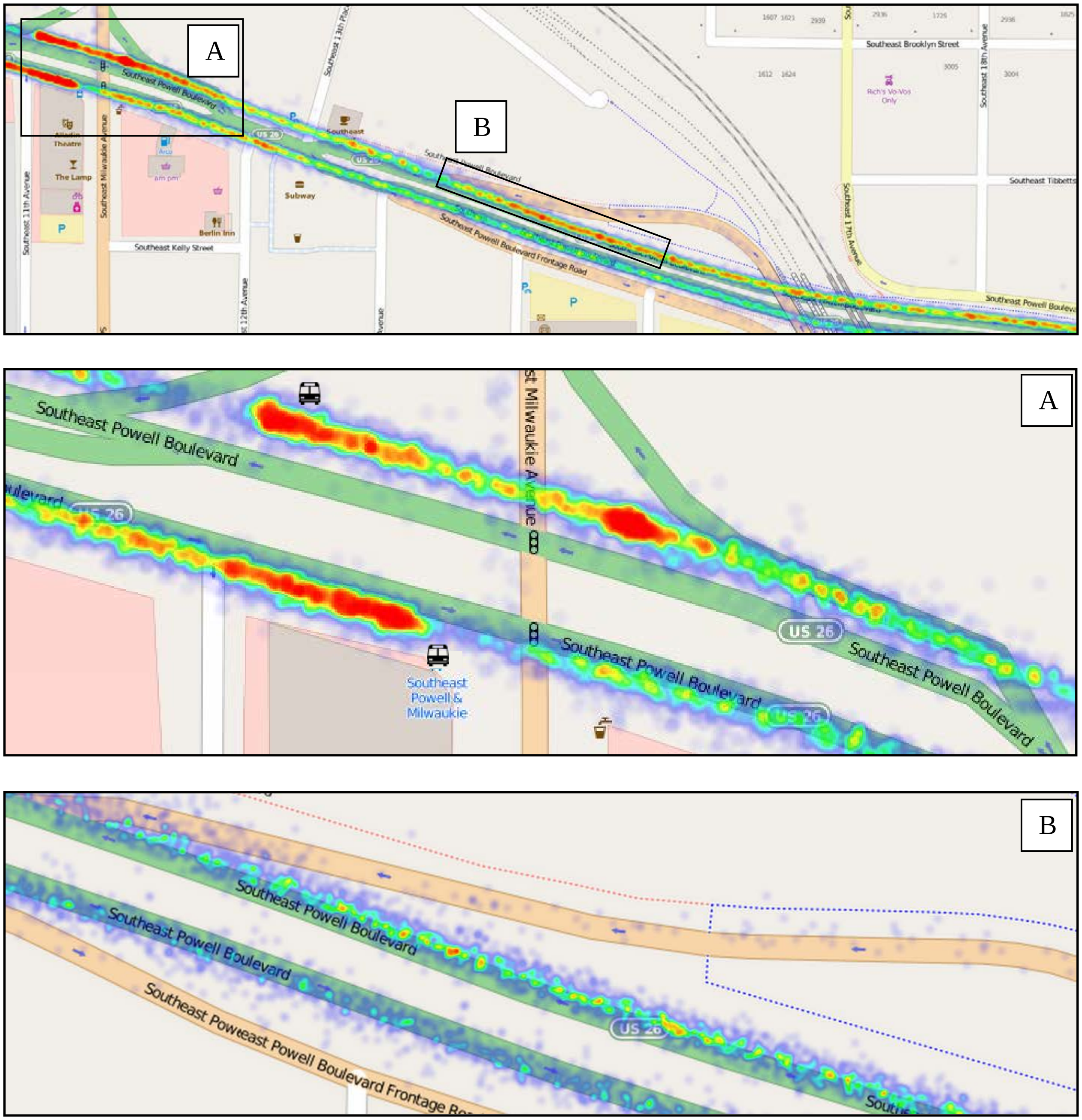


Figure 9: Example of heat map output.

(Top) Analysis segment stretching along SE Powell from 14th to 11th. (Middle) Zoomed in portion of Box A. Within Box A both delay caused by an intersection and by bus stops is visible. Box B indicates congestion for westbound traffic. (Bottom) Within Box B is a zoomed in view of westbound congestion commenced at the merger of 17th and Powell.

Box B of
Figure 9 illustrates another useful application of the heat map, finding locations of congestion. Because the maps show concentration of points, extended areas of high concentration indicate frequent points generated from slow-moving traffic. This stretch of road along Powell from 14th to 11th is notoriously congested in the morning peak. The congestion can be seen to begin with a right-lane merger from SE 17th and continue through the right edge of the figure. Differences in color and intensity between the different panels of
Figure 9 are a result of different blur factors and zoom extents.

This tool was used to examine general behavior of buses and select areas that necessitated further exploration. The tool also includes the functionality to switch data sets, giving it the ability to examine any data set with GPS coordinates. From this initial data exploration, four distinct segments were chosen for further numerical analysis.

3.2.2 Numerical Method

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

First, the length of time (in seconds) and distance (in feet) is calculated between each pair of consecutive GPS points. To extract two GPS points from each bus, points of interest (POI) are defined by GPS coordinates. The two points around a POI (i.e., one point downstream to the POI and one point upstream) for a selected direction of travel are compiled for all the buses that pass by that POI and are going in the same direction. Once these point-pairs and the average speed between these points are determined for a specific location, the process of examining a specific point can begin. By doing the same analysis many times, each time moving the POI ~25 feet downstream, entire segments can be analyzed in high detail. For a given day of analysis, there are, on average, 70 point-pairs (one point upstream and one point downstream of the POI for the same bus trip) surrounding any given POI. If all 15 weekdays were analyzed, this results in over 1,000 point-pairs. Figure 10 shows the westbound bus stop at Milwaukie and SE Powell (same as seen in Figure 11). The absence, or light cloud, of points, as seen in the space in front of a bus stop in the heat map, can also be seen in this analysis. When 5-SR starts recording again after stopping at a bus stop, the points have more variability on where they are located, and thus do not form large concentrations as seen at intersections or when buses are at a bus stop.

Figure 10: Example POI.
This is the bus stop at Milwaukie and SE Powell for westbound traffic. Using data from one day worth of buses, the concentration of points before the bus stop and the elongated tail of points where GPS starts recording again are visible.

Starting with a specific POI, like the one used in Figure 10, average speed over that point can be calculated for any length of time, given access to the appropriate data. This single-point analysis also forms the basis for a segment-level analysis. The same process that is applied to individual POIs can also be applied to a range of POIs that occur over a specified segment. When metrics for each POI of a segment are calculated and related to each other, information about the entire segment can be visualized.

For this paper, four of these segment-level analyses were completed, with the average distance between consecutive POIs ranging from 25 to 30 feet. To illustrate an example of these final visualizations, Figure 11 shows the same segment as viewed in the
Figure 9 heat map. For this illustration color represents speed, with color ramping from red to green, where green indicates faster speeds. Due to the 35 mph speed limit on Powell, all buses with speeds over 35 mph are represented by the highest level green. To account for missing data within a given segment, missing speeds were imputed using the missForest R package [27]. The y-axis is created by ordering all bus observations by time of day. In doing so, behavior during morning peak (indicated as 6:30-9:30 a.m.), midday off-peak (9:30 a.m.-4:30 p.m.), and evening peak (4:30-7:30 p.m.) can be more easily examined. Horizontal lines are included in these plots to clearly distinguish the different time periods. The x-axis of these visualizations represents distance, in feet, from the starting POI to the final POI, and is equivalent to the length of the analysis segment. Direction of travel is given along the top border of each plot. Geometry of the segment, including intersection locations, bus stops or other design features, are ordered across the bottom of the plots. Keeping with previous examples, the stretch of SE Powell from 14^{th} to 11^{th} is included in Figure 11, with a satellite image of the segment in Figure 12. The bus stop at SE Powell and Milwaukie is clearly visible as a vertical band of low speeds that stretches through the entire day (highlighted in Box A in Figure 11).

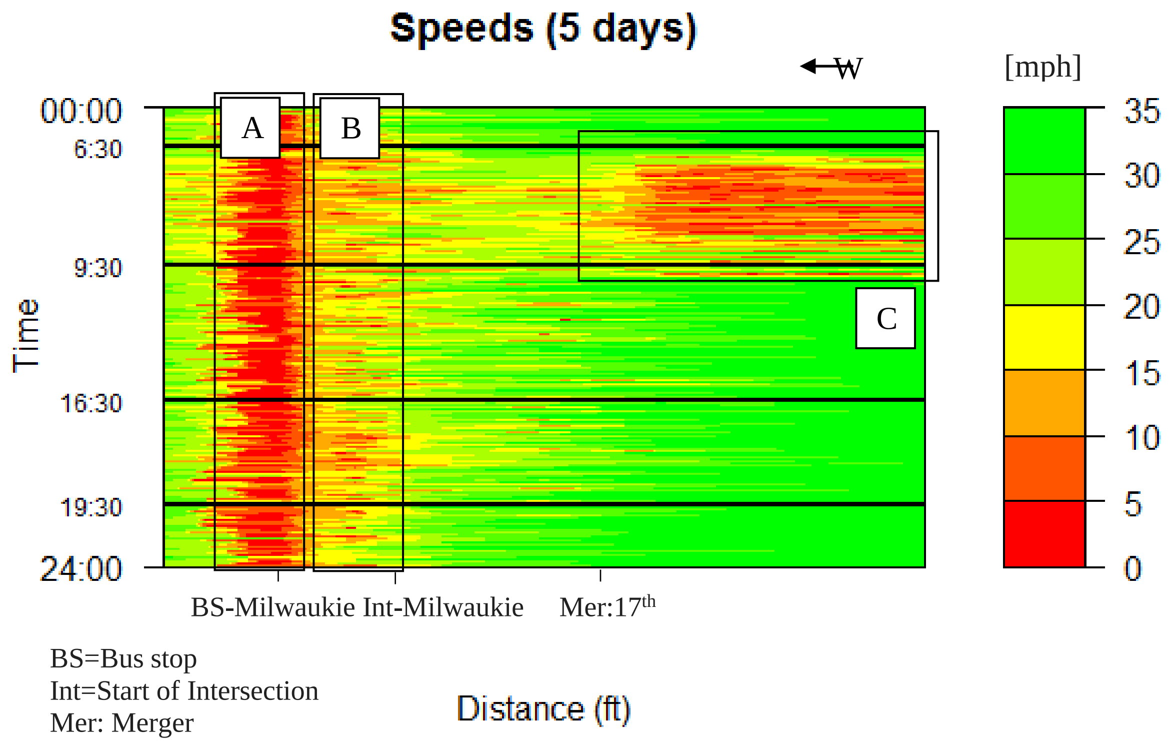


Figure 11: Speed heat map for SE Powell segment between 14th and 11th.
Box A indicates a bus stop at Milwaukie. Box B indicates delay from the intersection of Milwaukie and SE Powell. Box C indicates congestion during the morning peak resulting from the Powell and 17th Avenue merger. Direction of travel is indicated as westbound.

Slower speeds as caused by congestion and delay at the intersection of SE Powell (ADT ≈ 42,000) and Milwaukie (ADT ≈ 20,500) are also clearly visible (Box B), and during the morning peak we can see traffic is experiencing delays that extend outside the scope of the segment (Box C). The severely low speeds begin at the merger of 17th (ADT ≈ 8,500) and SE Powell; 17th feeds northbound traveling traffic onto Powell. This delay, however, dissipates as the day progresses and is generally gone by 10 a.m.

Figure 12: Google Satellite image of Powell Boulevard and the merging of 17th Avenue.
This area is causing the congestion seen in Box C of Figure 11.

4.0 APPLICATION

4.1 ANALYSIS OF SE POWELL BETWEEN 33RD AND SE 42ND

SE Powell Boulevard runs from the nearby city of Gresham and enters into Portland's downtown core from the southeast. Powell Boulevard is a major arterial in the Portland metropolitan area and carries upwards of 45,000-50,000 vehicles a day. It is a popular commuter route during the morning hours; it ferries people from neighboring suburbs into downtown. Speed limits along Powell do not exceed 35 miles per hour. TriMet bus Route 9 runs directly along the corridor. Bus stops are located in varying proximity to intersections, offering a variety of unique situations to investigate. Two segments along Powell were chosen to be examined in more detail. One of these segments was used above to illustrate the exploratory tools created to examine delay on SE Powell between 14th and 11th (Figure 11). The other is a segment of SE Powell from SE 42nd to SE 33rd (Figure 13).

This segment stretches nearly half a mile, and within the segment are four bus stops and one signalized intersection at SE Powell and SE Cesar E. Chavez Boulevard. The bus stops are clearly visible as vertical red bands that last throughout most of the day (Figure 13). The percentage of buses that stop at Cesar E. Chavez is compared to several other bus stops nearby, which confirms what is seen in Figure 13. While almost 100% of buses stop at 39th for most of the day, in Figure 13 seen as the dense vertical red band, the same cannot be said for the 36th or 40th avenue bus stops. The sporadic, slow vertical red bands which appear at 36th and 40th, Figure 13, in the morning hours dissipate by the middle of the evening peak. Figure 14 indicates that this is a result of a lower percentage of buses actually stopping at these bus stops. The Cesar Chavez bus stop is noticeably, by visual inspection and quantitative analysis, the most frequented bus stop in this segment. Between the morning peak and midday off-peak, intersection delay is also noticeable at Cesar Chavez Boulevard (Figure 13, Box B) and between the 40th Avenue bus stop and the Cesar Chavez bus stop. During the morning peak, there are also thin horizontal bands of slow speeds that stretch the width of the segment (Figure 13, Box A). Because of the time of day of these bands, and given the proximity to a high school, these bands potentially represent queueing caused by students driving to school.

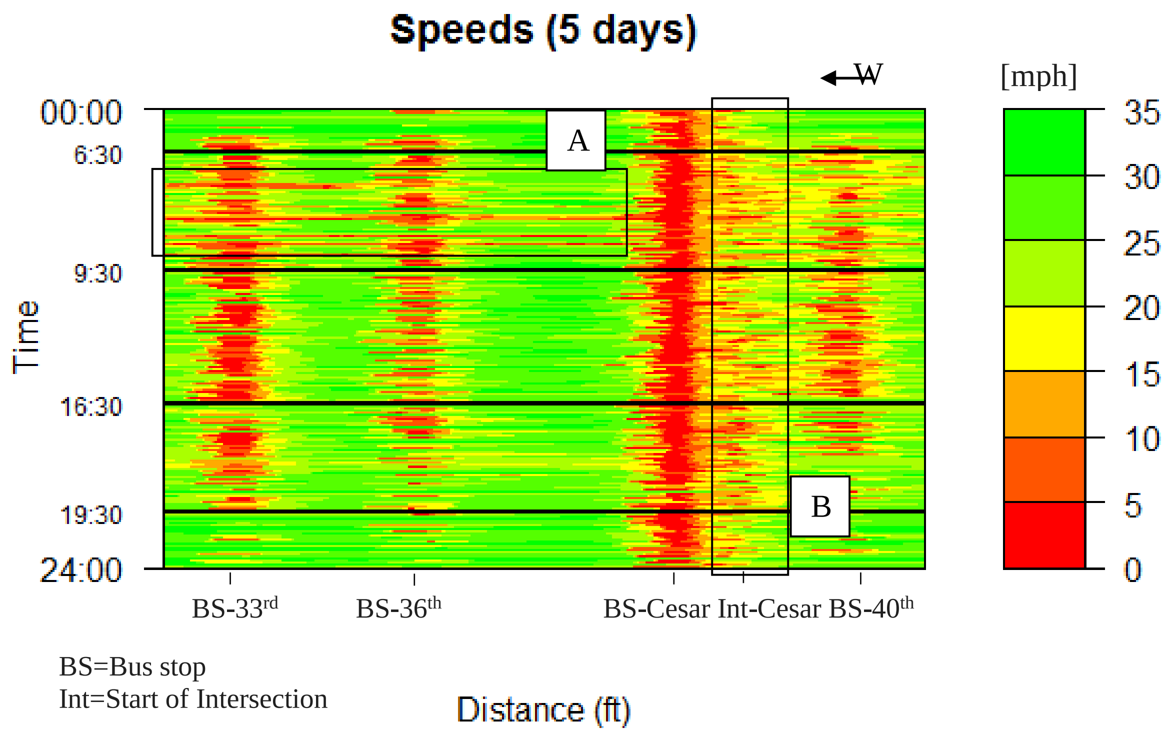


Figure 13: Speed plot between 42th and 33rd along SE Powell Boulevard.
Box A shows congestion potentially caused by students entering the nearby high school, and Box B highlights the congestion caused by the intersection of Cesar Chavez and SE Powell.

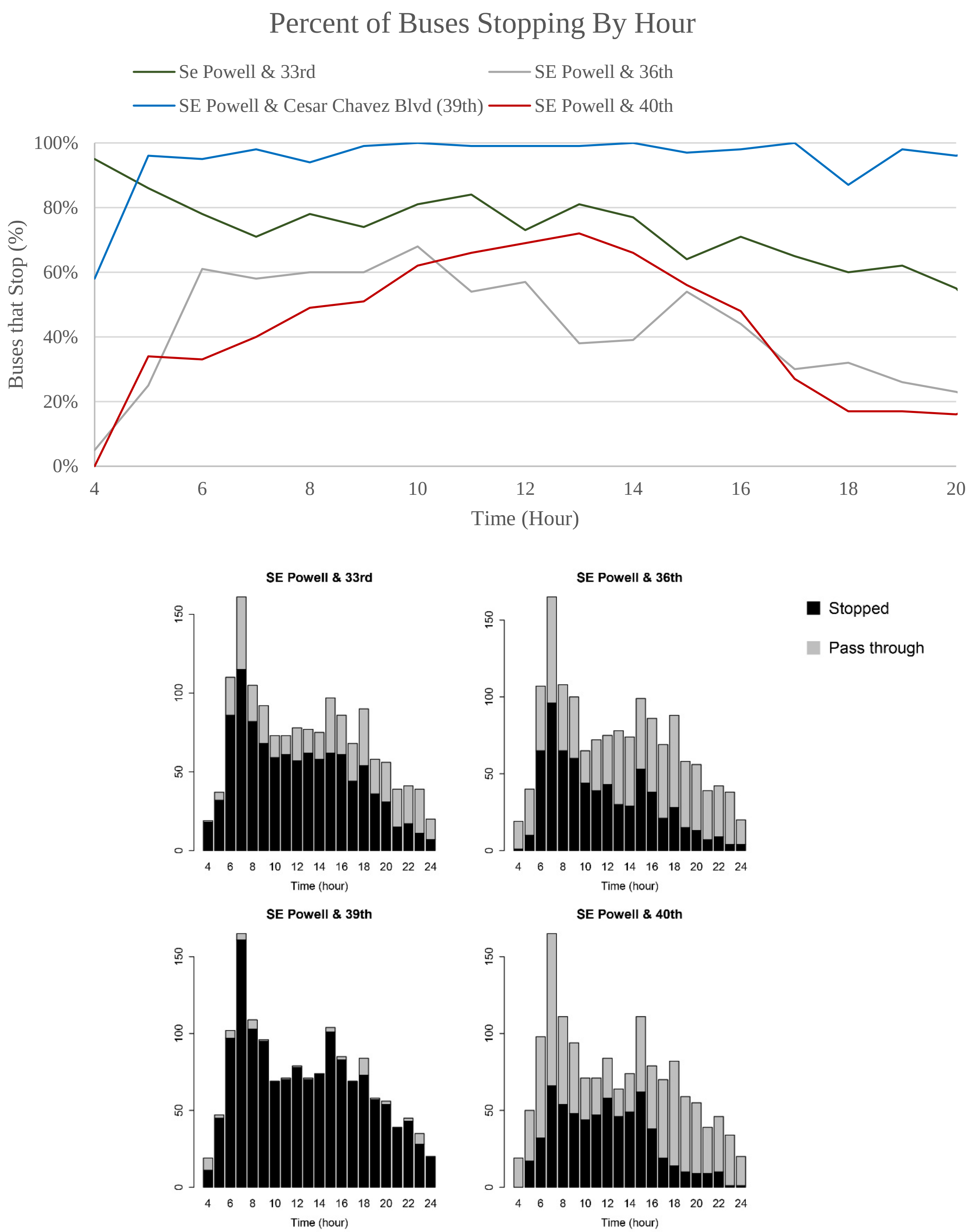


Figure 14: Percent of buses stopping by time of day near Cesar Chavez (39^{th}).

4.2 ANALYSIS OF URBAN STREETS

Urban streets behave differently than arterial corridors. They are characterized by lower speeds and increased stop-and-go traffic as a result of a more densely laid out grid and, consequently, more frequent intersections. Both the heat map and numerical method were applied along two different urban streets to understand what could be discovered about traffic performance. Route 9 enters Portland from the southeast, and heads north along SW 6th Avenue (ADT ≈ 12,000); 5-SR data from November 2014 was used again to examine this urban street. A second street, SW 4th Avenue (ADT ≈ 11,000), was also chosen because it contains highly trafficked pedestrian crosswalks, bus stops and intersections. A different set of 5-SR data was used for this street, from February 4, 2015, and contained all buses that traversed along this segment of 4th Avenue (TriMet routes 12, 43, and 44). To supplement analysis along 4th Avenue, footage of bus movements was also recorded and analyzed. Our video footage was able to more accurately portray when a bus is stopping, how long a bus is stopping, and when a bus starts moving again. In plots of downtown speeds, a 25-mph cap on speeds was used for the upper speed limit. Note that signal timing in the downtown core of Portland is set to ~15 mph.

4.3 SW 6th BETWEEN JACKSON AND SW MONTGOMERY

This 1,100-foot segment spans several intersections with no bus stops, allowing us to see how buses interact solely with closely spaced intersections. Figure 15 shows the four intersections covered by this segment. The intersections at College and Montgomery cause the most delay, and buses can pass through Hall and Harrison streets rather unencumbered. Time of day is seen to be unimportant in determining traffic performance on this stretch of urban streets. Traffic levels are likely more consistent downtown, and speeds are more dependent on signal timing and infrastructure. Because intersections are more closely spaced, and no bus stops are in the segments, the benefits of signal timing and hitting consecutive green lights can be seen in the various green horizontal bands that stretch the width of the segment.

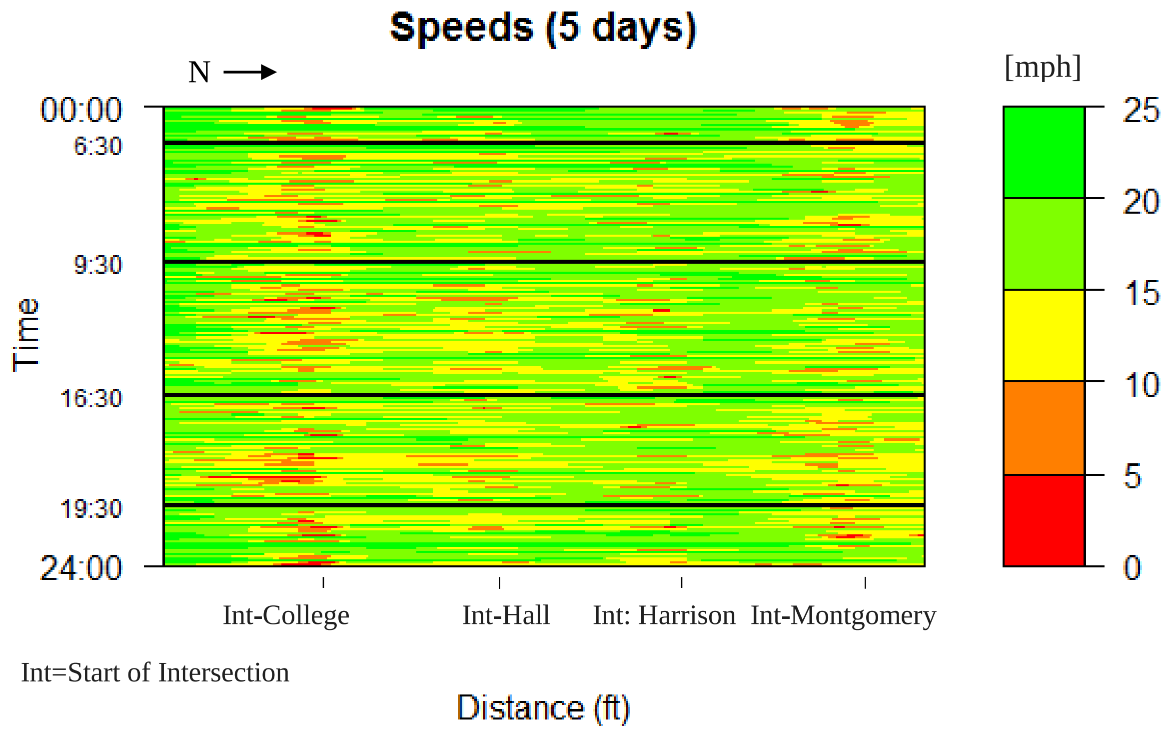


Figure 15: SW 6th from SW Jackson to SW Montgomery.

4.4 SW 4th BETWEEN SW CARUTHERS AND SW MILL

The second urban street segment selected is a stretch of arterial road that feeds into the southwest corner of downtown Portland. This segment, stretching along SW 4th Avenue from Caruthers to Mill Street includes one bus stop. Directly upstream from this stop is a series of two crosswalks, and slightly farther upstream a signalized intersection and right-hand-side merger from I-405 North. There are also two signalized intersections and two crosswalks downstream of the bus stop (Figure 17). The 5-SR data for this segment is from February 4, 2015, and was used in conjunction with other research to examine the extent to which bus stops can be seen in the 5-SR data set. The visualizations from this stretch of arterial roadway capture delay caused by crosswalk activity (Figure 16: Box A & Box C), as well as delay caused by the upstream intersection at Lincoln. Crosswalk activity can be seen during morning peak and midday off-peak. This is likely a result of high pedestrian traffic at these times, as this is a popular crosswalk for Portland State University and professionals who work in the area. Furthermore, thin bands of higher speeds can be seen upstream. These, however, are interrupted occasionally by the signalized intersection.

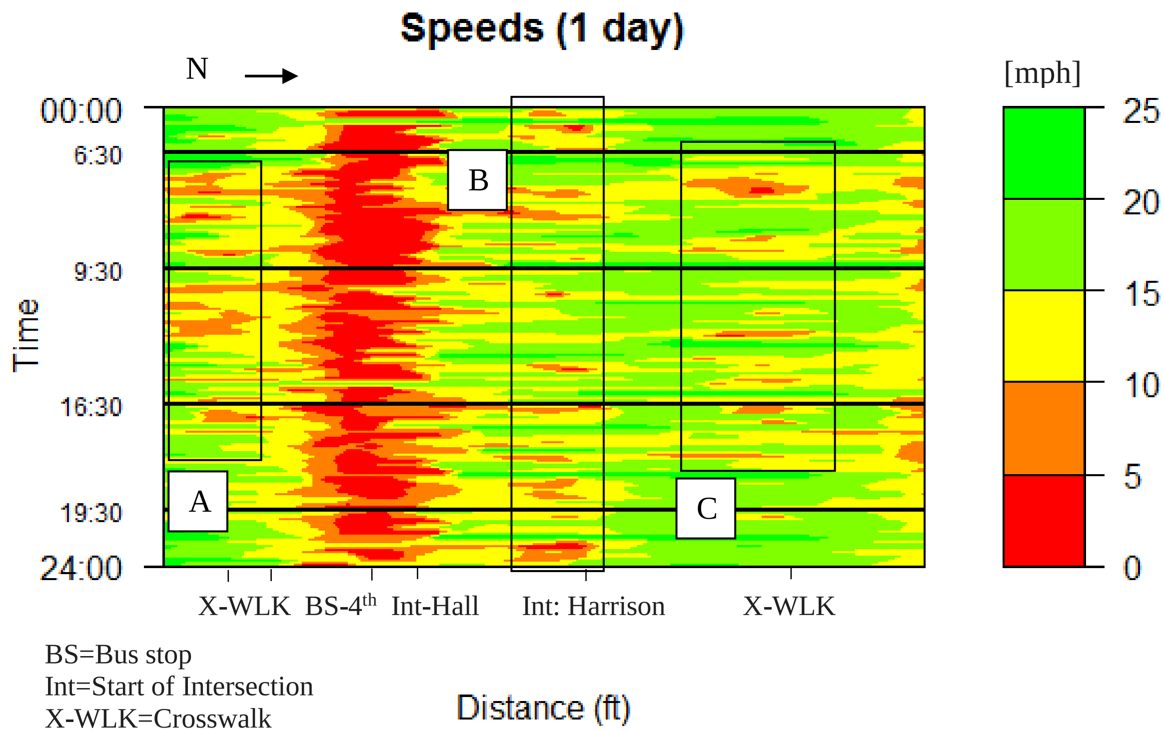


Figure 16: 4th Avenue plots.
(Top) Upstream of the bus stop and includes an intersection and merger. (Bottom) Includes crosswalks and bus stops.

Figure 17: Satellite view of crosswalks.
(Left) Close-up satellite view of crosswalk at College (A in Figure 16) and (Right) Close-up satellite view of crosswalk at Montgomery (B in Figure 16)

5.0 TRIP TIME MODEL

Travel time is the duration of a passenger trip from the origin to the destination of the transit trip over a specified route. The travel time was calculated from the layover stop at the beginning of the route to the layover stop at the end for the inbound direction, westbound. Travel time, reported as a time value, is closely tied to travel speed, reported as a travel rate. The conversion between travel time and travel rate is the distance between stops along the route. Travel time is of interest to the public, decision-makers, transit managers and transportation planners, as it is a performance measure understood by all. It is used to monitor service and measure passenger comfort (TCRP 88, 2003).

Travel time is one of the key performance measures that needs to be monitored and maintained. With an entire month's worth of data, it is possible to create and verify trip time models.

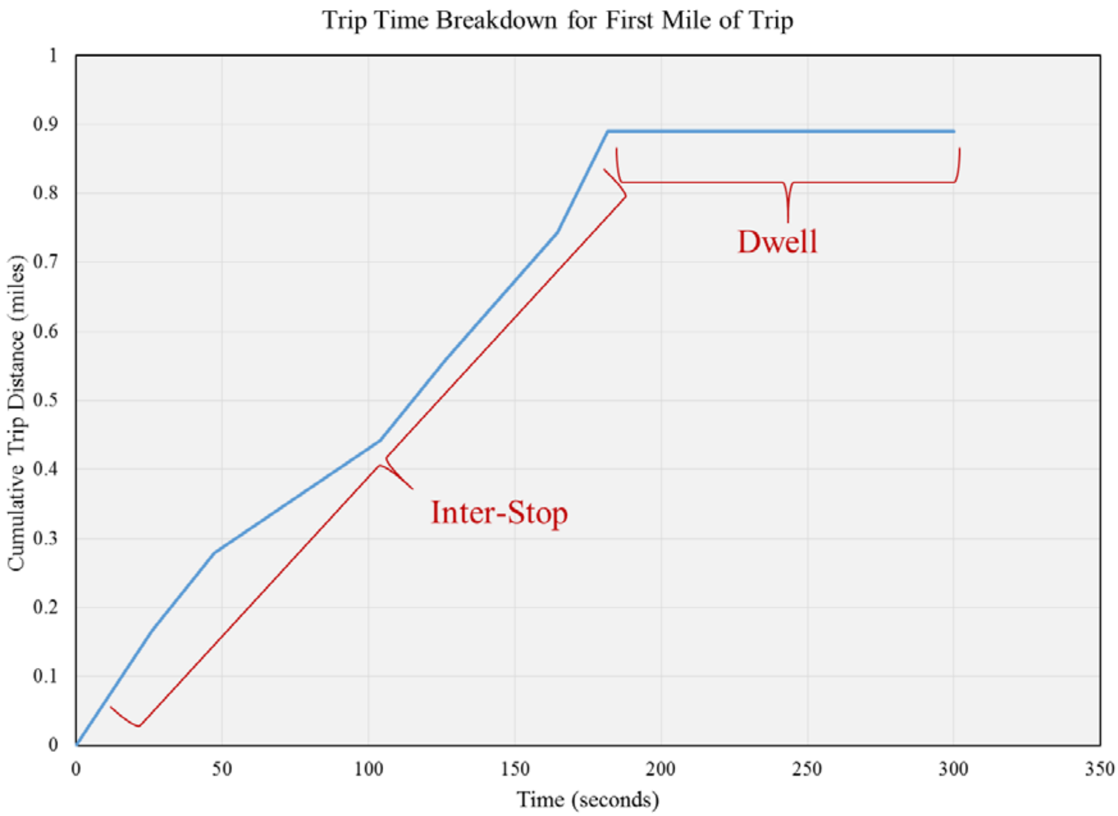


Figure 18: Inter-stop time vs. dwell time for first mile of trip.

Newell (1995) split inter-stop time and dwell time to analyze both of them separately. Figure 20 replicates the illustration from Newell using real data from the first-mile segment (eight stops) of Route 14. The inter-stop portion varies in slope (different speeds) for each of the segments traveled. Additionally, the dwell time adds to the horizontal line, but each stop varies in passenger movements. Therefore, in order to create a transit trip time model, a model needs to be developed for dwell time and inter-stop time separately.

5.1 DWELL TIME

Dwell time is an important parameter that affects transit service quality (Levinson, 1983). Dwell time is the time the doors of the bus are open to allow passengers to board and alight, which is a vital part of the trip time model. Originally, the trip time model combined all of the passenger movements (boarding and alighting) for a simple linear regression model.

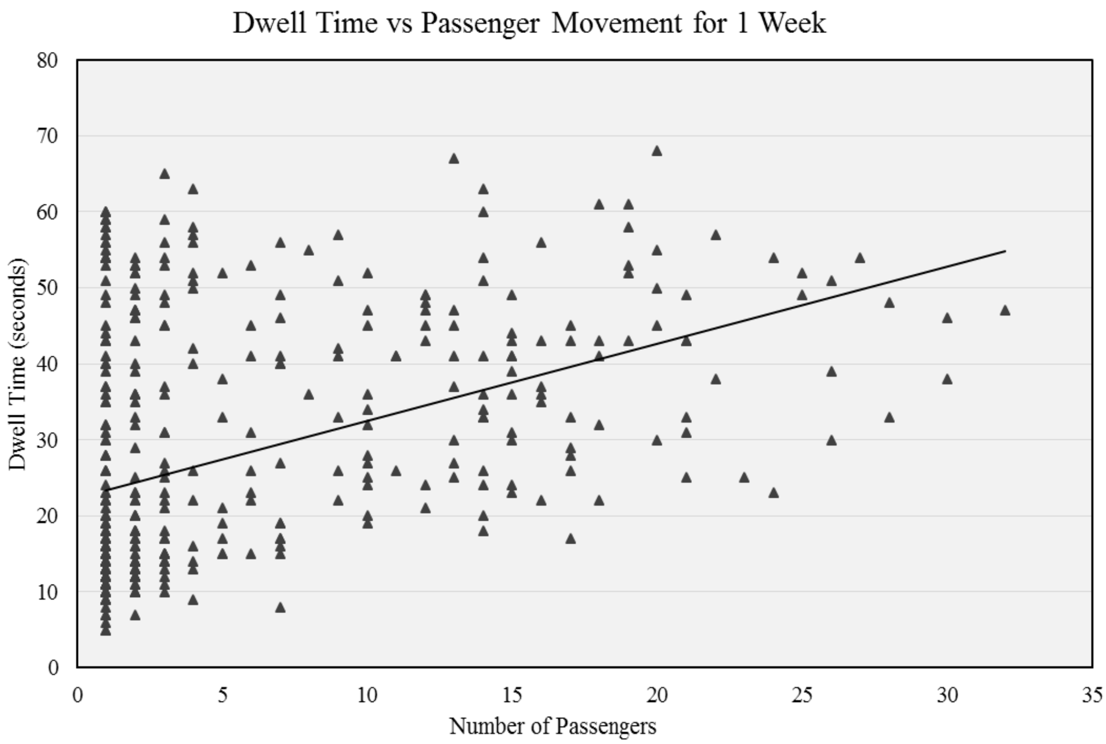


Figure 19: Dwell time vs. passenger movement for one week.

Figure 21 illustrates the original model: dwell time and passenger movement for all trips spanning from October 7-9, 2014. However, when alightings and boardings were combined, the regression output revealed a poor fit, R-squared value of 0.21. Therefore, that model was discarded in favor of another model estimated using separate coefficients for the number of boarding and alighting passengers. Instead of using simple linear regression, a bivariate regression is used to measure the dwell for only alighting, only boarding, and for both. This improved model incorporated how many times the bus actually stopped at a bus stop, the number of passengers who boarded and the number of passengers who alighted.

5.2 INTER-STOP TIME

Similar to dwell time, inter-stop time (travel time subtracted by dwell time) is also critical for the trip time. The next step was to investigate the relationship between inter-stop trip time and distance. The inter-stop time is the difference between the time the door was closed at the previous stop and the time the door was opened at the next stop. The inter-stop time is not a simple linear model, the slope (speed) varies between each stop. Figure 22 represents the inter-stop distances and times for the first mile of the trip.

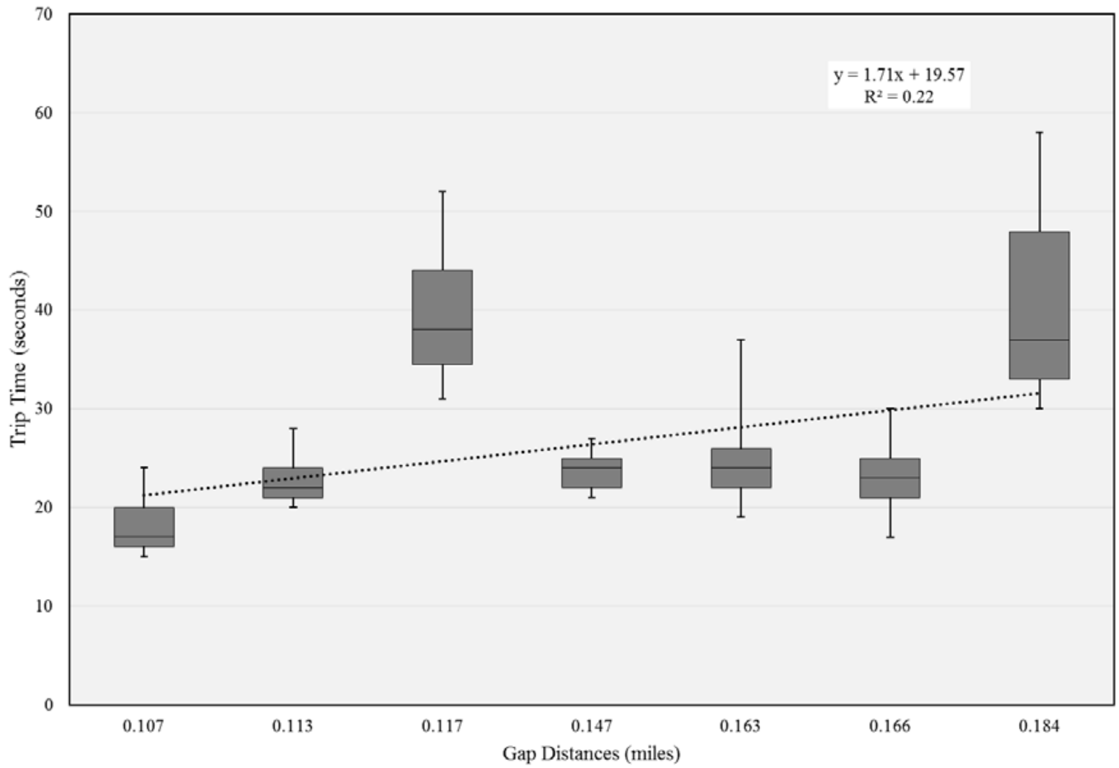


Figure 20: Boxplot of trip time vs. distance for first mile of trip.

The boxplot emphasizes that the inter-stop time is not a linear average; the times are variable for each distance between consecutive stops. The segments with 0.117 and 0.184 miles difference had the highest variability; and the segment with 0.117 miles had the higher average inter-stop travel time even though it is nearly half of the distance. Although the inter-stop time varies between each stop, a simplified approach was taken by Newell (1995) for the trip time model.

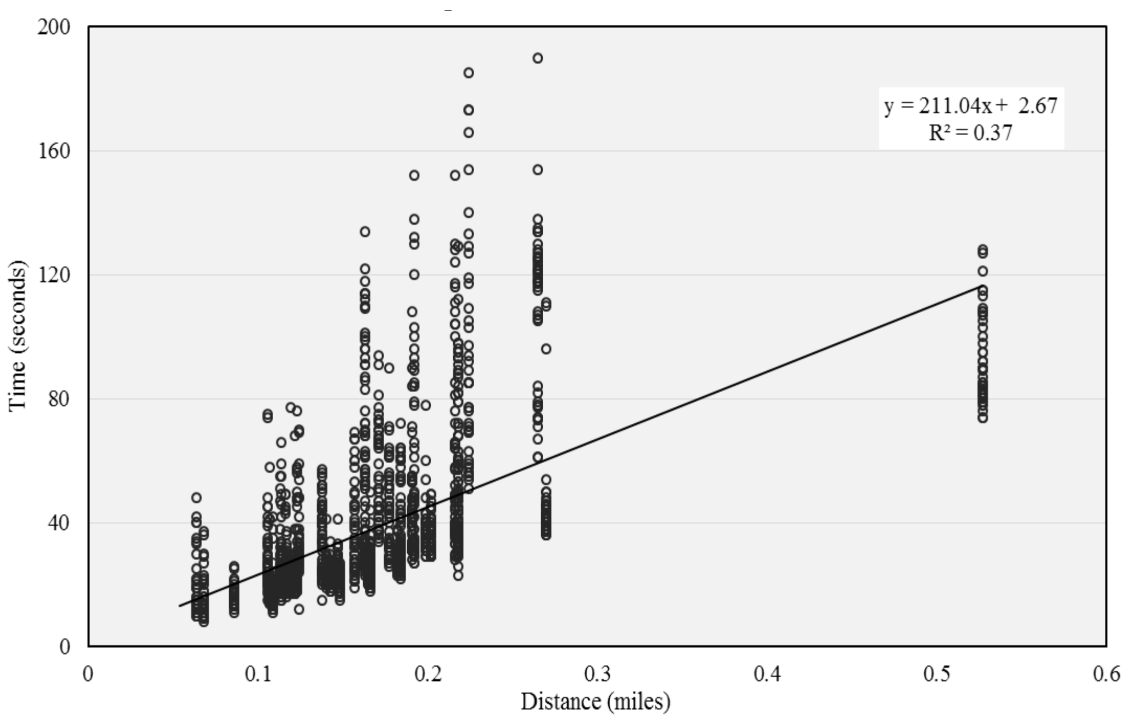


Figure 21: Inter-stop time vs. distance.

Figure 23 represents the inter-stop trip times between consecutive stops. A simple linear regression was used to estimate a linear relationship between trip time in seconds and distance in miles. The reason that the majority of the points are vertical at various locations is because the location of the bus stops does not change. Most of the stops are spaced between 0.1 and 0.25 miles apart, except for two stops which are spaced about half a mile apart. This larger distance is from the bus crossing the Hawthorne Bridge. The model output confirms the graphical representation as:

$$\text{Inter-stop time (seconds)} = 211.04 * (\text{distance}) + 2.67$$

These results indicate that approximately three seconds of time lost is attributable to the deceleration and acceleration required for stopping. This value appears to be extremely low for the entire trip, but the amount of travel associated with each mile at 211 seconds appears to be reasonable compared to the 118.5 seconds for each kilometer, which corresponds to approximately 191 seconds per mile, from the Newell trip time model (Bertini and El-Geneidy, 2004). The regression output revealed an R-squared value of 0.37 with parameters significant at the 95% level. Although the parameters were significant, the regression output does not have a strong correlation; this may be improved with the use of higher-resolution data.

5.3 NEWELL TRIP TIME MODEL

There have been several methods to build a trip time model; splitting the run time and the dwell time was considered to be the best procedure. The dwell time and inter-stop time models are combined for a trip time model, defined below, built upon the methodology from Newell (1964) and further developed by Bertini and El-Geneidy (2004).

$$T = T_0 + aN_d + bN_a + cN_b$$

Where T_0 = average inter-stop trip time
N_d = number of dwells (stops)
N_a = number of passengers alighting
N_b = number of passengers boarding

This trip time model had statistically valid parameters that described the transit trip in a reasonable way. The next step was to further validate and test this model using 2014 archived data from the same Route 14 from TriMet. This is evident in Table 3, which confirms that the previous trip time model is still relevant.

Table 3: Newell Trip Time Model Summary for 2003 and 2014

Model	2003	2014
R Square	0.4	0.37
Intercept	26.0	19.33
ONS	3.6	3.61
OFFS	0.85	1.38
Units	(km)	(mi)
Intercept	20.2	2.67
Nonstop	118.5	211.7
Mean Error	0.05	0.03

Although the model was developed using kilometers, it was created using the same length for the route, 7.2 miles or 11.6 kilometers. The mean error from the actual vs. predicted values for trip times produced convincing numbers in 2003 and 2014. The Newell Trip Time Model is a good tool to predict transit trip times and impacts of various bus stops.

5.4 NEW INTER-STOP MODEL

The previous trip time model, similar to the majority of models, was deterministic. However, Hans et al. (2015) developed a combination of deterministic and probabilistic distributions for dwell time and trip time. The data used to calibrate this model was also archived from TriMet's database along Route 72. There are two dwell time models; the first model uses dwell time to create a distribution for prediction, which is highly variable. The second model uses passenger movement to determine the amount of time spent at each stop, which the Newell model fully covered and proved to be a strong predictor. Therefore, this model will focus on the inter-stop portion of the trip.

The inter-stop models that will be recreated use travel time distributions with archived transit data and signal locations. The models that were from Hans (2015) also included travel time based on synthetic and realistic trajectories with signal settings, velocity characteristics of buses and traffic flow from loop detectors. Although readily available, this advanced signal information was not used in the following analyses.

5.4.1 Trip Time Model 1: Random Events

A bus can be delayed by traffic signals, traffic flows and other random occurrences during its movement between two consecutive stops. In order to account for various delays in between stops, a "random event" is added to the initial, average speed inter-stop model. This variable is an addition to the average inter-stop time that can range from zero seconds to 60 seconds. However, a random event may become negligible compared to delays occurring at signals. After discussions and further research into this type of random model behavior, this probabilistic model was not created.

5.4.2 Trip Time Model 2: Signals

Instead of considering all links to be the same, it is proposed to distinguish links without a traffic signal and with a traffic signal present. The variability in inter-stop time is likely due to the effect of the delay superimposed by signals encountered. Signal delay is the main factor in varying inter-stop time (Hans et al., 2015). If the signals were consistent or if none were present, Newell's average inter-stop time model would be sufficient. The bus encounters signals at various times and locations throughout the day; therefore, this previous model is not susceptible to delay and needs to be enhanced.

All of the inter-stop segments were analyzed by subtracting the arrival time at the stop by the leave time at the previous stop. Each segment was analyzed for all trips: 45 stops producing 44 inter-stop segments. Table 4 represents individual inter-stop segments for all trips for the work week of October 7-9, 2014.

Table 4: Individual Inter-Stop Data Summary for One Week

4.0	**Inter-Stop Time**		**Distance (mi)**		**Speed (mph)**	
	Mean	**St. Dev**	**Mean**	**St. Dev**	**Mean**	**St. Dev**
None	0:00:27	0:00:14	0.140	0.037	20.6	5.7
Signal	0:00:44	0:00:31	0.185	0.087	17.9	6.3

As expected, the mean travel time for the inter-stop segments without a signal between stops was lower than the mean travel time for inter-stop segments with one or more signals in between stops. The majority of the segments with signals only had one signal, and the only time there are segments with two signals are in the Portland downtown area. There are only three segments which have more than one signal, therefore, all segments with one or two signals were all grouped together. In addition to a higher average travel time, the standard deviation is also much higher than for segments without a signal. Although the segments with a signal are slightly longer segments, the average speed is a better component to compare because it incorporates the distance and time. Similarly, the average speed displays the same effect: segments with signals have a lower average speed and higher standard deviation.

Instead of building an extensive model to predict each inter-stop segment, the total inter-stop trip times were analyzed. Table 5 presents a summary of the total trip inter-stop times for each time period for the work week of October 7-9, 2014.

Table 5: Total Inter-Stop Trip Time Characteristics for One Week

Time Period	Mean	St Dev	Min	Max	Speed (mph)
AM	**1669**	**157**	1454	**1999**	**15.5**
MID	1575	129	1376	1878	16.5
PM	1619	121	1473	1903	16.0
LATE	1461	81	**1334**	1589	**17.7**
ALL	1600	143	1334	1999	16.2

The average total inter-stop time is the highest for the AM peak period. This time period also has the highest standard deviation and maximum travel time. The late-night period has the highest average speed. It appears that the variability in inter-stop travel time is highly dependent on whether or not the bus had to stop at a signal. Instead of relying on a "random event" to add into the trip time model, an inter-stop model with signal dependence needed to be created. After examining all of the signal locations along the bus route, it became apparent that it is not possible to create a model including signals using the BDS data. However, the higher-resolution data provides further insight to what is occurring between stops. As shown in Figure 24, when the five-second data has extended horizontal lines (at the same location for a period of time) it appears to portray traffic signal delay. Therefore, it is possible to create a model based on the number of signals encountered for the entire trip.

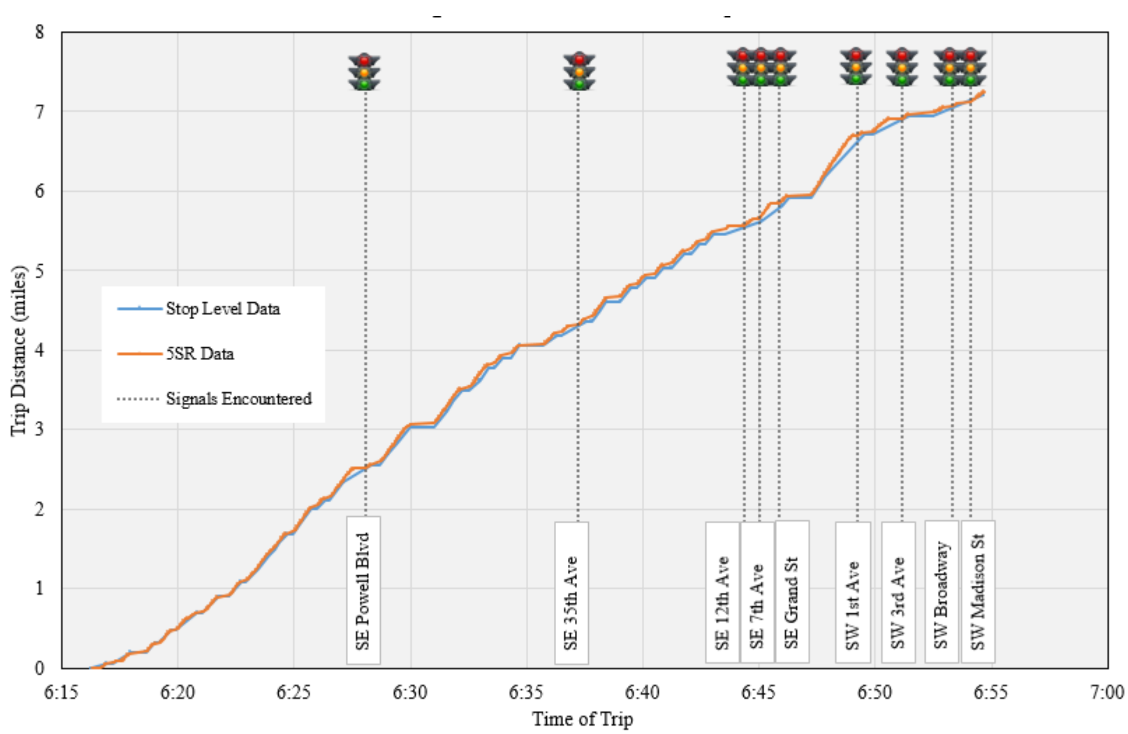


Figure 22: Signals encountered for one trip with BDS and 5-SR.

There are nine signals encountered in Figure 24, and it can be seen that the five-second resolution data fluctuates above and below the stop-level data. Figure 25 zooms in to one of the segments to further illustrate the higher resolution of the five-second data.

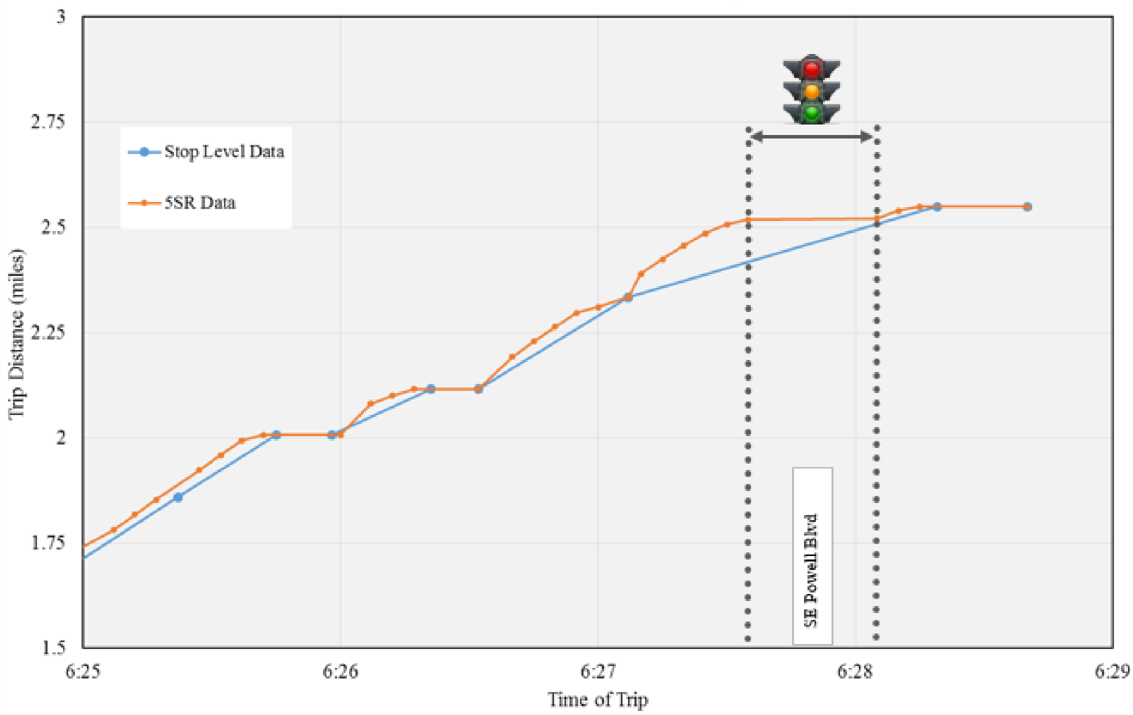


Figure 23: Signals encountered for one trip at SE Powell Boulevard.

A closer look allows the higher-resolution data to stand out and identify locations of traffic congestion or signal delay. On Tuesday, October 7, 2014, at 6 a.m., a bus approached SE Powell Boulevard to pick up passengers at the far-side stop. However, as shown by the 5-SR data, the bus had to stop and wait approximately 30 seconds for the signal to change. Once the bus passed the intersection, it quickly stopped again in order to pick up the passengers at the bus stop, as shown by the horizontal dwell time. A better representation of the intersection and the far-side bus stop is shown in Figure 26 using Google Maps. As mentioned in the route description, the bus route crosses SE Powell, also known as US 26, and is a major arterial that typically causes the bus to stop at the intersection before the bus stop.

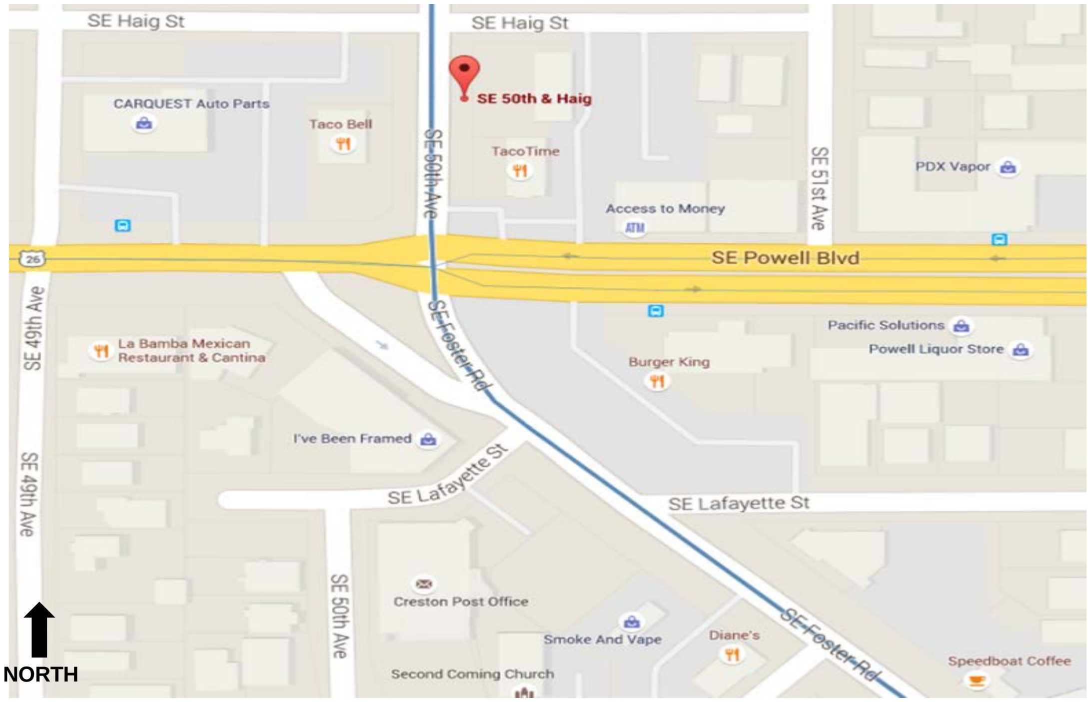


Figure 24: Google Maps image of far-side bus stop at SE Powell Boulevard.

The higher-resolution data is able to determine whether or not the bus stops for a signal. Stop-level data must be used to distinguish between a bus stopping for dwell time and stopping for a prolonged time outside of bus stops. A preliminary model was created to determine the linear relationship between signals encountered and inter-stop trip time. Figure 27 represents the linear relationship of signals encountered and total inter-stop time for an entire day, Tuesday, October 7, 2014.

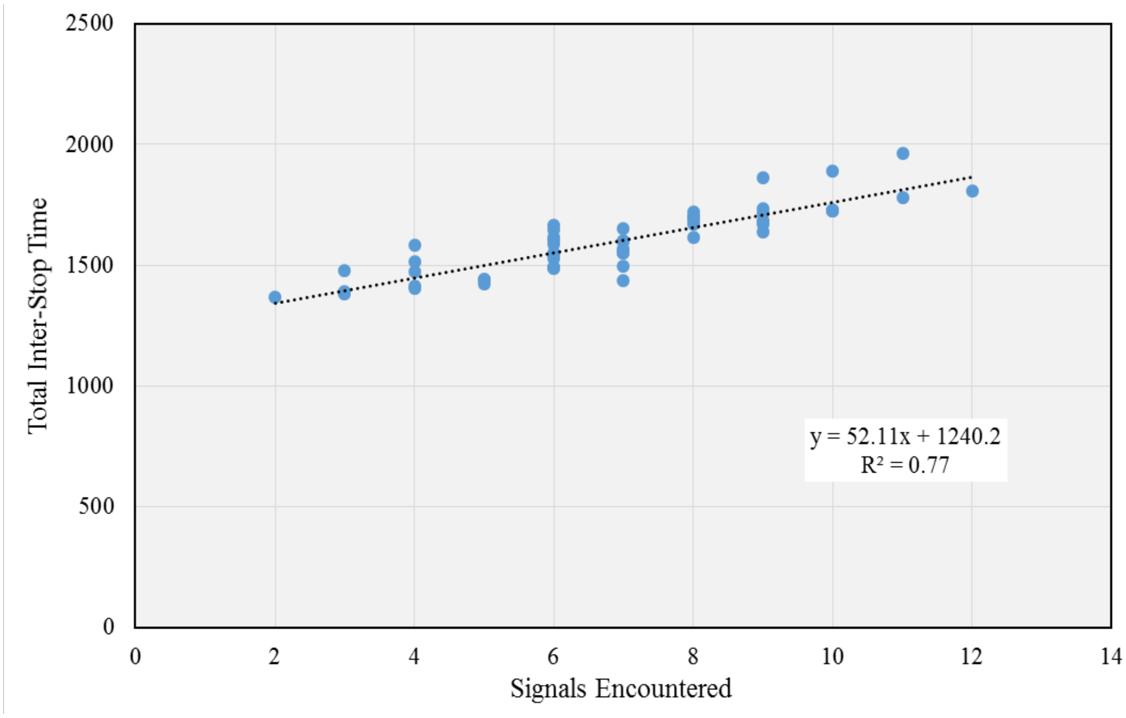


Figure 25: Signals encountered vs. total inter-stop time for all day.

There is a strong correlation as shown by the points on the line, and the R squared value. The linear regression equation suggests that each signal encountered adds approximately 52 seconds to the total inter-stop trip time. The equation also suggests that the inter-stop time is 1,240 seconds if zero signals are encountered for the 7.2-mile route, which translates to about 21 mph.

In order to improve the model, signals and time period are taken into consideration for multivariate regression. Similar to creating correlations and decision trees in SAS, this software developed a regression model incorporating time period as a categorical variable and signals encountered as a continuous variable to forecast total inter-stop time. Figure 28 replicates the same model for signals encountered all day, but focuses on the AM peak period.

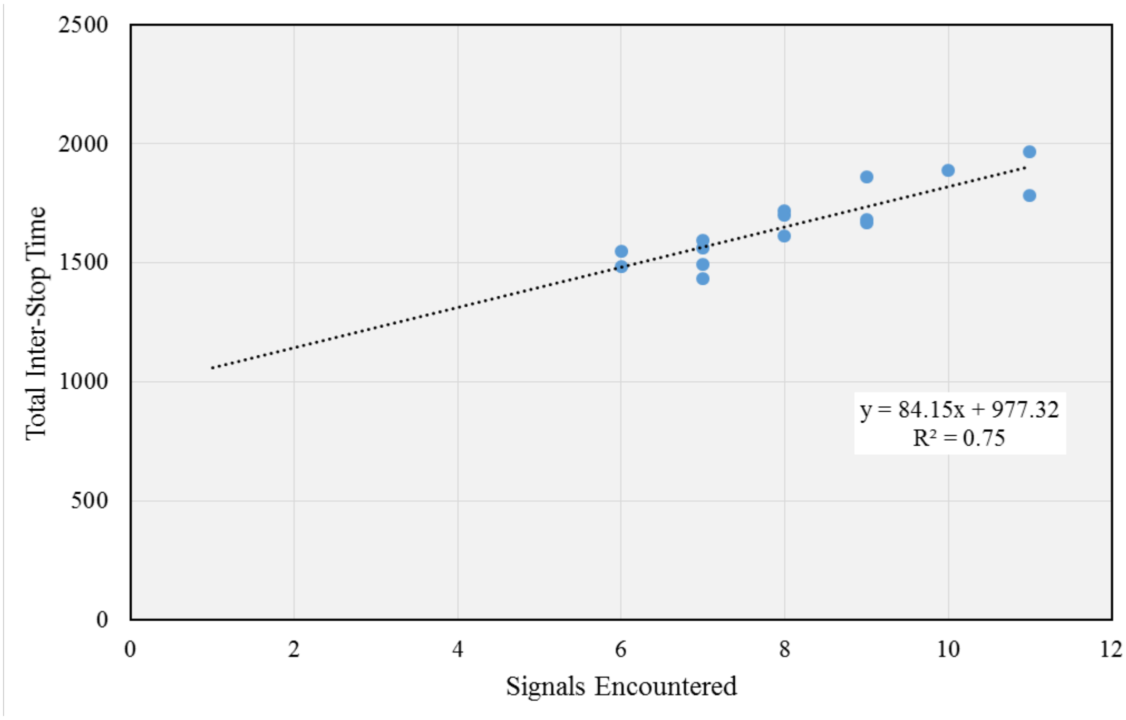


Figure 26: Signals encountered vs. inter-stop time AM peak period

There is a very strong linear relationship between the signals encountered for the AM peak period, which matches the strength for the signals encountered all day. This procedure was repeated for all of the time periods. The linear regression models for each time period are shown in Table 6, where the signal delay coefficient denotes the amount of time (seconds) each signal delays the trip.

Table 6: New Inter-Stop Trip Time Models

Time Period	Intercept	Signal Delay Coefficient	R-Squared
AM	977.3	84.2	0.75
MID	1242.5	49.9	0.80
PM	1334.4	40.8	0.76
LATE	1287.9	41.1	0.64

The formulas include an intercept for the inter-stop time if zero signals are encountered and a constant for the impact of each signal. The AM peak period has the lowest intercept, but makes up for the inter-stop time with the highest constant for each signal. The AM peak period is the most congested time period, with the majority of people traveling from the southeast suburbs into downtown Portland. The late-night period may not have the lowest intercept or constant, but it had a lower number of signals encountered and ended up with the shortest inter-stop trip times. This new inter-stop trip time model will be compared to the previous Newell trip time model in the next section after validating the minimum sample size.

6.0 CONCLUSIONS

The objective of this research was to explore the potential benefits and applications of new higher-resolution transit data on one transit route. 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 and to predict travel times.

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 alone. 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 indicates congestion before buses were able to reach their stop destinations, especially for bus stops shortly following signalized intersections such as SE 82nd Avenue and SE 39th Avenue. An analysis of average speed created using 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 one hour 17 minutes. 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 27-38% of the time was spent stopped.

Using new high-resolution bus location data, we have developed tools that can help to quickly locate and examine sources of delay along these road systems. These tools are beneficial for finding delay on both urban corridors and urban streets. Identification of such problem areas is crucial to being able to understand and respond with appropriate performance measures. By using buses as probes and examining aggregated bus behavior, contoured speed plots can be used to understand the behavior of roadways outside the zone of influence of bus stops. Our analysis found that these speed plots can be used to discover trends and travel patterns quickly, and with only a few days' worth of data. Congestion and speed variation can be viewed by time of day, and with knowledge of a transportation network these plots can help indicate congestion caused by intersections, crosswalks or bus stops. Further analysis can be done to merge this research, which looked more closely at travel behavior outside the influence of bus zones, with research specifically looking at the data directly around bus stops.

Transit travel time on TriMet's inbound trip on Route 14 for October 2014 was also analyzed. The inbound route typically has the highest usage and lowest reliability because of the congestion from commuters. On this route, the Newell trip time model was recreated using high-resolution 2014 BDS data. This trip time model resulted in statistically significant parameters and proved to still be applicable. However, the Newell model took a simplified approach for the inter-stop portion of the trip by using a single value of average speed. The higher-resolution data provides increasingly valuable and more highly granular information between stops. This data allows for more realistic conditions to be examined, and potential congestion and traffic conditions to be analyzed. The variability in inter-stop time is likely due to the effect of the delay superimposed by traffic signals and other traffic-stream elements encountered. A new and improved inter-stop trip time model was developed based on the number of signals encountered during each time period. This model resulted in statistically significant results and provides more accurate predictions of inter-stop trip times.

6.1 FUTURE RECOMMENDATIONS

As with any observational data mining method, this study could benefit from larger sample sizes. The minimum sample size requirements were met, but a larger sample size could be used for each of the analyses performed. This could include more days, directions, routes, and segregation according to weather or season. The methods used in this report should be easily transferable to other locations where archived transit data is implemented.

This analysis calls for a recommendation for a change in TriMet's 5-SR data. It is recommended that reports should be made every five seconds regardless of bus motion. This will allow for accurate stop times and the locations of these stops to be directly analyzed. Currently, only an assumption of slow speed can be used and actual stopping time is uncertain. In addition, it should be noted that without a few additional pieces of information, 5-SR data is not accessible on its own. It requires that BDS data be used to compare and extract the data. This could be resolved by including additional fields in the data about train and trip number. Wheel-sensor movement data could be another complementary dataset to overcome the limitations in this study.

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