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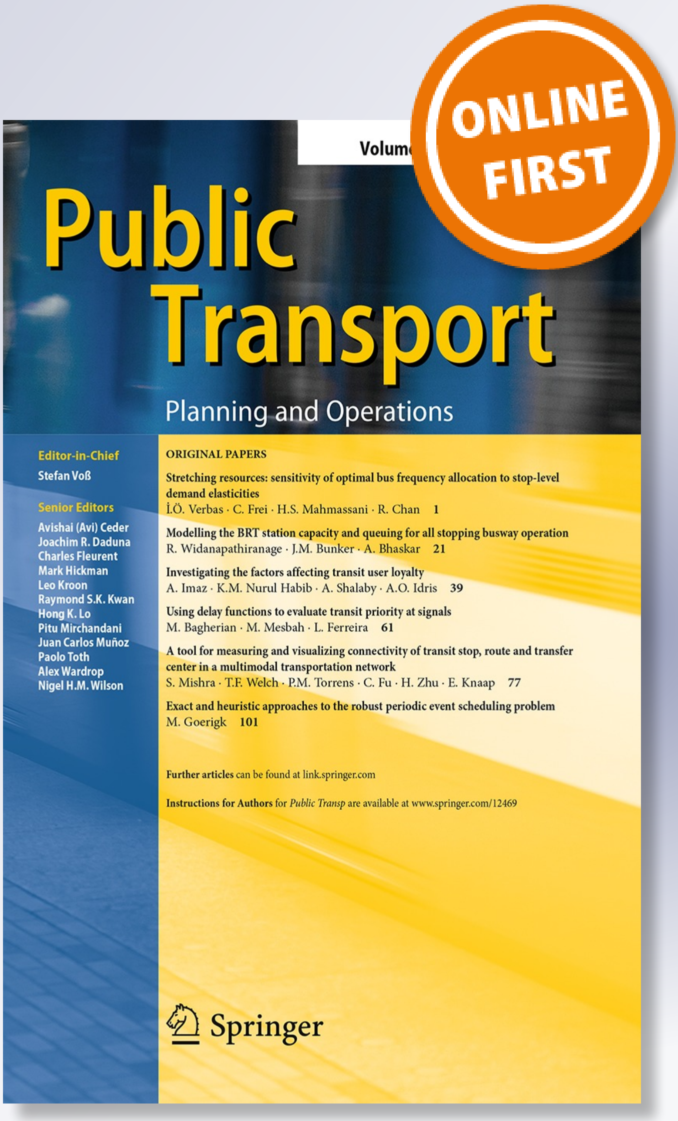
Public Transport
Planning and Operations

ISSN 1866-749X

Public Transp
DOI 10.1007/s12469-015-0105-8



Springer

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ORIGINAL PAPER

Quantifying the joint impacts of stop locations, signalized intersections, and traffic conditions on bus travel time

Wei Feng[1] · Miguel Figliozzi[2] · Robert L. Bertini[3]

Abstract Quantifying factors that affect bus travel time along arterials is necessary to prioritize investments to reduce bus travel time and its variability and to design advanced prediction and traveler information systems. The joint effects of bus stop location (near vs. far side), intersection delay and traffic conditions on travel time have not been addressed in the literature. To fill this research gap, this study integrates detailed transit, signal phase and traffic data at the stop-to-stop level. Statistical modeling results indicate that red time and the proportion of red time per cycle are the key traffic signal timing factors that affect bus stop-to-stop travel time variability. Bus stop location also has a statistically significant effect on intersection signal delay and passenger boarding times. The impact of traffic volumes on delay is not as high as signal delay but it is significant and varies drastically by segment and time of day.

Keywords Bus travel time and variability · Intersection delay · Signal delay · Traffic volume · Bus stop location

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1 Introduction and background

Transit travel time is important to both passengers and transit agencies. Slow and unreliable transit service may increase transit user costs in the short term and reduce transit mode share and ridership in the long term, which in turn may lead to higher levels of congestion, emissions, energy consumption, and auto dependency in urban areas. In addition, bus travel time variability is important to schedulers because to improve on-time performance slack time is added to transit schedules.

Many factors affect bus travel time and its variability such as uncertain passenger demand, traffic conditions, driver behavior, signal delay at traffic signals, bus stop location, road geometry, vehicle incidents/accidents, and weather (Turnquist 1981; Levinson 1991; Ceder 2007). If the impacts of these factors on bus travel time and its reliability can be quantified, transit agencies can prioritize investments on strategies and policies to reduce bus travel time and its variability. Travel time models can also provide real-time predictions for advanced traveler information and fleet management systems.

Since the introduction of automatic vehicle location (AVL) and automatic passenger count (APC) data collection systems, factors affecting bus travel time and service reliability have been studied at the route level (Abkowitz and Engelstein 1984; Strathman et al. 2000), time point segment level (Bertini and El-Geneidy 2004; El-Geneidy et al. 2011; Figliozzi and Feng 2012; Slavin et al. 2013) and stop-to-stop segment level (Albright and Figliozzi 2012). Other studies analyzed bus travel time delay/deviation (Diab and El-Geneidy 2012; El-Geneidy et al. 2011, 2009; Strathman et al. 1999), travel time standard deviation (Mazloumi et al. 2010) and travel time coefficient of variation (Diab and El-Geneidy 2013). Dueker et al. (2004) and Milkovits (2008) also studied bus dwell time. Common factors impacting bus travel time and dwell time include: distance, the number of bus stops and signalized intersections, passenger boarding/alighting activities, lift use, bus load, time of day, travel direction, driver experience, departure delay, bus vehicle type, route type and weather.

Several studies have investigated the impact of signalized intersections on bus travel time. Abkowitz and Engelstein (1984), El-Geneidy et al. (2009), McKnight et al. (2004) and Albright and Figliozzi (2012) found that each intersection adds an average of 8–26 s to bus travel time. Mazloumi et al. (2010) found that each additional number of intersections per kilometer increases travel time variation by 22 %. El-Geneidy et al. (2009) and Figliozzi and Feng (2012) also found that each stop sign adds an average of 12–16 s to bus travel time. Figliozzi and Feng (2012) found that the average additional travel time due to a bus passing through, turning left and turning right at an intersection are 5, 20 and 38 s, respectively. No previous study has quantified the effect of signalized intersections on bus travel time variability by incorporating intersection specific signal timing data.

Traffic conditions also affect bus travel time and its variability, but most research has used proxies such as "time of day" or "travel direction" instead of actual traffic count data. The only exception is Mazloumi et al. (2012) that found that traffic flow explained 20–50 % of bus travel time variability and that the impact of traffic flow can be approximated by time of day variables. These results were obtained at the time point segment level and the impacts of signal delay and passenger activities were not accounted for.

The impact of bus stop location, near-side (the bus stops before crossing the intersection, near the intersection stop bar) versus far-side (the bus stops after crossing the intersection) placement is a long-standing controversial research and design question (Furth and SanClemente 2006). Albright and Figliozzi (2012) showed that stop-to-stop segments with a near-side bus stop have an average of 3.7 s shorter travel time than those segments with a far-side stop. However, the different effects of signal delay and traffic volumes between near-side and far-side bus stops have not been yet studied.

In summary, there is no previous research that has analyzed the joint impact of bus stop location, signal delay, and traffic conditions on bus travel time at the stop-to-stop segment level. To address this gap in the literature it is necessary to integrate bus, signal controller and traffic detector data. This study has had access to bus AVL/APC data provided by the Tri-County Metropolitan Transportation District of Oregon (TriMet), the Sydney Coordinated Adaptive Traffic System (SCATS) signal phase log data and intersection traffic count data provided by the Portland Bureau of Transportation in the City of Portland, Oregon. The integration of these data sources allows a novel analysis of bus travel time and its variability at the stop-to-stop level.

This paper is organized as follows. Section 2 describes the study area and data sources. Section 3 describes variable statistics. Section 4 presents regression model specifications. Section 5 discusses results. Section 6 ends with conclusions.

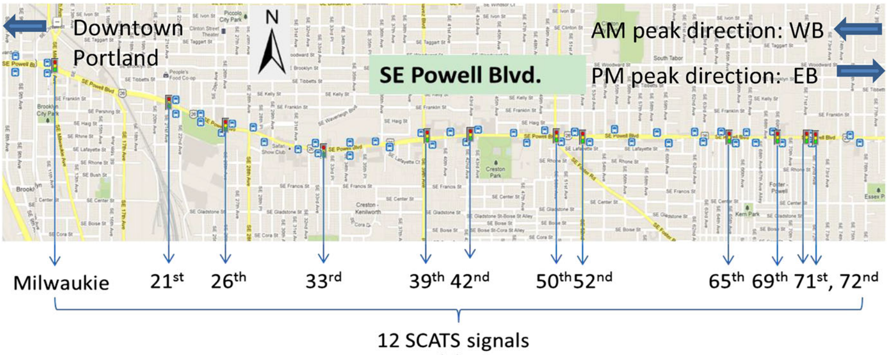
2 Study corridor and data descriptions

2.1 Study corridor description

The study corridor is a 4-mile urban arterial segment along SE Powell Boulevard in Portland, Oregon (Fig. 1a) with two lanes (mixed traffic lanes, no dedicated bus lanes) in each direction. TriMet route 9 runs east–west with an average headway of 15 min during midday and an average headway of 6–7 min during the morning and evening peak periods.

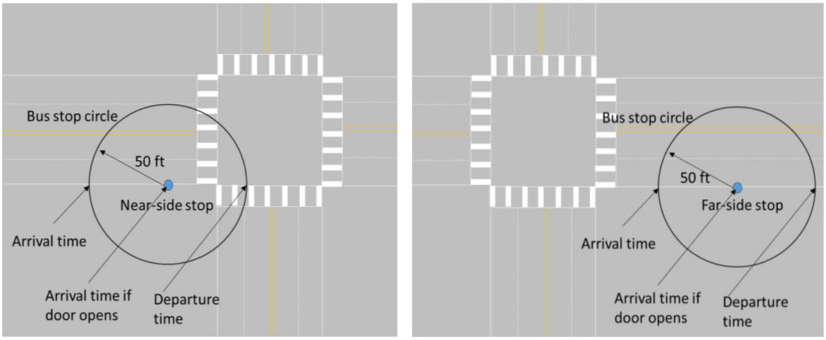
The SCATS system is implemented at 12 signalized intersections between Milwaukie Ave. and 72nd Ave. Cycle lengths at each intersection is an average of 120 s. Red phase duration varies significantly across intersections; buses may experience longer delays at some major intersections such as Milwaukie (MKE), 39th, 50th and 52nd Ave. Figure 1b shows the geometries of one major signalized intersection and one minor signalized intersection. More detailed intersection geometry information can be found in the following link on GoogleMaps: https://goo.gl/maps/2YuCv.

There are 22 bus stops and 21 bus stop-to-stop segments in each direction between Milwaukie and 72nd Ave., classified into four categories:



(a)

(b) Major (39th) and Minor (65th) Cross Street Examples



(c) (Bertini and El-Geneidy, 2004)

Fig. 1 Study corridor overview and examples of intersection geometry

1. *Near-side segment:* departure stop of the stop-to-stop segment is a near-side stop; there is only one signalized intersection in the segment.
2. *Far-side segment*: arrival stop of the stop-to-stop segment is a far-side stop; there is only one signalized intersection in the segment.
3. *Segment with two or more signals*: there are two or more signalized intersections within a stop-to-stop segment, for example, the departure stop is a near-side stop and the arrival stop is a far-side stop.
4. *Segment without a signal*: there is no signalized intersection within the segment.

This study only focuses on the near-side (1) and far-side (2) segments.

2.2 Data description

The arrival time, departure time and schedule time are recorded in the AVL/APC system each time a bus stops; stop location, vehicle information, passenger activities, onboard passengers and dwell time are also recorded. As shown in Fig. 1c, each TriMet stop is referenced by a 50-foot stop circle in the agency's Geographic Information System (GIS). *Arrival time* is the time that a bus first enters the stop circle except if a door opening occurs, *arrival time* is the door opening time. *Departure time* is the time when a bus leaves the 50-foot stop circle. However, all near-side bus stops are close enough to the intersection stop bar (less than 50 feet) that signal delay for buses at near-side stops is not included in the time interval between the departure time from this near-side stop and the arrival time in the next bus stop. This leads to different modeling strategies for near-side and far-side stop segments to study the impact of signal delay on bus travel time reliability. *Schedule time* is the scheduled departure time for a bus stop (TriMet 2013).

SCATS signal phase data records the start time and end time of each phase including regular green phase, red phase and transit signal priority phases (green extension and early green). SCATS system also provides vehicle count data for each approaching lane of an intersection at the 15-min intervals.

TriMet archives AVL and APC data on a daily basis on all routes and all vehicles; route 9 AVL and APC weekday data for March and May 2013 were provided by TriMet. The City of Portland archives daily SCATS signal phase log data and traffic loop count data for all intersections in the corridor. Datasets were downloaded for all weekdays and all intersections during March and May 2013. A more detailed description of the data formats can be found in Feng (2014). The three data sources were integrated to compute the regression model variables.

Synchronizing the datasets was an important step. To guarantee that times in different data sources are synchronized and comparable, 4 h of video were analyzed at two different intersections. Bus departure time, bus arrival time, signal phase change times (red, green and yellow), and transit signal priority (TSP) phase data were compared. A 5-s offset was found between buses and signal phase data and times were properly adjusted in the integration process. A sensitivity analysis indicated that the regression results were not affected by small changes in bus arrival times.

3 Variable descriptions

Table 1 summarizes the dependent and independent variables that are used in the bus travel time models. Both departure-to-arrival time and arrival-to-arrival time are used as dependent variables. Independent variables can be grouped into four categories: travel impedance variables; signal delay variables; departure stop activity variables; and segment characteristics variables.

Table 1 Description of variables

	Description
Dependent variables	
Departure-to-arrival time	Arrival time at downstream (arrival) stop minus departure time at upstream (departure) stop (seconds)
Arrival-to-arrival time	Arrival time at downstream (arrival) stop minus arrival time at upstream (departure) stop (seconds)
Independent variables	
Travel impedance variables	
Distance	Travel distance between upstream and downstream stops (miles)
Traffic volume	Thousands of through vehicles per hour (kvph)
Peak	1, if between 7–9 a.m. in WB direction or 4–6 p.m. in EB direction
Signal delay variables	
Red	1, if the bus encountered a red signal
Red time	Red phase duration (seconds) if bus encountered a red signal
RC ratio	Ratio between median red phase duration for bus movement direction and median cycle length at an intersection
Departure stop activity variables	
Ons	Number of boarding passengers at departure stop
Offs	Number of alighting passengers at departure stop
Lift	Number of lift uses at departure stop
Departure delay	Actual departure time—scheduled departure time (minutes)
Skip	1, if bus skipped departure stop;
Segment characteristics variables	
Near-side	1, if stop-to-stop segment is a near-side segment

Table 2 presents a summary of segment characteristic variables, means and standard deviations of key variables for each individual segment and the average of far-side segments and all stop-to-stop segments. The number of observed bus stop-to-stop trips in each segment ranges between 2760 and 2930. Segment distance ranges between 0.1 and 0.24 miles. The mean distances of far-side segments and all segments are 0.13 and 0.14 miles, respectively. The mean departure-to-arrival travel speed for all far-side segments is 14.2 mph, which is much lower than the speed limit (35 mph) for this corridor. Mean travel speeds are highly dependent on travel time direction and time of day.

Red/cycle (RC) ratios range between 0.1 and 0.55. The total numbers of bus trips for far-side segments and all stop-to-stop segments are 34,070 and 51,307, respectively. Departure-to-arrival time and departure delay for near-side segments are not available because signal delay will be excluded (see explanation in Sect. 2.2). Results show that the means and standard deviations of departure-to-arrival time and arrival-to-arrival time are higher at segments with large RC ratios.

Table 2 Variable descriptive statistics

Segments	No. of obs.	Dist. (mile)	RC ratio	Departure-to-arrival time (s)		Arrival-to-arrival time (s)		Traffic volume (kvph)		Peak	Red	Ons		Offs		Lift		Departure delay (min)		Skip
				m	sd	m	sd	m	sd	m	m	m	sd	m	sd	m	sd	m	sd	m
26th EB (near)	2936	0.18	0.31	–	–	66	30	1.0	0.5	0.2	0.5	1.9	3.6	4.1	18.9	0.0	0.1	–	–	0.2
26th WB (near)	2757	0.13	0.31	–	–	45	26	1.1	0.4	0.2	0.3	2.1	4.3	2.7	17.3	0.0	0.1	–	–	0.2
33rd EB (near)	2927	0.12	0.14	–	–	35	17	1.2	0.5	0.2	0.2	0.4	0.9	2.2	16.1	0.0	0.1	–	–	0.4
33rd WB	2756	0.14	0.14	25	10	39	18	1.2	0.4	0.2	0.1	0.9	1.2	2.3	15.8	0.0	0.1	1.3	2.4	0.4
39th EB	2938	0.16	0.55	51	27	58	29	0.9	0.4	0.2	0.4	0.3	0.8	1.6	13.7			1.5	3.3	0.6
39th WB	2760	0.11	0.55	44	27	52	30	0.9	0.3	0.2	0.4	0.3	0.7	1.7	12.7	0.0	0.0	0.7	2.4	0.6
42nd EB (near)	2937	0.24	0.21	–	–	48	19	0.9	0.4	0.2	0.3	0.3	0.7	2.0	15.3	0.0	0.0	–	–	0.5
43rd WB (near)	2757	0.13	0.21	–	–	33	19	0.9	0.3	0.2	0.3	0.6	1.0	1.2	11.5	0.0	0.0	–	–	0.5
50th EB	2935	0.16	0.42	43	23	49	26	0.7	0.3	0.2	0.3	0.3	0.9	1.5	12.8	0.0	0.1	1.9	3.3	0.6
50th WB	2762	0.14	0.47	50	29	77	40	0.7	0.3	0.2	0.5	1.8	2.6	2.8	16.9	0.0	0.1	0.5	2.3	0.1
52nd EB	2928	0.10	0.35	33	25	50	34	0.7	0.3	0.2	0.3	0.7	1.4	3.5	17.8	0.0	0.1	2.1	3.3	0.3
52nd WB	2761	0.16	0.28	37	18	48	23	0.9	0.4	0.2	0.2	0.6	1.0	2.1	13.7	0.0	0.0	0.1	2.3	0.4
65th EB	2920	0.14	0.13	22	8	27	12	0.8	0.4	0.2	0.1	0.1	0.4	1.1	12.1	0.0	0.0	1.7	3.4	0.7
65th WB	2760	0.10	0.13	19	7	30	16	0.8	0.3	0.2	0.1	0.6	1.0	1.2	11.1	0.0	0.0	0.6	2.2	0.5
69th EB	2932	0.11	0.10	19	6	26	13	0.8	0.4	0.2	0.0	0.2	0.6	1.5	13.3	0.0	0.0	1.5	3.4	0.6
71st EB	2930	0.13	0.15	23	10	30	16	0.9	0.4	0.2	0.1	0.2	0.5	1.0	11.0	0.0	0.1	1.4	3.4	0.6
72nd EB (near)	2933	0.18	0.18	–	–	40	18	0.8	0.4	0.2	0.2	0.4	0.9	2.3	16.0	0.0	0.2	–	–	0.4
72nd WB	2761	0.17	0.16	30	10	37	15	0.8	0.3	0.2	0.1	0.4	0.8	0.7	8.7	0.0	0.1	0.7	2.1	0.6
Far-side segments	34,070	0.13	0.29	33	22	43	26	0.8	0.4	0.2	0.2	0.5	0.2	1.8	13.5	0.0	0.1	1.2	2.9	0.5
All segments	51,307	0.14	0.27	–	–	44	27	0.8	0.5	0.2	0.3	0.7	1.8	2.0	14.4	0.0	0.1	–	–	0.5

m mean, *sd* standard deviation

The mean values of the red variable indicate that the percentage of bus trips that encountered a red phase delay is also higher at segments with large RC ratios.

Mean traffic volume is higher at segments that are close to the west side of this corridor. About 20 % of the bus trips were made in peak hours at all segments. Departure delay, as an indicator of service reliability, varies significantly across segments. The percentage of bus trips that skipped the departure stop is higher at far-side segments. Passenger activities are higher at the departure stop of near-side segments. Traffic volume for a bus stop-to-stop trip is the equivalent number of through vehicles per hour in the bus travel direction in the 15-min interval when the bus arrives at the downstream stop. The red binary variable indicates whether a bus trip encountered a red signal. The value of this variable is determined by comparing bus stop-to-stop travel time intervals with red phase intervals of an intersection. As shown in Fig. 2, τ is defined as the travel time from the upstream bus stop to the intersection. The red variable is equal to 1 for bus trip i if the following conditions are met by any red phase interval j:

$$dt_i + \tau \leq R_j^e < at_i \tag{1}$$

$$R_j^s < dt_i + \tau \tag{2}$$

Expression (1) is a logical constraint that ensures bus i experiences red phase delay if its arrival time at the intersection ($dt_i + \tau$) is before the end (R_j^e) of a red phase j; and that bus arrival time at the downstream stop (at_i) is after the end (R_j^e) of the red phase j. Expression (2) is another logical constraint that ensures the arrival time of bus i at the intersection ($dt_i + \tau$) occurs after the red phase begins (R_j^s).

To estimate τ, travel time data for each stop-to-stop segment is grouped by direction of travel and time of day (early morning off-peak, morning-peak, midday

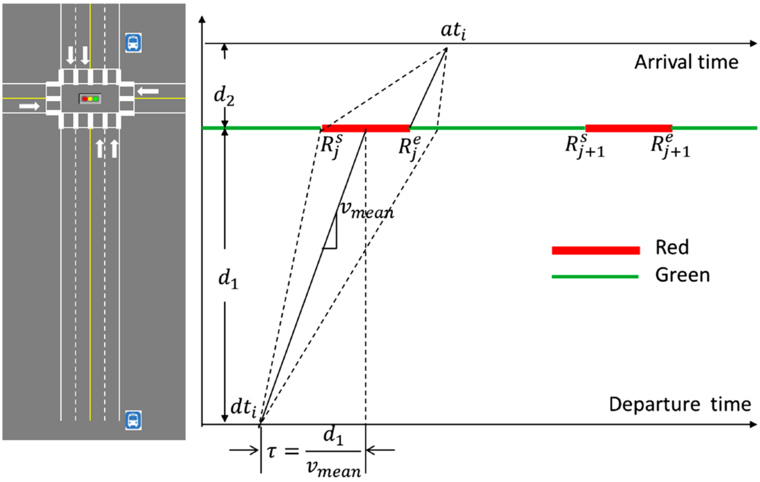


Fig. 2 Time-space diagram for a bus that encounters a red signal

off-peak, evening peak, and evening off-peak) and subsequently ordered from lowest to highest in each stop-to-stop segment in each time of day. It is assumed that the buses with higher travel times have experienced signal delay and therefore the top $n \times R/C$ observations are not included in v_{mean} process, where n is the number of observations in any stop-to-stop segment in any time of day, R is the intersection average red time, and C is the average cycle time. The mean non-stop travel speed (v_{mean}) for each segment, travel direction and time of day is used to estimate the travel time $\tau = \frac{d_1}{v_{mean}}$ as shown in Fig. 2. Note that the top $n \times R/C$ observations were not removed from the model estimation, all data records were utilized in the regression models.

The red time variable is the actual red phase duration in seconds multiplied by the red binary variable. Therefore, if a bus encountered a red signal in cycle j, red time is equal to $R_j^e - R_j^s$, where R_j^s and R_j^e are the start and end times of the red phase in cycle j. If a bus did not experience a red signal (red dummy equal to 0), red time is 0. Some intersections with high cross street traffic volumes have long red phase durations for the EB and WB directions, such as Powell Blvd at 26th, 39th, 50th and 52nd Ave.

The distance, RC ratio and Near-side independent variables are constant for different trips made in each stop-to-stop segment and therefore they can explain bus travel time variability only between stop-to-stop segments. The remaining independent variables can change among trips in the same stop-to-stop segment; these variables can explain bus travel time variability within each stop-to-stop segment and also between segments.

4 Model specifications

Table 3 summarizes the variables used in pooled and individual regression models: (1) far-side segments departure-to-arrival time model estimates only the effects of signal delay and traffic conditions on bus travel time eliminating the effects of departure stop passenger activities; (2) far-side segments arrival-to-arrival time model incorporates passenger activities to model (1) to observe the impact of passenger activity on travel time variability and model (1) stability; (3) all segments arrival-to-arrival time model aims to quantify the simultaneous effects of signal delay, traffic conditions, passenger activities and bus stop location on bus stop-to-stop travel time; and (4) and (5) individual segment stop-to-stop travel time aim to reveal more details about how those effects vary across intersections and travel directions. The arrival-to-arrival time model at each individual segment is estimated to validate the robustness of estimated coefficients for each far-side segment and to compare the difference between far-side segments and near-side segments.

The departure-to-arrival time model is better in quantifying the effects of signal delay and traffic conditions on bus travel time because passenger activity variability at the departure stop can be excluded; however, this model is only estimated for far-side segments. The arrival-to-arrival time model is estimated for both far-side and near-side segments because departure time is not accurate at near-side stops. To

Table 3 Regression model specifications

Variable	Far-side segments		All segments	Individual segments	
	1. Departure-to-arrival	2. Arrival-to-arrival	3. Arrival-to-arrival	4. Departure-to-arrival	5. Arrival-to-arrival
Distance	•	•	•		
Traffic volume	•	•	•	•	•
Peak	•	•	•	•	•
Red				•	•
Red time	•	•	•		
RC ratio	•	•	•		
Ons		•	•		•
Offs		•	•		•
Lift		•	•		•
Departure delay	•	•		•	
Skip	•	•	•	•	•
Near			•		

compare results, both travel time models are estimated for a group of segments together (pooled regression models) and for each segment individually (individual regression models).

5 Results

This section presents the results of the pooled and individual regression models (using the R statistical programming package). An alpha level of 0.05 was used for the statistical tests. Ordinary least squares regression, R^2 change (ΔR^2), and a stepwise model selection process (testing different variable sequences) were used to find candidate final models. A preferred final model was selected based on the joint consideration of lower Akaike Information Criterion (AIC), higher adjusted R^2, and inclusion of intuitive signs (in all cases the key significant variables with high ΔR^2 had the expected signs) in the set of significant explanatory variables.

The estimated unstandardized coefficients, standard errors, *t*-value, R^2 change (ΔR^2) and mean contribution (%) are reported. The R^2 change (ΔR^2) was computed by squaring the semi-partial correlation coefficient of each variable estimated by the R package "ppcor" (Kim 2013). The R^2 change represents the contribution of each variable to travel time variability and is estimated by removing one variable at a time *ceteris paribus*. The mean contribution (%) is calculated by the product of variable coefficient and variable mean value, divided by mean travel time.

5.1 Far-side segments stop-to-stop travel time models

Table 4 shows the results of the far-side segments departure-to-arrival time model and arrival-to-arrival time model. Non-linear models for variables such as traffic volume and red time were estimated but non-linear effects were not significant or the R^2 values were lower. Variables without estimated coefficients are not significant at the 0.05 level; variables that are not estimated in the model are shown as "–". The total number of bus stop-to-stop trips for far-side segments is 34,070. The far-side segments departure-to-arrival time model and the arrival-to-arrival time model explain 78 and 75 % of the total travel time variation, respectively.

Most of the estimated coefficients between the two models are similar except for passenger activity variables and the skip variable. These results indicate that the impacts of between-stop variables (e.g. distance, traffic volume, peak, red time and RC ratio) are independent of the impacts of at-stop variables (e.g. ons, lift, skip) and that the estimated coefficients are stable in sign and magnitude.

All three travel impedance variables (distance, traffic volume and peak) are significant and positive. Each one-mile increase in distance results in an average of 137 and 115 s increase in bus departure-to-arrival time and bus arrival-to-arrival time, respectively, controlling for other variables. This is equivalent to an average speed of 26 and 31 mph, respectively. For each 1000 vehicles per hour increase in traffic volume, bus travel time increases by 2 s. If a bus travels during the AM peak hours in the westbound direction or in the PM peak hours in the eastbound direction, the departure-to-arrival time and arrival-to-arrival time will increase an average of 2.4 and 2.7 s, respectively.

The regression results indicate that the impacts of traffic on travel times are non-linear. The impacts of traffic are the sum of two variables: (a) travel time increases linearly as a function of traffic volumes and (b) travel time increases as a step function (non-linear) during peak travel times. These results are supported by traffic flow models where travel times are a non-linear functions of traffic flows. Removing the peak travel time variable, a model (not presented here) with traffic volume and square of traffic volume is also significant as expected from theoretical models. The model with volume and volume squared have a slightly lower R^2 and all other variables (except peak travel time) are still significant and with values that are similar to the ones presented in Tables 3, 4 and 5. Because link capacity is greatly reduced at intersections with high R/C ratios, the variables red time and RC ratio are likely to capture delays at intersections whereas the traffic volume and peak variables are likely to capture delays in the links connecting intersections. Hence, the impacts of volume/capacity ratios are implicitly captured by variables in the model.

Signal delay variables (red time and RC ratio) are also significant and positive. Results indicate that if a bus trip experiences a red signal, the average signal delay will be equal to 70 % of the red phase duration. Also, segments with 10 % higher RC ratios have an average of 1.42 s (and 1.75 s) additional delay for the departure-to-arrival time (and arrival-to-arrival time). For example, the average red phase durations for 39th EB and 65th EB are 66 and 16 s, respectively, and the average cycle lengths are almost the same between the two segments (120 s). Therefore, the

Table 4 Far-side segments stop-to-stop travel time models

Far-side segments	Departure-to-arrival time					Arrival-to-arrival time				
	Coeff.	SE	t value	ΔR^2	% Contribution	Coeff.	SE	t value	ΔR^2	% Contribution
Intercept	1.6	0.4	4.5		5	19.1	0.5	39.2		44
Distance (miles)	136.8	2.4	58.0	0.022	54	115.3	3.2	35.8	0.009	35
Volume (vph × 1000)	2.1	0.2	11.6	0.002	5	2.4	0.2	9.8	0.008	5
Peak	2.4	0.2	14.4	0.013	1	2.7	0.2	11.8	0.015	1
Red time (s)	0.7	0.0	273.3	0.496	25	0.7	0.0	202.3	0.358	19
RC ratio	14.2	0.4	37.0	0.245	12	17.5	0.5	33.6	0.193	12
Ons	–	–	–	–	–	3.4	0.1	50.1	0.077	4
Offs	–	–	–	–	–					–
Lift	–	–	–	–	–	37.1	1.1	35.0	0.011	0
Depart delay (min)	−0.1	0.0	−7.2	0.001	0	−0.2	0.0	−6.4	0	−1
Skip	−2.8	0.1	−24.7	0.003	−4	−18.1	0.2	−106.4	0.079	−21
R^2	0.78					0.75				
Adj. R^2	0.78					0.75				
N	34,070					34,070				

Table 5 All segments arrival-to-arrival time model

	Coeff.	SE	t value	ΔR^2	% Contribution
Intercept	18.3	0.5	40.4		42
Distance	114.6	3.2	36.3	0.007	37
Distance × near	23.9	4.2	5.7	0.009	3
Volume (kvph)	2.4	0.2	15.6	0.007	5
Volume × near					
Peak	3.1	0.2	18.4	0.013	1
Peak × near					
Red time (s)	0.71	0.00	207.2	0.258	19
Red time × near	−0.03	0.01	−4.8	0.093	0
RC ratio	17.7	0.5	34.7	0.162	11
RC ratio × near	−12.1	1.9	−6.4	0.006	−2
Ons	3.6	0.1	54.7	0.057	5
Ons × near	−1.8	0.1	−22.6	0.034	−1
Offs					
Offs × near					
Lift	37.1	1.0	35.6	0.008	0
Lift × near	−12.3	1.7	−7.4	0.005	0
Skip	−17.3	0.1	−126.0	0.078	−18
Near	−2.9	0.7	−4.2	0.002	−2
R^2	0.74				
Adj. R^2	0.74				
N	51,307				

RC ratios at these two segments are 0.55 and 0.13, respectively. The average values of the red time variable are 28.3 and 1.7 s, respectively. The average signal delays for 39th EB and 65th EB segments are 27.6 s (0.55 × 14.2 + 28.3 × 70 %) and 3.1 s (0.13 × 14.2 + 1.7 × 70 %), respectively. The RC ratio coefficient is slightly higher in the arrival-to-arrival time model; this may be because the queuing effect in far-side segments may extend to the upstream stop of a stop-to-stop segment.

Passenger activity variables (ons, offs and lift) are only estimated in the arrival-to-arrival time model. The effects of passenger boarding and lift use are significant and positive. Each additional passenger boarding increases bus arrival-to-arrival time by 3.4 s and each additional lift use increases bus arrival-to-arrival time by 37.1 s. The effect of passenger alighting is not significant.

The departure delay and skip variables are both significant and negative. Results indicate that for each additional minute in departure stop schedule delay, bus travel time decreases by 0.1 s. If a bus skips the departure stop, bus departure-to-arrival time and arrival-to-arrival time decrease by 2.8 and 17.9 s, respectively. This is because stop skipping only saves partial acceleration delay for departure-to-arrival time, but it saves acceleration and deceleration delay, as well as dwell time for arrival-to-arrival time.

Regarding contributions to travel time and its variability, the data clearly show that Distance is the main contributor to mean travel time but has a relatively low R^2 change value. On the other hand, red time and RC ratio have the largest R^2 changes in both models. These results suggest that for most of the buses within segment stop-to-stop travel time variability is explained by signal delay (red time and queuing) after controlling for the effects of the other variables. After signal delay, passenger activity (skip and ons) variables have the highest R^2 change values.

5.2 All segments arrival-to-arrival time model

The results of all segments arrival-to-arrival time model are presented in Table 5. This model explains 74 % of the bus travel time variation with 51,307 bus trip observations. Because bus stop location may influence other variables' effects on bus arrival-to-arrival time, interaction effects between the Near-side binary variable and other variables were tested. Results show that most of the interaction effects are significant, which means most of the effects are significantly different between near-side and far-side segments. For those variables that are interacted with the Near-side binary variable, the coefficients of original variables represent their effects for far-side segments; the coefficients of the interaction variables represent the difference of those effects between near-side and far-side segments. Results show that the coefficients of those original variables are the same as in the far-side segments arrival-to-arrival model, which indicates the estimated coefficients are robust. The effects of distance and volume are slightly different between near-side and far-side segments. For each mile increase in travel distance, bus travel time increases by 114 and 138 s for far-side and near-side segments, respectively. For each 1000 vehicle per hour increase in traffic volumes, bus arrival-to-arrival time increases by 2.4 s, this is not significantly different between far-side and near-side segments. Peak hour effect is also not significantly different between near-side and far-side segments. If a bus travels in the peak hours, travel time increases by an average of 3.1 s.

The effects of signal delay are significantly different between near-side and far-side segments. The average signal delay for far-side and near-side segments are 71 and 68 % of the red phase duration, respectively. The additional queuing delay increases by 1.77 and 0.56 s for each 10 % increase in RC ratio for far-side and near-side segments, respectively. Regression results show that signal delay is lower at near-side segments.

The interaction effects in Table 5 indicate that the effects of passenger boarding and lift use are significantly different between near-side and far-side segments. Each additional passenger boarding increases bus travel time by 3.6 and 1.8 s for far-side and near-side segments, respectively. Each additional lift use increases bus travel time by 37.1 and 24.8 s for far-side and near-side segments, respectively. These differences are likely because some buses serve passengers when they are waiting for a red signal at a near-side stop. Also, near-side bus stops are usually very close to intersections and buses tend to be in front of the queue that forms during a red phase. Field and video observations corroborate this interpretation.

The stop skipping effect is the same between the two segment types. If a bus skips a departure stop of a segment, bus travel time decreases by 17 s on average.

Bus arrival-to-arrival time is 2.9 s less at near-side segments than at far-side segments and this result is consistent with previous research along the same corridor; Albright and Figliozzi (2012) found that bus stop-to-stop travel times are about 3–4 s less at near-side segments than far-side segments. The value of the estimated coefficient for the Near variable was very stable and not affected by the interaction terms between near-side and other variables shown in Table 5.

SCATS has improved flows along the corridor. Previous research along the same 5-mile corridor (at the corridor level, not on a segment by segment level) has shown that SCATS reduced bus travel times by 33–43 s; this was done by comparing bus travel times before and after SCATS implementation during peak and off-peak hours (Slavin et al. 2013).

The average delay per bus stop, without boarding and alighting time, as estimated from the datasets is approximately 10 s. This delay is related to bus acceleration, deceleration, and merging into the traffic flow when there is a bus bay. A significant variable in the arrival to arrival models is skipped stop with a negative value between 17 and 18 s. We can speculate that green progression saves between 7 and 8 s per segment on average. In the study corridor buses do not benefit from progression as much as passenger vehicles do because most buses usually stop at least once between any two consecutive signalized intersections. Bus dwell time is a function of the numbers of boardings and alightings and typically ranges from 3 to 25 s. The benefits of green progression for many bus trips are reduced due to stop related delays caused by bus deceleration, bus acceleration, and bus dwell time while passengers board and alight.

R^2 changes and % contributions of the estimated variables have very similar results as those in the far-side segment arrival-to-arrival time model; the intercept and distance account for approximately 80 % of the average travel time. Signal delay (red and R/C) variables account for most of the travel time variability as measured by the change in R^2 values.

5.3 Individual segment models

Individual segment stop-to-stop travel time models are estimated to gain more insights into the effects of signal delay and traffic volume on bus stop-to-stop travel time at each individual segment. Both departure-to-arrival time models and arrival-to-arrival time models are estimated for each individual far-side segment, and an arrival-to-arrival model is estimated at each individual near-side segment. The model specifications are shown in Table 3.

Individual segment model R^2 values vary across segments. The far-side segments departure-to-arrival time models (Model I) explain 40–82 % of the travel time variation. The far-side segments arrival-to-arrival time models (Model II) explain 57–77 % of the travel time variation. Segments with high RC ratios have slightly higher R^2 values in the departure-to-arrival time models than in the arrival-to-arrival time models; however, segments with low RC ratios have higher R^2 values in the arrival-to-arrival time models than in the departure-to-arrival models. This may be because the proportion of bus stop-to-stop travel time variation explained by signal delay is higher along segments with large RC ratios. Near-side segments arrival-to-arrival time models (Model III) explain 56–74 % of total travel time variation.

The red binary variable in these individual segment models is used to assess the average signal delay if a bus trip encounters a red signal. The coefficients of this variable are significant and positive for each segment. These coefficients are robust because they are almost the same between the departure-to-arrival time models and the arrival-to-arrival time models for far-side segments.

The values of these coefficients are linearly related to the average red phase durations (or RC ratio). Figure 3 shows the relationship between the estimated coefficients of the red binary variables and the average red phase durations at all stop-to-stop segments. There is a clear linear relationship between the estimated red binary variable coefficients and the average red phase durations; equations for the three fitted lines are shown below:

Model I (far-side segment departure-to-arrival time): $Y = 0.6X + 12.1$, R^2: 0.84
Model II (far-side segment arrival-to-arrival time): $Y = 0.6X + 12.1$, R^2: 0.83
Model III (near-side segment arrival-to-arrival time): $Y = 0.6X + 3.9$, R^2: 0.97

In all three models, even with the small number of observations a statistically significant linear relationship is indicated. The slopes of the three lines are the same (0.6) which indicates that the waiting time for a red signal component of the signal delay is on average 60 % of the red phase duration in individual stop-to-stop models. The line fitting far-side segments overlap since they have the same intercept and slope using one decimal.

However, some estimated red variable coefficients are far from the fitted lines. For example, the average red phase delay at 52nd EB and 50th WB are higher than expected and lower than expected at 39th EB. These deviations are likely due to differences in geometric design and signal timing. The 52nd EB and 50th WB

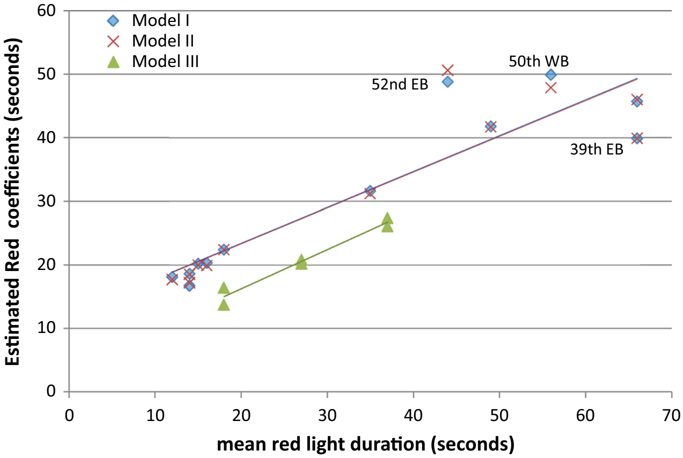


Fig. 3 Red binary variable coefficients vs. median red phase durations

segments have high RC ratios and only two approaching lanes exist (no left turn lane); therefore, buses have higher probabilities of waiting in a long queue at these two segments than at other segments. The 39th EB segment has a high RC ratio but the intersection has three through lanes and a left turn lane. All other segments with high RC ratios have at most two through lanes.

The individual regression models show that the effects of traffic volume vary significantly across segments and between peak and off-peak hours. Traffic volume effects are higher at segments with high RC ratios. The effects of passenger activities, departure delay and stop skipping vary slightly across segments.

6 Conclusions

This study has analyzed the joint impact of intersection bus stop location, signal delay and traffic conditions at the stop-to-stop segment level. Bus AVL/APC data, SCATS signal phase log data and traffic count data were integrated for the first time to analyze stop-to-stop segment travel times. Departure-to-arrival time and the arrival-to-arrival time models were estimated for far-side segments and an arrival-to-arrival time model was also estimated for all stop-to-stop segments to examine the effect of bus stop location on bus travel time. In addition, individual segment models were estimated.

Results from the models provide valuable information for transit agencies to understand factors that affect bus travel times across intersections. Travel distance is the main factor affecting average travel time followed by skipping a stop, and red delay. Red signal phase duration and the red/cycle ratio are key variables to estimate travel time variability at the stop-to-stop segment level. Results from pooled and individual segment modes indicate that signalized intersection delay is best estimated as a linear function of red signal phase duration (approximately 0.6–0.7 of the red phase duration). These variables also have the highest contributions to travel time variability as indicated by their R^2 change (ΔR^2) values.

Bus stop location also has a statistically significant effect on intersection signal delay and passenger boarding times. Results seem to indicate that stops with a high number of boardings or wheelchair lifts should be located near-side. The impact of traffic volumes on delay is not as high as signal delay but it is significant and varies drastically by segment and time of day.

In addition to pooled regression models, models utilizing only individual segment data are valuable to detect intersections or segments with unusual large or small red phase delay. For example, EB 39th has relatively long red times but less expected delay (see Fig. 3) because there is an additional lane to accommodate right turning traffic.

Acknowledgments The authors gratefully acknowledge the National Institute for Transportation Community (NITC) for funding this research. We thank Steve Callas and David Crout from TriMet who have provided valuable assistance, advice, and bus transit data as well as match for the NITC project. The authors would also like to thank Willie Rotich from the Portland Bureau of Transportation for providing SCATS and TSP data and valuable assistance. Any errors or omissions are the sole responsibility of the authors.

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