Have they bunched yet? An exploratory study of the impacts of bus bunching on dwell and running times

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ABSTRACT

If transit agencies wish to retain and attract riders, they need to provide reliable and efficient services. Transit agencies tend to run high-frequency bus routes during peak hours, and in many cities, different routes can also overlap along major corridors. In some instances, consecutive buses can arrive at a shared stop simultaneously or one bus may arrive while another bus is currently servicing the stop. This phenomenon, known as bus bunching, can delay buses and passengers, and is usually inefficient. In this study, we attempt to understand how bus bunching from the same or different routes can impact bus operations, specifically dwell and running times. This research uses stop-level records obtained from automatic vehicle location (AVL) and automatic passenger counter (APC) systems from TriMet, Portland, OR. Using linear modeling, we find that bus bunching increases both dwell and running times. Specifically, when different routes bunch or are scheduled to arrive at a bus stop within a short time frame, or when buses from the same route arrive with a short time frame, dwell times increase by ~10 s. Similarly, bus bunching from the same route or different route prolongs running times by ~40 s. Our findings suggest that bus schedulers and operators should consider adding more time between consecutive buses from different routes at shared stops to minimize the negative impacts that we observed from bus bunching.

KEYWORDS: Running time, Dwell time, High-frequency, Bunching, Delay, Overlap

INTRODUCTION

In an effort to attract and retain bus riders, transit agencies continuously adjust bus schedules and routes. These adjustments aim to improve bus running times as well as to increase the transit coverage within cities. Customers view both as crucial components of any transit system and these features are important to compete with other modes, specifically private vehicles.

Nevertheless, some bus operations can have unintended consequences. In particular, while providing frequent service and what some customers deem as highly reliable since they can expect buses to arrive with regular headways, high-frequency bus routes (with headways of 10 minutes or less) can become victims of bus bunching (Daganzo, 2009). Bus bunching has frequently surfaced in public conversations, and its impact on user's perception frequently dominates the headlines (Merevick, 2015; Provost, 2015; Simcoe, 2015). Generally, bus bunching results in consecutive buses arriving at a bus stop within a short amount of time, typically caused by headway deviations due to traffic or other road condition . For transit operators, bunching may result in inefficient capacity utilization, while frustrating customers who may need to wait longer for subsequent buses (TCRP, 2013a). In addition to high-frequency services, transit agencies also tend to run several routes into central business districts through shared corridors. In effect, buses starting from different points will converge onto a corridor and share a series of stops. This service pattern, known as service overlap, can also result in bus bunching and increase running time for both routes. Here we attempt to answer the following research question: how does bus bunching from buses on the same or different route affect dwell times and thus running time? If transit planners have a clearer understanding of the nuances of bunching at bus stops with overlapping service, then appropriate measures could be taken to mitigate the causes and effects of bus bunching.

What follows is a case study of the impact of bus bunching on bus operations on a corridor with overlapping bus routes in Portland, OR. This paper starts with a literature review on running and dwell time models, as well as an overview of bus bunching. Next, we describe the bus route studied in this paper and our methodology. Third, we present our results and findings from the models. Finally, we discuss our findings and propose potential policies based on our results.

LITERATURE REVIEW

For customers, a quick and reliable bus service is essential; importantly, travel time ranks consistently high on satisfaction surveys, along with waiting time (Diab, Badami, & El-Geneidy, 2015; Hensher, Stopher, & Bullock, 2003; Yoh, Iseki, Smart, & Taylor, 2011). Therefore, from an operator's perspective, both running and waiting times are important factors to measure and maintain within acceptable bounds. For example, research has consistently found that reduced running times can attract and maintain riders (Boyle, 2006; Hollander, 2006). Moreover, riders also value frequent service (Strathman et al., 1999). Nonetheless, a compromise between frequent service and reliability, in terms of service variability, can influence customer satisfaction since some studies show that customers prefer consistent bus arrivals over frequent service (Daskalakis & Strathopoulos, 2008; Paulley et al., 2006).

Many important characteristics can influence running time, which is the time taken for a bus to run its customer-serving route. Rider activities like boardings and alightings, lift activity, time of day, as well as unforeseen circumstances due to traffic or weather, impact running time (Abkowitz & Engelstein, 1983; Levinson, 1983; Strathman et al., 2000). Transit agencies attempt to control several factors to optimize running time. Newer work reveals that additional strategies, such as reserved lanes, transit signal priority and bus stop consolidation can reduce running times, while smartcard fare collection systems and articulated buses can prolong running times (Diab & El-Geneidy, 2012; El-Geneidy, Strathman, Kimpel, & Crout, 2006; El-Geneidy & Vijayakumar, 2011; Suprenant-Legault & El-Geneidy, 2011).

An important contributor to running times is the dwell time, defined typically as the length of time a bus stops to serve passengers at a stop; both door and passenger activities are considered in dwell time models (Dueker, Kimpel, Strathman, & Callas, 2004; El-Geneidy & Vijayakumar, 2011). Dwell time contributes anywhere between 10–30% to running time (Barr, Beaton, Chiarmonte, & Orosz, 2010; Levinson, 1983); understanding the factors underlying dwell time can aid transit agencies to minimize dwells and speed up bus operations (Abkowitz & Engelstein, 1983; Levine & Torng, 1997). Passenger activity and bus load (number of passengers on board) play a large role in determining dwells, and low-floor buses and articulated buses can reduce dwell times (Diab & El-Geneidy, 2015; Dueker et al., 2004; El-Geneidy & Vijayakumar, 2011; Levine & Torng, 1997). Fare collection procedures at the first door, lift operations, stop shelters and signalized intersections can prolong dwell times (Diab & El-Geneidy, 2015; Dueker et al., 2004).

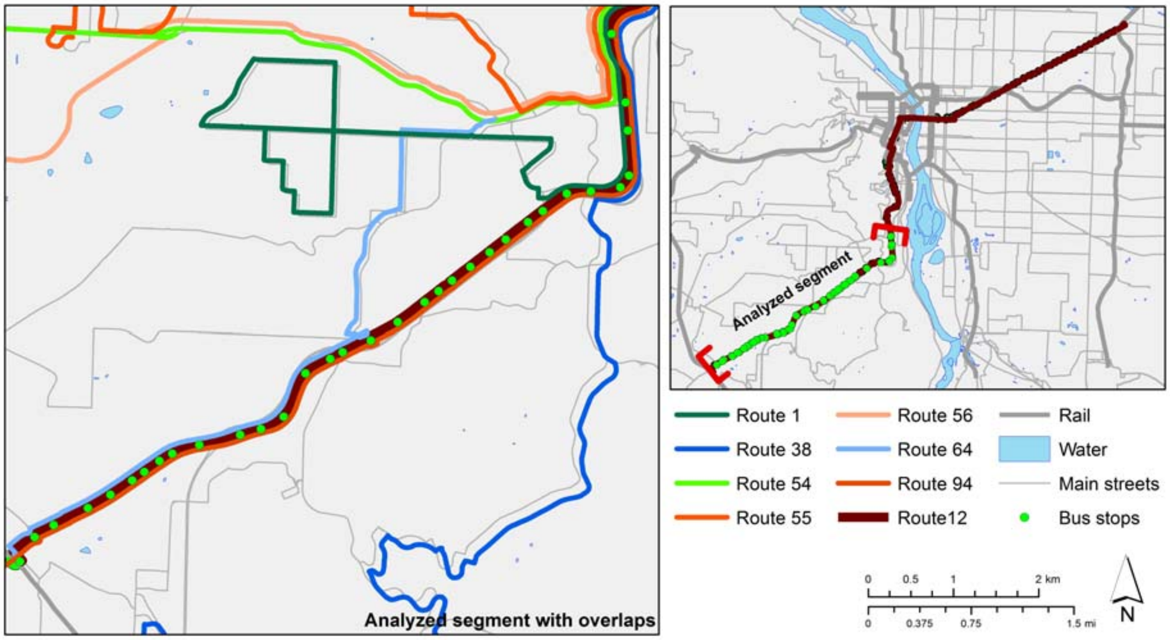
Despite extensive work on dwell and running times, less work has been conducted on bus bunching and its impact on operations. Bunching occurs when buses arrive at a stop nearly simultaneously, or when a bus arrives at a stop recently served by a preceding bus. Bunching results from disrupted scheduled headways between buses, represents wasted capacity for operators, and prolongs wait times for customers because of overcrowded lead buses (TCRP, 2013b). Bus bunching has previously been researched in order to better understand its causes or its overall impact on service levels. For instance, the occurrence of bus bunching increases with route length (Feng & Figliozzi, 2015). Moreover, using simulations, holding points were found to reduce the levels of bunching on a high-frequency circular bus route (Holroyd & Scraggs, 1996). Most research on bus bunching has used mathematical approaches to generate theoretical holding techniques to eliminate or reduce bunching (Daganzo, 2009; Daganzo & Pilachowski, 2011; Eberlein, Wilson, & Bernstein, 2001; Hickman, 2001), or to model causes of or to predict bus bunching (Moreira-Matias, Ferreira, Gama, Mendes-Moreira, & de Sousa, 2012; Moreira-Matias, Gama, Mendes-Moreira, & de Sousa, 2014). Nevertheless, how bus bunching can impact dwell and running times is unknown, especially with regard to overlapping services. Previous work on a shared local and express service corridor in Montreal found that after implementing articulated buses for the express service, running time was increased for both the express and local services (Diab & El-Geneidy, 2012). This finding demonstrates the importance of elucidating the impacts of overlapping services along a shared corridor. Though scheduled bunching between different routes may enable transfers, it remains unknown how bunching from the same or different routes may differentially affect running and dwell times.

METHODOLOGY

The main goal of this paper is determine how the dwell and running times of a bus service are impacted by the fact that it shares a corridor with other overlapping bus services. We study two situations: (1) how an arriving bus's dwell and running times is impacted by bunching with a bus from the same route along a specific segment of a bus route that is shared with many bus services, and (2) how an arriving bus's dwell and running times is impacted by bunching with a bus from a different route along a specific segment of a bus route that is shared with many bus services. By studying these situations, we can provide planners with appropriate ways to understand the impacts of bunching within a shared corridor.

Case study

We used stop-level AVL/APC from TriMet, Portland, Oregon for Route 12 along the Barbur Blvd. corridor (Figure 1). We chose this route primarily because it experienced no changes in terms of route structure and schedule, has variety along its route, and has overlapping service routes along some segments. Route 12 runs east-west crossing through downtown Portland and overlaps with several routes, including Routes 1, 38, 54, 55, 56, 64, and 94. The average headway of Route 12 is 15 min, with a minimum headway of 5 min during peak hours and a maximum of 27 min during off-peak hours. The average stop spacing of the corridor is about 320 meters. A total of 25 signalized intersections are functioning along the analyzed segment (Figure 1, *analyzed segment*).



Data Source: TriMet & DMTI

Projection:NAD 1983 HARN StatePlane Oregon North

Figure 1. TriMet's Route 12 and analyzed segment of SW Barbur Blvd.

The AVL/APC archived data originate from 1st of September 2014 until 28th of November 2014 for Route 12 as well as for other overlapping routes (listed above). Given the relatively short time frame inspected, seasonal variations may be unaccounted for. Since all TriMet buses are equipped with AVL coupled with APC technology, we were able to accurately calculate bus dwell times and running times, as well as bunching as we describe below. Moreover, detailed trip information, like scheduled departure time, arrival time and actual departure times, along with passenger activity is available for every stop. It should be noted that all buses and signals along the studied corridor are equipped with an operational transit signal priority (TSP) system that was active during the data collection period.

Data preparation for dwell time model

For the dwell time model, over 800,000 records for all bus stops served by all the aforementioned routes were first examined. We cleaned the source data by removing system recording errors, duplicated records, and holiday and weekend trips. Using this AVL/APC data, we first calculated dwell time, defined as bus departure minus bus arrival at individual stops.

In previous work investigating bunching, such as for holding strategies aimed at correcting bunching (e.g., (Berrebi, Watkins, & Laval, 2015; Cats et al., 2012; Daganzo, 2009; Hammerle, Haynes, & McNeil, 2005)), bunching was visualized using time-space diagrams, or defined using headway variations or headway differences between consecutive buses (e.g., subtracting departure times for consecutive buses (Figliozzi, Feng, & Lafferriere, 2012)). To determine bus bunching here, we took a similar approach to previous work using TriMet AVL/APC data (Figliozzi et al., 2012) by investigating headways between consecutive buses.

We created dummy variables aimed to capture bus bunching, so if headways between consecutive buses fell within a predefined range, we defined this headway or bus arrangement as 'bus bunching'. This 'bus bunching' headway was calculated as: (arrival time of a bus of interest, *i*,) – (departure time of a previous bus, *i-1*). Therefore, bus bunching refers to a bus arriving when a previous bus is still servicing or standing at the bus stop, or when a bus arrives and the leader bus has left the stop within a predefined temporal range. A negative value for this variable indicates that a leader bus, *i-1*, is still servicing a stop when a bus of interest, *i*, arrives, or in other words, that the bus of interest, *i*, arrives before the leader bus, *i-1*, departs. A value of 0 indicates that a leader bus, *i-1*, is departing when a bus of interest, *i*, arrives. Finally, a positive value indicates that a leader bus, *i-1*, has left the stop when a bus of interest, *i*, arrives; note that this is the 'typical' scheme for arrivals and departures.

Previous research used three-minute headways between consecutive bus departures as a threshold for bus bunching, acknowledging that this arbitrary threshold may be modified for a given research question (Figliozzi et al., 2012). Here, to determine the headway threshold that could qualify as bus bunching, we defined different ranges of headways between consecutive buses as bus bunching (for example, bus of interest arriving between 30–60 s of previous bus' departure) and used the generated dummy variables in dwell time models; this procedure was used to validate a chosen headway range based on the model output and how variables in a dwell time model should preform given previous work. The time intervals we specified are: a bus of interest, *i*, arriving within 40–20 s and 20-0 s of a previous bus, *i-1,* still at the stop (negative values for arrival – departure), a bus, *i*, arriving as a previous bus, *i-1*, has just departed (0 s), and a bus, *i*, arriving within 0–20 s and 20–40 s of the previous bus, *i-l*, departing (positive values for arrival – departure). Please see Table 1 for detailed variables. These time intervals are expressly short in order to capture the effects of bunching within a small time window; these values are more conservative than a previous study that used a three-minute time window (Figliozzi et al., 2012).

Moreover, we determined whether this previous leader bus, *i-l*, was from the same or different route as an arriving bus of interest, *i*. When bus *i-1* was from a different route, we also specified whether departure of the bus of interest, *i*, was scheduled to occur before the departure of the previous bus, *i-1*; we called this 'scheduled overlap'. To determine 'scheduled overlap', we first determined whether the scheduled departure time of bus *i* was scheduled to occur before the scheduled departure time of bus *i-1*. If this situation occurred, we generated a dummy variable equal to 1. This dummy variable was then multiplied by another dummy variable that coded for our definition of 'bus bunching', that is, when this arrangement occurred and the headways (bus *i* arrival time – bus *i-1* actual departure time) were within our defined ranges. When these two conditions were met, this is what we called 'scheduled overlap'. If a bus, *i*, departed from a stop when a previous bus, *i-1* (from a different route), was present and this was unscheduled, we called this occurrence 'unscheduled departure or bunching from a different route'. In this way, we captured how bus bunching/overlap that occurs from the same service or different service may impact dwell and running times.

We analyzed dwell times of Route 12 stops over ~10.5 km (6.5 mi) between SW Barbur and Capitol Hwy intersection south west of the downtown and the intersection at SW Main and Pacific Hwy in the south west because of the availability of AVL/APC data for all routes that share this segment (Routes 1, 38, 54, 55, 56, 64, and 94), which makes it possible to investigate the impact of overlapping services on Route 12 (Figure 1). After calculating dwell times and headways between buses, we removed data from stops from other routes, leaving over 250,000 stop-level records for Route 12. Since bus bunching can involve two buses at one stop simultaneously and the trailing bus may not experience passenger activity, essentially resulting in dwell times equal to 0, we kept stops with dwell times equal to 0 in our dataset specifically because of our interest in bus bunching. We then removed the 1st and 99th percentiles of dwells, as well as first stops, layovers, and stops without data pertaining to physical characteristics of the bus stop, leaving 216,323 records. We also removed questionable data entries, for example, records with large numbers of boardings and alightings, or lift activities, but with dwell times too short to be plausible (two such records). Finally, we removed stops where a bus of interest, bus *i*, arrived and a previous bus, bus *i-1*, was at the stop for more than 40 s because these rare occurrences (70 records) may represent atypical situations caused by road incidents or traffic conditions, for instance; moreover, dummy variables for this arrangement yielded difficult to interpret coefficients in the dwell time model output. The final dataset used to model dwell time included 216,253 records. Descriptions of all variables used in the models are shown in Table 1.

Table 1. Description of variables used in both models.

Variable name	Description
Dwell time (s)	Dwell time measured in seconds between the arrival and departure of a bus (dependent variable)
Running time (s)	Total travel time measured in seconds along a specified segment of Barbur Blvd. (dependent variable)
AM peak	Dummy variable equal to 1 if the dwell (or trip) occurred between 7–9 a.m.
PM peak	Dummy variable equal to 1 if the dwell (or trip) occurred between 4–6 p.m.
Evening and night	Dummy variable equal to 1 if the dwell (or trip) occurred between 6 p.m. and midnight
Overnight	Dummy variable equal to 1 if the dwell (or trip) occurred between midnight and 7 a.m.
Ons	Total number of boarding passengers at a stop (or trip)
Offs	Total number of alighting passengers at a stop (or trip)
Direction	Dummy variable equal to one for inbound trips
Total passenger activity	Total number of passengers boarding and alighting at a stop (or trip)
Total passenger activity^2	The square of the total number of passengers boarding and alighting at a stop (or trip)
Lift	Total lift activity at a stop (or along a trip segment)
Passenger load	The total number of passengers on a bus at a stop (or maximum for a trip)
Passenger load^2	The square of the total number of passengers on a bus at a stop (or maximum for a trip)
Delay at the start (s)	The delay at the start of a trip in seconds (difference between actual departure time and scheduled time at the first stop of a route)
Stop made	Dummy variable equal to 1 if an actual stop was made (or sum of all stops made for trip for running time)
Unscheduled stop	Dummy variable equal to 1 if a stop is an unscheduled stop along a trip
Stop at time point	Dummy variable equal to 1 if a bus stop is a holding point (or total

Variable name	Description
	number of time points for trip for running time)
Signalized intersection	Dummy variable equal to 1 if the bus stop is at a traffic light that is equipped with an operational transit signal priority (TSP) system
Shelter	Dummy variable equal to 1 if a stop has a bus shelter
Dwell time	
Previous -40 – -20 – same	Dummy variable equal to 1 if a bus, *i*, arrives at a stop between 20–40 s BEFORE the departure of a previous bus, *i-1*, of the SAME route
Previous -40 – -20 – different scheduled overlap	Dummy variable equal to 1 if a bus, *i*, arrives at a stop between 20–40 s BEFORE the departure of a previous bus, *i-1*, of a DIFFERENT route and this is scheduled overlap
Previous -40 – -20 – different unscheduled	Dummy variable equal to 1 if a bus, *i*, arrives at a stop between 20–40 s BEFORE the departure of a previous bus, *i-1*, of a DIFFERENT route and this is unscheduled departure (or bunching)
Previous -20 –0 – same	Dummy variable equal to 1 if a bus, *i*, arrives at a stop between 0–20 s BEFORE the departure of a previous bus, *i-1*, of the SAME route
Previous -20 –0 – different scheduled overlap	Dummy variable equal to 1 if a bus, *i*, arrives at a stop between 0–20 s BEFORE the departure of a previous bus, *i-1*, of a DIFFERENT route and this is scheduled overlap
Previous -20 –0 – different unscheduled	Dummy variable equal to 1 if a bus arrives, *i*, at a stop between 0–20 s BEFORE the departure of a previous bus, *i-1*, of a DIFFERENT route and this is unscheduled departure (or bunching)
Previous 0 – same	Dummy variable equal to 1 if a bus, *i*, arrives at a stop at the SAME TIME a previous bus, *i-1*, is departing and is from the SAME route
Previous 0 – different scheduled overlap	Dummy variable equal to 1 if a bus, *i*, arrives at a stop at the SAME TIME a previous bus, *i-1*, is departing and is from a DIFFERENT route and this is scheduled overlap
Previous 0 – different unscheduled	Dummy variable equal to 1 if a bus, *i*, arrives at a stop at the SAME TIME a previous bus, *i-1*, is departing and is from a DIFFERENT route and this is unscheduled departure (or bunching)
Previous 0–20 – same	Dummy variable equal to 1 if a bus, *i*, arrives at a stop 0–20 s AFTER a previous bus, *i-1*, has left and is from the SAME route
Previous 0–20 – different	Dummy variable equal to 1 if a bus, *i*, arrives at a stop 0–20 s AFTER a previous bus, *i-1*, has left and is from a DIFFERENT route
Previous 20–40 – same	Dummy variable equal to 1 if a bus arrives, *i*, at a stop 20–40 s AFTER a previous bus, *i-1*, has left and is from the SAME route
Previous 20–40 – different	Dummy variable equal to 1 if a bus, *i*, arrives at a stop 20–40 s AFTER a previous bus, *i-1*, has left and is from a DIFFERENT route
No bunching (40+) – same	Dummy variable equal to 1 if a bus, *i*, arrives at a stop 40 s AFTER a previous bus, *i-1*, has left (no bunching) from the SAME route (base condition)
No bunching (40+) – different	Dummy variable equal to 1 if a bus, *i*, arrives at a stop 40 s AFTER a previous bus has, *i-1*, left (no bunching) from a DIFFERENT route
Running time	
First trip	Dummy variable equal to 1 if the trip is the first trip of the day
Sum of previous -40–0 – same	Occurrences along a trip segment when a bus, *i*, arrives at a stop 0–40 s BEFORE the departure of a previous bus, *i-1*, of the SAME route
Sum of previous -40–0 – different scheduled overlap	Occurrences along a trip segment when a bus, *i*, arrives at a stop 0–40 s BEFORE the departure of a previous bus, *i-1*, of a DIFFERENT route and is scheduled overlap
Sum of previous 0–40 – different	Occurrences along a trip segment when a bus, *i*, arrives at a stop 0–40 s AFTER the departure of a previous bus, *i-1*, of a DIFFERENT route
Sum of no bunching (40+) – different	Occurrences along a trip segment when no bunching occurred with a bus, *i-1*, of a DIFFERENT route previously servicing the stop

In this paper, we aim to understand how bus bunching, that is, consecutive buses arriving within short (<40 s) time windows at a stop by using the dummies we constructed for different temporal aspects of bunching, can impact dwell times. Table 1 includes a list and detailed descriptions of dummy variables used to explore bunching, as well as other variables incorporated in the statistical analysis. For example, in our dwell time model, one dummy variable 'previous 20–40 – different' is meant to capture instances where a bus of interest, *i*, arrives at a stop 20 to 40 s after a bus *i-1* from a different route has left the stop. According to previous studies, the general factors affecting dwell time include passenger activity in terms of boarding and alighting, lift usage, time of the day, and delays at the beginning of a trip (Dueker et al., 2004). A positive coefficient value for a variable indicates that this variable will increase dwell time, while a negative value signifies that this variable will decrease dwell time of the bus of interest (bus *i*).

Data preparation for running time model

Using the same dataset as above, we analyzed nearly 8,000 trips of Route 12 along the southwest Barbur Blvd. corridor. Segments analyzed included westbound and eastbound trips, specified by a dummy variable for downtown-bound (eastbound) trips that started at SW Barbur and Capitol Hwy (westbound) and had between 24–28 stops, and trips that started at SW Main and Pacific Hwy (eastbound/downtown-bound) and had between 27–30 stops. Upon analyzing these trips, trips with passenger activity below three were removed, and the 1st and 99th percentiles of running times were also removed. As above, trips where bus bunching occurred with a previous bus standing for more than 40 s after the arrival of the bus of interest were discarded. After this cleaning process, the running time model used 7,724 trips. The dependent variable, running time, was calculated as arrival time at the first stop minus departure time at the last stop of the studied segment (without including the layovers). To capture bunching at the segment-level, we summed instances of bunching as defined in our dwell time model to calculate the number of occurrences of different types of bus bunching. For example, 'sum of previous 0–40 – different' dummy captures the number of times along a trip segment that a bus of interest, *i*, arrives at a stop 0 to 40 s after a bus from a different route (*i-1*) has serviced the same stop. These dummy variables will allow us to understand how different types of bunching, namely with a bus of the same or of a different route, can influence running time.

RESULTS

Descriptive statistics

Table 2 presents summary statistics for the variables in the dwell time model, while Table 3 presents summary statistics for the data used in the running time model. Along the studied corridor, Route 12 has average dwell times of 9.49 s, with a deviation around the mean of 13.89 s (Table 2). Moreover, the average running time for Route 12 along the segment of interest is 1342.98 s (or about 22 min) with a standard deviation of 192.32 s (or about 3 min) (Table 3). Below, we present the results of regression models.

Table 2. Dwell time model summary statistics.

Variable name	Mean	Std. Dev.	Minimum	Maximum
Dwell time (s)	9.49	13.89	0	84
AM peak	0.13	0.33	0	1
PM peak	0.12	0.32	0	1
Evening and night	0.27	0.45	0	1
Overnight	0.07	0.26	0	1
Ons	0.46	1.05	0	24
Offs	0.42	0.98	0	30
Total passenger activity^2	2.96	11.88	0	1296
Lift	0.002	0.042	0	3
Passenger load	11.60	8.98	0	80
Passenger load^2	215.07	290.14	0	6400
Delay at the start (s)	82.80	173.07	-3208	2391
Stop made	0.42	0.49	0	1
Unscheduled stop	0.017	0.13	0	1
Stop at time point	0.051	0.22	0	1
Signalized intersection	0.17	0.37	0	1
Shelter	0.25	0.43	0	1
Previous -40 – -20 – same	0.0002	0.012	0	1
Previous -40 – -20 – different scheduled overlap	0.0002	0.016	0	1
Previous -40 – -20 – different unscheduled	0.0001	0.009	0	1
Previous -20 – 0 – same	0.0006	0.025	0	1
Previous -20 –0 – different scheduled overlap	0.0003	0.017	0	1
Previous -20 –0 – different unscheduled	0.0003	0.017	0	1
Previous 0 – same	0.0001	0.007	0	1
Previous 0 – different scheduled overlap	0.00002	0.004	0	1
Previous 0 – different unscheduled	0.0001	0.009	0	1
Previous 0–20 – same	0.006	0.077	0	1
Previous 0–20 – different	0.003	0.053	0	1
Previous 20–40 – same	0.006	0.079	0	1
Previous 20–40 – different	0.002	0.041	0	1
No bunching (40+) – same	0.92	0.28	0	1
No bunching (40+) – different	0.065	0.25	0	1

N = 216,253 stop-level observations

Table 3. Running time model summary statistics.

Variable name	Mean	Std. Dev.	Minimum	Maximum
Running time (s)	1342.98	192.63	931	2089
AM peak	0.13	0.33	0	1
PM peak	0.10	0.30	0	1
Evening and night	0.26	0.44	0	1
Overnight	0.092	0.29	0	1
Direction	0.48	0.50	0	1
Total passenger activity	24.59	11.30	4	104
Lift	0.067	0.31	0	6
Maximum of passenger load	18.74	11.76	0	73
Maximum of passenger load^2	489.76	479.76	0	5329
Delay at the start (s)	77.29	162.78	-1877	2391
Total stops made	11.51	3.39	1	22
First trip	0.014	0.12	0	1
Sum of previous -40–0 – same	0.014	0.16	0	4
Sum of previous -40–0 – different scheduled overlap	0.013	0.12	0	2
Sum of previous 0–40 – different	0.11	0.49	0	5
Sum of no bunching (40+) – different	1.70	2.23	0	8

N = 7,724 trips

Dwell time model

We developed a linear regression model using dwell time in seconds as the dependent variable. Only variables that displayed significance or are policy relevant variables were maintained in the model. The output of this model is reported in Table 4, and contains 216,253 records and explains 65% of the variation in dwell time. This proportion of explained variation is consistent with previous models (Diab & El-Geneidy, 2015; Dueker et al., 2004; El-Geneidy & Vijayakumar, 2011).

Regarding key policy variables, we find generally, that compared to no bus bunching, bus bunching prolongs dwell time. If a bus arrives at a stop while a previous bus has not departed for 20–40 s, then the dwell of this arriving bus is increased by 10.63 s if it is bunched with a bus from the same route. If a bus arrives at stop and a bus from a different route (scheduled stop) has not departed for 20–40 s, then 12.99 s is added to dwell time of the arriving bus. If unscheduled bunching occurs with a bus of a different route (bus arrives and previous bus from a different route has been standing for 20–40 s), then dwells are lengthened by 10.69 s. These findings suggests that bunching prolongs dwell times, likely due to passenger transfers between different bus routes, as well as maneuvering resulting from closely spaced buses.

If this time window (bus *i* arriving while a previous bus *i-1* is still standing) is between 0–20 s at a scheduled service overlap (different routes), then 3.35 s are added to dwells, while

4.57 s are added to dwells if the stop from a different route was unscheduled. If a bus *i* from the same route arrives and the previous bus has been at the stop for 0–20 s and is from the same route, then 1.62 s are added to the dwell time of bus *i*. This is likely because the preceding bus from the same route will have picked up most passengers. Overall, the presence of a standing bus will prolong dwells of an arriving bus because of increased maneuvering time and passenger activity related to the previous bus. In addition, the impact of bus bunching on dwell times does not depend on whether the previous bus servicing a stop is from the same or a different route. In other words, the differences between bunching from different or the same routes are minor.

Table 4. Dwell time model.

Variable name	Coefficient	*t*-statistic	95% CI Lower bound	95% CI Upper bound
Constant	**0.91*****	**20.28**	**0.82**	**1.00**
AM peak	**-0.58*****	**-10.16**	**-0.69**	**-0.47**
PM peak	**0.59*****	**9.83**	**0.47**	**0.71**
Evening and night	**-0.27*****	**-6.20**	**-0.36**	**-0.19**
Overnight	**-1.08*****	**-15.01**	**-1.22**	**-0.94**
Ons	**4.86*****	**143.76**	**4.79**	**4.93**
Offs	**2.97*****	**85.38**	**2.90**	**3.04**
Total passenger activity^2	**-0.14*****	**-49.87**	**-0.14**	**-0.13**
Lift	**31.37*****	**74.74**	**30.56**	**32.20**
Passenger load	**-0.11*****	**-22.22**	**-0.12**	**-0.099**
Passenger load^2	**0.0022*****	**14.37**	**0.0019**	**0.0025**
Delay at the start (s)	**-0.0006*****	**-5.59**	**-0.0008**	**-0.0004**
Stop made	**11.9*****	**192.24**	**11.76**	**12.01**
Unscheduled stop	**3.23*****	**19.13**	**2.90**	**3.56**
Stop at time point	**7.01*****	**75.60**	**6.83**	**7.19**
Signalized intersection	**3.97*****	**81.42**	**3.88**	**4.07**
Shelter	**1.72*****	**35.82**	**1.63**	**1.81**
[a]Previous -40 – -20 – same	**10.63*****	**7.40**	**7.82**	**13.45**
[a]Previous -40 – -20 – different scheduled overlap	**12.99*****	**11.44**	**10.77**	**15.21**
[a]Previous -40 – -20 – different unscheduled	**10.69*****	**5.46**	**6.85**	**14.52**
[a]Previous -20 – 0 – same	**1.62****	**2.24**	**0.20**	**3.04**
[a]Previous -20 –0 – different scheduled overlap	**3.35****	**3.14**	**1.26**	**5.44**
[a]Previous -20 –0 – different unscheduled	**4.57*****	**4.28**	**2.48**	**6.66**
[a]Previous 0 – same	0.97	0.41	-3.70	5.64
[a]Previous 0 – different scheduled overlap	-5.67	-1.37	-13.75	2.42
[a]Previous 0 – different unscheduled	-1.26	-0.61	-5.30	2.78
[a]Previous 0–20 – same	**-1.33*****	**-5.29**	**-1.82**	**-0.84**
[a]Previous 0–20 – different	0.39	1.16	-0.27	1.04
[a]Previous 20–40 – same	**-1.30*****	**-5.11**	**-1.80**	**-0.80**
[a]Previous 20–40 – different	**2.33*****	**5.32**	**1.47**	**3.10**
[a]No bunching (40+) – different	**0.40*****	**5.24**	**0.25**	**0.55**
N		216,253		
Adjusted R^2		0.65		
F statistics		(30, 216222) 13234.53		
F significance (Prob > F)		0.00		

[a] compared to No bunching (40+) after a stop was serviced by the *SAME* route
***Significant at 99%; **Significant at 95%

When a bus *i* arrives at a stop after a previous bus *i-1* from the same route has been departed for 0–20 s, then 1.33 s are saved on dwells, and this savings is also similar to buses arriving after a bus has left for 20–40 s and is from the same route. These results suggest that dwells of subsequent buses are shorter because the previous bus will have picked up most passengers. In contrast, if the arriving bus is from a different route that has departed for 20–40 s, then 2.33 s are added to the dwell time compared to a bus that arrives after 40 s from the same route. This may be explained by users' behavior at stops with overlapping routes, since after the arrival and departure of a bus, riders waiting for another route may leave the proximity of the stop and thus take longer to board the subsequent arriving bus they are waiting for. Finally, dwell time of an arriving bus is minimally impacted (increased by 0.40 s) by a bus from a different route that has been departed for more than 40 s, compared to the base situation of a bus arriving more than 40 s after a departed bus is from the same route. This may be explained by drivers' behavior; drivers may slow down their departure at stops with overlapping service to ensure that they pick up passengers waiting for this trip.

The control variables in the dwell time model behave as largely expected based on previous literature (Dueker et al., 2004; El-Geneidy & Vijayakumar, 2011; Stewart & El-Geneidy, 2014). Dwells will be shorter in the AM peak, likely because of regular customers' familiarity with bus boarding, but PM peak dwells are longer. Evening and night dwells, as well as overnight dwells, are both shorter than off-peak dwells. Every passenger boarding and alighting adds 4.86 s and 2.97 s, respectively, while the passenger activity squared-term indicates that every additional passenger quickens dwells by about 0.14 s. Lift activity increases dwell time, as does making an unscheduled stop. Buses stopping at a signalized intersection stop will increase dwells by nearly 4 s because red lights can prolong bus standing, while a stop made at stop with a shelter will increase dwells by nearly 2 s because passengers take longer to board the bus in these areas.

Running time model

Next, we developed a bus running time model to understand how the bus bunching that we found prolongs dwell times may impact running time. We tested how the frequency of bus bunching occurrences affected running times; we tested different time intervals and bus arrangements and dropped from the model those variables, like *occurrences of buses arriving as a bus from the same route is leaving* (*sum of previous 0 – same*), that were not significant. Moreover, only variables that display significance or are policy relevant variables were maintained in the model. Our model, which analyzed 7,724 trips, explains 60% of the variation in running time, comparable with similar models (Diab & El-Geneidy, 2013; Kimpel, Strathman, Bertini, & Callas, 2005).

Interestingly, our model (Table 5) reveals that each time a bus *i* arrives at a stop and the previous bus *i-1* from the same route has been standing for 0–40 s, then the running time of the arriving bus increases by 43.93 s. This value represents about 3% of the segment average running time (Table 3). If this situation occurs with a bus from a different route and is a scheduled overlap (scheduled arrivals occurring within 40 s of each other), then 37.17 s are added to the arriving bus' running time. Once bunched, running time will be added to the following bus since it needs to wait for the preceding bus to depart from a stop or maneuver around it. Each time a bus from a different route arrives at a stop after a previous bus has left for 0–40 s, the running time of the bus is 9.11 s longer, while 8.49 s is added to running time if a bus arrives and no bunching occurs and the previous bus was from a different route. These findings suggest that service overlapping increases running times. As mentioned in the previous section (**Dwell time model**) this likely results from drivers' behavior. It seems that drivers slow down their departure at stops with overlapping service to ensure that they are not missing any passengers waiting for this trip.

Table 5. Running time model.

Variable name	Coefficient	*t*-statistic	95% CI Lower bound	95% CI Upper bound
Constant	**1115.30*****	**177.38**	**1102.97**	**1127.62**
AM peak	7.36	1.57	-1.85	16.57
PM peak	**114.55*****	**22.28**	**104.47**	**124.62**
Evening and night	**-106.93*****	**-29.77**	**-113.97**	**-99.89**
Overnight	**-187.78*****	**-33.33**	**-198.82**	**-176.74**
Direction	**14.12*****	**4.56**	**8.05**	**20.20**
Total passenger activity	**4.59*****	**17.44**	**4.06**	**5.09**
Lift	**39.53*****	**8.56**	**30.48**	**48.59**
Maximum of passenger load	**-1.80*****	**-5.51**	**-2.45**	**-1.16**
Maximum of passenger load^2	**0.034*****	**3.75**	**0.016**	**0.051**
Headway delay at the start (s)	**-0.075*****	**-8.49**	**-0.092**	**-0.058**
Total stops made	**12.61*****	**16.56**	**11.11**	**14.10**
First trip	**-29.02****	**-2.23**	**-54.57**	**-3.47**
Sum of previous -40–0 – same	**43.93*****	**5.03**	**26.81**	**61.05**
Sum of previous -40–0 – different	**37.17****	**3.16**	**14.09**	**60.24**

Variable name	Coefficient	*t*-statistic	95% CI Lower bound	95% CI Upper bound
scheduled overlap				
Sum of previous 0–40 – different	**9.11****	**3.13**	**3.41**	**14.82**
Sum of no bunching (40+) – different	**8.49*****	**11.51**	**7.04**	**9.94**
N			7,724	
Adjusted R^2			0.60	
F statistics			(16, 7707) 712.97	
F significance (Prob > F)			0.00	

***Significant at 99%; **Significant at 95%

The remaining variables show that running times are longer during the afternoon peak, but substantially shorter during evening and overnight trips. Inbound trips are 14.12 s longer than outbound trips, likely due to peak-hour traffic. Passenger activity adds about 4.59 s, and lift activity adds 39.53 s to running time. Delays at the beginning of a trip will shorten total running time, likely because drivers attempt to make up this delay, which is consistent with previous research (Diab & El-Geneidy, 2013). Finally, the first trip of the day has short running times, mostly due to fewer stops made (which add 12.61 s per stop to running time) and less passenger activity.

CONCLUSIONS AND DISCUSSION

The main objective of this article is to understand the impact of bus bunching on bus dwell and running times while accounting for overlapping bus routes. Using two statistical models, we analyzed archived data obtained from TriMet's AVL and APC systems for a corridor in Portland, OR served by high-frequency bus routes to determine how bunching impacts bus operations. The first model is a dwell time model and investigated the impacts of bunching and overlapping service stops on disaggregated dwell times. The second model is a running time model, examining the impacts of bus bunching and overlapping service stops on the segment route-level of analysis. We found that bus bunching increases both dwell and running times. The amount of time added by bunching does not depend on whether the previous bus servicing a stop is from the same or different route. Instead, the added time depends to a larger extent on amount of time between arriving and departing buses. In other words, our study revealed that bunching and overlapping service from different routes impact bus operations almost similarly to bunching by the same route. Thus, while scheduling near-simultaneous arrivals for different routes could facilitate route transfer, transit agencies should overlap bus routes with caution in order to minimize delays on the system.

One important contribution of this research is that transit planners and schedulers should add more time between trips, particularly from different routes in order to decrease dwell time and running time delays that result from overlapping services at stops. Specifically, our work indicates that scheduled overlaps or bunched vehicles where different routes arrive and depart within 40 s of one another will prolong both dwells (adding about 10 s) and running times (adding about 37 s). These values decrease if the routes arrive and depart within 20 s, and bunching adds only about 3 seconds to dwell time and with no significant impact on running time. Given this finding, to ensure minimal delays, schedulers and operators should ensure that buses from different routes should have actual headways of more than 40 seconds. We recognize that this may not always be possible given transfer times or passenger activity. However, considering bunching is important at the planning stage in order to decrease service delays during actual operations. In addition, our research indicates that using holding or other control techniques to decrease bunching and inserting more time between buses is useful (Moreira-Matias, Mendes-Moreira, de Sousa, & Gama, 2015).

Previous work has studied the general causes of bus bunching, namely headway delays at the start of the route (Hammerle et al., 2005), or focused on corrective action by implementing holding points along a route (Holroyd & Scraggs, 1996) or by adjusting bus cruising speeds (Daganzo & Pilachowski, 2011). As dwells directly affect running time—a feature valued by customers (Diab & El-Geneidy, 2014; Vuchic, 2005)—our models predict that both dwells and running times will be increased by bunching. As a result, bunching can adversely affect customer satisfaction (Merevick, 2015; Provost, 2015; Simcoe, 2015). Importantly, not all bunching affects dwell or running times similarly, and our novel findings reveal some nuances of bunching depending on arrivals and departures.

Overall, we found that impacts of bus bunching on dwell times varies based on the arrivals and departures of the buses, so that the longer a bus has been servicing a stop, more time is added to the dwell time of the subsequent bus. Given the previous finding that bunching worsens along the length of the route (Feng & Figliozzi, 2015) suggests that these prolonged dwells will increase the running time of buses along the same route and therefore overall running time, which we confirmed in the running time model. One potential strategy to reduce bunching could be to introduce more holding points at the operational stage to avoid the penalties of bunching on dwell and running times. Therefore, transit agencies will need a trade-off between the added amount of slack time for bus holding and delay if bunching happened. Thus, a study that focuses on this trade-off is recommended. Finally, this study offers transit planners and policy makers a better understanding of the impacts of bunching along a shared corridor on the service dwell time and travel time. These findings are not limited to TriMet, as other transit agencies, by using a similar methodology, can use our models to understand how overlapping service and bunching may influence the system performance at different locations and stop setups. Minimizing bunching while providing reliable and frequent service remains a challenge for transit agencies.

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