Bus transit service reliability: Understanding the impacts of overlapping bus service on headway delays and determinants of bus bunching

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ABSTRACT

To retain and attract new riders, transit agencies are frequently in search for ways to improve system reliability. Transit agencies typically operate several routes that partially or fully overlay (or overlap) one another in order to offer a better service coverage to reach various destinations. While previous research has focused on understanding the general factors that impact headway adherence and delay, there has been little effort to address the effects of overlapping bus routes on service headway adherence and service bunching. This research investigates the impacts of bus route overlapping on service headway delay and probability of bunching at the stop-level of analysis. The study uses automatic vehicle location (AVL) and automatic passenger count (APC) systems data collected from TriMet, the public transit provider for Portland, Oregon, USA, along one of its heavily utilized bus corridors, the Barbur bus corridor. It is shown that service overlapping can increase headway delay by 3.8 seconds, with no impacts on service bunching. It is also shown that headway delay is a function of scheduled headway between trips. Thus, scheduling more time between trips decreases the service delay, with a minimum of delay occurring at 20 minutes. Trips starting late at the beginning of a route increase the odds of bunching for the following trip on schedule more than its delay. This study offers transit agencies and schedulers a better understanding of the effects of service overlapping on service headway delays from schedule and the determinants of us bunching, which are important components of transit service reliability.

Keywords: Reliability, Headway delay, Bus Transit, Service Overlapping, Bus Bunching

INTRODUCTION

Public transportation systems are essential features contributing to the sustainability and liveability of any city. One of the main challenges facing transit agencies is to offer consistent, reliable service, with minimal variability and few delays as compared to the schedule. Passengers wait time, which is a key component contributing to the attractiveness of the system to travellers, is directly related to the difference between the scheduled service headway and the actual service headway, which is the delay. Delays and inconsistencies in transit service can precipitate bus bunching. Bus bunching occurs when buses are unable to maintain their scheduled headways, resulting in buses arriving at a stop at the same time, or in front of their subsequent scheduled trip of the same route. In this scenario, the late bus usually carries more passengers, delaying it further and falling behind the schedule, while the other bus (the following bus) would serve fewer passengers, making it faster and ahead of schedule. Bunching therefore leaves some passengers stranded. As such, bus bunching represents poor quality service from the perspective of passengers; it dramatically increases waiting times for some riders, while overcrowding the delayed trip due to uneven passenger distribution. From the perspective of transit agencies, bus bunching represents an inefficient use of resources that leads to poor quality of service and increased costs.

Accordingly, if agencies wish to minimize the occurrence of bus bunching to improve service efficiency and rider satisfaction, and reduce operational costs, they require a clearer understanding of the factors influencing bus headway delay and bunching. Another related issue is service overlapping where some routes share common stops. Transit agencies typically operate several routes that overlap with each other in order to offer a better service coverage to reach various origins destinations and to make the network more convenient (with less transfers) and easy to understand. However, there has been little effort to address the impacts of overlapping bus routes on service headway adherence and service bunching. This paper aims to evaluate the impacts of overlapping routes on service headway delay and bunching at the stop-level of analysis. This is done through the analysis of archived automatic vehicle location (AVL) and automatic passenger count (APC) systems' data collected from TriMet, the public transit provider for Portland, Oregon, USA. The paper begins with a literature review of headway delay and bus bunching. This is followed by a description of the studied route. The next section describes the methodology used to prepare and analyze the data. This is then followed by a discussion of the results of the analysis, and wraps up with a summary of the main conclusions.

LITERATURE REVIEW

Bus transit headway is the length of time between the departures of two vehicles on a route measured at a given bus stop (*1*). Headway delay is the difference between the actual headway and scheduled headway (*2*). Variations in headways and the resulting delays indicate deterioration of service. Researchers have tended to investigate the impacts of the general factors on headway and delay (*2-4*). For example, Kimpel (*4*), using AVL and APC data from TriMet, found that the delay variation at a prior time point impacts the headway delay variation and departure delay variation downstream. El-Geneidy et al. (*3*), by studying AVL and APC records from Metro Transit in Minneapolis, found that headway deviation depends on a number of variables, including lift use and passenger activities. However, there has been little effort to investigate how different routes that have overlapping or shared stops may impact headway delay. This is an important issue since the effects of service overlapping on transit operations must be considered and integrated by schedulers during various operational stages to add the appropriate amount of recovery time. In addition, as discussed in the literature, passengers are concerned about their waiting time and its day-to-day variability, which ultimately affects their decision-making and time-planning processes (*5-7*). Thus, transit agencies are interested in providing reliable service that is fast and with minimal delays. Additionally, an increase in service delays can increase transit agency costs by requiring additional buses to maintain a given level of frequency, adding to operator costs. Reducing service delays can offer the opportunity to provide additional trips since the recovery time added to schedules between trips can be reduced.

Previous efforts to investigate bus bunching also examined the impacts of a range of factors on service levels. For example, Figliozzi et al. (*8*) indicated that bus bunching, as defined by headways of less than 3 minutes for TriMet Route 15 in Portland, increased with the route length. They used AVL/APC stop-level data and visualized bunching by plotting headway delay records. Bunching increased along the route length but a time point (used for holding) decreased the delay, suggesting that these time points help maintain regular headways. Hammerle, Haynes & McNeil (*9*), using archived operational data, revealed that bus bunching is mainly related to uneven departure headways at the terminals. However, despite these efforts, none of the aforementioned studies have focused on understanding the impacts of service overlapping on the service operations in terms of headway delay and bus bunching. Instead, most research on bus bunching has used mathematical approaches to generate theoretically holding techniques to eliminate or reduce bunching instead of understanding the sources and impacts of bus bunching (*10-12*) or focused on corrective action by implementing holding points along a route (*13*) or adjusting bus cruising speeds (*14*). Only one previous study by Diab and El-Geneidy (*15*) used AVL/APC data from STM, Montreal and from TriMet, Portland to investigate the impacts of service overlapping on dwell time. They indicate that service overlapping has inconsistent effects on dwell time. Nevertheless, they used variables to control for service overlapping in terms of whether a bus stop was served by another route, and thus did not account for the temporal side of this overlap in terms of the actual arrivals from other routes. Therefore, a better understanding of the service overlapping impacts on the service quality is needed. With the availability and the accuracy of AVL/APC data, we are now able to investigate how bus routes that serve a common corridor may influence bus service operation, specifically service headway delay, while isolating the effects of different influential variables on the service. The use of archived AVL/APC data is common in the transit literature to understand these types of changes in service quality (*2; 4; 16*).

METHODOLOGY

The objective of this analysis is to examine and understand the impacts of service overlapping on the headway delay of a bus route and bus bunching at the stop-level of analysis. The data used in our analyses come from a sample of TriMet's AVL and APC archived data system for a bus corridor, the Barbur bus corridor, Route 12 (see Figure 1). This route was chosen primarily because it experienced no changes in terms of route structure and service planning during the study period and it provides a variety in term of route structure and performance and presents a good example of service overlapping. Route 12, which runs east-west crossing through the Portland City Center, overlaps with several routes, including Routes 1, 38, 54, 55, 56, 64 and 94. The average headway for Route 12 is 15 minutes, with minimum headway of 5 minutes during peak hours and a maximum of 27 minutes during off-peak hours. The average stop spacing of the corridor is about 320 meters.

The data used in this study come from TriMet's archived AVL/APC systems. AVL/APC data are recorded at the stop level. Importantly, since all of TriMet's buses are outfitted with AVL/APC, it was possible to calculate the actual headway between all buses at the individual stop level. In addition to trip information, the AVL/APC data include information related to bus arrival time, leave time, schedule, number of passengers on board, and number of passengers boarding and alighting at each stop. Over 600,000 individual stop-level observations for Route 12 were collected from the TriMet's dispatch system over a three month period between September 1, 2014 and November 28, 2014. Another AVL/APC dataset was obtained for the same time period for all abovementioned overlapping routes to study their potential impacts on the Route 12 operations. Moreover, all buses in Portland are equipped with an operational transit signal priority (TSP) system.

In this research, to capture and isolate the effects of the service overlapping on service headway delay and bus bunching, we will focus on developing and testing two statistical models. The first model is a headway delay model used to estimate the effects of bus service overlapping at the stop-level of analysis. Headway delay is the difference between actual and scheduled headway. Actual headway is calculated based on departure times from each bus stop. In the analysis, we kept only trips made by Route 12 on the southwest and northeast segments' stops (Figure 1) while removing data from other routes and from segments that cross through the Portland City Center. The southwest segments analyzed in this paper stretches for about 10.5 km (6.5 mi) between SW Barbur and Capitol Hwy intersection in the east and SW Main and Pacific Hwy in the west. The segment was chosen primarily due 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. The northeast does not include any service overlap and stretches for about 7.1 km (4.4 mi) between NE Sandy Blvd and NE 96th Ave intersection in the east and NE Sandy Blvd and NE 24th Ave intersection in the west.

After processing the raw AVL/APC data, including making checks to remove system recording errors, duplicate records, holiday and weekend trips, layover stops (first and last stops of each trip), first trips during the day and unused bus segments, about 445,000 stop-level observations are included in the final database used for the model. Additional datasets to control for bus stop location impacts on headway delay were collected by using field observations conducted in 2014 and with GIS shapefiles provided by TriMet.

In order to reveal the potential causes of bus bunching while understanding the impacts of service overlapping, we also developed a bus bunching model. For this model, we used the same dataset as above, but focused on the first locations where bunching began to occur, as well as one stop that was randomly selected from each trip (i.e., one stop per trip) where no bunching occurred, to serve as controls. We defined bus bunching locations as stops that were served by a bus before it was served by its leader bus. A total of 8,913 stop level observations were included in the final database used for this model. Figure 2 illustrates bus bunching, when the bus in question (B2) moves in front of the bus ahead of it (B1). Therefore, for each observation, data from the previous scheduled trip (B1) and from the one prior (B0) are used to better understand the bus bunching phenomenon. The two buses (B1 and B0) were selected to be include in the analysis, since if B1 is only slightly late, it will, in addition to its normal load, pick up passengers who would have taken the next bus if B1 had not been late. These extra passenger boardings cause additional delay to bus B1. In contrast, bus B2, the one behind the late bus, will have a lighter passenger load and lower level of passenger activity than it otherwise would have, and thereby may run ahead of schedule and end up passing bus B1. Finally, bus B0 may also have an impact on bus B2 if it runs early, leaving passengers behind for the following trip (B1), which would delay it even further.

Table 1 lists the variables incorporated into the statistical analysis with a detailed description. Squared terms of certain independent variables are used to account for a possible non-linear relationship between them and the dependent variable, if such a relationship is observed. Other variables have been tested but were eliminated from the study due to their non-significance, such as *overlap at the previous stop*. According to previous studies, the general factors affecting headway and its delay include passenger activity, lift usage, stop sequence, time of day (morning peak, off-peak, afternoon peak), and delays at the beginning of a trip (*3; 4; 8*). Dummy variables for direction and corridor segments are included in the models to isolate the impacts of traffic congestion or other unseen variables on bus headway delay and bus bunching.

Two variables were included in the models to reveal the potential effect of service overlap on headway delay and bus bunching. The first is a dummy variable that captures whether a bus stop was serviced by another route prior to the arrival of a Route 12 bus. In other words, this dummy variable distinguishes the temporal and spatial overlapping to clarify the impacts of service overlap on transit service quality. The second variable is scheduled headway between trips; we employed this variable to consider and control for the amount of time scheduled between trips (between the current trip in question and its pervious trip) on headway delay and bunching. Other variables were used to control for bus stop placement, unscheduled stops, and the presence of reserved bus lanes on headway delay.

This paper uses a headway model to uncover the overall quality of data used in this study, to identify its consistency with previous research, and to reveal potential effects of the service overlap on headway. A negative value for headway delay means that a bus is falling behind its leader and is behind schedule, while a positive value means that a bus is gaining on its leader bus. The model specification is:

1. *Headway delay (s) = f(Direction, AM peak, PM peak, Night, Midnight and early morning , Actual stops made, Lift, Total passenger activity, Total passenger activity^2, Passenger load, Friction, Headway Delay at the start (s), Distance, Stop sequence, Stop at time point, After unscheduled stop, Near-side stop, Midblock stop, Signalized intersection, Reserved lanes in operation, Barbur southwest segment, overlapping trips, scheduled headway (s), scheduled headway^2)*

The second model is the bus bunching model that is used to account for factors that are associated with the probability of bunching. In this model, cumulative passenger activity, delay at the start of trip, stop sequence, and scheduled headway between trips were controlled for their impact on bus bunching. Other variables have been tested but they were eliminated from the study due to their statistical non-significance such as *stop type*, *distance between stops*, and *lift usage* or due to correlation to other used variables (with a Pearson coefficient of greater than 0.80) such as *the cumulative number of time points* variable. The model specification is:

2. *Bus bunching = f(Direction, Barbur southwest segment , AM peak, PM peak, Night, Early morning , cumulative passenger activity, cumulative passenger activity^2, delay at start (s), Stop sequence, overlapping trips, scheduled headway (s), B1 delay at the start (s), B1 cumulative passenger activity, B1 cumulative passenger activity^2, B0 bus delay at the start (s), B0 cumulative passenger activity, B0 cumulative passenger activity^2)*

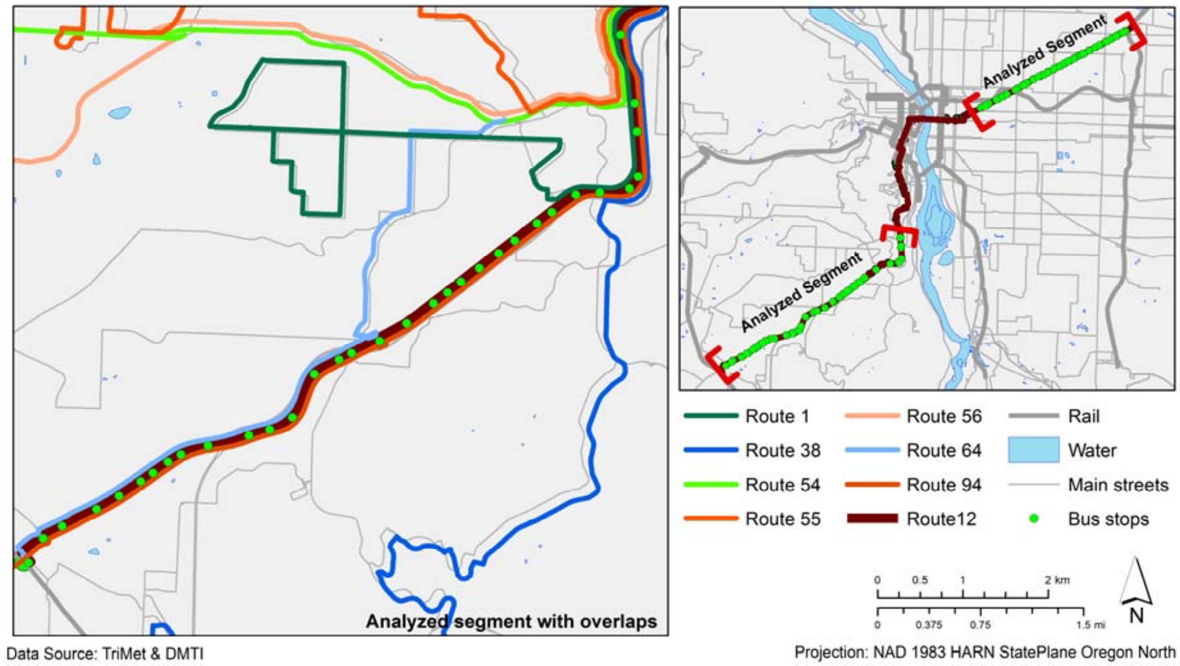

FIGURE 1: TriMet Route 12

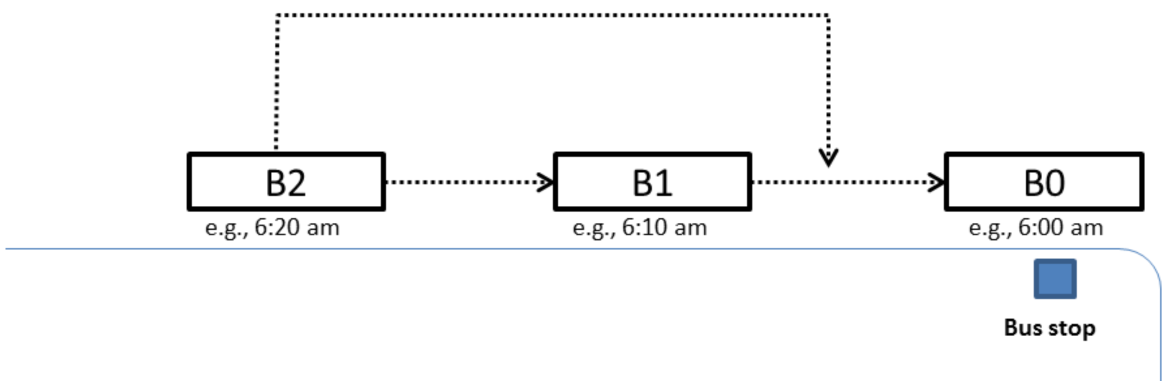

FIGURE 2: Bus bunching

TABLE 1: Description of variables used in the model

Variable Name	Description
Headway delay (s)	Headway delay measured in seconds at the end of the stop-segment as the difference between the actual headway time and the scheduled headway time (dependent variable)
Bus bunching	A dummy variable equal to one if the bus left a bus stop before its leader according to the bus schedule and zero otherwise (dependent variable)
Direction	Dummy variable for in-bound trips toward Downtown Portland
AM peak	A dummy variable equal to one if the headway occurred between 7:00 am to 9:00 am and zero otherwise
PM peak	A dummy variable equal to one if the headway occurred between 4:00 pm and 6:00 pm and zero otherwise
Night	A dummy variable equal to one if the headway occurred between 6 pm to 12:00 am and zero otherwise
Early morning	A dummy variable equal to one if the headway occurred between 12:00 am and 7:00 am and zero otherwise
Actual stops made	A dummy variable equal to one if the headway occurred at an actual stop that was made by bus during a trip
Lift	Total wheelchair lift activity along stop-segment
Total passenger activity	The total number of passengers boarding or alighting through all doors at a stop.
Total passenger activity^2	The square of the total number of boardings and alightings through all doors at a stop during a trip
Passenger load	The total number of passengers on a bus at a stop
Friction	The total number of standees plus the sum of the total boardings and alightings at a stop
Headway delay at the start (s)	The headway delay at the start of a trip in seconds, which is the difference between the actual headway time and the scheduled headway time at the first stop of a route
Distance	Distance traveled in meters before reaching the bus stop from the previous bus top
Stop sequence	Stop sequence along the route
Stop at time point	A dummy variable equal to one if a bus stop is located at a time point or holding point
After unscheduled stop	A dummy variable equal to one if a stop occurs after an unscheduled stop along the trip
Near-side stop	A dummy variable equal to one if the bus stop is on the near side of an intersection
Midblock stop	A dummy variable equal to one if the bus stop is within a block
Signalized intersection	A dummy variable equal to one if the bus stop is at a traffic signal. All traffic signals are equipped with an operational transit signal priority (TSP) system
Reserved lanes in operation	A dummy variable equal to one for stops that occurred while operating in reserved bus lanes
Barbur southwest segment	A dummy variable equal to one for stops along the Barbur bus corridor's southwest segment
Overlapping trips	A dummy variable equal to if the there is a scheduled trip from another route before this trip along Route 12

Variable Name	Description
Scheduled headway (s)	The scheduled headways at a bus stop between the current trip in question and its pervious trip.
Scheduled headway^2	The square of the scheduled headway
Delay at the start (s)	The delay at the start of a trip in seconds, which is the difference between the actual leave time and the scheduled leave time at the first stop after the layover of a trip
Cumulative passenger activity	The cumulative number of passengers boarding or alighting along a trip up until it reaches the bus stop in question
Cumulative passenger activity^2	The square of the cumulative number of passengers boarding or alighting along a trip until it reaches the bus stop in question.
B1 delay at the start (s)	The delay at the start of a trip in seconds for the scheduled leader bus (B1). When bunching occurs, this bus would fall behind the current bus in question (B2).
B1 cumulative passenger activity	The cumulative number of passengers boarding or alighting for the scheduled leader bus (B1). When bunching occurs, this bus would fall behind the current bus in question (B2).
B1 cumulative passenger activity ^2	The square of the cumulative number of passengers boarding or alighting for the scheduled leader bus (B1). When bunching occurs, this bus would fall behind the current bus in question (B2).
B0 delay at the start (s)	The delay at the start of a trip in seconds for the scheduled leader bus (B0) When bunching occurs, this bus would run in front of the current bus in question (B2).
B0 cumulative passenger activity	The cumulative number of passengers boarding or alighting for the scheduled leader bus (B0) When bunching occurs, this bus would run in front of the current bus in question (B2).
B0 cumulative passenger activity^2	The square of the cumulative number of passengers boarding or alighting for the scheduled leader bus (B0) When bunching occurs, this bus would run in front of the current bus in question (B2).

ANALYSIS

DESCRIPTIVE STATISTICS

Table 2 presents summary statistics for the variables used in this study at the stop level of analysis. Also in the table, route statistics are differentiated according whether there is an overlap or not at the bus stop. Regarding the key policy variable, generally (for all data used in the analysis), the overall mean headway delay is 0.79 seconds with a standard deviation of 293 seconds. The mean headway delay at stops where there was no overlap is 0.55 seconds with a standard deviation of 298 seconds, while the mean headway delay at stops with overlapped service is 7.3 seconds with standard deviation of 290 seconds. This indicates that segment headway delay at stops with overlapping service is typically longer than other stops with no overlaps by 6.8 seconds, with 8 seconds less variation. This suggests that service overlap consistently contributes to increased delays while decreasing its range of variation compared to other stops with no overlaps. Regarding bus bunching, when service is not overlapped, the mean number of situations where buses bunched and had arrived at a stop ahead of its leader is 0.06 buses with a standard deviation of 0.24. In contrast, the mean number of buses bunching at stops with overlaps is 0.03 buses with a standard deviation of 0.17 buses. This indicates that bunching at stops with overlaps is less likely to occur with less variance around the mean. Nevertheless, in order to better understand how overlapping impacts headway delay and bunching while controlling a set of influential variables, two statistical models are presented in the following section.

TABLE 2: Descriptive statistics

	All data		**Without overlap**		**With overlap**	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Headway delay (s)	0.79	297.3	0.55	297.5	7.31	290.2
Direction	0.50	0.50	0.50	0.50	0.62	0.48
AM peak	0.13	0.34	0.13	0.33	0.24	0.43
PM peak	0.13	0.34	0.13	0.33	0.23	0.42
Night	0.26	0.44	0.27	0.44	0.11	0.32
Midnight and early morning	0.06	0.24	0.06	0.24	0.10	0.30
Actual stops made	0.44	0.50	0.44	0.50	0.44	0.50
Lift	0.01	0.08	0.01	0.09	0.00	0.05
Total passenger activity	1.03	1.88	1.02	1.87	1.27	2.15
Total passenger activity^2	4.61	141.35	4.54	143.94	6.23	20.04
Passenger load	10.93	9.14	10.79	9.01	14.85	11.53
Friction	0.91	6.21	0.84	5.96	2.92	10.67
Headway Delay at the start (s)	-9.27	221.4	-9.52	221.8	-2.75	208.8
Distance	320.5	735.6	317.9	743.7	391.5	471.1
Stop sequence	40.0	26.8	40.1	27.0	37.2	22.6
Stop at Time point	0.07	0.25	0.06	0.23	0.26	0.44
After unscheduled stop	0.20	0.40	0.20	0.40	0.20	0.40
Near-side stop	0.39	0.49	0.39	0.49	0.34	0.47
Midblock stop	0.34	0.47	0.33	0.47	0.48	0.50
Signalized intersection	0.32	0.47	0.33	0.47	0.20	0.40
Reserved lanes in operation	0.04	0.19	0.03	0.17	0.29	0.45
Barbur southwest segment	0.48	0.50	0.46	0.50	1.00	0.00
Overlapping trips	0.04	0.19	0.00	0.00	1.00	0.00
Scheduled headway (s)	978	370	981	375	912	187
Scheduled headway^2	1,094,029	1,070,600	1,102,593	1,085,530	867,424	491,013
Number of cases	445,316		429,100		16,216	
Bus bunching	0.06	0.24	0.06	0.24	0.03	0.17
Direction	0.50	0.50	0.50	0.50	0.47	0.50
Barbur southwest segment	0.48	0.50	0.46	0.50	1.00	0.00
AM peak	0.13	0.34	0.13	0.33	0.22	0.42
PM peak	0.14	0.35	0.14	0.35	0.20	0.40
Night	0.29	0.45	0.30	0.46	0.12	0.33

	All data		**Without overlap**		**With overlap**	
Early morning	0.05	0.21	0.04	0.21	0.06	0.24
Cumulative passenger activity	53.7	47.7	53.4	47.7	61.8	48.4
Cumulative passenger activity^2	5166	7277	5129	7261	6158	7631
Delay at the start (s)	83.7	188.8	83.8	187.6	82.9	217.2
Stop sequence	40.5	26.6	40.4	26.8	42.5	22.5
Overlapping trips	0.04	0.19	0.00	0.00	1.00	0.00
Scheduled headway (s)	1013	477	1018	484	901	188
B1 delay at the start (s)	84.4	183.7	85.5	183.0	54.7	199.1
B1 cumulative passenger activity	56.9	49.7	56.8	49.9	59.5	45.0
B1 cumulative passenger activity ^2	5704	7893	5709	7936	5567	6660
B0 delay at the start (s)	80.9	177.2	81.1	178.6	76.4	136.1
B0 cumulative passenger activity	55.8	48.7	55.6	48.8	61.9	45.2
B0 cumulative passenger activity^2	5490	7630	5475	7662	5864	6741
Number of cases	8,913		8,587		326	

HEADWAY DELAY MODEL

A linear regression model was developed using headway delay in seconds as the dependent variable. The output of this model is reported in Table 3. The t-statistics and the statistical significance are reported in the table along with their coefficients. The model contains 445,316 observations and explains 32% of the variation in headway delay. This proportion of explained variance is considered relatively high and comparable to this type of model in the literature (*2; 17*).

Regarding the key policy variables, the models shows that service overlapping increases headway delay by 3.8 seconds. This may be understood due to a few reasons. When more than one route share a corridor, buses may have to operate at slower speeds, as well as stop behind one another at shared stops to serve passengers wishing to board different routes. Also, in some cases, buses may stop where passengers are waiting with no boardings and alightings, or slow down when approaching a stop to ensure whether there are passengers at the bus stop, or the bus may need to wait for a previous bus to clear the stop. Our model also includes a '*Scheduled headway*' variable to capture the impacts of the amount of scheduled time between trips on headway delays. The model indicates that headway delay in the service is expected to decrease by 0.11 seconds for every second of increase in the scheduled headway. Nevertheless, the scheduled headway square term (which is used to account for non-linear relationships) has a statistically significant positive contribution to headway delay, indicating that after a certain level of scheduled headway, no decrease in delays can be expected. In the following section, we describe a sensitivity analysis using the headway model coefficients in order to better understand the impact of these two variables on headway delay.

In accordance with previous work (*2-4; 18*), the remaining control variables in the model perform as expected with regard to the expected sign and significance. The total passenger activity (boarding and alighting) increases headway delays by 14.4 seconds per passenger compared to the scheduled headway, while the passenger activity squared term indicates that each additional passenger adds less time to overall dwell time compared to the preceding passenger, consistent with previous studies (*19-21*). Each lift use increased the headway delay by 47.2 seconds compared to the schedule. Although lift operation is an infrequent event, knowing the amount of delay its use entails can inform scheduling decisions. For every stop made along the route, 12.5 seconds are added to the headway delay due to acceleration and deceleration at each stop; this finding is also consistent with previous work (*18*).

Passenger load increases headway delay by 2.9 seconds for each additional passenger compared to scheduled headway, while the passenger friction factor, which is used to account for passenger activity on crowded buses with standees, increases headway delay by 0.5 seconds for every additional passenger. Therefore, our model suggests that heavily loaded buses are expected to have greater delays. This can be related to passenger behavior in overcrowded buses and to the conflict between the number of standees and passenger movement (*20; 21*). Distance between stops decreases the headway delay; for every additional meter, headway delays are expected to decrease by 0.01 seconds. Realistically, this suggests that larger distances between stops can directly reduce bus delays. Route direction and section also affects headway delay, likely resulting from traffic conditions and other unseen factors that are not explained by the model's variables scheduling, which can be found in previous operational models (*19-21*). Time-of-day has a statistically significant effect on headway delay. Compared to off-peak periods, headways taking place during the afternoon peak are less delayed compared to scheduled headway. Headways taking place during the night and early morning are notably more delayed than the schedule. Therefore, revisions to the night and early morning schedules can be recommended.

Headway delays at the beginning of a trip increase headway delay at subsequent stops by 0.7 seconds for every second of delay at the beginning of the route. This is means that operators would compensate about 30% of the delay that they have from the start during the trip, which is also consistent with previous studies (*16*). Stop sequence, which has been used as a proxy of route length, increases headway delay by 0.15 seconds for every additional stop, which has been previously suggested (*8*). The occurrence of unscheduled stops increases headway delay by 15.7 seconds compared to schedules, while stopping at time points (or holding points) corrects headway delay and decreases it by 43.4 seconds. Therefore, transit agencies interested in decreasing delays and improving bus service should discourage the use of unscheduled stops by operators, while providing holding points that allow better schedule fidelity.

Other variables have statistically significant effects and should reduce headway delay compared to schedule, namely bus stop location, reserved bus lanes, and transit signal priority systems. In other words, for example, moving bus stops from the near-sides to far-sides of intersections will decrease headway delay by 3.5 seconds. Using reserved bus lanes decreases headway delay by

16.7 seconds, and equipping the system intersection with a TSP system decreases headways delays by 4.7 seconds compared to scheduled headways. Therefore, transit agencies can consider moving bus stops, and implementing reserved bus lanes and TSP systems along their routes in order to decrease headway delays, ultimately reducing passengers' waiting time and lowering operational costs.

TABLE 3: Headway delay model

Variable	Coefficients	*t*-stat	95% Conf. Interval Lower Bound	95% Conf. Interval Upper Bound
Constant	**14.06*** **	**4.05**	**7.26**	**20.85**
Direction	**-7.55*** **	**-9.72**	**-9.07**	**-6.03**
Barbur southwest segment	**-2.87*** **	**-3.45**	**-4.49**	**-1.24**
AM peak	-0.15	-0.13	-2.53	2.23
PM peak	**-2.06* **	**-1.69**	**-4.44**	**0.33**
Night	**5.36*** **	**5.37**	**3.41**	**7.32**
Midnight and early morning	**8.98*** **	**5.60**	**5.84**	**12.12**
Actual stops made	**12.45*** **	**12.62**	**10.52**	**14.39**
Lift	**47.15*** **	**10.13**	**38.02**	**56.27**
Total passenger activity	**14.41*** **	**47.22**	**13.81**	**15.01**
Total passenger activity^2	**-0.05*** **	**-14.97**	**-0.05**	**-0.04**
Passenger load	**2.86*** **	**60.74**	**2.76**	**2.95**
Friction	**0.54*** **	**7.91**	**0.40**	**0.67**
Headway Delay at the start (s)	**0.72*** **	**434.35**	**0.72**	**0.73**
Distance	**-0.01*** **	**-10.24**	**-0.01**	**0.00**
Stop sequence	**0.15*** **	**10.27**	**0.12**	**0.18**
Stop at Time point	**-43.44*** **	**-25.20**	**-46.82**	**-40.06**
After unscheduled stop	**15.73*** **	**15.53**	**13.75**	**17.72**
Near-side stop	**3.53*** **	**3.71**	**1.66**	**5.40**
Midblock stop	**10.13** **	**9.60**	**8.06**	**12.20**
Signalized intersection	**-4.67*** **	**-4.84**	**-6.56**	**-2.78**
Reserved lanes in operation	**-16.66*** **	**-7.96**	**-20.76**	**-12.56**
Overlapping trips	**3.81** **	**1.81**	**-0.31**	**7.93**
Scheduled headway (s)	**-0.11*** **	**-22.16**	**-0.12**	**-0.10**
Scheduled headway^2	**0.001*** **	**25.00**	**0.000**	**0.001**
N	445,316			
R2	0.32			
F statistics	(24, 445291.0) 8,661			
F significance (Prob > F)	0.00			

Bold indicates statistical significance
*** Significant at 99% ** Significant at 95% * Significant at 90%

BUS BUNCHING MODEL

The second model is a binary logistic model that is used to analzye the probability of bus bunching. In the analysis, bus bunching (as illustrated in Figure 2) is coded as "1," whereas being on schedule in terms of staying and leaving a stop behind its scheduled leader bus is coded as "0." Table 4 presents the results of this model. Our model contains 8,913 stop-level observations and explains 41% of the variation in bunching. Although it is rare to find bunching models in the literature, the proportion of explained variance is comparable to other binary logistic models that investigate on-time performance (*22*).

Regarding the key policy variables, the model indicates that service overlapping at stops has no significant impact on the odds of being bunched and departing the stop prior to its scheduled leader bus departs. This result indicates that the expected bunching at stops with and without overlapping service is nearly similar. The scheduled headway variable reveals a negative and statistically significant effect on the odds of being bunched, keeping all other variables at their mean values. Scheduled headway decreases the odds of being bunched by 0.1% for every one second increase in scheduled headway between trips along the route. This suggests that the practice of scheduling additional time between trips could indeed help mitigate bus bunching.

Regarding the other remaining control variables, direction and route section have statistically significant impacts on bus bunching. The in-bound (toward Downtown) direction increases the odds of being bunched by 270% compared to out-bound, and the outer south-western section of the bus corridor decreases the odds of being bunched by 64%. This may be explained by the difference in route structure, traffic congestion and the urban environment. Compared to the off-peak period, the morning and afternoon peaks have no significant impacts on bunching, while the odds of being bunched decreases by 36% and 86% during the night and early morning, respectively. These findings are consistent with our headway delay model (Table 3) that uncovered an increase in headway delays during these operating periods. The cumulative number of passengers boarding or alighting along a trip up until it reaches the bus stop in question decreases the odds of being bunched by 3% for every additional passenger. The squared-term of the cumulative number of passengers' activity increases the odds of being bunched by 0.1% for every additional passenger, which indicates that cumulative passengers' activity would decrease the odds of being bunched until a certain point, when it has no further impact. As expected, a delay at the beginning of the route decreases the odds of being bunched by 0.3% for every second of delay at the beginning of the route. This means that late buses generally will not go in front of their leaders. The stop sequence also increases the odds of bunching by 3.5% for every additional stop that the bus passes, which is also consistent with previous studies (*8*).

Every second of delay at the beginning of the route for B1 (the bus in front of the current bus in question) is expected to increase the odds of being bunched by 0.5%. This means that if B1 started late, the odds of bunching for the current bus (B2) more than its delay (as mentioned above) are increased by 0.2%. Therefore, transit agencies and policy makers should track delay at the beginning of routes, since when departure delay occurs it is expected to increases the odds of being bunched for the following scheduled trip. The cumulative number of passengers boarding or alighting for B1 increases the odds of being bunched for the current trip in question (B2) by 2%. This confirms the previous theoretical framework indicated in the methodological section. More passengers boarding and alighting for bus B1 will increase the odds of bus B2 being bunched. Finally, while the delay for bus B0 at the beginning of the route has no significant impact on bunching, the cumulative quantity of passenger activity for bus B0 has a statistically significant effect on being bunched. Every additional passenger decreases the odds of being bunched by 1.0% for B2 trips. This means that when B0 picks up successively more passengers, delays for B1 will decrease, which will consistently decrease B2 bunching. The squared-term of the cumulative number of passengers activity for B0 indicates that cumulative passenger activity for B2 would decrease the odds of being bunched until a certain point, when it has no further impact in terms of decreasing bunching.

TABLE 4: Bus bunching model

Variable	Coefficient	Z	Odds ratio	95% Conf. Interval Lower Bound	95% Conf. Interval Upper Bound
Constant	**-3.795**	**149.73*** **	**0.022**		
Direction	**1.004**	**40.16*** **	**2.730**	**2.001**	**3.725**
Barbur southwest segment	**-1.036**	**40.93*** **	**0.355**	**0.258**	**0.488**
AM peak	-0.044	0.06	0.957	0.683	1.341
PM peak	-0.027	0.03	0.973	0.713	1.329
Night	**-0.444**	**8.77*** **	**0.642**	**0.478**	**0.861**
Early morning	**-1.933**	**8.78*** **	**0.145**	**0.040**	**0.520**
Cumulative passenger activity	**-0.029**	**48.11*** **	**0.971**	**0.963**	**0.979**
Cumulative passenger activity^2	**0.000**	**26.61*** **	**1.001**	**1.000**	**1.001**
Delay at the start (s)	**-0.003**	**110.77*** **	**0.997**	**0.996**	**0.998**
Stop sequence	**0.035**	**85.77*** **	**1.035**	**1.028**	**1.043**
Overlapping trips	0.519	2.00	1.681	0.819	3.451
Scheduled headway (s)	**-0.001**	**38.36*** **	**0.999**	**0.998**	**0.999**
B1 delay at the start (s)	**0.005**	**386.59*** **	**1.005**	**1.004**	**1.005**
B1 cumulative passenger activity	**0.020**	**27.30*** **	**1.020**	**1.013**	**1.028**
B1 cumulative passenger activity ^2	0.000	1.43	1.000	1.000	1.000
B0 delay at the start (s)	0.000	2.38	1.000	1.000	1.001
B0 cumulative passenger activity	**-0.010**	**6.03** **	**0.991**	**0.983**	**0.998**
B0 cumulative passenger activity^2	**0.000**	**9.07*** **	**1.000**	**1.000**	**1.001**
N		8913.00			
Nagelkerke R Square		0.41			
Log likelihood		2653.15			

Bold indicates statistical significance
*** Significant at 99% ** Significant at 95% * Significant at 90%

SENSITIVITY ANALYSIS

A sensitivity analysis is conducted in order to clarify the impact of scheduled headway on headway delay while keeping all variables constant at their mean values. This helps to understand the non-linear relationship between the scheduled headway and headway delay. Figure 3 shows the expected headway delays at an in-bound stop during the evening time period. As we can see the figure, headway delay decreases sharply with an increase in scheduled headway until a certain point where the delay begins to flatten. The minimum delay occurs at a scheduled headway of approximately 20 minutes between trips. Therefore, transit agencies that have bus stops serviced by multiple routes should aim to schedule an average combined headway of 20 minutes between trips to minimize headway delays and reduce passenger waiting time. The fitted line and the equation representing the expected headway delay is displayed in the figure which can be utilized by transit agencies in order to predict the amount of delay that they may expect due to increases or changes in scheduled headway. In other words, for example, if transit agencies need to operate the service at 10 minutes headway (or combined headway). This would mean that the agency should expect a delay of about 0.4 minutes (24 seconds) on average at each stop. This amount of delay needs to be integrated and added to schedule to avoid delays and to avoid bunching. The presence of control points to apply bus holdings is key towards avoiding bus bunching and such time for bus holdings should be integrated in the schedules especially with shorter.

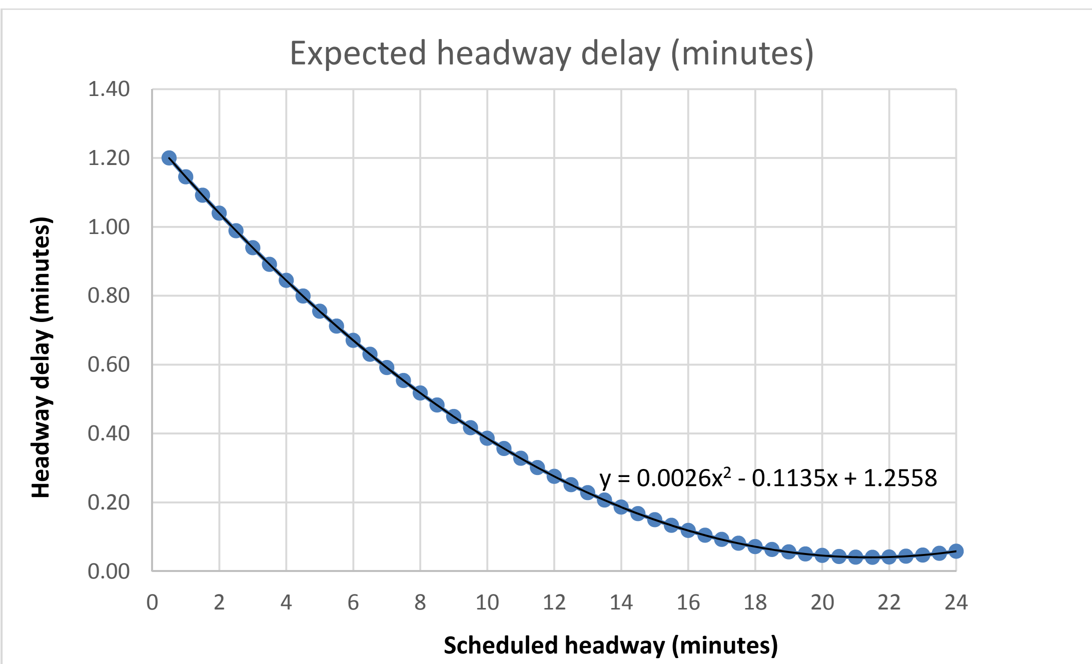

FIGURE 1: Headway delay in relation to scheduled headway

CONCLUSION

The main objective of this study was to evaluate the impact of overlapping services on headway delay. We analyzed archived data obtained from TriMet's AVL and APC systems for Portland's Route 12 using two statistical models. The models indicate that service overlapping increases the headway delay by 3.8 seconds, and accordingly, contributes to passengers' waiting times. Headway delay is also a function of scheduled headway between trips. Increasing the scheduled headway between trips would decrease the headway delay to a certain extent. The minimum headway delay occurs at a scheduled headway of 20 minutes at a given bus stop. In other words, service reliability in terms of decreasing headway delay can be achieved by operating two routes serving same stop that each have a headway of 40 minutes with a combined scheduled headway of 20 minutes. Other variables that have statistically significant positive effect in terms of decreasing headway delay, namely bus stop placement, reserved bus lanes, transit signal priority systems and time points. For example, moving bus stops from near-side stops to far-stops will decrease headway delay by 3.5 seconds. Using bus reserved lanes decreases headway delay compared to schedules by 16.7 seconds. Therefore, transit agencies may consider these strategies in order to decrease headway delays, and importantly, decreasing passengers' waiting time.

Since it is rare to find bus bunching models in the literature, one of the key, important findings of this model is delay at the beginning of the route for the scheduled leader bus (B1). The model indicates that if B1 started late that will increase the odds of bunching for the current bus (B2) more than its delay. Therefore, transit agencies and policy makers should track delays at the beginnings of routes, since it would decrease the odds of being bunched for the following scheduled trip when it is prevented. Then, they can implement appropriate strategies, such as using time points, to maintain the scheduled headway between trips and minimize bunching. Finally, the recommendations from this study are not limited to TriMet, transit agencies could expect similar impacts of overlapping service on transit system performance. In addition, by using a similar methodology and type of data, they may understand these impacts at different setups and locations.

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