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Empirical Analysis of Bus Bunching Characteristics Based on Bus AVL/APC Data

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Abstract

Bus bunching takes place when headways between buses are irregular. Bus bunching is associated with longer waiting times for riders, overcrowding in some buses, and an overall decrease on the level of service and capacity. Understanding the temporal and spatial characteristics and the causes and effects of bus bunching incidents from archived bus data can greatly aid transit agencies to develop efficient mitigation strategies. This paper presents methods to identify and visualize specific time periods and segments where bus bunching incidents occur based on automatic vehicle location (AVL) and automatic passenger count (APC) data. The paper also proposes methods that help analyze the causes and effects of bus bunching based on AVL/APC data. Temporal and spatial distributions of bus bunching events indicate high concentration during high frequency service hours and segments, and increasing concentration toward downstream. Time point bus stops can help reduce bus headway variability but with limited capability. Results indicate that irregular departure headway at the initial stop is the key cause of bus bunching rather than downstream traffic conditions and passenger demand uncertainty. A bus departure headway control at the initial stop of high frequency service zone is highly recommended, and a switch from schedule-based control to headway-based control strategy at time point stops in high frequency service zone is suggested.

Keywords: bus bunching, performance measure, headway, causes and effects

1 INTRODUCTION

A healthy and efficient public transit system is indispensable to reduce congestion, emissions, energy consumption, and car dependency in urban areas. However, low service quality makes transit unattractive for users of private transportation. This is true in areas served by bus routes that chronically underperform.

In a stochastic environment, deviations from schedules are unavoidable. Uncertain travel times and passenger demand preclude schedule adherence and headway uniformity. A late bus usually encounters more passengers and the extra passengers may create further delays. Meanwhile, if the following bus encounters fewer passengers it tends to run faster. If two buses become too close, "bus bunching" takes place. Bus bunching is associated with longer waiting times for some riders, overcrowding in late buses, and an overall decrease on level of service and capacity.

It is important for transit agencies to identify and understand the mechanics of bus bunching, especially recurrent bus bunching events during certain time periods or route segments, as it may be due to a scheduling issue rather than an operational problem. If transit agencies can identify and understand the spatial and temporal characteristics of bus bunching problems, detect the causes and measure the effects of recurrent bus bunching problems, transit agencies can propose useful and efficient strategies to improve bus service reliability.

Since the introduction of automatic vehicle location (AVL) and automatic passenger count (APC) data collection systems, studies have been using performance measures and visualization tools to help identify and evaluate transit operations performance. Bertini and EI-Geneidy *(1)* presented initial work on the utilization of ALV/APC data to measure bus performance. Based on the archived AVL/APC data from the Tri-County Metropolitan Transportation District of Oregon (TriMet), they proposed system level, route level, segment level and stop level performance measures. Also based on the "drill-down" method, Berkow et al. *(2)* further claimed the power of using visualization as a tool to present performance measures to help analysts easily understand large amounts of information.

Kimpel et al. *(3)* and Strathman et al. *(4)* utilized regression models and found statistically significant relationships between headway deviation and number of on board passengers, as well as between running time variation and operator years of experience. Albright and Figliozzi *(5)* found that transit signal priority (TSP) has significant impacts on bus headways. However, both positive and negative effects were observed; for example, when two bunched buses are late, TSP may further reduce the headway between the two buses because the TSP control strategy is designed primarily for bus departure delay (single bus) instead of headway control (multiple buses). Hammerle et al.*(6)* analyzed two causes of bus bunching: on-street effects and beginning of the terminal. Time-space trajectory graphs of several bus trips were plotted to help identify bus bunching problems and causes. Results showed that most of the bus bunching problems originate as a result of irregular headways at the terminals. Although time-space trajectory graphs provide much detailed information about when, where, and which buses are bunched, they can only be used to show a limited time period. For identification of recurrent bus bunching problems over a long time period the time-space trajectory graph is not powerful. Mandelzys and Hellinga *(7)* developed an automatic method to identify causes of poor on time performance. Using archived ALV/APC data they measured the frequency of each cause that is related to poor on time performance over all records.

Other research proposed operational control strategies to mitigate bus bunching incidents *(8–10)*, but this study focuses on identifying and analyzing bus bunching characteristics.

The goal of this research is to develop methods that help transit agencies identify specific time periods and segments where bus bunching happen frequently, understand the causes and effects of bus bunching based on archived AVL/APC data.

2 ROUTE CONFIGURATION AND DATA DESCRIPTIONS

Route configuration

This study focuses on TriMet's Route 15, which experiences difficulties in terms of schedule adherence and headway regularity. Route 15 is characterized by long travel distances across congested areas and high buffer times to absorb delays and variability. Route 15 runs east-west, crossing downtown Portland, with the east terminal located at the Gateway Transit Center and two terminals located at the west end of the route: 1) Montgomery Park, and 2) NW Thurman & 27th. Figure 1 and Table 1 show the route schematic as well as the time point bus stop names for both westbound and eastbound services.

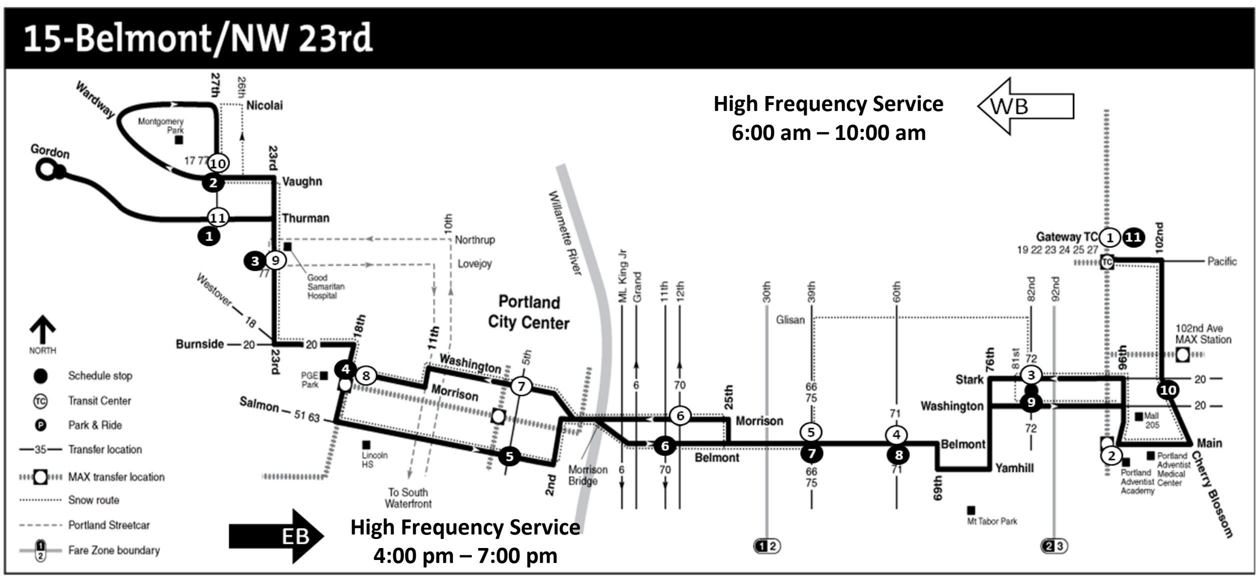

Figure 1. Route 15 Schematic (source: TriMet)

Time point stops (bus stops with scheduled departure times) are depicted by the numbered circles in the route schematic of Figure 1. White circles with black numbers indicate stops for the westbound route; and black circles with white numbers indicate stops along the eastbound route. Table 1 lists names of all time point stops along the route. For the majority of the day, Route 15 is in low frequency service where headways between buses are approximately 15 minutes. However, in the a.m. peak hours, westbound passenger demand is much higher than other times of day due to morning commute to work in downtown Portland. Therefore, additional short trips are added to the route in the a.m. peak hours for westbound travel. These additional short trips run from the stop at SE Stark & 93rd to the stop at SW Morrison & 17th, and therefore reduce the departure headways of stops within this zone to 5-8 minutes, which is so-called high frequency service. Similar additional short trips are added to the eastbound travel direction during the p.m. peak hours due to evening commute to home from downtown Portland. In eastbound high frequency service, additional short trips start from SW Salmon & 5th, but may end at any of the three downstream time points, SE Belmont & 39th, SE Belmont & 60th, or SE Washington & 82nd. The approximate time periods for high frequency service are shown in Figure 1: 6-10 a.m. for westbound and 4-7 p.m. for eastbound. The time point stops that are within the high frequency zone of the route are indicated in bold typeface in Table 1.

Table 1. Route 15 Time point stops

Eastbound	***Westbound***
1. NW Thurman & 27th	1. Gateway TC
2. Montgomery Park	2. SE 102nd & Washington
3. NW 23rd & Marshall	**3. SE Stark & 82nd**
4. SW 18th & Morrison	**4. SE Belmont & 60th**
5. SW Salmon & 5th	**5. SE Belmont & 39th**
6. SE Belmont & 11th	**6. SE Morrison & 12th**
7. SE Belmont & 39th	**7. SW Washington & 5th**
8. SE Belmont & 60th	**8. SW Morrison & 17th**
9. SE Washington & 82nd	9. NW 23rd & Lovejoy
10. SE Washington & 103rd	10. Montgomery Park
11. Gateway TC	11. NW Thurman & 27th

The studied data period ranges from 14 September 2009 to 26 February 2010 and includes all weekdays (totaling 115 days). TriMet has implemented a bus dispatching system (BDS) that records and archives AVL/APC data for later analysis. A sample of the archived stop-event data for Route 15 is shown in Table 2.

Table 2. Stop Event Data Sample of Route 15

Date	**Leave _time**	**Train**	**Stop _time**	**Arrive _time**	**Dwell**	**Stop_id**	**Door**	**Lift**	**ons**	**offs**	**Load**	**Mileage**
9/14/2009	21150	1501	21120	21136	0	8989	0	0	0	0	2	8.1
9/14/2009	21216	1501	21194	21182	10	7162	1	0	2	0	4	8.3
9/14/2009	21262	1501	21248	21238	7	8963	1	0	2	1	5	8.5
9/14/2009	21294	1501	21286	21278	0	7174	0	0	0	0	5	8.6
9/14/2009	21344	1501	21327	21320	6	718	2	0	1	0	6	8.7
9/14/2009	21384	1501	21373	21360	0	749	0	0	0	0	6	8.8
9/14/2009	21430	1501	21407	21394	5	8511	1	0	1	0	8	8.9
9/14/2009	21496	1501	21480	21472	8	6911	2	0	0	1	7	9.1
9/14/2009	21590	1501	21575	21582	0	5016	0	0	0	0	7	9.3
9/14/2009	21636	1501	21611	21602	0	5014	0	0	0	0	7	9.4

Whenever a bus arrives at or departs from a stop, a new record is entered. The column “Leave_time” is the actual departure time of that bus at the stop; “Stop_time” is the scheduled departure time of that bus at that stop; and “Arrive_time” is the actual arrival time for that bus at that stop, all of which is expressed in seconds after midnight. There is no scheduled “Arrive time" for any stop. The "Stop_time" for time point stops is the actual scheduled departure time; for other bus stops, the "Stop_time" is interpolated. The "Dwell" time here is recorded as the time (in seconds) that the door is open; therefore, dwell time is usually not equal to the difference between actual departure time and actual arrival time. All the other information shown in Table 2 is self-explanatory. Note that there is additional information in the stop event data that is not shown in this sample, such as route number, direction, and x-y coordinates.

3 BUS BUNCHING IDENTIFICATION

3.1 Bus bunching events spatial-temporal distribution

Headway between two consecutive buses at each stop is used to identify bus bunching incidents instead of distance between two consecutive buses. In the literature or transit industry, there is no standard minimum headway threshold to define bus bunching. Therefore, an arbitrary value of two minutes is used to determine bus bunching, which means if a departure headway between two buses at a stop is smaller than two minutes, this headway is identified as a bus bunching event. Depending on service frequency in different bus routes or at transit agencies, this threshold may be different.

Based on half-year's wealth of AVL/APC data, bus departure headways at each bus stop along Route 15 are calculated and grouped into 24 hours in a day. Those headways that are smaller than the two-minute threshold are shown in Figure 2.

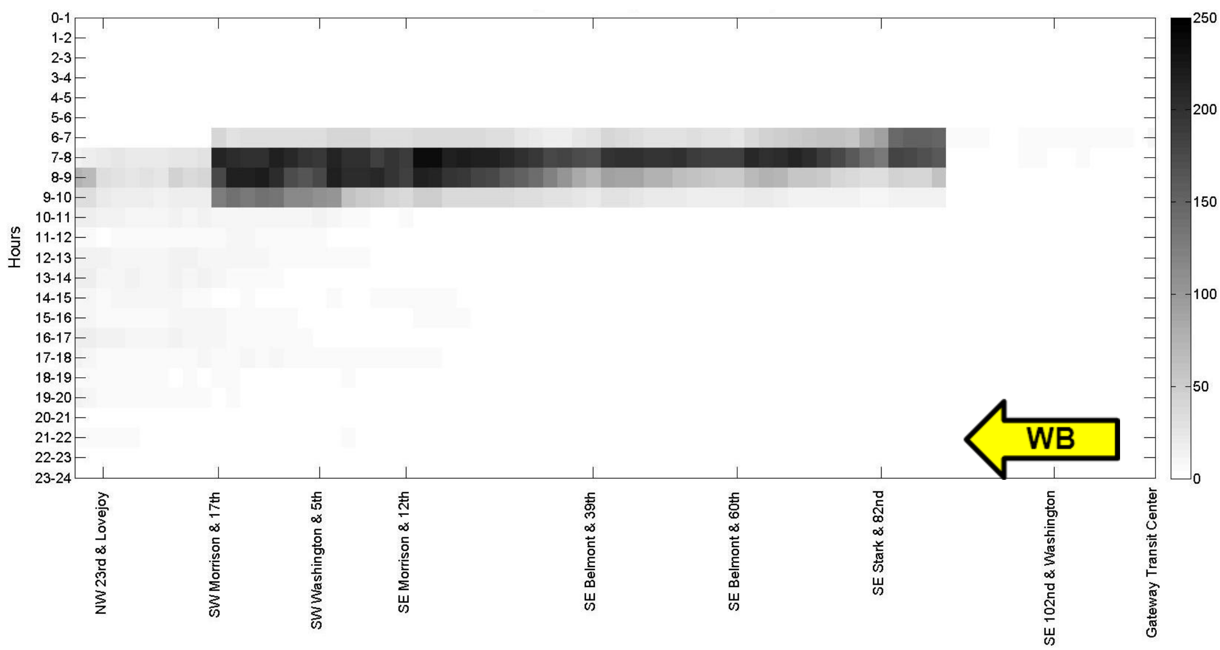

Figure 2. Bus bunching events for route 15 westbound (headway threshold: < 2 minutes)

With the exception of the two-branches of stops at the western-most end of the route, the x-axis shows all bus stops along westbound Route 15. The y-axis shows the hours of a day. Colors from white to black represent bus bunching counts of 0 to 250 for the six-month's worth of data. Recall that the studied data set consists of 115 days; therefore, a value of 230 counts indicates that for a particular stop during a particular hour there are, on average, two bus bunching events

(230/115) occurring every day. Figure 2 shows that most of the bus bunching problems were found within the high frequency service (between 6:00 a.m. and 10:00 a.m., and between the stops at SE Stark & 93rd and SW Morrison & 17th) where average headway is about seven minutes. Also, there appears to be excessive bus bunching events taking place even during the low frequency service period after SW Washington & 5th, emphasizing poor headway regularity. Furthermore, during the high frequency service period, the sequence of gradual color changes between each two bus stops suggests that the frequency of bus bunching increases after each bus stop and then decreases significantly at the subsequent time point stop. This indicates some control strategies, such as schedule-based holding, might be taking place during these time periods and at these stops. Figure 2 shows the results using two minutes (120 seconds) as the bus bunching threshold. It is also worthwhile to show how bus bunching frequency responds to different thresholds.

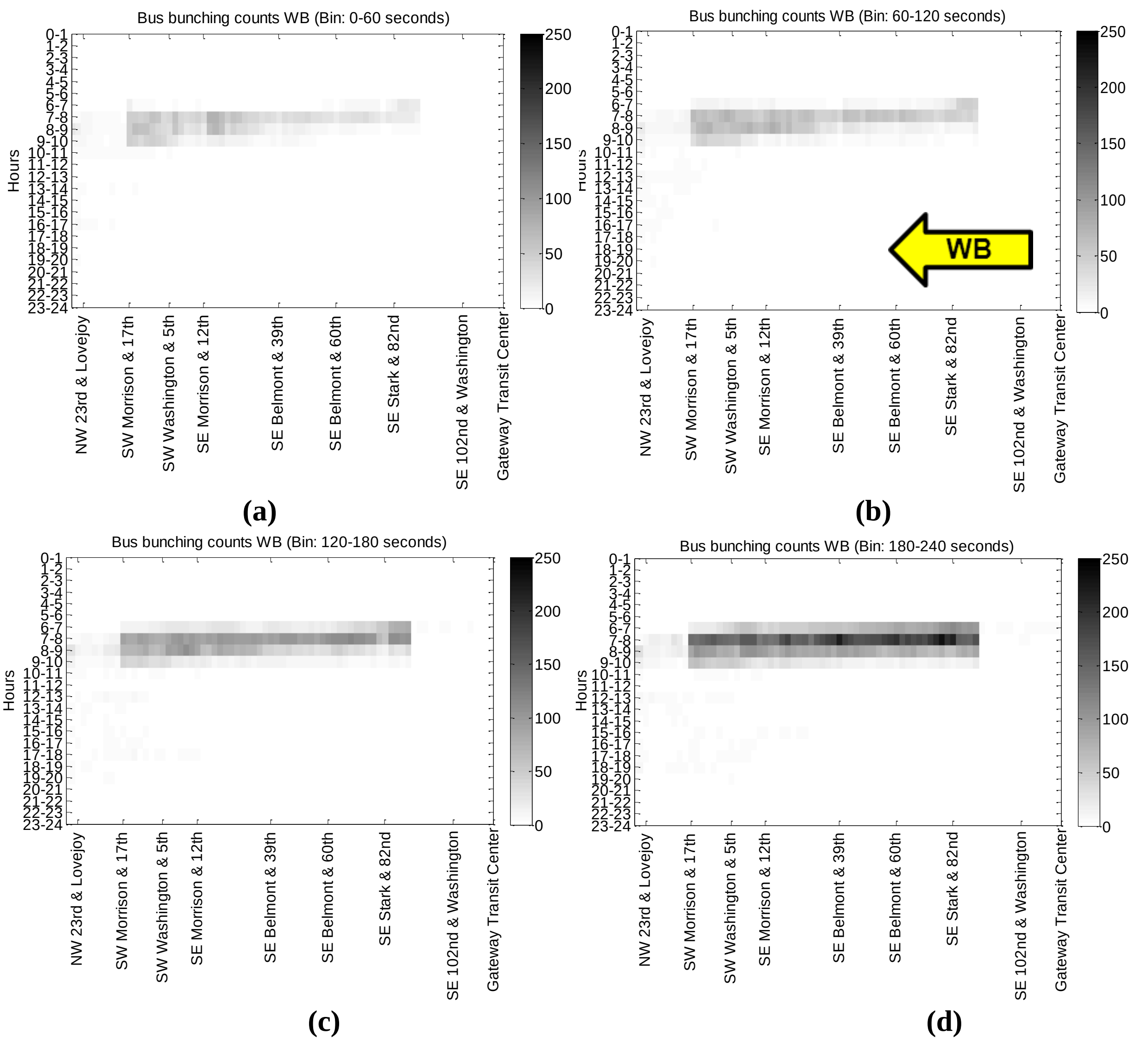

Figure 3. Bus bunching events for route 15 westbound in different levels: (a) 0-1 minute; (b) 1-2 minutes; (c) 2-3 minutes; (d) 3-4 minutes.

Figure 3 shows the bus bunching frequency distribution for four different short headway threshold levels, again over time and space. The color bar and relative values are the same as in Figure 2. The general behavior to note is that as the short headway threshold increases, the bus bunching frequency also increases. Further, most of the identified short headways are occurring during the high frequency service period.

The above mentioned method can generate all of the identified bus bunching events, while when two buses are bunched together at some stops along a route, they will probably continue to bunch together downstream. Therefore, it is also worth to identify when and where buses started to bunch together. Figure 4 shows the number of bus bunching initials.

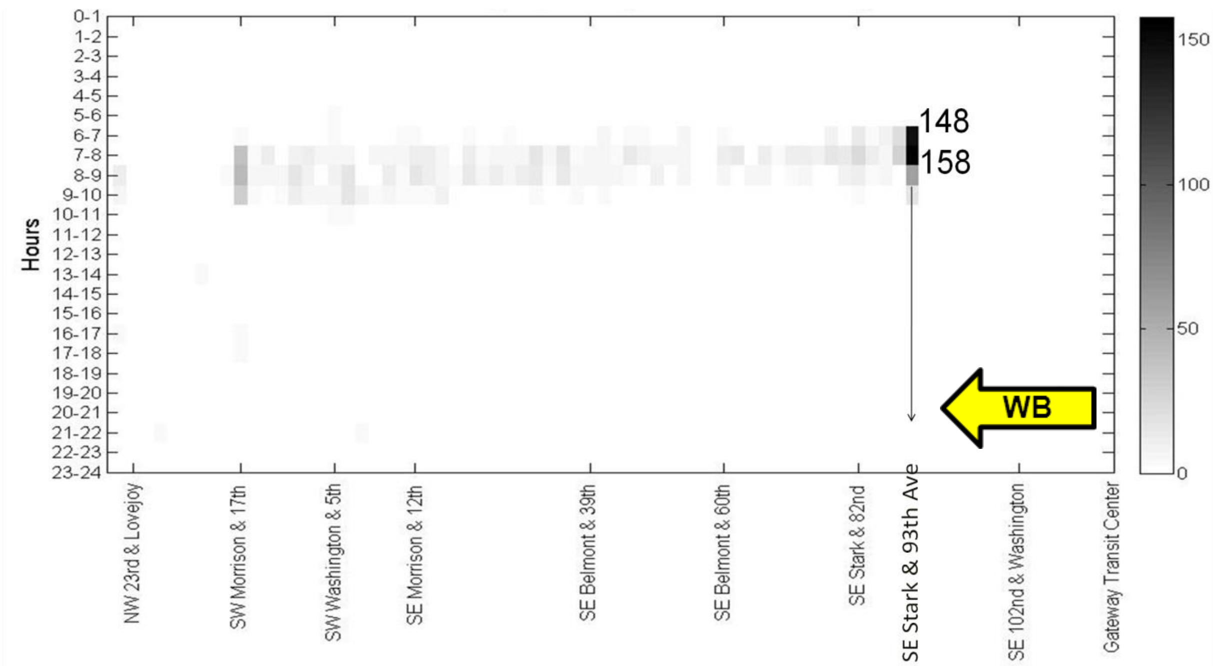

Figure 4. Bus bunching initial formations for route 15 westbound (headway threshold: < 3 minutes)

As shown in Figure 4, most of the bunching patterns start from the same stop “SE Stark & 93rd Ave” in the morning peak hours. The numbers 148 and 158 are the total counts during the 115 weekdays; therefore, on average, there is more than one bus bunching events start at this stop every weekday every hour between 6 am to 8 am. This stop is the first stop for the high frequency service segment along westbound, which means additional buses join in the westbound trip at this stop during the morning peak hour. There are basically two potential reasons for this. First, according to the current TriMet schedule-based operating strategy, even if a bus upstream of stop SE Stark & 93rd is late, buses that are scheduled to start service from this stop will still be on time. Second, bus operators may not start the trip on time if they arrived back late to the garage from an opposite trip because there are labor laws dictating rest time for bus operators.

3.2 Headway Delay and Actual Headway Spatial Distributions

The above section identifies the bus bunching event counts defined by departure headway at any stop using predefined thresholds. Large headway gap distributions and unusual headways are also necessary to analyze because they have significantly negative impacts on passenger waiting times. Therefore, we also provide another two outputs that show headway delay and actual headway distributions as shown in Figure 5 and Figure 6.

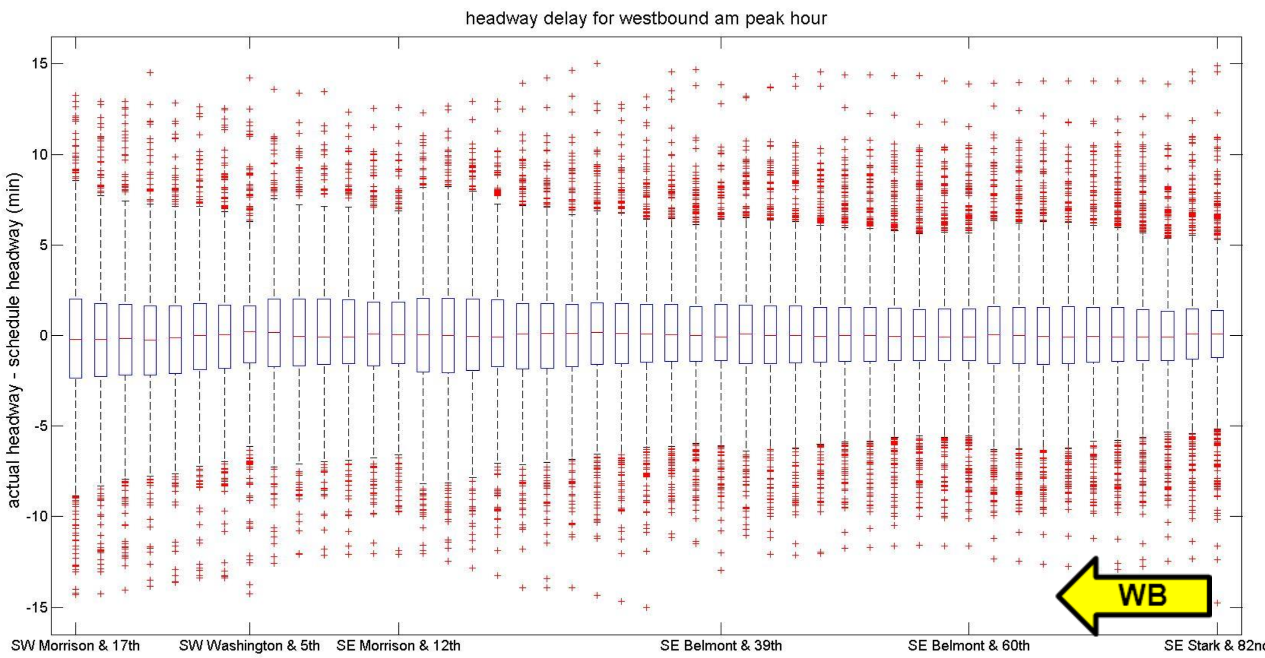

Figure 5. Headway delay spatial distribution for route 15 westbound a.m. peak hours

Figure 5 shows the headway delay (actual headway – schedule headway) distribution for all westbound stops in the high frequency service zone in a.m. peak hours; 50% of headway delays (blue box for each stop) are within 2 minutes for all westbound stops. The boundaries of headway delay records (dashed line outside the blue box at each stop) grow gradually towards east end from $\pm$ 5 minutes to $\pm$ 8 minutes, and decrease after each time point. This graph indicates that headway variability increases with travel distance while a time point stop helps maintain regular headways.

Figure 6 shows the proportions of actual headways in different bins for all westbound stops in the high frequency time and zone. Around 25% - 35% of the actual headways are within the scheduled headway boundary (5-7 minutes) for all stops except the stop at SE Stark & 82nd (40%). The proportion has a decreasing trend towards the east end with mild increase at each time point. This figure also shows the proportion change for all other levels of irregular headways, which have a general increasing trend towards the east end and a mild decrease at each time point.

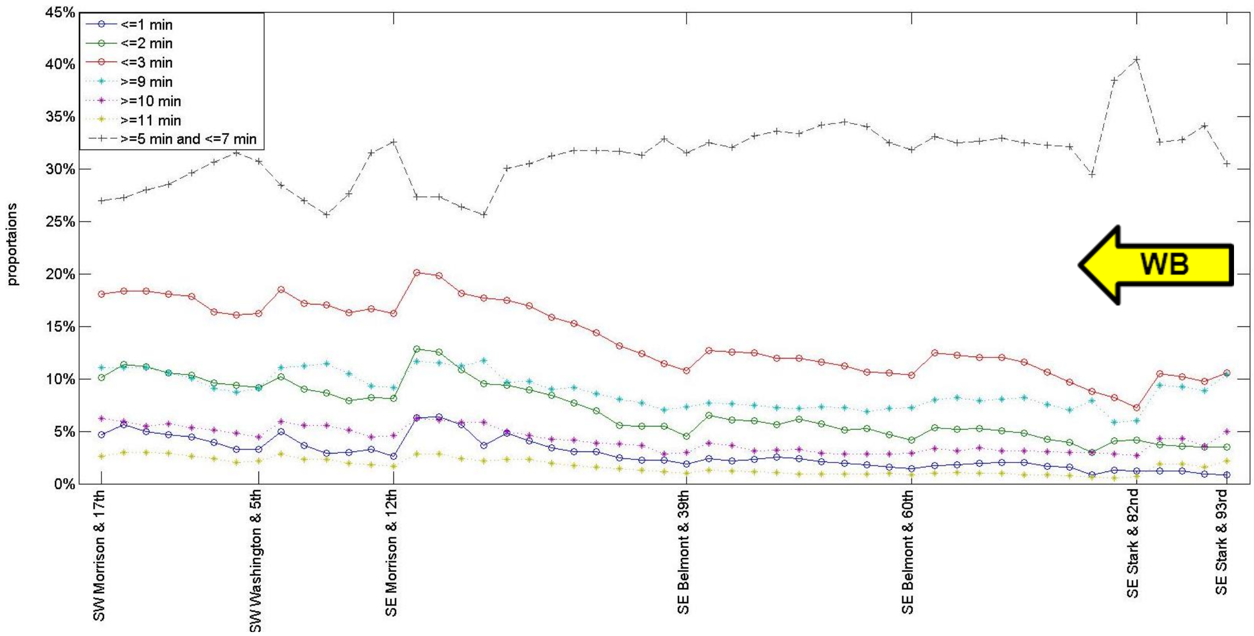

Figure 6. Actual headway proportions spatial distribution for route 15 westbound a.m. peak hours

3.3 Bus Bunching Formation and Dissipation

The above section shows the spatial and temporal distribution of bus bunching event defined by the departure headway at each stop; however, these bus bunching events are identified independently without knowing which trips they belong to. It is important to know where buses get bunched or separated along the bus route for each pair of bus trips. Therefore, we developed another method to identify bus bunching trips and where buses get bunched and separated for each pair of trips.

Figure 7 shows bus bunching trips formation and dissipation for route 15 westbound in the a.m. peak hours. In this figure, each horizontal line represents an identified bus bunching trip in which at least one stop has a departure headway that is smaller than bunching threshold (e.g. two minutes). In each horizontal line, blue dots represent bunching records at corresponding bus stops. If two consecutive bus stops in one pair of trips are identified bunching, blue lines connect them.

From Figure 7, we can visualize where bus bunching trips form and dissipate. It is obvious that most of the bus bunching trips start at the stop SE Stark & 93rd, because this stop is the start of the high frequency service segment. If any trip starting from the west terminal arrives at this stop late, while an additional short trip starts from this stop on time, there might be a bus bunching event. Similarly, most of the dissipation of bus bunching trips occur at the SW Morrison & 17th stop. The figure also shows how the bus bunching density increases to the west until the stop at SW Morrison & 17th.

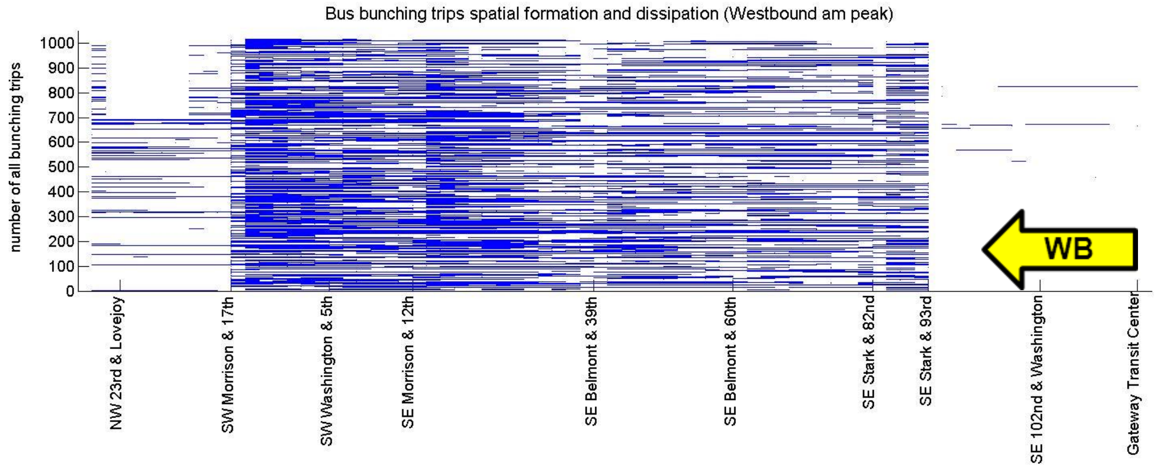

Figure 7. Bus bunching trips spatial formation and dissipation for route 15 westbound a.m. peak hours (headway threshold: < 2 minutes)

While Figure 7 shows the formation and dissipation of all bus bunching trips, it is also worth knowing where they first formed and finally dissipated. Figure 8 further shows the percentage of first formation and last dissipation of all bus bunching trips at each stop along the route, particular control strategies can be implemented at those stops. The blue bars represent the percentages of first formation, and red bars represent the percentages of last dissipation. Figure 8 shows that almost 15% of all the westbound a.m. peak bus bunching trips first formed at the stop SE Stark & 93rd, with all the other stops are less than 5%. On the other hand, almost 20% and 25% of all the bus bunching trips dissipated at SW Morrison & 17th and its downstream stop, totaling 45%. This observation also indicates that once a pair of buses get bunched, they are more likely to continue until the end of high frequency service zone. Therefore, a better headway-based control at this stop in the morning peak hours is highly recommended.

Figure 9 further shows the probabilities of downstream bus bunching trips at different departure headway bins at the stop SE Stark & 93rd for westbound a.m. peak hours, with three different headway threshold levels. For example, if bus bunching is defined as headway threshold < 1 minute, and departure headway at the trip beginning is in the 0-1 minute bin, the probability of a downstream bus bunching trip is 70% (blue line); if the departure headway at the beginning trip is in the 4-5 minutes bin, the probability of a downstream bus bunching trip is less than 10%. Similar interpretations apply for the green line (headway threshold < 2 minutes) and red line (headway threshold < 3 minutes). The general trends for all three lines are decreasing as the departure headway bins at the beginning trip increases, which indicates that the shorter headway at the starting trip, the higher probability of downstream bus bunching trips. Based on regression model results on the same route, Albright and Figliozzi *(5)* also found that initial stop headway significantly affect downstream stop headways.

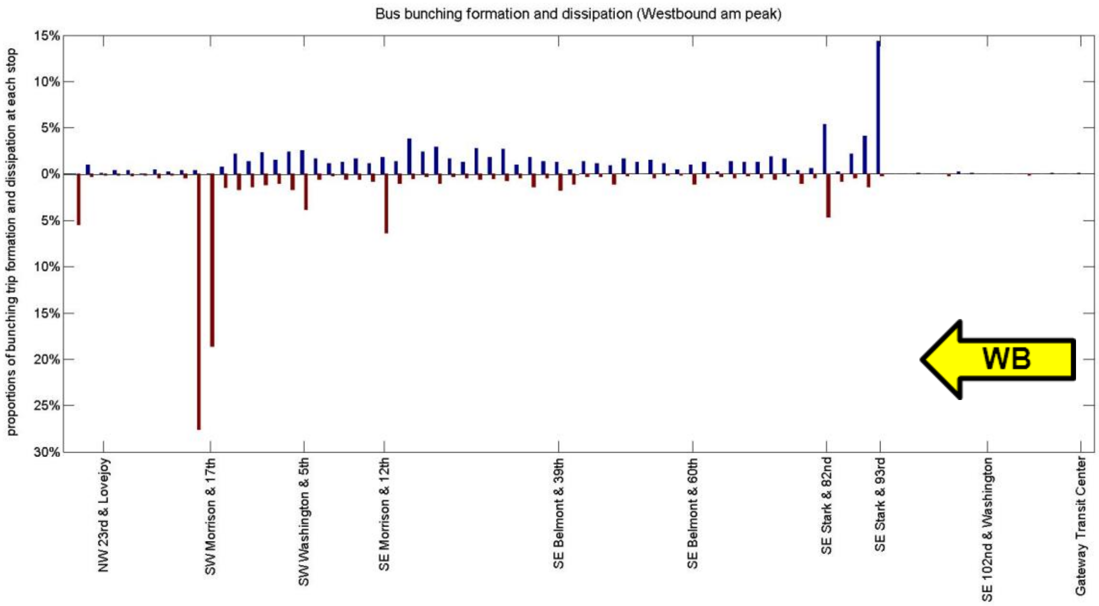

Figure 8. Bus bunching trips first formation and last dissipation spatial distribution for route 15 westbound a.m. peak hours (headway threshold: < 2 minutes)

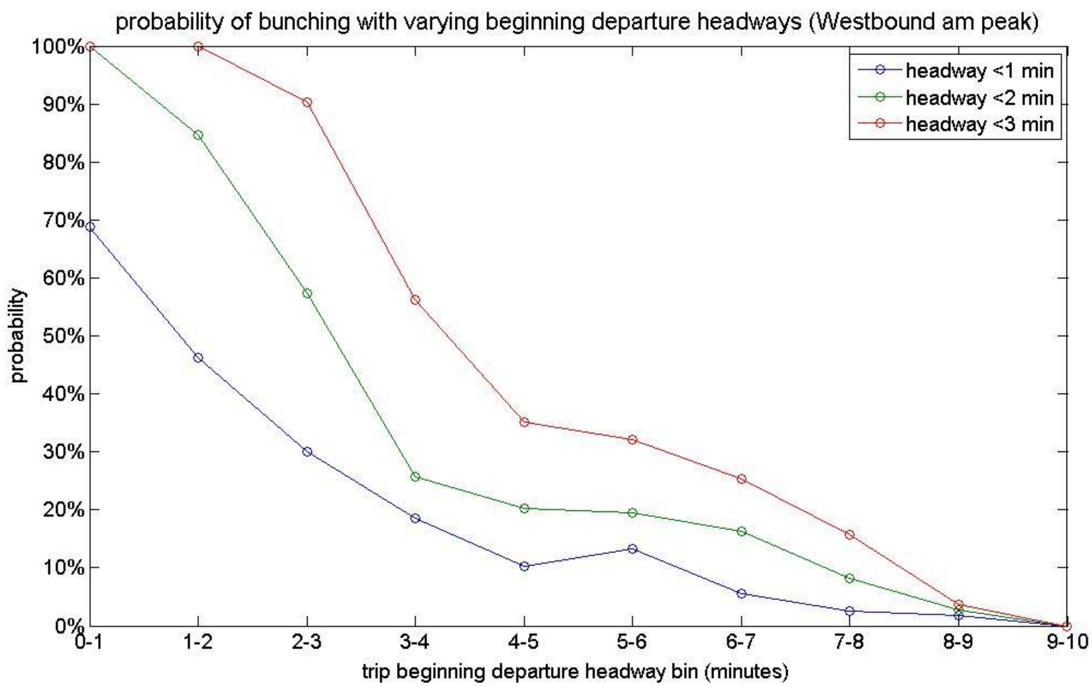

Figure 9. Probability of downstream bunching with varying trip beginning departure headways and headway thresholds for route 15 westbound am peak hours

3.4 Bus Bunching Effects

Bus bunching has several negative impacts from the aspect of passengers such as longer waiting times and overcrowding. In a pair of bunched buses, the leading bus is usually late and the following bus is usually earlier than its scheduled departure times. Therefore, passengers who wait for the leading bus may have to wait longer than a scheduled headway at any stop, while passengers who arrive at a stop after the leading bus departure and before the following bus arrival may have relatively short waiting times. However, the number of passengers who wait for the leading bus is usually more than those passengers wait for the following bus, and therefore may result in a weighted average waiting time for passengers that are involved in a pair of bunching trips longer than normal average waiting time. To evaluate if this is true, Figure 10 shows the average times for normal buses, leading buses, following buses, and weighted average waiting time for both leading and following buses in a pair of bunching trips. It shows that waiting time for leading bus is almost 1.5 minutes more than normal bus, and almost 4 minutes more than following bus in an environment where scheduled headway is between 5 and 7 minutes. Also, the weighted average waiting time for both leading and following buses in a bunching trip is about half minutes longer than the normal buses over all stops. If we assume the average penalty of passenger waiting time is $20/hr, 10% bus bunching trips at a stop, and passenger demand is 600 people per hour, the annual cost will be over $328,500 (0.5 minute * $20/hour * 600 people/hour * 10% * 3 hours * 30 stops * 365 days) only for stops in the westbound a.m. peak hours, not to mention the p.m. peak hours, the opposite direction and other bus routes.

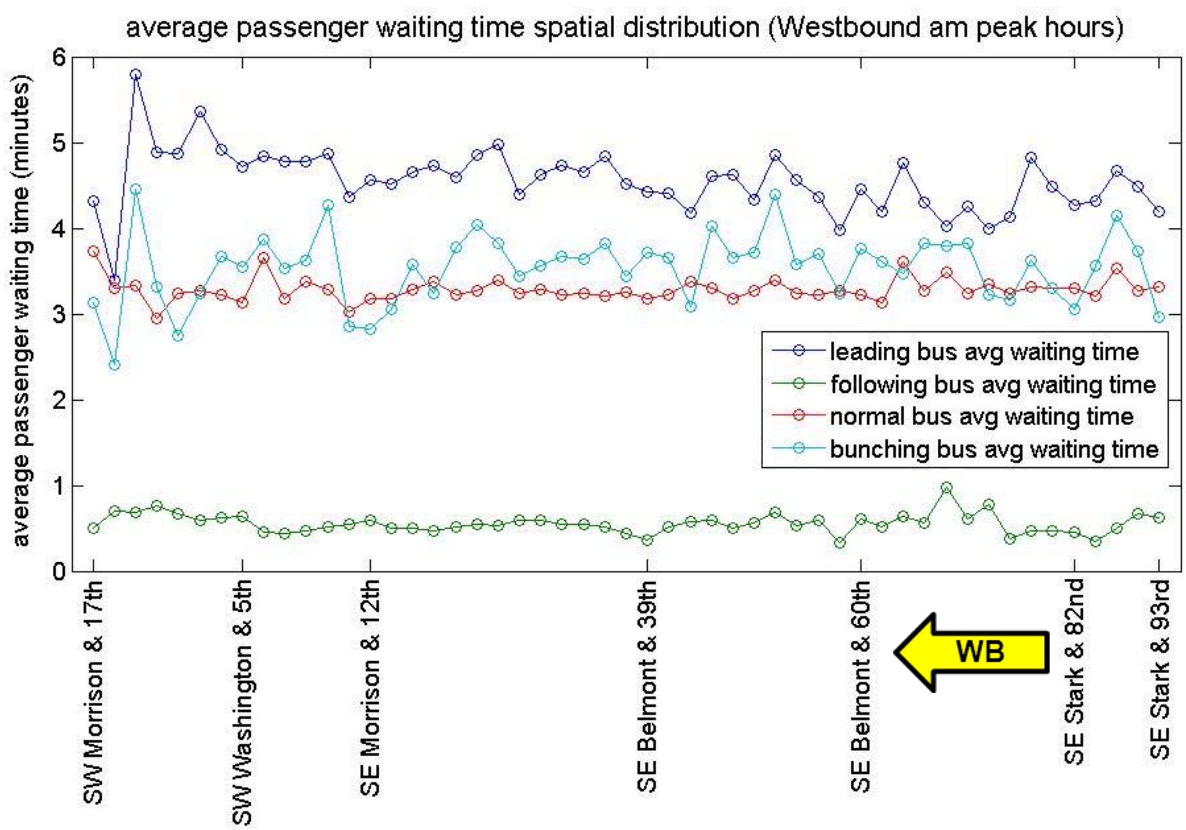

Figure 10. Average passenger waiting time spatial distribution for route 15 westbound am peak hours (headway threshold: < 2 minutes)

Figure 11 shows that, between the stops at SE Start & 82nd Ave. and SW Washington & 5th Ave., the average passenger load on a leading bus is almost 10 people more than the load on a normal bus and 20 people more than the load on a following bus. However, the weighted average load for a pair of bunching buses is the same as the passenger load for a normal bus. For all other bus stops, the difference is not significant due to low passenger demand. Although the average load on a normal bus is almost the same as the weighted average load on a pair of bunching buses, it still indicates overcrowding in the leading bus and low occupancy in the following bus, which results in a loss of attractiveness to passengers and reduction in bus utilization efficiency.

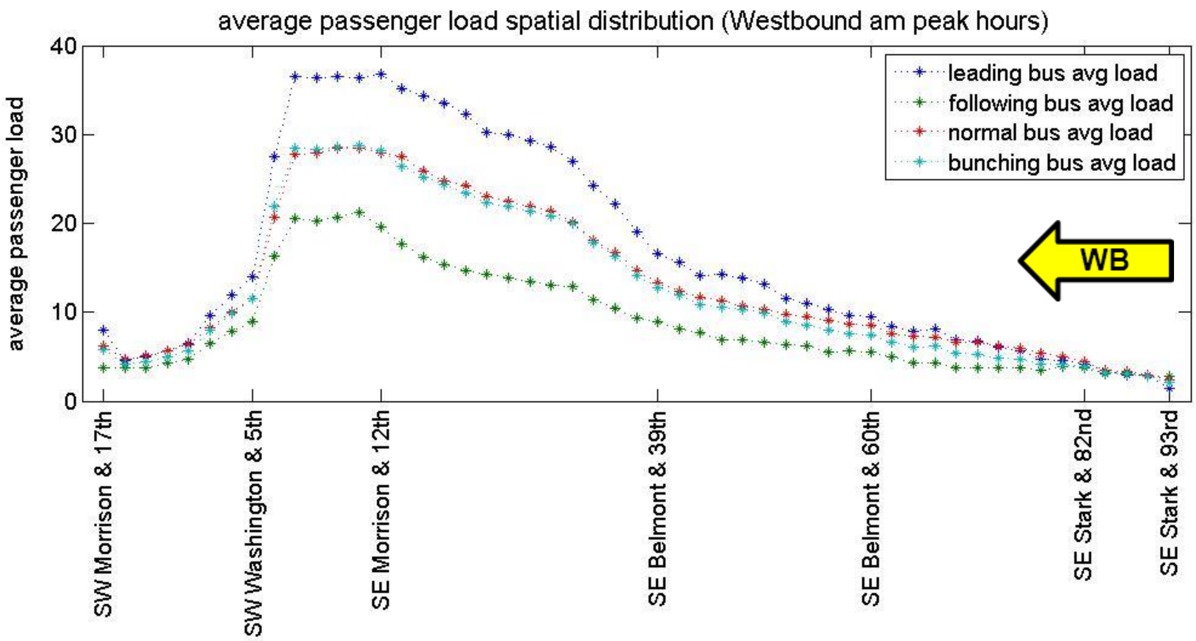

Figure 11. Average passenger load spatial distribution for route 15 westbound am peak hours (headway threshold: < 2 minutes)

4 CONCLUSION

This study developed algorithms to help transit agencies identify recurrent bus bunching incidents distribution and understand the causes and effects of bus bunching trips based on archived AVL/APC data. The results have demonstrated how bus bunching incidents can be summarized for different temporal and spatial aggregation levels. The thresholds (defined in our study as the headway between two consecutive bus departures at a bus stop) for identifying bus bunching are flexible and can be modified as needed by transit agencies. Results indicate that bus bunching usually takes place in the high frequency service time and segments, mainly because the schedule headway is too short. Bus bunching trips usually start at the first stop of high frequency service zone, where additional short trips are added to trips that pass along the stop. Once buses get bunched at the beginning of high frequency zone, they are likely to remain bunched the rest of the trip until the end of high frequency service zone.

Schedule-based control at downstream time point stops can help regulate headways. The weighted average passenger waiting time due to bus bunching is 0.5 minutes longer than the average passenger waiting time for unbunched bus trips. Therefore, headway control at beginning stops of high frequency service zone is highly recommended. The algorithms utilized in this study are easily transferable to other bus routes and transit agencies.

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REFERENCES

1. Bertini, R., and A. El-Geneidy. Generating Transit Performance Measures with Archived Data. *Transportation Research Record*, Vol. 1841, 2003, pp. 109–119.
2. Mathew Berkow, A. M. E.-G. Beyond Generating Transit Performance Measures: Visualizations and Statistical Analysis with Historical Data. *Transportation Research Record: Journal of the Transportation Research Board*, pp. 158–168.
3. Kimpel, T. J., J. G. Strathman, and S. Callas. Improving Scheduling Through Performance Monitoring. In *Computer-aided Systems in Public Transport*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 253–280.
4. Strathman, J. G., T. J. Kimpel, K. J. Dueker, R. L. Gerhart, and S. Callas. Evaluation of Transit Operations: Data Applications of Tri-Met's Automated Bus Dispatching System. *Transportation*, Vol. 29, 2002, pp. 321–345.
5. Albright, E., and M. Figliozzi. Analysis of the impacts of transit signal priority on bus bunching and performance. Santiago, Chile, 2012.
6. Hammerle, M., M. Haynes, and S. McNeil. Use of Automatic Vehicle Location and Passenger Count Data to Evaluate Bus Operations: Experience of the Chicago Transit Authority, Illinois. *World Transit Research*, Jan. 2005.
7. Mandelzys, M., and B. Hellinga. Identifying Causes of Performance Issues in Bus Schedule Adherence with Automatic Vehicle Location and Passenger Count Data. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2143, No. -1, Dec. 2010, pp. 9–15.
8. Daganzo, C. F. A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons. *Transportation Research Part B: Methodological*, Vol. 43, No. 10, Dec. 2009, pp. 913–921.
9. Daganzo, C. F., and J. Pilachowski. Reducing bunching with bus-to-bus cooperation. *Transportation Research Part B: Methodological*, Vol. 45, No. 1, Jan. 2011, pp. 267–277.
10. Xuan, Y., J. Argote, and C. F. Daganzo. Dynamic bus holding strategies for schedule reliability: Optimal linear control and performance analysis. *Transportation Research Part B: Methodological*, Vol. 45, No. 10, Dec. 2011, pp. 1831–1845.