Developing a bus service reliability evaluation and visualization framework using archived AVL/APC data

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ABSTRACT

Transit service reliability is important for both transit agencies and passengers. Transit agencies are interested in ways of measuring and evaluating their service quality, identifying reliability problems, understanding causes and effects of unreliable services, and proposing strategies to improve overall service quality. However, the vast amount of automatic vehicle location (AVL) and automatic passenger counter (APC) data have not been fully utilized in many transit agencies. Therefore, the objective of this study is to develop a framework that can translate massive AVL and APC data into valuable reliability measures that can help transit agencies to evaluate and visualize their service quality and identify reliability problems in the route level. Both aggregated performance measures and detailed operational records are calculated and visualized based on the archived AVL and APC data. Aggregated performance measures are useful in identifying recurrent reliability problems and evaluating performance, such as schedule deviation, headway variation, and bus bunching incidents; while detailed operational records are helpful to understand specific problems, examples include time-space diagram and animation of bus movements. Results show the proposed examples can help identify reliability problems.

INTRODUCTION

A reliable transit service system is important for both transit agencies and passengers. Buses are expected to run according to some pre-determined schedules. However, in a stochastic environment, uncertain travel times and passenger demand preclude schedule adherence and headway uniformity. Unreliable transit service not only affects passengers' level of service (increased waiting time and in-vehicle travel time, overcrowding, etc.) but also reduces efficiency and productivity of transit agencies. Low service quality makes transit unattractive to users compared to private transportation.

The ability to accurately and effectively analyze service reliability is fundamental for a transit agency to determine how well it is adhering to its service standards. A number of low-cost surveillance, monitoring and management systems as part of Intelligent Transportation Systems (ITS) programs now exist, enabling transit agencies to collect advanced operational data for testing and analyzing operating efficiency and service reliability (Furth 2000; Furth et al., 2006; Bertini and El-Geneidy, 2003; Berkow et al., 2007). Although the availability of such rich archived AVL and APC data make it possible for transit agencies to generate valuable transit performance measures, a large amount of useful information is underutilized due to the sheer volume of information available. This vast amount of data impel the need to explore and employ visualization techniques as a way to comprehensively convey the key. Kimpel (2006) addresses the potential of overall data visualization for enhancing exploratory analysis, pattern identification and hypothesis development. He explores methods of reporting enhancements such as traffic lighting to enhance tabular output or the inclusion of hyperlinks in reports. Other transit data visualization examples offered by Kimpel (2006) include general mapping of quantity information, linear referencing, time-distance diagrams and 3-D visualization. Berkow et al. (2009) investigated the power of data visualization to understand the capacity for Bus Dispatching Systems (BDS) data. However, most of the visualization tools are examples for illustration. They do not support an interactive interface with users (users may want to evaluate performance with different time periods or time of day). Liao and Liu (2010) developed a data processing framework that provides a user interactive interface to select any time point-level or route-level performance measures that can be directly read or computed from the dataset (one month sample). Feng et al. (2011) developed a web-based interface that can convert historical bus operational data into a dynamic visualization framework, where the users can choose any date and time of day over a six-month period.

Therefore, the objective of this study is to develop a bus service evaluation and visualization framework that can translate the vast amount of AVL and APC data into valuable and visual performance measures, and allow users to select different routes, time periods, or time of day, so as to help transit agencies evaluate how well it is adhering to their service standards and identify potential problems. The focus of this paper is to introduce service reliability evaluation measures and visualization techniques for high frequency service (where headways are less than 10 minutes) at the route level. Both aggregated performance measures and detailed operational records are calculated and visualized based on the archived AVL and APC data. Aggregated performance measures are useful in identifying recurrent reliability problems and evaluating system performance, such as schedule deviation, headway variation, and bus bunching incidents at each stop along the route. Detailed operational records are helpful to understand specific problems, including time-space diagrams and animations of bus movements.

ROUTE CONFIGURATION

This study utilizes TriMet's Route 15 for illustration, which experiences difficulties in terms of schedule adherence and headway regularity. Route 15 runs east-west, crossing downtown Portland; with the east terminal station 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 key stop names for both westbound and eastbound services.

Time points (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 points along the route. For the majority of the day, Route 15 provides low frequency service, where headways between buses are approximately 15 minutes. However, in the morning peak hours, westbound passenger demand is much higher than during other times of the day due to morning commute to work in downtown Portland. Therefore, additional short trips are added to the route in the morning 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 segment to 5-7 minutes, which is called high frequency service. Similar additional short trips are added to the eastbound travel direction during the afternoon peak hours due to evening commute 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, 6:30 – 10:00 am for westbound and 4:00 – 6:30 pm for eastbound. The time points that are within the high frequency zone of the route are indicated in bold typeface in Table 1.

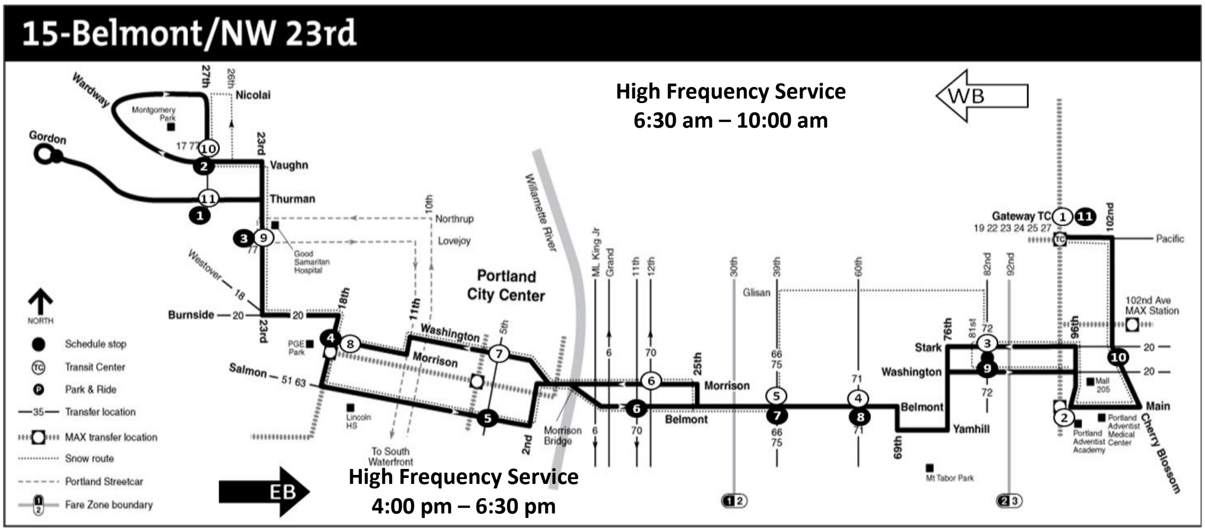

Figure 1. Route 15 Schematic

Table 1. Route 15 Time points

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

DATA DESCRIPTION

TriMet has employed the Bus Dispatching Systems (BDS) as part of its overall operation and monitoring control system. Strathman et al. (2001) described the usage of automated BDS data based on GPS-based AVL-APC technology, dead reckoning sensors, and voice and data communication within a mobile radio system. In addition to the above mentioned technologies, each TriMet bus has an on-board computer and a control head displaying schedule adherence to drivers, detection and reporting of schedule and route deviations to dispatchers, and two-way, pre-programmed messaging between drivers and dispatchers. The BDS implemented by TriMet collects and archives stop-level data as part of its overall service control and management system. A sample of the archived stop-event data for Route 15 is shown in Table 2.

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 from that 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. Also, the "stop_time" for time points along the route is the real scheduled departure time, for all other stops, this "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 smaller than the actual departure time minus actual arrival time. All the other information shown in Table 2 is self-explanatory. Note that there are additional columns in the stop event data which are not shown in this sample, these include route number, direction, x-y coordinates, etc. The evaluated data period ranges from 14 September 2009 to 26 February 2010, including all weekdays (totaling 115 days).

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
…	…	…	…	…	…	…	…	…	…	…	…	…

DETAILED BUS OPERATIONAL RECORDS

This section focuses on visualization of the most detailed operational records of all buses along a selected route, and therefore it is usually appropriate to show only a specific time of day on a specific day, according to user's input. Two visualization tools are developed in this section: static visualization (time-space diagram) and dynamic visualization (a Google map-based application).

Static Visualization

Time-space diagrams are a very useful tool to visualize a large amount of tabular data in one figure. It is helpful in identifying bus operations and scheduling problems and evaluating the effectiveness of management interventions (Liao and Liu, 2010; Hranac et al., 2011). However, this tool is mainly used by researchers for analyzing particular problems, such as for a specific time of day. It will be convenient for users (such as transit agencies) if a data processing framework is developed, where theroute, travel direction, date and time period (as long as it is within the archived database) can be selected and a time-space diagram would pop up showing the scheduled and actual trajectories of all buses running along that route and direction during that time period.

The theory of plotting time-space diagrams is the same universally, but due to the difference in archived database among transit agencies, data processing frameworks for plotting such diagrams are usually agency-specific.

An example is shown below in Figure 2, where the user selected the date Sep 16th, 2009, westbound travel direction in the morning peak hours between 6:30 and 9:30 am. The time-space diagram will show up and the title will update automatically, where the x-axis represents time, and the y-axis shows time point names and distances to terminal. The solid lines represent actual travel trajectories and dashed lines represent scheduled travel trajectories, and the trips are separated by colors. Trip numbers and relative colors are shown to the right in the legend. It is very easy to identify bus bunching trips from this diagram.

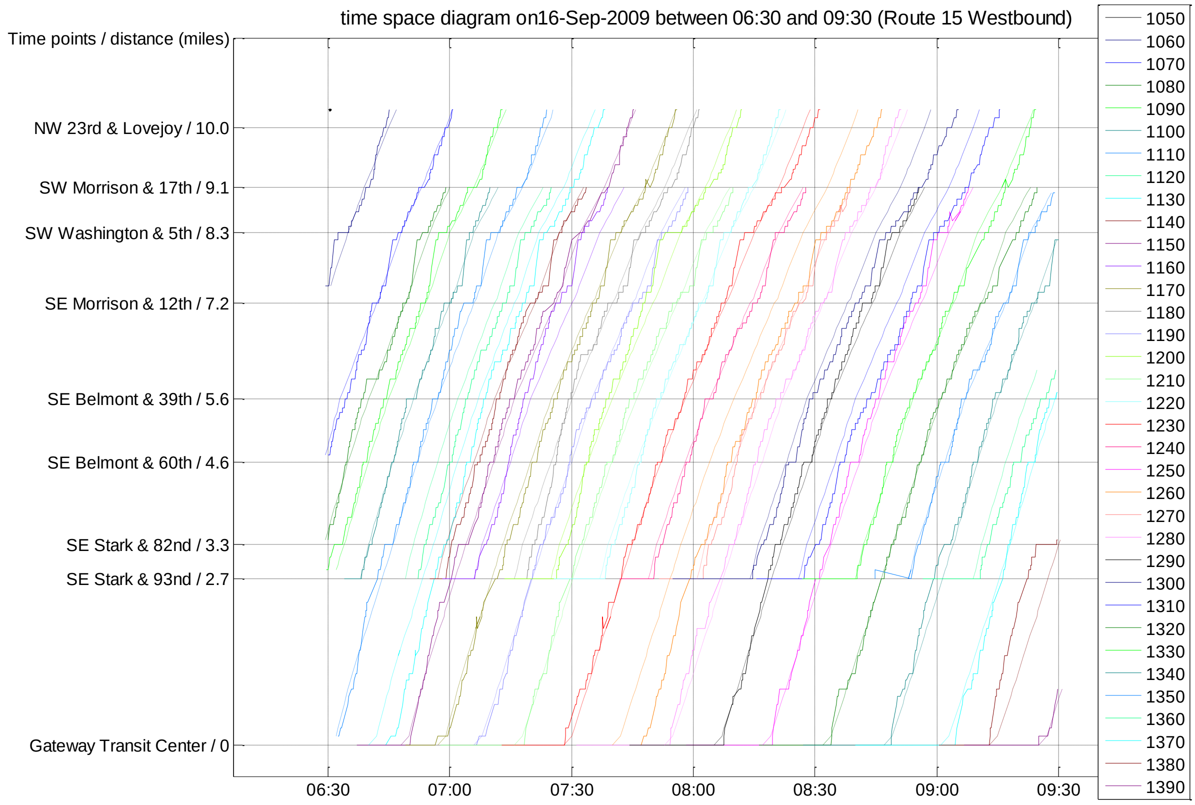

Figure 2. Time-space diagram example

Although the time-space diagram can show movements of all buses along a route in one direction for a certain time of day, detailed information for each bus is not displayed. For example, how do the two buses get bunched? What are their schedule adherence and departure headways at each stop? What was the passenger demand at the time? To help transit agencies to examine more detailed information for particular buses during a certain time, an interactive dynamic visualization tool is developed.

Dynamic Visualization

One of the issues with static analysis of historical data is the difficulty to understand some of the finer details of what is happening within the system. That is, it tends to provide a macro-level view of the system. Therefore, we argue that both macro-level as well as more detailed micro-level information are necessary components to understand such complex systems. However, the overwhelming amount of micro-level data for such large-scale systems can lead to looking at irrelevant data. The ability to dynamically visualize how buses in a route move spatially and temporally is extremely useful for understanding transit operations performance, particularly to better understand how the impacts of decreased on-time performance and increased headway deviations propagate spatially and temporally and result in effects such as bus bunching. Therefore we propose a time-varying display of the archived data.

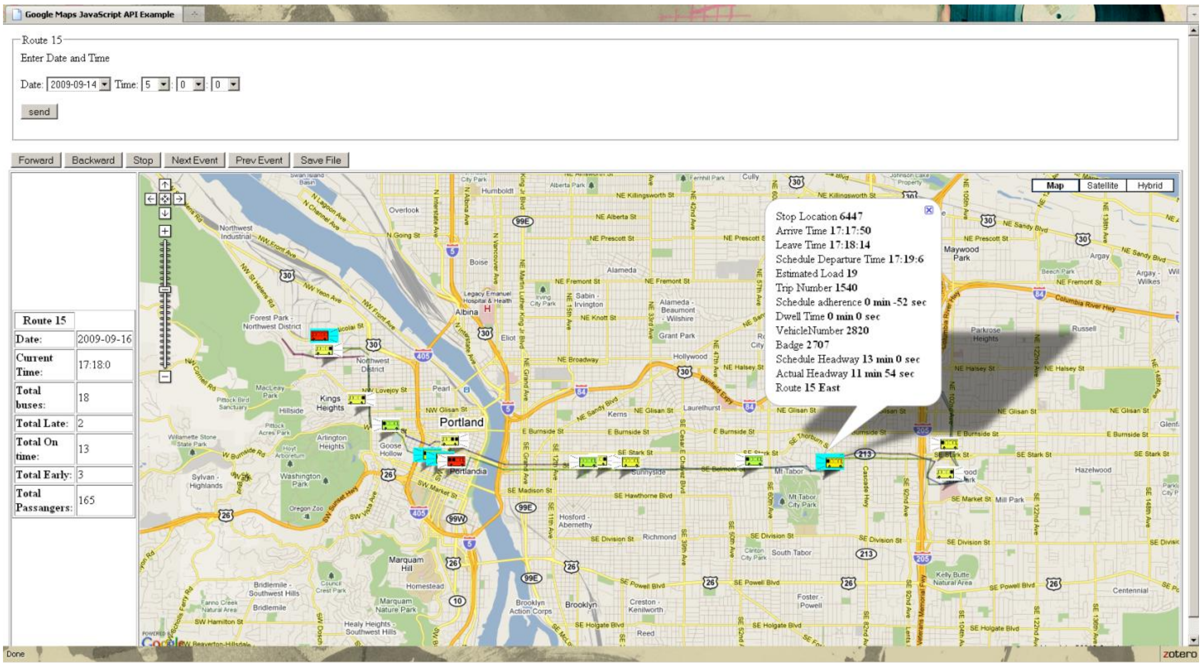

Figure 3. Dynamic visualization framework interface snapshot for TriMet Route 15

Table 3. Descriptions of Map Features

Route Map	Direction Indicator	Estimated Passenger Loads	Bus Stop Service Indicator	On-Time Performance Indicator
• Purple = Westbound • Green = Eastbound	• Distinguished by rear emission • Opposite of emission direction • Also indicated in pop-up window	• Shown using window icons • Number of black windows represent estimated passenger load: 1. ≤ 25% 2. 25% - 50% 3. 50% - 75% 4. >75% • Bus capacity = 60	• Depicted by background color of bus icon • Blue = bus serving stop • White = bus running between stops	• Shown by colors of bus icons • Red = Late; schedule adherence > 5 minutes • Green = Early schedule adherence < -1 minute • Yellow = On time; -1 minute < schedule adherence < 5 minutes

Figure 3 provides a snapshot of the framework showing all of the buses that are running along the route at this time. On the upper left corner the user selects which day and time period to use for the visualization. The "play" function provides both "forward" and “backward” moving options for users to observe how bus bunching propagates over time and space. The time period to “play” can either be a fixed time interval (which should be larger than the load time – five seconds in this case) or by an event-based moving interval; i.e., whenever there is a bus arrival or departure activity, reload the map. Double clicking the “Forward” or “Backward” button can speed up the animation speed. The information displayed in the pop-up window is pulled directly from the database or by using basic math functions. Table 3 provides further details of additional map features. For more detailed information about this dynamic visualization framework, refer to Feng et al. (2011).

Currently, the dynamic visualization is based on archived historical data, and some of the performance measures need records that are later than the current time. Therefore, it cannot be directly implemented into the real-time bus monitoring system. Most of the information uses previous time records. Therefore if new data communication technology can be implemented in TriMet, real-time bus monitoring system with some real-time operational performance measures can be developed easily based on the work here, and it will help dispatchers to make real-time decisions when there is minor disruptions, so that major disruptions can be avoided as early as possible.

A preliminary version of the dynamic visualization tool is available for use and exploration at the following web address: http://web.cecs.pdx.edu/~zaral/portals/trimetportalgraph.php for route 15, and http://web.cecs.pdx.edu/~eea/trimetViz/tspviz.php for route 9 and route 66.

AGGREGATED RELIABILITY EVALUATION

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 delay. 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, uneven passenger distribution, overcrowding in late buses, and an overall decrease in level of service and capacity. When bus bunching occurs frequently, schedule adjustments may be necessary. Hence, it is crucial for transit agencies to monitor headways and detect bus bunching during high frequency service. This is especially important if there are recurrent bus bunching problems during certain times of day and/or in a certain segment of the route, where there might be a scheduling problem rather than an operational problem. This section focuses on high frequency service reliability, therefore, headway regularity and bus bunching are computed directly from the archived data and shown graphically.

Headway distribution

In this reliability evaluation framework, two performance measures are proposed to represent headway regularity in the route level: headway deviation and actual headway distribution. They are directly computed from the archived data.

Figure 4 shows the spatial distribution of headway delay (actual headway – schedule headway) for all westbound stops in the high frequency service segment in the morning peak hours. Half of the 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) grows gradually towards the east end from $\pm$ 5 minutes to $\pm$ 8 minutes, and decreases after each time point. This indicates that the longer distance has a higher probability of large headway delays, and that time points help maintain regular headways.

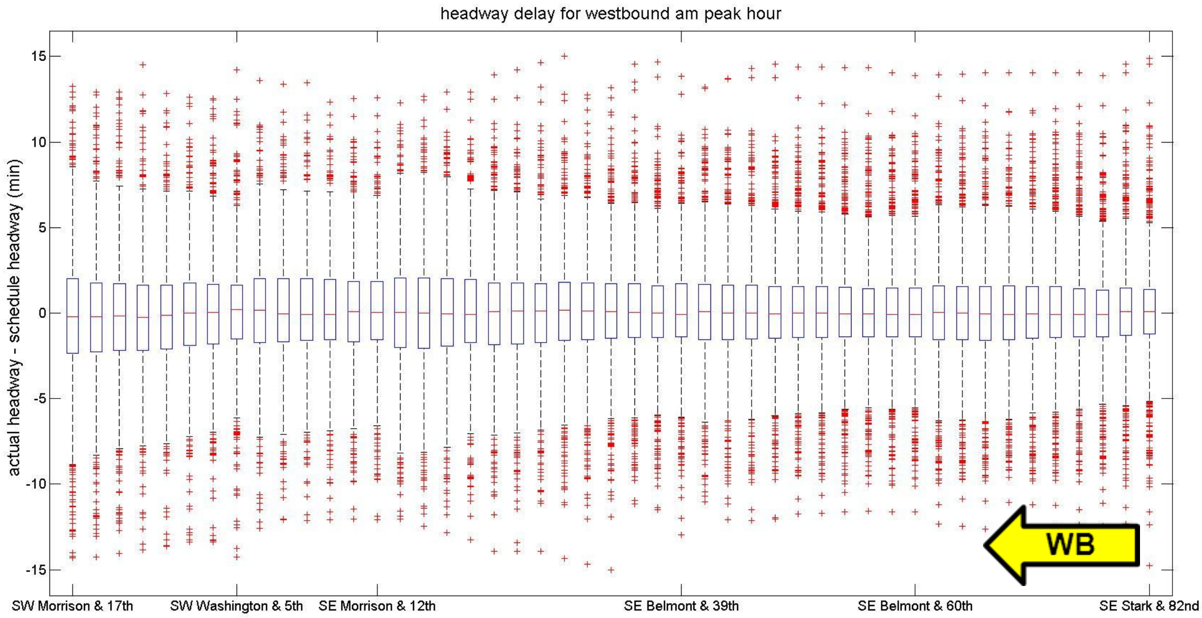

Figure 4. Headway delay spatial distribution for route 15 westbound am peak hours

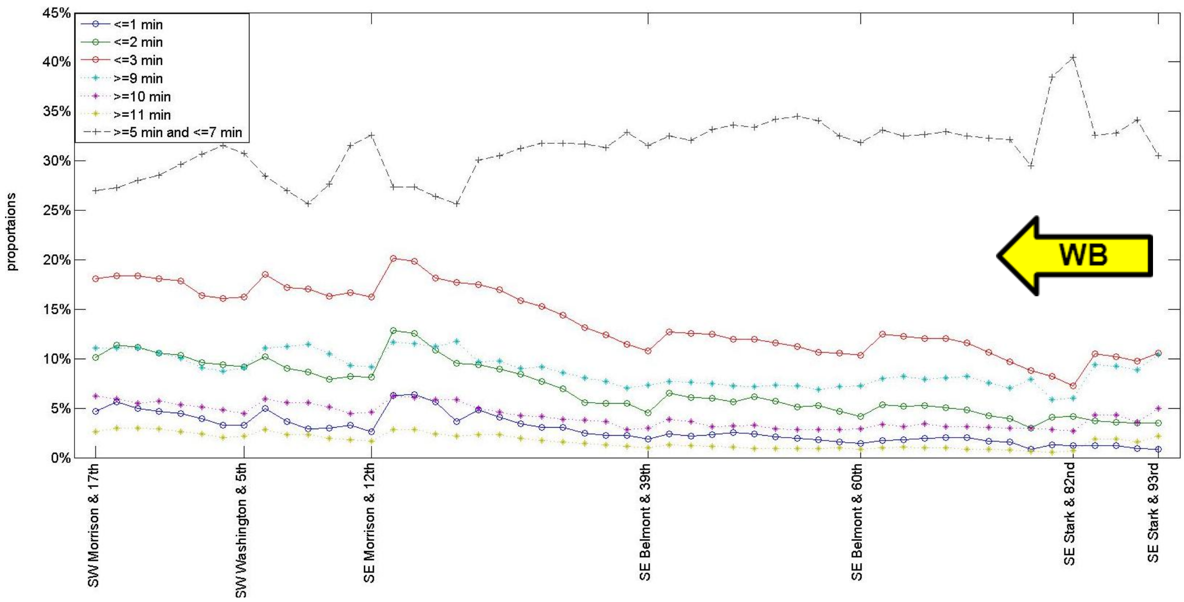

Figure 5. Actual headway spatial distribution for Route 15 Westbound AM peak hours

Figure 5 shows the proportions of actual headways in different bins for all westbound stops in the high frequency time and segment. 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%), this proportion has a decreasing trend towards the east end with a 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 mild decrease at each time point. These regular and irregular headway bins can be adjusted by the user.

Both Figure 4 and Figure 5 show a low performance of headway regularity for Route 15 westbound in morning peak hours.

Bus bunching formation and dissipation

In high frequency service, since scheduled headways between buses are short and passenger demand is relatively high, buses become bunched more easily due to a smaller buffer time in the schedule. Bus bunching is associated with longer waiting times for some riders, uneven passenger distribution, overcrowding in late buses, and an overall decrease on level of service and capacity. Therefore, it is important for transit agencies to understand the characteristics of bus bunching, so as to propose corrective strategies. With the availability of archived bus operations data, this subsection shows techniques that transfer massive operational records into bus bunching trips with spatial formations and dissipations. Additionally, this subsection evaluates the impacts of bus bunching on passenger waiting times and on board passengers.

Figure 6 shows the results of the formation and dissipation for all bus bunching trips over the 115 weekdays for Route 15 westbound in the morning 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 a user defined bus bunching threshold (e.g. headway < 2 minutes). In each horizontal line, blue dots represent bunching records at corresponding stops, if consecutive stops are identified as bunching, a blue line connects them.

From Figure 6, we can visualize where bus bunching trips form and dissipate most frequently. It is very obvious that most of the bus bunching trips start at the stop located at SE Stark & 93rd, because this stop is the starting point of the high frequency service segment. At this location additional short trips are added to the entire bus trips. If any trip that starts from the west terminal arrives at this stop (SE Stark & 93rd) late, and meanwhile a short trip that starts from this stop on time, there might be a bus bunching at this stop. Similarly, most of the dissipation of bus bunching trips happen at the stop located at SW Morrison & 17th, which is the end point of high frequency service segment. One can also visualize that the bus bunching density increases to the west until the stop at SW Morrison & 17th.

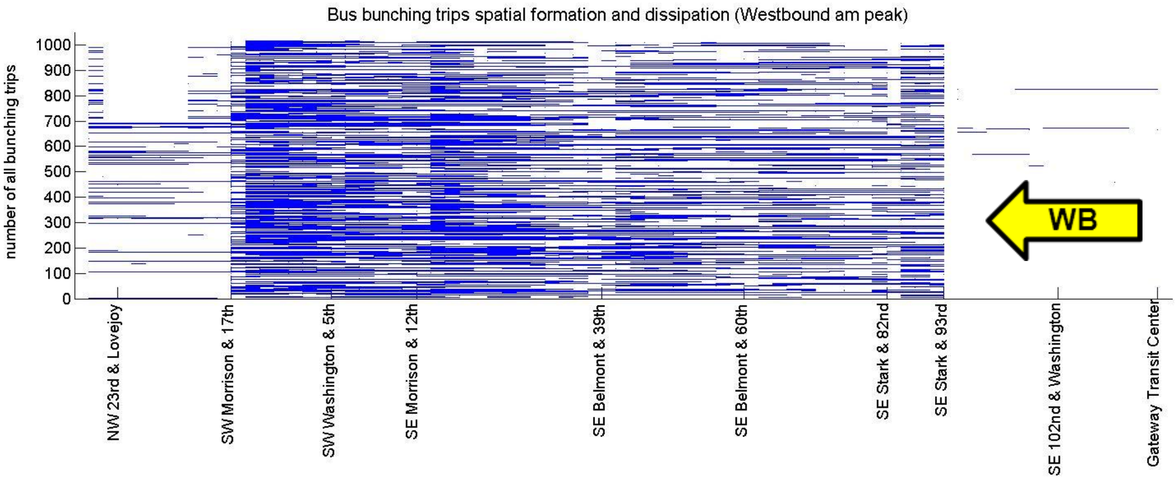

Figure 6. Bus bunching trips spatial formation and dissipation for route 15 westbound am peak hours (bus bunching threshold: headway < 2 minutes)

While Figure 6 shows the formation and dissipation of all bus bunching trips, it is also worth knowing where they first formed and where they finally dissipated. Figure 7 further shows the percentage of first formation and last dissipation of all bus bunching trips at each stop along the route, so that particular control strategies can be implemented to those stops. The blue bars represent the percentages of formation, and red bars represent the percentages of dissipation. Figure 7 shows that almost 15% of all the westbound AM 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 finally dissipated at the stop SW Morrison & 17th and its downstream stop, totaling 45%. This observation also indicates that once a pair of buses get bunched, it is most likely that they will remain bunched until the end of the high frequency service segment. Therefore, headway-based operational control at the starting stop of high frequency service segments in the morning peak hours is highly recommended.

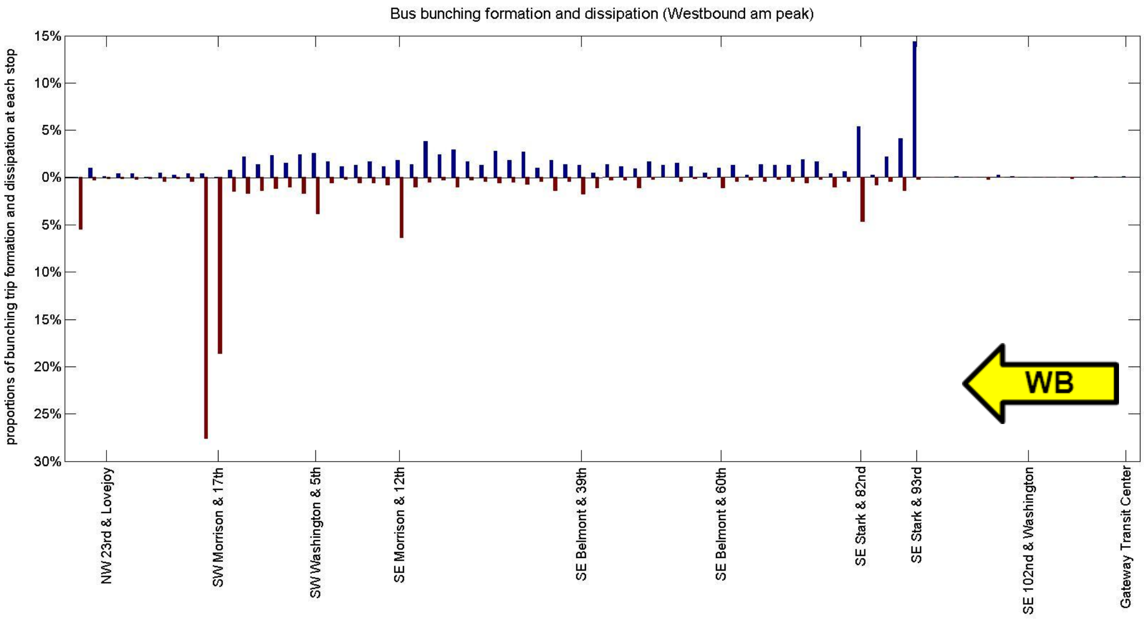

Figure 7. Bus bunching trips first formation and last dissipation spatial distribution for route 15 westbound am peak hours (bus bunching threshold: headway < 2 minutes)

Bus bunching impacts

Bus bunching has several negative impacts that are of great concern for passengers, including 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 the 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 a very short waiting time. However, the number of passengers who wait for the leading bus is usually more than the passengers who wait for the following bus. This may result in a weighted average waiting time for passengers that are involved in a pair of bunching trips longer than normal average passenger waiting time. To evaluate if this is true, Figure 8 shows the average waiting 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 the leading bus is almost 1.5 minutes more than the normal bus, and almost 4 minutes more than the following bus in an environment where scheduled headways are between 5 and 7 minutes. Also, the weighted average waiting time for both leading and following buses in a bunching trip is about half a minute more than normal buses on average over all stops. The impact may not seem large, but assume that the average penalty for passenger waiting time is $20/hr, 10% of the trips are bunched, and passenger demand is 500 people per hour, then the annual cost will be over $3,000 only for this route, this direction during the morning peak hours. This example of the impact of bus bunching doesnotinclude the afternoon peak hours,other routes, and potential ridership decreases, which would all make the impact even greater than it already is.

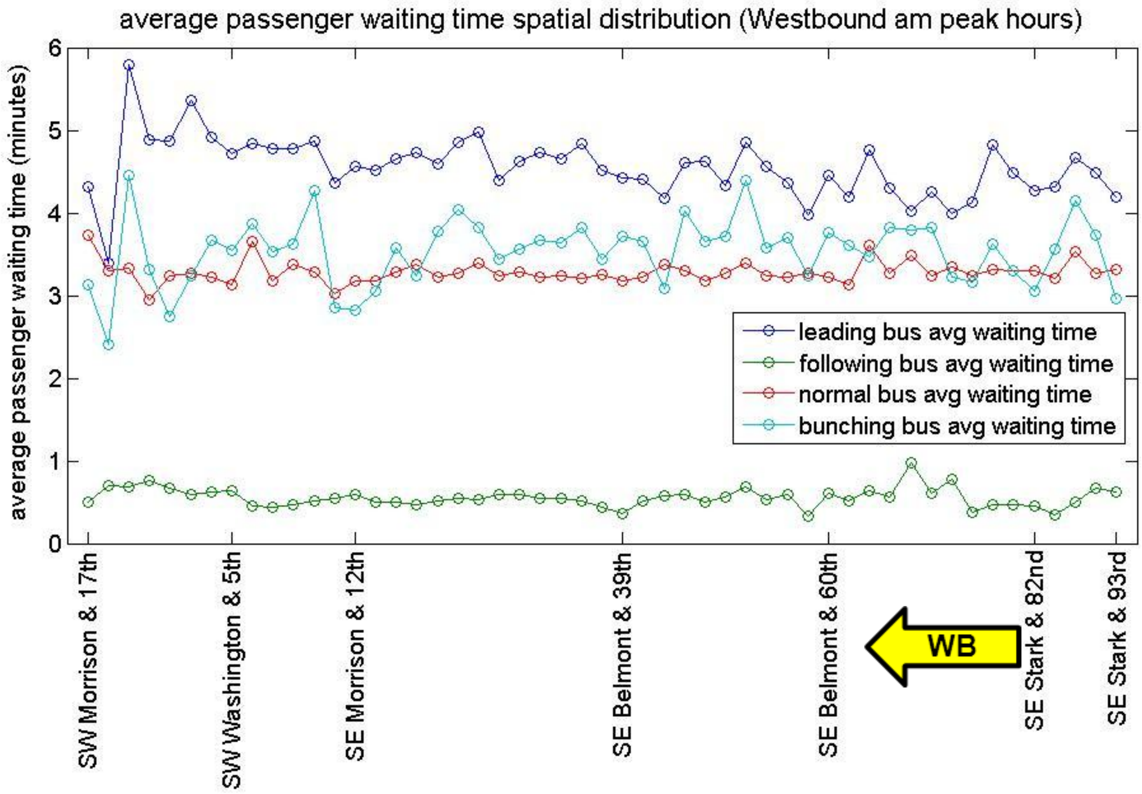

Figure 8. Average passenger waiting time spatial distribution for route 15 westbound am peak hours (bus bunching threshold: headway < 2 minutes)

Figure 9 shows that the average passenger load on a leading bus is almost ten passengers more than that on a normal bus, or weighted average of all bunching buses, and 20 more than that on a following bus, between the stops at SE Belmont & 39th and SW Washington & 5th. For all other 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 that an 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.

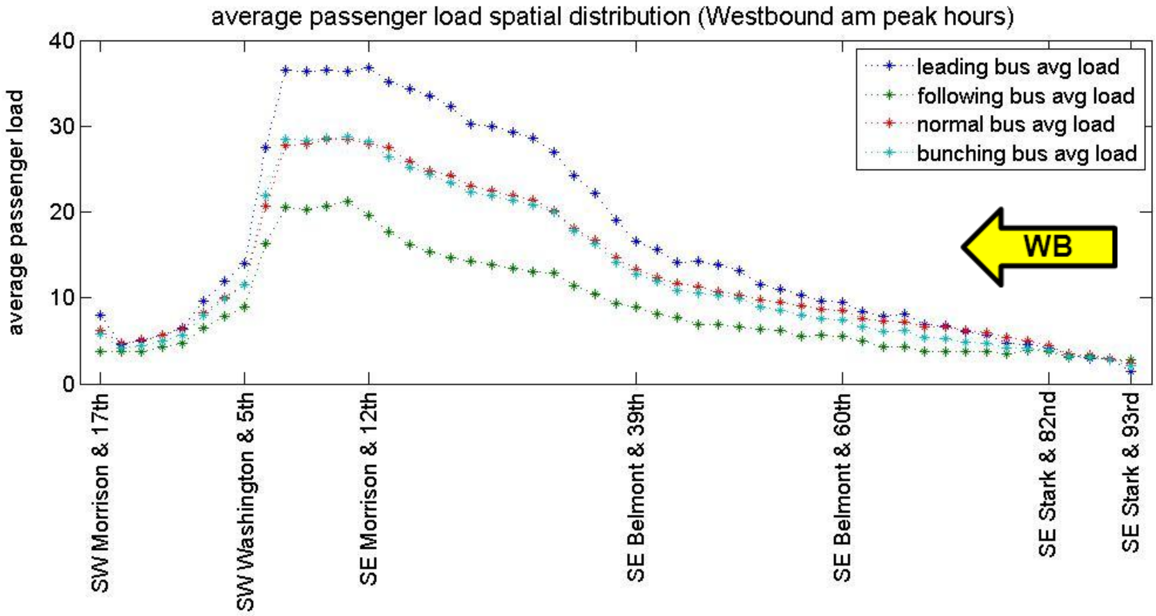

Figure 9. Average passenger load spatial distribution for route 15 westbound am peak hours (bus bunching threshold: headway < 2 minutes)

SUMMARY AND DISCUSSIONS

In conclusion, this paper shows some techniques that can convert massive AVL/APC data into valuable reliability performance measures, and convert detailed operational records into graphical display and dynamic visualizations for closer investigation. The reliability evaluation techniques focus on high frequency service, and therefore focus on headway regularity and bus bunching characteristics. Examples have shown how these techniques can identify recurrent reliability problems. Additionally, these graphical evaluation techniques are flexible for users to select different times of day, and adjust parameters and thresholds for sensitivity analysis.

This is ongoing research, so there are items that still need to be included. First off, there are some changes that need to be made in the programming of this tool., Currently, all of the results are computed and displayed by MATLAB except for the dynamic visualization part, which is written in PHP. Therefore, to provide users (transit agencies or passengers) an interactive web-based evaluation framework interface, these codes have to be rewritten by a web-based programming language. This would directly connect the database, run the query based on users' input, compute performance measures, and display results. Second, the examples shown in this paper are only for Route 15, they have to be expanded to all other routes in the future.

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