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# Comparative analysis of various bus control strategies

## A case study of the UC Berkeley Bear Transit System

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**Abstract** Bus systems are known to be unstable. Earlier buses need to pick up fewer passengers and tend to be earlier, and vice versa. This vicious circle can be broken with interventions, either in the form of stop skipping, boarding limit, or holding strategies. Various studies have been carried out to study these strategies, but many of them have not been implemented in the field or even tested against field data. This paper compares various anti-bunching holding strategies using a case study simulation of the UC Berkeley Bear Transit bus system. Demand and travel time data are collected from the field, and a simulation is built based on that data to compare these different strategies. Our simulation shows that buses are extremely likely to bunch, in light of the ongoing consolidation efforts. We also find that among the strategies analyzed, the simple control proposed by Xuan et al. (2011) provides the best tradeoff between commercial speed and service reliability.

**Keywords** bus operations · bus bunching · holding strategy · simulation · cost-benefit analysis

## 1 Introduction

Bus transit systems are inherently unstable—buses running in an uncontrolled fashion will invariably deviate from their schedule. The reason for this, as first

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discovered by Newell and Potts (1964), is that the time a bus spends serving passengers at a station generally increases with the time between consecutive bus arrivals to that station. Therefore, a bus arriving early to a station spends less time serving passengers and arrives even earlier to its next station. Similarly, a bus arriving late to a station spends more time serving passengers and falls even further behind schedule. This positive feedback loop results in the infamous phenomenon commonly known as "bus bunching".

Bunching is very damaging to the operation of a bus transit system. It negatively affects the performance of the system and increases average passenger waiting times. This alone can cause users to shift away from bus transportation to other, less unstable, modes. Additionally, bunching damages the reliability of the system because when buses bunch a schedule can no longer be maintained. This is especially important because system reliability has been found to be one of the highest concerns of transit users (Paine et al., 1967; Golob et al., 1972; Wallin et al., 1974).

For these reasons, a variety of control strategies have been proposed to mitigate the instability present in bus systems and improve the reliability of its operation. One strategy suggests that buses running behind schedule might skip stations, allow the late buses to catch up to the schedule (Sun and Hickman, 2005). A modification of this approach involves limiting the number of passengers that are allowed to board the bus at certain stations (Delgado et al., 2009). However, while these two strategies have shown to be able to prevent bunching, they also leave potential users stranded, which will diminish confidence in the system. Potentially getting stranded by a bus might be viewed by some passengers as worse than unreliable service.

Another way to mitigate the problem is to use holding strategies, which hold (or slightly delay) buses at specific stations (Osuna and Newell, 1972; Newell, 1974; Eberlein et al. , 2001; Zhao et al., 2006; Daganzo, 2009; Daganzo and Pilachowski, 2011; Xuan et al., 2011). Stations where buses are held are known as control points. While these holding strategies do not leave passengers stranded, they do decrease average commercial speeds since buses are delayed at the control points. Conventional holding strategies are generally either schedule based or headway based. In schedule-based holding strategies, buses are held at the control points only if they are early, and cannot depart from these locations ahead of schedule. In headway-based holding strategies, buses are held only if their headway is short, and cannot depart with shorter headways than a specified threshold. Recently, Xuan et al. (2011) thoroughly studied a more general case when holding time linearly depends on the deviation of all buses in the system from a virtual schedule. This general holding strategy includes as special cases the conventional schedule-based holding and the dynamic holding proposed in Daganzo (2009) and Daganzo and Pilachowski (2011). Using this framework, the authors then propose a simple near-optimal dynamic holding strategy that requires minimal information.

While it has been theoretically proven that most of these control strategies (boarding limits, stop skipping, schedule-based holding, headway-based holding, and simple dynamic holding) can eliminate bunching and keep the system running on schedule, many have not been tested in the field, or even tested with simulations that are based on empirical field data. Furthermore, the effects of these strategies have not been compared on the same system to determine which most efficiently improves operations.

In light of this gap in the literature, this paper proposes to compare these various anti-bunching strategies using a case study simulation of the UC Berkeley Bear Transit bus system. Information for this case study was obtained as a part of a previous analysis (Argote et al., 2011), which included a full audit of current operating and demand conditions. The resulting data is used in this analysis with the objective to achieve a quantitative comparison of the gains provided by each of the various control strategies operating under a realistic scenario. As demand rate for Bear Transit is low, we did not in our study consider stop skipping and boarding limit, as these strategies generally requires heavy demand rate. Also, it is politically difficult to refuse students to board campus buses.


**Fig. 1** UC Berkeley Bear Transit perimeter bus departing from the downtown Berkeley stop(*source: UC Regents*)

The remainder of this paper is organized as follows. Section 2 describes the UC Berkeley shuttle system and empirical data that will be used as a part of this case study. Section 3 discusses the simulation methodology that is used to test the different control strategies. Section 4 presents the the results of the simulation, including a comparison of the different strategies. Finally, Section 5 discusses the conclusions and recommendations from this work.

## 2 Case study

Data for this analysis were taken from a previous study (Argote et al., 2011) that performed a comprehensive examination of operating conditions of the UC Berkeley campus shuttle system (known more commonly as Bear Transit). When this examination was performed, the Bear Transit system consisted of three unique routes: 1) the Perimeter route, which ran clockwise around campus; 2) the Reverse route, which ran counter-clockwise around campus; and, 3) the Central route, which bisected the campus in the longitudinal direction. A fourth route, the Hill route, was also in operation; however, this route was excluded from this examination because it primarily served off-campus origins and destinations. A map of these three routes can be found in Figure 1. The Perimeter line is served by 2 buses and has average headways of 12 minutes, while the remaining two lines are each served by one bus with 27 minute headways on the Reverse route and 20 minute headways on the Central route.

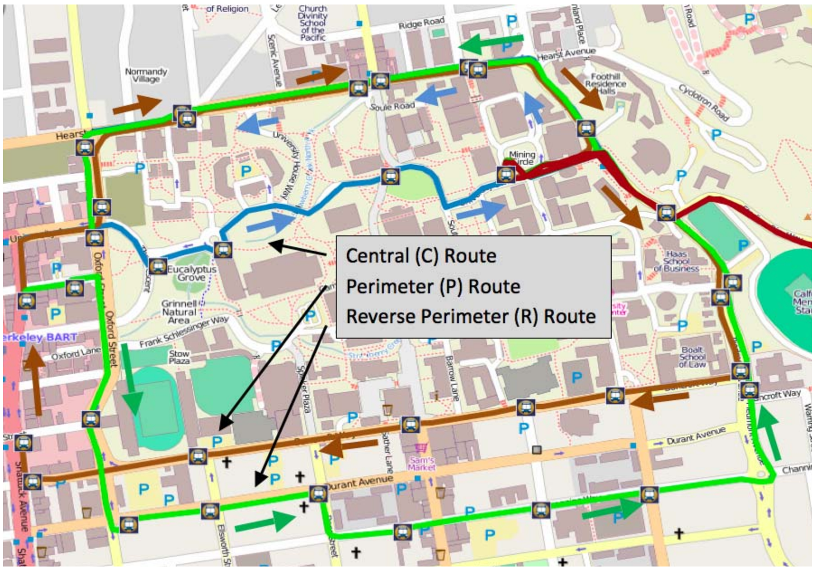


**Fig. 2** Routes operated by Bear Transit in the main UC Berkeley campus

As a part of the Argote et al. (2011) study, data were collected to determine travel demands, demand patterns and operating conditions of the system. Two distinct means were used in the data collection process: 1) a passenger survey, and 2) an audit of current operating conditions (see Appendix A for more information on the data collection effort). The survey was given to all passengers that entered the bus during various times of day, and was completed by an estimated 95% of riders. It consisted of several questions that collected information on trip motivation, origins and destinations, and demographics. Responses revealed travel demand patterns on the Bear Transit System and highlighted key movements across the campus. The audit was performed by members of the research team who rode the system and collected information on passenger movements (e.g., boardings and alightings at all stations) and travel times between stations. Care was taken to ensure that the audit covered most operating hours on typical class days (Monday-Thursday) to get an accurate depiction of system use.

From this comprehensive examination, it was clear that the Perimeter route carried the vast majority of passengers (greater than 70%). By combining the data collected from the audit and survey, the authors also determined that average passenger travel times (including access, riding and waiting time) could be improved by over 15% if the Reverse and Central routes were eliminated and their buses moved to serve the Perimeter line. However, such a configuration could be problematic since running more buses with smaller headways (about 6 minutes) on this short route could lead to bunching, which would negate any positive effects achieved by running buses at lower headways.

To determine how harmful the bunching instability will be, the data collected from the audit and survey will be used to simulate the evolution of this system under expected operating conditions under the new configuration. Different control strategies will then be applied to the simulation to determine the effectiveness of each. This case study will provide a good comparison of the different strategies because the same (real) data will be used in each case, so a direct comparison can be made.

## 3 Formulation and simulation methodology

To analyze how the proposed operational changes will affect the system, an event-based simulation model was created. This simulation approach allows to model the operation of a system as a chronological sequence of events. In the case of a bus line, the event set only includes three possibilities: cruising, boarding, and holding. This simulation approach, instead of simulating the evolution of the entire system state at regular time steps, just keeps track of the current simulation time, which jumps between the different system events the clock skips to the next event start time as the simulation proceeds. The following figure shows a time-space diagram where 4 buses operate for 15 minutes.

The key component in an event-based simulation is the definition of how the different events relate between them. For example, while the cruising time of a bus can be independent of any other event, the holding time of that same bus at a particular stop will depend on the departure time of the previous bus from that stop. However, in order to define the system dynamics, let us first introduce the notation and assumptions that will characterize the motion of the buses in our system.

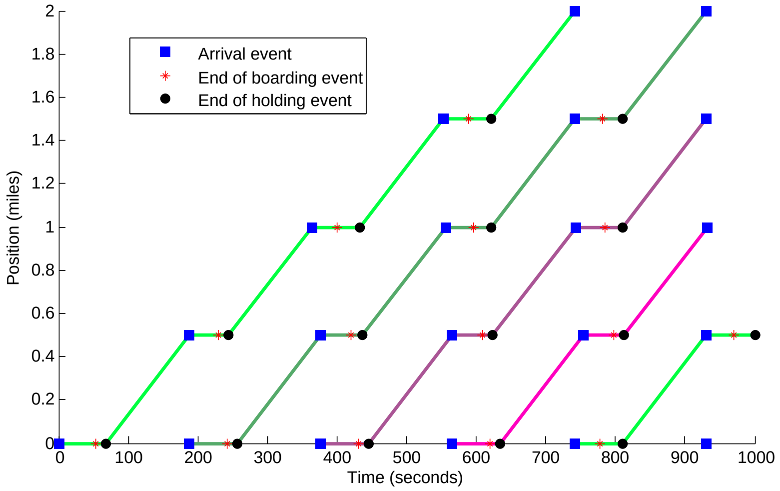


**Fig. 3** Time-space diagram reflecting the event-based simulation approach

### 3.1 System description and motion assumptions

As mentioned in Section 2, the results of the assessment of the Bear Transit system (Argote et al., 2011) suggest suppressing the Reverse and Central lines and increasing the level of service in the Perimeter line by operating all the available buses on it. Thus, four buses will be now operated on the Perimeter route. To analyze the system, we assume that these four buses operate in a common fashion. The following assumptions describe the proposed operation of the campus shuttle:

(i) Buses are initially dispatched on time with equal headways from the Downtown Berkeley station and continuously loop along the line. This is reasonable if the operational design of the bus line is appropriately addressed (e.g. choosing the appropriate headway for the system) and it is consistent with the current operation of the Bear Transit system.
(ii) The bus capacity of the buses is considered unlimited. In the case of the Bear Transit system, the demand levels are such that very rarely the capacity of the shuttles is reached.
(iii) Buses stop and holding time is applied at all stations. This facilitates both the formulation and simulation of the system and it is reasonable as long as the sum of boarding and holding times is considerably shorter than the inter-arrival time between buses.
(iv) Enough slack time is inserted in the schedule so that holding never runs short.
(v) Buses are allowed to pass each other when cruising. This is consistent with the Bear Transit system, since most of the streets surrounding the campus have multiple lanes per direction.

(vi) The cruising times of the buses between stops are stochastic but independent, which is reasonable since most of the time the streets on the perimeter route do not present congestion.
(vii) The passenger boarding time is stochastic and is characterized as a Poisson process with an arrival rate proportional to the time difference between a bus arrival and its preceding bus departure from the stop. The proportionality constants are location specific and depend on the demand level observed at each stop on the audit data (see Appendix A). This is reasonable if the bus drivers allow boarding during the holding time.
(viii) The holding process starts as soon as the final passenger waiting in line at the stop is boarded and only those passengers that arrived during the buses' inter-arrival time will board.

### 3.2 Looping bus line formulation

In this section we present the formulation used to characterize the motion of the buses under the previous assumptions. The model presented in this section could be applied to any bus line where buses constantly loop. First, let us use $s = 0, 1, 2, 3, \cdots, S$ as the stopsíndex, and $n = 0, 1, 2, 3, \cdots, N$ as the busesíndex (the Bear Transit case study has $S = 14$ and $N = 3$). An ideal representation of such system is sketched in the following figure:

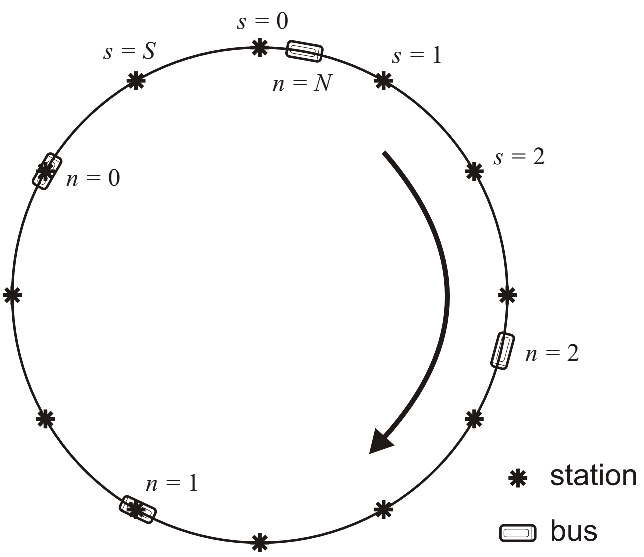


**Fig. 4** Ideal representation of a bus line with $S$ stations and $N$ buses

Because of the looping nature of the bus line, we use the $n \oplus 1$ and $s \oplus 1$ (or $\ominus$) notation to indicate the addition (or subtraction) modulo $N$ or $S$ respectively, following Daganzo and Pilachowski (2011). The parameters that describe the motion of the buses, based on Xuan et al. (2011), are:

- $t_{n,s}$ is the scheduled arrival time of bus $n$ at station $s$.
- $a_{n,s}$ is the actual arrival time of bus $n$ at station $s$.
- $\varepsilon_{n,s} = a_{n,s} - t_{n,s}$ is the deviation from schedule of bus $n$ at station $s$ or its delay.
- $h_{n,s} = a_{n,s} - a_{n\ominus 1,s}$ is the headway time between bus $n$ and its leading bus at station $s$.
- $H$ is the scheduled headway.
- $C_{n,s}$ is the a random variable that determines the cruising time of bus $n$ from station $s$ to $s+1$, including the acceleration and deceleration times.
- $c_s$ is the mean of $C_s$.
- $\sigma_s^2$ is the variance of $C_s$.
- $D_{n,s}$ is the holding time applied to bus $n$ at station $s$.
- $d_s$ is the slack time inserted at station $s$, i.e. the actual holding time if the bus arrives on time.
- $\beta_s$ is a dimensionless measure of the demand rate at station $s$, equivalent to the ratio between the demand rate (in passengers/hour) and the passengers boarding rate (also in passengers/hour). Thus, the passengers boarding time at station $s$ increases by $\beta_s$ if the headway increases by one unit time.

Based on the above notation and the previous section assumptions, the system headway can be obtained as:

$$NH = \sum_{s=0}^{S} d_s + c_s + \beta_s H, \tag{1a}$$

$$H = \frac{\sum_{s=0}^{S} d_s + c_s}{N - \sum_{s=0}^{S} \beta s}. \tag{1b}$$

In addition, the scheduled arrival times obey:

$$t_{n,s\oplus 1} = t_{n,s} + d_s + c_s + \beta_s H. \tag{2}$$

The actual arrival times, on the other hand, are given by:

$$a_{n,s\oplus 1} = a_{n,s} + D_{n,s} + C_{n,s} + \beta_s h_{n,s}. \tag{3}$$

If we subtract equations 2 from 3 we obtain the dynamic equations in terms of the deviations from schedule:[1]

$$\varepsilon_{n,s\oplus 1} = \varepsilon_{n,s} + \beta_s(\varepsilon_{n,s} - \varepsilon_{n\ominus 1,s}) + (C_{n,s} - c_s) + (D_{n,s} - d_s). \tag{4}$$

[1] Note that the headway of bus $n$ at station $s$ can be expressed as $h_{n,s} = H + \varepsilon_{n,s} - \varepsilon_{n\ominus 1,s}$.

Then, we assume that $D_{n,s}$ can be conveniently written as a general linear function of the deviation from schedule of the different system buses at station $s$:

$$D_{n,s} = d_s + [(1+\beta_s)\varepsilon_{n,s} - \beta_s \varepsilon_{n\ominus 1,s}] + \sum_i f_i \varepsilon_{n\ominus 1,s}. \tag{5}$$

Where $f_i\ \forall i \in \mathbb{Z}$ are the control coefficients, whose value depends on the holding strategy considered. The general linear formulation of the holding time simplifies the dynamic equation in 4 to a linear homogeneous function of the deviation from schedule terms:

$$\varepsilon_{n,s\oplus 1} = \sum_i f_i \varepsilon_{n\ominus 1,s} + (C_{n,s} - c_s). \tag{6}$$

As shown in Daganzo (2009) and Xuan et al. (2011) this type of function facilitates the analysis of the different control strategies performance. Both papers show promising stability results.

However, these strategies have not been tested under realistic conditions. In view of this and considering how likely it is that the proposed perimeter route would suffer severe bus bunching, we decided to compare through simulation the performance of five holding control strategies plus the uncontrolled scenario. Therefore, we will now present the different strategies considered, under the formulation framework developed by defining the values of their control coefficient vector $\mathbf{f} = [\cdots, f_{-1}, f_0, f_1, \cdots]$.

(I) *Uncontrolled Motion*

The uncontrolled motion corresponds to the case where $f_0 = 1 + \beta_s$, $f_1 = -\beta_s$ and $f_i = 0\ \forall i \notin \{0, 1\}$. In this case $D_{n,s} = d_s = 0$, therefore no holding is applied and buses circulate without any kind of external control.

(II) *Conventional Schedule-Based Control*

The conventional schedule-based control corresponds to the case where $f_i = 0\ \forall i$, so that $D_{n,s} = d_s - [(1+\beta_s)\varepsilon_{n,s} - \beta_s \varepsilon_{n\ominus 1,s}]$. With these control coefficients the buses are held at the control locations until the disturbances are completely absorbed through the holding operation.

(III) *Forward Headway-Based Control*

The forward headway-based control, as included in Daganzo (2009), is the special case with $f_0 = 1 - \alpha$, $f_1 = \alpha$, $f_i = 0\ \forall i \notin \{0, 1\}$, where $\alpha$ is a constant that must satisfy $0 < \alpha < 1$ for stability reasons. Therefore, the holding time is $D_{n,s} = d_s - (\alpha + \beta_s)(\varepsilon_{n,s} - \varepsilon_{n\ominus 1,s})$.

(IV) *Backward Headway-Based Control*

As recently proposed in Bartholdi and Eisenstein (2012), the holding time can also be based on the deviation from schedule of the follower bus. The control coefficients take the values $f_{-1} = \alpha$, $f_0 = 1 + \beta s - \alpha$, $f_1 = -\beta_s$ and $f_i = 0\ \forall i \notin -1, 0, 1$. In this case $\alpha$ can be freely chosen and $D_{n,s} = d_s + [\alpha\varepsilon_{n\oplus 1,s} - \alpha\varepsilon_{n,s}]$.

(V) *Two-way Headway-Based Control*

The Eulerian version of the (Lagrangian) method in Daganzo and Pilachowski (2011), which is based both on the forward and backward headways, can be formulated with $f_{-1} = f_1 = \alpha$, $f_0 = 1 - 2\alpha$, $f_i = 0$ $\forall i \notin \{-1, 0, 1\}$. Then the resulting holding time is $D_{n,s} = d_s + [\alpha\varepsilon_{n\oplus 1,s} - (1 - 2\alpha)\varepsilon_{n,s} + \alpha\varepsilon_{n\ominus 1,s}]$.

(VI) *Simple Control*

The Simple Control is a reduced version of the optimal linear control introduced in Xuan et al. (2011). This control strategy, which is near-optimal, is simply defined by the following control coefficients: $f_0 = \alpha$, $f_i = 0\ \forall i \notin \{0\}$. Thus, the holding time for this strategy can be calculated as $D_{n,s} = d_s + [(1 + \beta_s - \alpha)\varepsilon_{n,s} - \varepsilon_{n\ominus 1,s}]$.

These control coefficients are also critical in determining the value of the slack time, $d_s$. As per assumption (iv), the slack time needs to be large enough so that the holding time never runs short. This is achieved, as shown in Xuan et al. (2011), by computing the upper bound of the standard deviation of the actual holding time, $\sigma^2_{D_{\cdot,s}}(\mathbf{f})$, for a specific stop $s$. This parameter, if we consider $f_{i|j}$ to denote the $i$th

### 3.3 Simulation mechanics

Our simulation is built in MATLAB. It largely follows the model presented above. Different from Xuan et al. (2011), which assumes demand rate and travel time are identical across stations, the simulation runs with real demand and travel time from the field, where both are station dependent.

The model is generally built on ideal assumptions to keep tractability. This is relaxed to some extend in the simulation. For example, the fact that holding time can never be negative introduces nonlinearity into the formulation of holding time, making analytical almost impossible. Therefore our model does take negative holding time, though the value of the holding time and its likelihood to appear is very low (less than 1%).

Another assumption that is relaxed in the simulation is the fact that passengers can still board a bus while it is holding. This indicates that passenger boarding time is actually not proportional to the inter-arrival time of buses, but to the interval between leader bus' departure and follower bus' arrival. Figure 5 demonstrate this situation: passengers arriving in the $h_{n\oplus 1,s} - d_s$ interval, not $h_{n\oplus 1,s}$, board the bus.

Some of the holding strategies involve backward headway, $h_{n\oplus 1,s} = \varepsilon_{n\oplus 1,s} - \varepsilon_{n,s}$. This is generally non-causal, because when bus $n$ arrives at station $s$, bus

$n \oplus 1$ has not arrived yet. While the headway can be inferred from spacing, in our simulation, we make the assumption that the schedule deviation of bus $n \oplus 1$ at station $s$ equals its last known schedule deviation.

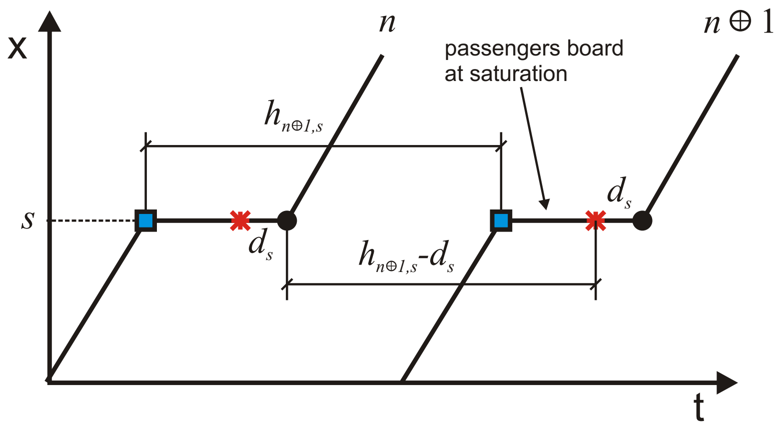


**Fig. 5** Boarding process of bus $n$ and $n \oplus 1$ at station $s$

## 4 Analysis of results

Table 1 compares different strategies based on various performance metrics. There are two categories of performance metrics. The first category is related to speed, and includes commercial speed (in kilometers/hour) and holding time percentage. Commercial speed is the average operation speed of the buses, considering cruising, passenger boarding and holding (if applicable). Holding time percentage is the percentage of the bus holding time out of the total travel time of buses, including cruising, passenger boarding and holding.

The second category is related to reliability, and includes standard deviation of headway (in seconds), standard deviation of schedule deviation (in seconds), on-time percentage, bunching percentage, and headway adherence. The standard deviation of headway ($h_{n,s}$) and schedule deviation ($\varepsilon_{n,s}$) are calculated across all buses and all stations. The on-time percentage is defined to be the percentage of bus arrivals that are less than one minute early and less than five minutes late ($\Pr\{\varepsilon_{n,s} > -1 \text{ min} \;\&\; \varepsilon_{n,s} < 5 \text{ min}\}$), per Bates (1986). The bunching percentage is defined to be the percentage of bus headways that are less than one minute apart ($\Pr\{h_{n,s} < 1 \text{ min}\}$), per CTA (2012). Headway adherence is defined by TCQSM (2004) to be the ratio of standard deviation of headway deviation over scheduled headway ($\text{std}(h_{n,s} - H)/H$).

Not surprisingly, the uncontrolled strategy has the highest speed among all strategies, because no holding is applied to buses. Besides the fact that buses will bunch in this case, as shown in Figure 6(a), the reliability of the system is also the worst among all strategies, due to the nasty positive feedback of the system with no intervention.

The rest of the control strategies generally exhibit a less extreme tradeoff. At least all of them are able to eliminate bus bunching, given the low demand of Bear Transit. The schedule-based control has the best reliability performance among all strategies, while it is the slowest and requires the largest amount of holding time.[2]

The rest four strategies have parameter(s) to be tuned, and the simulation result for each strategy in the table is just one (but reasonable) possibility. As stated in Xuan et al. (2011), simple control is an approximation of the optimal general control, and therefore exhibits the best property. The simple control produces the highest commercial speed among strategies with intervention, and ranks second for reliability. Figure 6(b) and Figure 6(c) also show the bus trajectories for schedule-based control and simple control. The simple control requires much less slack time, leading to shorter cycle time and service of higher frequency given the same fleet.

**Table 1** Simulation results for the different control strategies

| Performance Metrics | Strategies | | | | | |
|---|---|---|---|---|---|---|
| | No control | Schedule-based | Forward-headway $f_0=0.8$ $f_1=0.2$ | Backward-headway $f_{-1}=0.25$ $f_0=0.758$ $f_1=-0.008$ | Two-way looking $f_{-1}=0.1$ $f_0=0.8$ $f_1=0.1$ | Simple $f_0=0.8$ |
| Commercial Speed (km/hr) | 11.42 | 7.08 | 8.72 | 8.46 | 9.27 | 9.31 |
| Holding Time Percentage | 0% | 37.4% | 23.8% | 26.0% | 19.0% | 18.8% |
| Standard Deviation of Headway (sec) | 361.7 | 29.2 | 46.3 | 47.7 | 44.1 | 47.9 |
| Standard Deviation of Schedule Deviation (sec) | 366.2 | 20.6 | 85.1 | 133.2 | 119.9 | 34.1 |
| On-Time Percentage | 39.0% | 99.2% | 73.0% | 50.3% | 67.8% | 95.6% |
| Bunching Percentage | 34.1% | 0% | 0% | 0% | 0% | 0% |
| Headway Adherence | 1.074 | 0.054 | 0.104 | 0.104 | 0.106 | 0.115 |

## 5 Discussion and recommendations

The model elaborated in Xuan et al. (2011) and Section 3.2 makes some ideal assumption, so that the solution to the control problem is tractable analytically

[2] In reality, schedule-based control is generally less effective, because its demanding requirement on holding time is not acceptable to passengers.

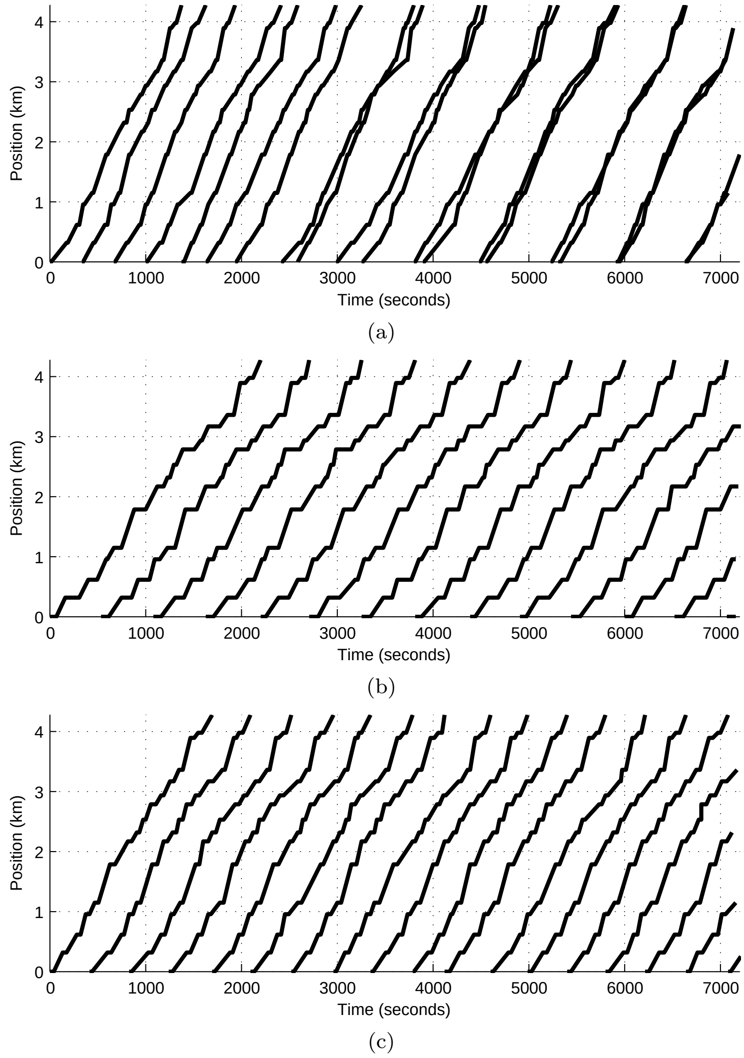


**Fig. 6** Sample bus trajectories. (a) No control. (b) Schedule-based control. (c) Simple control.

and insights can be derived from the model. We understand the limitation of the model, and this study adds some elements of reality. The demand rate and operational statistics of buses are all obtained from the field, and we no longer assume that the demand rate and the standard deviation of link travel time are identical at all stations. Admittedly, the simulation itself still represents some assumptions, and the best way to compare these control strategies is to test them in the field.

Given the current status of the Bear Transit, our simulation predicts that with four buses on the perimeter loop, they are extremely likely to bunch, which requires some level of intervention. Among the considered control strategies, the simple appears to be the best option, by providing a superior trade-off between speed and reliability. It is also much simpler to implement, by requiring less information, compared with the three headway based control strategies.

## 6 Acknowledgments

We would like to acknowledge fellow students Kristen Carnarius, Julia B. Griswold, Jeffrey Lidicker, Aditya Medury and Dylan Saloner for their collaboration in the initial stages of this project. Gratitude is also expressed to the Bear Transit administration and staff members that made the data collection possible, and each of the shuttle drivers for their support.

## A Perimeter line audit data

The perimeter route is a bus line that circumvents the main UC Berkeley campus. This route has 15 stops and it covers a total length of 4.31 km. Figure 7 shows the screenshot of a semi-automatic data collection tool that we used to record audit data from the field. The tool is a simple graphic user interface running in MATLAB (the choice is due to familiarity). The sample result of a one-hour audit is shown in Table 2. Table 3 shows the operational statistics of buses, including demand rate at each station and the mean and standard deviation of link travel times.

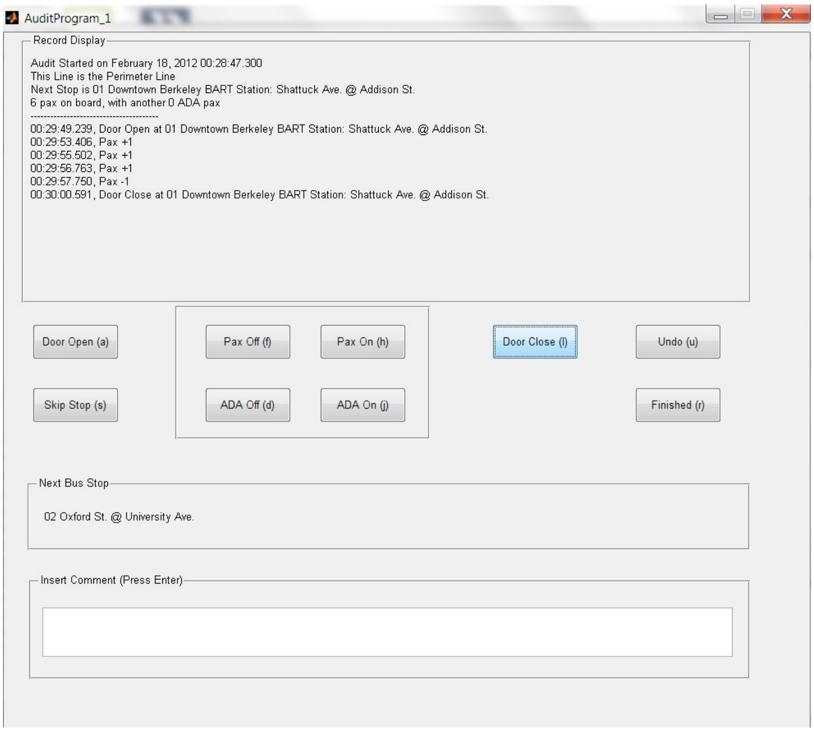


**Fig. 7** Screenshot showing the user interface of the audit data collection tool

**Table 2** Sample of a one-hour audit result

Audit Started on April 13, 2011 11:00:09.845
This Line is the Perimeter Line
Next Stop is 12 ASUC: Bancroft Way @ Telegraph Ave.
6 pax on board, with another 0 ADA pax

| Stop # | Stop Name | Door Open | Door Close | # On | # Off | Total Reg Pax | ADA/ Bike On | ADA/ Bike Off | Total ADA/ Bike |
|---|---|---|---|---|---|---|---|---|---|
| 12 | ASUC: Bancroft Way @ Telegraph Ave. | 01:00.8 | 01:00.8 | 0 | 0 | 6 | 0 | 0 | 0 |
| 13 | Recreastional Sports Facility: Bancroft Way @ | 02:30.3 | 02:46.0 | 7 | 0 | 13 | 0 | 0 | 0 |
| 14 | Banway Building: Bancroft Way @ Shattuck A | 04:19.6 | 04:24.2 | 1 | 0 | 14 | 0 | 0 | 0 |
| 15 | Shattuck Ave. @ Kittredge St. | 04:50.4 | 04:59.5 | 3 | 0 | 17 | 0 | 0 | 0 |
| 1 | Downtown Berkeley BART Station: Shattuck A | 05:56.4 | 07:27.2 | 18 | 0 | 35 | 0 | 0 | 0 |
| 2 | Oxford St. @ University Ave. | 09:53.3 | 10:04.8 | 3 | 1 | 37 | 0 | 0 | 0 |
| 3 | Tolman Hall: Hearst Ave. @ Arch St. | 11:57.5 | 12:32.3 | 14 | 0 | 51 | 0 | 0 | 0 |
| 4 | North Gate Hall: Hearst Ave. @ Euclid Ave. | 14:10.9 | 14:38.0 | 3 | 4 | 50 | 0 | 0 | 0 |
| 5 | Cory Hall: Hearst Ave. @ LeRoy Ave. | 15:40.5 | 16:02.3 | 0 | 6 | 44 | 0 | 0 | 0 |
| 6 | Evans Hall: Hearst Mining Circle Side | 18:30.0 | 18:47.2 | 2 | 2 | 44 | 0 | 0 | 0 |
| 7 | Gayley @ Stadium Rimway | 19:50.6 | 19:57.6 | 0 | 1 | 43 | 0 | 0 | 0 |
| 8 | Hass School of Business: Piedmont Ave. Side | 20:44.4 | 21:12.4 | 2 | 1 | 44 | 0 | 0 | 0 |
| 9 | International House: Piedmont Ave. @ Bancro | 21:45.9 | 22:02.8 | 1 | 5 | 40 | 0 | 0 | 0 |
| 10 | Kroeber Hall: Bancroft Way @ College Ave. | 23:27.6 | 23:32.8 | 1 | 0 | 41 | 0 | 0 | 0 |
| 11 | Hearst Memorial Gym: Bancroft Way @ Bowd | 24:14.9 | 24:17.8 | 0 | 0 | 41 | 0 | 0 | 0 |
| 12 | ASUC: Bancroft Way @ Telegraph Ave. | 25:40.7 | 25:50.3 | 1 | 0 | 42 | 0 | 0 | 0 |
| 13 | Recreastional Sports Facility: Bancroft Way @ | 27:01.5 | 27:01.5 | 0 | 0 | 42 | 0 | 0 | 0 |
| 14 | Banway Building: Bancroft Way @ Shattuck A | 28:24.8 | 28:24.8 | 0 | 0 | 42 | 0 | 0 | 0 |
| 15 | Shattuck Ave. @ Kittredge St. | 28:47.1 | 29:06.1 | 3 | 3 | 42 | 0 | 0 | 0 |
| 1 | Downtown Berkeley BART Station: Shattuck A | 29:54.4 | 30:36.5 | 11 | 3 | 50 | 0 | 0 | 0 |
| 2 | Oxford St. @ University Ave. | 32:25.8 | 32:31.5 | 1 | 0 | 51 | 0 | 0 | 0 |
| 3 | Tolman Hall: Hearst Ave. @ Arch St. | 33:58.2 | 34:06.2 | 2 | 0 | 53 | 0 | 0 | 0 |
| 4 | North Gate Hall: Hearst Ave. @ Euclid Ave. | 35:07.1 | 35:12.1 | 0 | 0 | 53 | 0 | 0 | 0 |
| 5 | Cory Hall: Hearst Ave. @ LeRoy Ave. | 36:20.5 | 36:36.6 | 1 | 4 | 50 | 0 | 0 | 0 |
| 6 | Evans Hall: Hearst Mining Circle Side | 38:39.6 | 40:00.5 | 2 | 0 | 52 | 0 | 0 | 0 |
| 7 | Gayley @ Stadium Rimway | 41:19.9 | 41:25.7 | 0 | 2 | 50 | 0 | 0 | 0 |
| 8 | Hass School of Business: Piedmont Ave. Side | 42:08.1 | 42:13.7 | 0 | 1 | 49 | 0 | 0 | 0 |
| 9 | International House: Piedmont Ave. @ Bancro | 42:55.2 | 43:06.9 | 0 | 1 | 48 | 0 | 0 | 0 |
| 10 | Kroeber Hall: Bancroft Way @ College Ave. | 47:01.7 | 47:16.0 | 1 | 2 | 47 | 0 | 0 | 0 |
| 11 | Hearst Memorial Gym: Bancroft Way @ Bowd | 48:16.4 | 48:21.7 | 1 | 0 | 48 | 0 | 0 | 0 |
| 12 | ASUC: Bancroft Way @ Telegraph Ave. | 50:35.2 | 50:59.6 | 1 | 2 | 47 | 0 | 0 | 0 |
| 13 | Recreastional Sports Facility: Bancroft Way @ | 52:23.8 | 52:42.4 | 2 | 1 | 48 | 0 | 0 | 0 |
| 14 | Banway Building: Bancroft Way @ Shattuck A | 54:40.0 | 54:48.8 | 0 | 1 | 47 | 0 | 0 | 0 |
| 15 | Shattuck Ave. @ Kittredge St. | 55:31.6 | 55:44.0 | 1 | 0 | 48 | 0 | 0 | 0 |
| 1 | Downtown Berkeley BART Station: Shattuck A | 56:23.8 | 56:33.6 | 0 | 3 | 45 | 0 | 0 | 0 |

**Table 3** Operational statistics of buses from the audit data

| Index $s$ | Description | post mile (km) | $\beta$ | $c_s$ (sec) | $\sigma_s$ (sec) |
|---|---|---|---|---|---|
| 1 | BART | 0 | 0.021 | 143.0 | 13.7 |
| 2 | University & Oxford | 0.31 | 0.007 | 104.7 | 11.9 |
| 3 | Hearst & Arch | 0.61 | 0.014 | 70.9 | 5.4 |
| 4 | Hearst & Euclid | 0.97 | 0.006 | 73.4 | 9.3 |
| 5 | Hearst & Cory Hall | 1.14 | 0.017 | 145.7 | 13.6 |
| 6 | Hearst Mining Circle | 1.79 | 0.017 | 102.8 | 13.0 |
| 7 | Hall & Gayley | 2.17 | 0.003 | 56.6 | 2.1 |
| 8 | Haas Business School | 2.33 | 0.003 | 44.6 | 2.2 |
| 9 | International House | 2.54 | 0.004 | 94.8 | 13.8 |
| 10 | Bancroft & College | 2.80 | 0.006 | 53.3 | 3.7 |
| 11 | Bancroft & Bowditch | 2.95 | 0.003 | 102.1 | 11.2 |
| 12 | Bancroft & Telegraph | 3.19 | 0.008 | 71.2 | 10.2 |
| 13 | Bancroft & Ellsworth | 3.38 | 0.003 | 80.4 | 6.1 |
| 14 | Bancroft & Fulton | 3.91 | 0.004 | 44.4 | 4.6 |
| 15 | Shattuck & Kittredge | 4.01 | 0.007 | 69.1 | 8.3 |

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