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DOI
10.1177/0361198119845369

Publication date
2019

Document Version
Final published version

Published in
Transportation Research Record

Citation (APA)
Soza-Parra, J., Cats, O., Carney, Y., & Vanderwaart, C. (2019). Lessons and Evaluation of a Headway Control Experiment in Washington, D.C. *Transportation Research Record*, *2673*(8), 430-438. https://doi.org/10.1177/0361198119845369

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Research Article

Transportation Research Record
1–9

DOI: 10.1177/0361198119845369
journals.sagepub.com/home/trr
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Lessons and Evaluation of a Headway Control Experiment in Washington, D.C.

Jaime Soza-Parra[1], Oded Cats[2], Yvonne Carney[3], and Catherine Vanderwaart[4]

Abstract

Headway management can potentially reduce passenger waiting time and on-board crowding on high-frequency services. In this study, a headway control experiment was conducted and evaluated for Washington Metropolitan Area Transit Agency routes 70 and 79 in Washington, D.C. The field experiment is evaluated by performing a before–after empirical evaluation. The organizational process and challenges involved with the implementation are discussed. Overall, a reduction of 26% in passenger excess waiting time was attained, which implies annual time savings that translate into US$1 million. Even though the field experiment implementation was far from ideal, the benefits obtained so far might pave the road to a long-term commitment to shift into a fully controlled headway-based management.

Service reliability, defined in relation to the certainty travelers have regarding their waiting time, their arrival time, or the comfort level they will experience inside the vehicle, is one of the most important attributes of a passenger trip. In a high-frequency context, poor reliability not only increases the risk associated with a travel alternative, but also worsens the experienced outcomes. For example, if the crowding level inside a vehicle is highly variable, the likelihood that a passenger will experience high-density crowding increases. This increases the average crowding experienced over time (*1*).

This paper focuses on high-frequency services in which customers arrive at a stop without consulting a schedule, typically services that come at least every 15 min. Both comfort and waiting time averages and variabilities in this high-frequency context are explained mainly by one attribute: headway regularity. A transit service is considered regular, in a frequency-based context, when consecutive headways are evenly distributed. When vehicles operate irregularly, passengers experience an extra amount of waiting, which has been coined excess waiting time. Besides, they experience more crowded vehicles because, as mentioned before, it is more probable that a passenger will arrive during a long headway interval (*2*). Moreover, additional costs are induced by irregular services. For example, if several bus routes are running along the same corridor, congestion around bus stops might arise. This issue adds extra travel time to the passengers on-board the vehicle and increases the waiting time for the passengers waiting at the bus stop.

In the absence of real-time headway control, bus services have an inherent tendency towards irregular operations as small variations in headways lead to uneven crowding, irregular dwell times, and further widening of gaps in service. The positive feedback loop between service headways, number of boarding passengers, and dwell times results in a deterioration of service regularity. The latter implies longer passenger waiting times, more uneven on-board crowding, and a skewed distribution of vehicle travel time, resulting in time losses and inefficient resource utilization.

Headway control strategies require real-time vehicle positioning information. The possibility of using fleet management systems for improving service regularity was conceived by Osuna and Newell (*3*). With the increasing availability of automatic vehicle location data, a growing number of studies have investigated the prospects of headway control strategies. Analytical and simulation studies have concluded that methods based on the

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regulation of bus movements in relation to the headways from the preceding and succeeding buses are most promising (*4*, *5*).

In this study, a headway control experiment that was conducted for routes 70 and 79 operated by the Washington Metropolitan Area Transit Agency (WMATA) is described and analyzed. These routes connect the northern part of Washington, D.C. with the city center. Prior to the experiment, the practice was to run these routes as schedule-based services, even though service frequency is six buses per hour. A before–after performance evaluation is performed based on data collected 6 months after the implementation of a headway-based control. In the analysis, we elaborate on the organizational processes and related implementation challenges. We also quantify the impacts on service users and the service provider. This supports an empirical-based evaluation of such experiments and allows future implementations to learn from the experiences gained in this pilot.

This paper is structured as follows. The next section describes past headway control experiences as well as some state-of-the-art conclusions about this issue. The paper then details the experimental design and implementation of the specific headway control experience on WMATA routes 70 and 79 in Washington, D.C. This is followed by a description of the before and after evaluation. The benefits quantification is then presented, considering both service users and service provider perspectives. Finally, the paper concludes and elaborates on the lessons gained and opportunities to move forward.

Headway Control: The Premise, the Promise and Potential Pitfalls

Even though methods for stabilizing service headways have been proposed for almost half a century, field experiments have not been documented in the research literature until fairly recently. Moreover, most of the field trials have been very limited and exhibited significant shortcomings in their implementation. Pangilinan (*6*) analyzed the results of a field trial on a single bus line in Chicago that relied on a dedicated dispatcher in the control room and street supervisors. The critical shortcoming in this implementation was that the dispatcher was the only one with access to real-time vehicle positions. This resulted in a prohibitive workload that did not allow the dispatcher to effectively monitor and respond to discrepancies to achieve the desired service performance.

Several studies have attempted to mitigate this shortcoming by providing operators with the means to monitor their relative positioning and instructions. However, technical difficulties were often prevalent and limited pilot execution and performance, resulting in experiments that were shorter and smaller-scale than planned. Lizana et al. (*7*) analyzed the outcomes of a 2-day pilot on a bus line in Santiago de Chile in which instructions were provided via tablets. They concluded that technical failures and operator compliance were persistent challenges. Tablets were also used by terminal personnel in a light-rail, multi-branch line in Boston to support an even-headway policy in their dispatching strategy (*8*). Berrebi et al. (*9*) reported small-scale implementations of headway control on the Atlanta streetcar system and a bus route in San Antonio. The former was operated by three vehicles and the latter lasted for 2 days. Based on their experiences, the authors concluded that headway control implementation involves technical challenges that may be overlooked in simulation experiments, including the quality and frequency of location data transmission and operators' response. Cats et al. (*4*) examined in a transit simulation model the implications of operator compliance and the frequency of vehicle positioning updates on the performance of headway control strategies. This robustness analysis was performed in preparation to a field experiment.

Ideally, bus operators should be directly and frequently informed about the instructions (i.e., speed adjustment between stops, holding at stops) resulting from a headway control strategy. A series of field experiments in Stockholm benefited from the presence of a computer display that is positioned in the bus operator cabin. All buses are equipped with a system that enables projecting to the operator the discrepancy from the desired bus location in minutes (i.e., negative values indicate that the bus is running behind, positive values imply running ahead). Cats (*2*) found a reduction of 38% in excess waiting times. In addition, he discusses the relevant considerations in extending field experiments into full-scale and long-term implementation of operation geared towards better regularity performance including aspects pertaining to performance monitoring, incentive schemes and business models. A detailed framework for quantifying the impacts of public transport interventions such as headway control strategy is provided by Fadaei and Cats (*10*). They concluded that the total service user and provider benefits associated with the latest experiment in the abovementioned series amounts to 36.8 million Swedish krona on an annual basis (approximately US$4.5 million). Following the field experiments, since 2015 the transport authority and the incumbent bus company agreed that all trunk bus lines in the Stockholm inner city would use a headway control strategy.

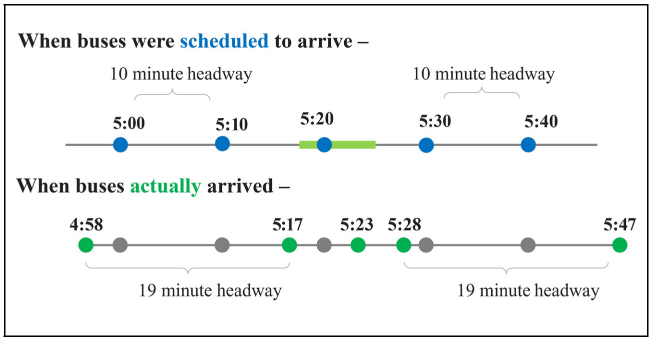

Figure 1. WMATA's schedule-based metric records the buses in green as on time.

Experimental Design and Implementation

Headway Management Background

WMATA, also known as Metro, is the largest transit agency in the Washington, D.C. region. WMATA operates six rail lines and 260 bus routes, with the bus system carrying about 380,000 people on an average weekday.

WMATA's bus service has been schedule-based, with on-time performance (OTP) measured at several timepoints on each route. A route's OTP is based on how often the bus arrives at a timepoint within a window of 2 min before to 7 min after the scheduled arrival time (i.e., [−2, +7]). This schedule-based metric works well on less frequent routes but has some significant weaknesses on frequent service. When buses are scheduled to come every 10 min, for example, most customers simply arrive at the stop and wait without consulting a schedule, so even spacing is more important than schedule adherence. The relatively large window within which a vehicle is considered "on time" is also not well-suited to these more frequent routes. Figure 1 illustrates this situation, in which all buses are considered on-time under a schedule-based OTP, but the average customer wait is approximately 7.99 min, instead of the 5 min one would expect in the event of a perfectly regular service.

WMATA staff began looking for ways to better manage and measure the service on frequent routes. Beginning in 2012, the agency had experimented with managing some frequent routes on a headway basis using street supervisors. These early efforts were generally successful but resource-intensive, and ultimately were discontinued because of a lack of resources. Since that time, several frequent routes have had published timetables that indicate that, for example, "Managers will schedule departures every 10 min until 5:30 p.m.," but little active management occurred on these routes. In the beginning of 2017 WMATA staff and management decided to renew efforts to actively manage frequent service on a headway basis.

Experiment Setup

The agency decided to start with one corridor to determine the best approach and demonstrate the benefits of the additional resources required. The corridor selected is known as Georgia Avenue and is served by two routes, the 70 and 79. These routes begin at the Silver Spring Transit Center in Maryland, near a job and population center, and travel in a mostly straight path down Georgia Avenue and 7th Street NW to the Washington, D.C. downtown core, with an end-to-end route length of about 7.5 mi (12 km). Traffic is a significant issue in the downtown core, where a major sports and event arena adjacent to the route can cause major disruption to route operations. The location of these lines can be observed in Figure 2.

A number of intersections on the corridor have transit signal priority, though the system is still relatively new. The parameters determining when priority is granted are conservative, so the benefits to travel time are modest. There is also a brief segment of dedicated bus lanes on the corridor, extending for four blocks.

Route 70 is a local route with 60 stops carrying nearly 11,000 passengers on an average weekday using both 40-ft and articulated buses. Route 79 is part of the "MetroExtra" set of limited-stop routes, averaging about 6,000 passengers on weekdays and serving 25 stops. The 79 runs from 5:00 a.m. to 8:00 p.m. seven days a week, whereas route 70 offers 24-h service. Exact frequency varies by the time of day, but during peak periods each route departs at least every 15 min.

Unlike many similar corridors in the region, the chosen corridor has a relatively simple service pattern, which made it an excellent candidate for headway management. The corridor is also among the highest ridership in the system, but performance has been relatively poor. OTP prior to the implementation of headway management was 65–75%. More details regarding the performance of routes 70 and 79 are shown in Figure 3. WMATA's systems report bunching as buses that arrive at less than 50% of the planned headway.

As with many busy, frequent urban bus routes, the service had a lot of short and long gaps. Specialists in the operations communications center were able to monitor these issues but had limited effectiveness at managing them. Specialists must call the operators on the radio to communicate problems. Since operators are required to stop and secure the bus prior to answering radio calls, these calls were often not answered in a timely manner. Street supervision was limited and focused on accidents, mechanical problems, and other incidents rather than on managing performance.

Managers and planning staff knew that the shift to headway-based operations would be both a logistical and a cultural change. Bus operators and street

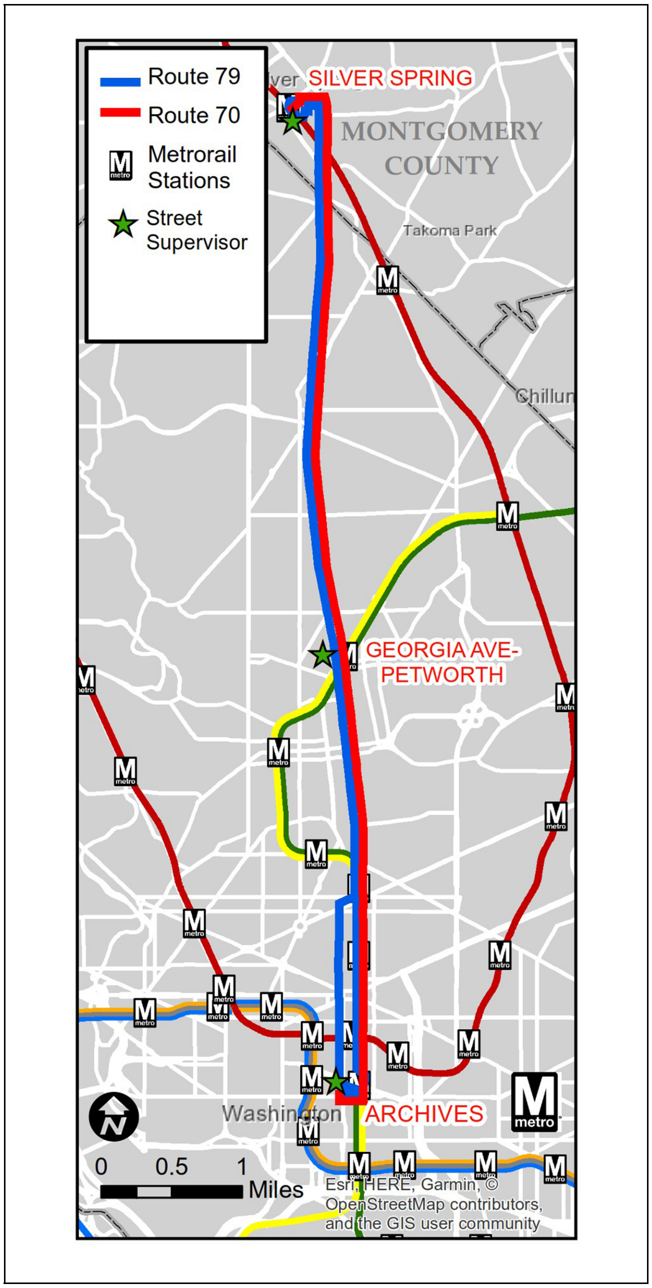

Figure 2. Routes 70 and 79 location map.

supervisors who for decades have been expected to adhere to schedules would need to be retrained. Service adjustments like holds would need to become more common to keep service evenly spaced. Passengers who were unaccustomed to these service adjustments might have questions. Performance metrics would need to be adapted to encourage even spacing over schedule adherence. Management decided that training a group of dedicated street supervisors to be stationed along the route would be the most effective way to make this transition.

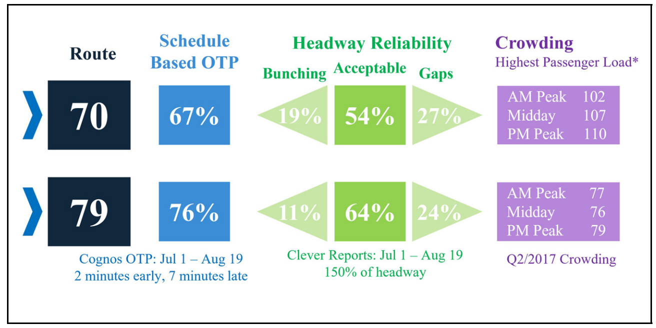

Figure 3. Performance indicators for routes 70 and 79.

Pilot Implementation

To implement headway management, bus operators and street supervisors were trained on headway management and active service management techniques. A "playbook" of techniques was provided, including information on holding, expressing, short-turning, and other options for restoring even headways when bunching and large gaps occur. A small number of "reserve" buses were also stationed in strategic locations near the route to be inserted as needed to fill gaps in service.

Street supervisors were stationed at key locations along the route, including both terminals, a major transfer point in the middle of the route near a rail station, and other locations as needed. This required seven full-time positions to ensure adequate coverage on the route across two shifts from the early morning through the early evening hours on weekdays. These supervisors were dedicated to the corridor, with no other duties, and were provided with new tablets equipped with software that displays the location of all vehicles on the route in real time. The communications center also dedicated specialists to managing the routes full time. These changes began in October 2017, with training for all operators complete in December of that year.

This approach to actively managing headways is resource-intensive. The agency hopes to move to a solution based on in-vehicle technology in the future, such as that in use in Stockholm and Santiago, as headway management is expanded to other frequent routes. This interim approach was adopted to demonstrate the performance improvements of a headway-based approach to build support for headway management techniques among bus operators, street supervisors, and other stakeholders. Although bus operators might at first be reluctant to change their working routine, Hlotova et al. (*11*) found that the headway-based strategy deployed in Stockholm resulted in lower stress levels based on the analysis of heart-rate measurements. The on-site staff have also played an important role in communicating

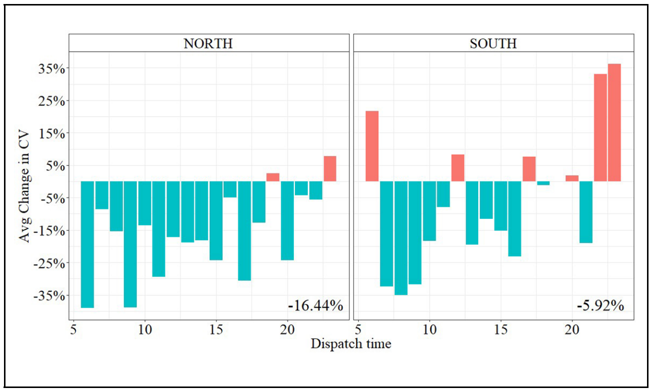

Figure 4. Average change of the coefficient of variation of headways per direction and dispatch time.

with customers about service adjustments, such as holds, that passengers may not be used to.

New performance metrics were defined to go along with the project. In particular, staff began reporting on headway adherence on these routes, defined as the percentage of timepoints where buses arrive within the scheduled headway plus 3 min (i.e., [0, h + 3]), rather than traditional schedule-based OTP. Comprehensive weekly reporting was implemented showing performance and other statistics such as accidents and incidents on the route.

For a more comprehensive performance assessment, automated vehicle location (AVL) data from April 2017 and April 2018 was analyzed for a before and after assessment. These months were chosen to capture an "after" period when the program had been fully established, and also because these time periods were relatively free of major disruptions. The AVL data is event-driven, with event records roughly every 15–30 s.

Before and After Performance Analysis

The following section describes and compares the level of service offered before and after the headway control implementation. The data used comprises the arrival time of every bus at every bus stop (even if they are not served) for the entire months of April 2017 and April 2018. Only working days were considered and all the figures refer to data from route 70, the primary line.

The most important outcome to analyze following this headway control experience are the consequences for passenger waiting times. Since headways are expected to be more regular after the implementation, we expect passengers to wait less on average. Assuming random arrival of passengers to bus stops, there is a direct relationship between average headway, $E\left(\hat{h}\right)$, headways coefficient of variation, $CV\left(\hat{h}\right)$, and the expected waiting time, $E(\hat{w})$ (*3*) shown as

$$E(\hat{w}) = \frac{E\left(\hat{h}\right)}{2} \cdot \left(1 + CV\left(\hat{h}\right)\right) \tag{1}$$

Instead of computing the coefficient of variation for the whole period of analysis, it was disaggregated per hour of the day. Figure 4 shows the average change observed between the before and after situation per direction and dispatch time between 6:00 a.m. and 11:00 p.m. Moreover, in the lower right corner of each direction box, the average change per direction is shown. This display shows how the improvements are distributed within the day.

A significant improvement in relation to headway variability is observed, with average reductions of 16.44% and 5.92% for north and south directions, respectively. Headways on the north direction have become almost always more regular, with the exception of 19–20 and 23–24 hours. Active headway management by street supervisors is not in place at these hours.

This improvement can be further analyzed to examine how the change in headways is spatially manifested along the route. Figure 5 shows the relative change of the coefficient of variation of headways per bus stop, dispatch time, and direction.

A visual inspection of this heatmap reveals that the only bus stop where regularity has systematically worsened rather than improved is bus stop number 31 in the northbound direction (located at the intersection of Georgia Ave. with Shepherd St). Noticeably, regardless of the regularity in the previous bus stops, the coefficient of variation is significantly worse at that specific bus stop compared with the before period. Particular characteristics of the on-street conditions could be causing this performance decline, such as signal timing, stop location, on-street parking, and so forth. Besides, this stop also comes just after a major transfer and supervision point at a rail station. During the time the data for the paper was collected, that rail station was a relief location where drivers switched off, which caused occasional long delays. Aside from this northbound stop, in the southbound direction a significantly worse situation is observed at the hours of 6–7 and 22–23. Note that street supervisors do not implement headway management control during those hours.

Benefits Evaluation

The following section presents the methodology, assumptions, and results of the benefit evaluation of the headway control strategy field experiment. The methodology is based on Fadaei and Cats (*10*), with some amendments tailored for this case study. The results are divided into three sections: passenger benefits, provider's costs, and overall evaluation.

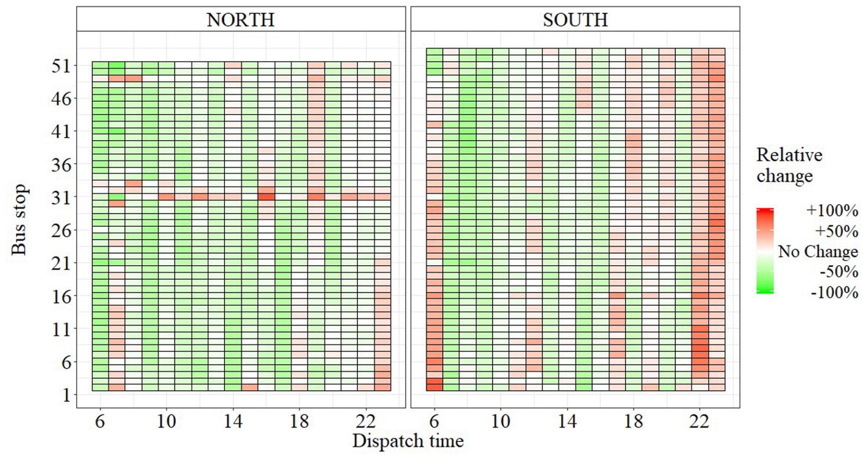

Figure 5. Relative change heatmap of the coefficient of variation of headways per bus stop and dispatch time.

Passenger Benefits

Passenger benefits are comprised of two components, as explained in the previous section: waiting times and travel times. For calculating waiting times, two variables are needed: actual headways and the corresponding number of passengers boarding each bus at each stop during the analysis period. With regards to the former, bus arrival time at each bus stop is sufficient to compute accurately the headway from the previous bus. The automatic passenger counter (APC) data collected in the case study is unfortunately deemed to be unreliable for individual trips, though it is able to produce reliable averages for boardings and alightings at each stop by time of day. Consequently, the following correction is made: based on the assumption of random passenger arrivals at bus stops, there exists a directly proportional relationship between the number of boarding passengers and headways. For instance, if a specific headway is twice as long as the planned headway, it is expected that the number of passengers boarding the bus is approximately double the historical average for the planned headway.

Mathematically, the number of boarding passengers, of a specific bus i and a specific bus stop s, $b_{i,s}$, that is within the time period t is

$$b_{i,s} = \overline{b_{t,s}} \cdot \frac{h_i}{h_t^p} \tag{2}$$

where h_t^p is the planned headway at the time period t, h_i is the headway of a specific bus, and $\overline{b_{t,s}}$ is the historical average number of boarding passengers at a time period t and bus stop s.

Then, the perceived average waiting time, assuming waiting times are valued twice as much as in-vehicle time (*12*), is

$$\mathrm{PAWT} = 2 \cdot \frac{\sum_{i,s} b_{i,s} \cdot \frac{h_i}{2}}{\sum_{i,s} b_{i,s}} \tag{3}$$

A similar approach is adopted for travel times. Again, the position information is accurate enough to estimate travel time between consecutive bus stops. However, it is not possible to rely on APC information for estimating the load on-board each vehicle. Thus, load information was estimated based on previously estimated boarding data, historical alighting patterns and the initial assumption of empty buses upon departure from the origin terminal. Then

$$l_{i,s} = l_{i,s-1} + b_{i,s-1} - l_{i,s-1} \cdot p_{t,s-1}^{\text{alight}} \tag{4}$$

where $l_{i,s}$ is the load of a specific bus i and a specific bus stop s, and $p_{t,s}^{\text{alight}}$ is the probability to alight at the time period t and bus stop s. An important side-effect of more evenly distributed headways is the reduction of average crowding on-board vehicles (*2*). Based on Björklund and Swärdh (*13*), a perceived measure of in-vehicle travel time depending on the crowding level can be computed. This means that travel time is perceived differently depending on whether one is seated or standing and also depending on the total number of people per square metre inside the vehicle. Then, the perceived average in-vehicle time is

$$\mathrm{PAIVT} = \frac{\sum_{i,s} p_{i,s} \cdot t_{i,(s-1,s)}}{\sum_{i,s} b_{i,s}} \tag{5}$$

where $t_{i,(s-1,s)}$ is the travel time between stops $s-1$ and s of a specific bus i, and the perception multiplier $\alpha_{i,s}$ is

Table 1. Total Daily Savings per Route and Direction

Total savings	70 North	70 South	79 North	79 South
PAWT minutes	846 min	3,648 min	4,171 min	3,392 min
PAWT seconds per passenger	19 s	94 s	201 s	230 s
PAWT dollars	\$203 USD	\$874 USD	\$1,999 USD	\$1,626 USD
PAWT cents per passenger	7 ¢	38 ¢	80 ¢	92 ¢
Total PAWT yearly savings		1,128,519 USD		
PAIVT minutes	–2,165 min	5,983 min	4,577 min	–662 min
PAIVT dollars	-\$519 USD	\$1,434 USD	\$1097 USD	-\$159 USD
Total PIVT yearly savings		444,789 USD		
Total time saving per passenger (PAWT + PAIVT)	–30 s	246 s	422 s	185 s
Fleet size	0.26 buses		–0.15 buses	
Hours of operation	6.11 h		–0.75 h	
Operator's savings	\$683 USD		-\$103 USD	
Total operator's yearly savings		\$139,279 USD		
Total yearly savings		\$1,712,587 USD		

Note: PAWT = perceived average waiting time; PAIVT = perceived average in vehicle time.

$$\alpha_{i,s} = \left(\min\{l_{i,s}, \delta_i\} \cdot \beta_{i,s}^{\text{sitting}} + \max\{0, (l_{i,s} - \delta_i)\} \cdot \beta_{i,s}^{\text{standing}}\right) \tag{6}$$

Considering δ_i as the number of seats of a specific bus i, and

$$\begin{aligned} \beta_{i,s}^{\text{sitting}} &= 0.973 + 0.0652 \cdot \gamma_{i,s} \\ \beta_{i,s}^{\text{standing}} &= 1.565 + 0.0685 \cdot \gamma_{i,s} \end{aligned} \tag{7}$$

$\gamma_{i,s}$ corresponds to the standing passenger density factor (i.e., the total amount of standing passengers divided by the available area inside the vehicle i).

Service Provider's Costs

The service provider's costs can also be divided into two parts: fleet size costs and vehicle-hour costs. Note that the distance traveled by buses remains unchanged in the field experiment.

Regarding fleet size costs, a fixed β^{fixed} cost is considered for each bus. For the variable costs, the fleet's requirements per time period z_t is calculated by

$$z_t = \frac{\mathrm{TT}_{t,P90\%}^{Nd} + \mathrm{TT}_{t,P90\%}^{Sd} + \varepsilon}{\left(\frac{h_t^{p,Nd} + h_t^{p,Sd}}{2}\right)} \tag{8}$$

where $\mathrm{TT}_{t,P90\%}^{\text{direction}}$ is the 90th percentile for the end-to-end travel time in a specific direction and time period, $h_t^{p,\text{direction}}$ is the planned headway for a specific direction and time period, and ε considers recovery and terminal layover times. The use of the 90th percentile running time is a widespread practice among public transport agencies to ensure fleet availability.

Then, the total service provider's cost is defined by the expression

$$c^{\text{operator}} = \sum_{\forall t}\left(\beta^{\text{fixed}} \cdot z_t + \frac{3600}{\left(\frac{h_t^{p,Nd} + h_t^{p,Sd}}{2}\right)} \cdot \left(\beta^{\text{hr}} \cdot \left(\overline{\mathrm{TT}}_t^{Nd} + \overline{\mathrm{TT}}_t^{Sd} + \varepsilon\right)\right)\right) \tag{9}$$

where β^{hr} is the cost per vehicle-hour and $\overline{\mathrm{TT}}_t^{\text{direction}}$ is the average end-to-end travel time in a specific direction and time period.

Overall Evaluation

Service users' waiting times and travel times as well as service provider savings or costs are calculated based on the comparison of AVL data of April 2017 and April 2018 and the estimated time-dependent passenger demand profile per line. The daily average difference per time period and passenger is calculated for each cost component. Then, these values are multiplied by the total number of passengers per time period and added up to obtain the overall daily savings/costs. Finally, time measures are multiplied by the value of time for commuting, which is assumed to be US\$14.38/hr for this case study area (based on White (*14*) for 2016 all-purposes value of travel time savings and adjusting the value by 1% each year).

The results are presented in Table 1. The assessment indicates annual savings of approximately US\$1.7 million associated with the field trial. Unlike what might be expected, holding buses does not necessarily slow down overall route operations. In this analysis, overall benefits in relation to passengers' travel time, hours of operation and fleet size can be observed. Even though service

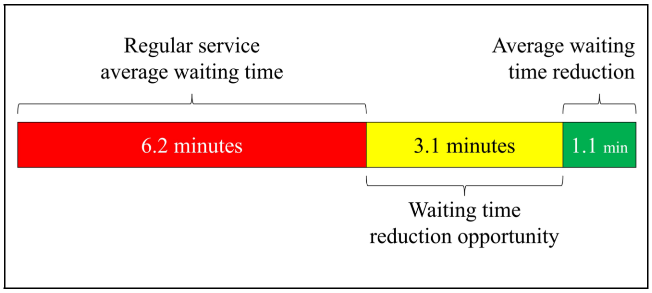

Figure 6. Case study waiting time decomposition.

regularity can lead to more even loads which can improve speeds, the headway control strategy is presumably not the only contributor explaining all these benefits. An analysis of the labor cost incurred by the experiment would enable an assessment of the effectiveness of the experiment execution. Some other facts that may explain these improvements may pertain to changes in traffic conditions related to roadworks and police enforcement. Notwithstanding, the most substantial change that is chiefly attributed to the control strategy pertains to waiting time savings, amounting to US$1.1 million per year of savings of social benefits for the passengers.

Conclusions

The potential advantages of headway control strategies on high-frequency routes have been examined and demonstrated in a large number of analytical and simulation studies. Nevertheless, the applicability of a headway-based holding strategy is still constrained by organizational and technical challenges, especially in circumstances in which buses are not equipped with monitoring displays and operators are not accustomed to follow such service management practices. In this study, we add to the accumulated empirical experience in implementing headway management by sharing the lessons gained from a field experiment in Washington, D.C.

The evaluation of the field experiment suggests that waiting time savings amount to a total of US$1.1 million per year. This outcome is achieved by reducing passenger waiting time by 1.1 min on average. Though substantial, further reductions can be potentially attained if key shortcomings in the experiment execution are overcome in the future. As can be seen in Figure 6, the additional potential waiting time reductions are approximately three times larger than those that have been already attained. Considering all time periods, the average headway was 12.4 min, which means that if services were running perfectly regularly, the average waiting time would be 6.2 min. The experiment reported in this study reduced the average waiting time from 10.4 min to 9.3 min, meaning that there are 3.1 min of excess waiting time remaining.

Service users expect service providers to leverage technological advancements. In the era of real-time journey planners and on-demand transport services, bus bunching is not only a costly phenomenon but also a visible indication of poor service performance. Real-time vehicle positioning data enables counteracting this otherwise inherent service deterioration. The design and deployment of data and communication systems has been traditionally driven by fleet circulation and fare collection considerations. Service management aspects should be taken into consideration when detailing the user cases, requirements, and purchasing details of automated data collection and communication systems to avoid hindering the applicability of operational and control schemes such as speed adjustments and holding strategies.

Shifting from schedule-based operations to headway management involves a substantial organizational shift for operators, street supervisors, and communications center staff. Many of the operational departments have been training staff on the importance of adhering to schedules for decades, meaning that significant training can be required to shift that mindset. To achieve this kind of change, it is important to communicate properly the positive impacts a measure like headway control might have for customers. Changing the performance metrics is hence an important aspect of the process. These new metrics should be passenger-oriented rather than operations-oriented and they should also be easily understandable for all the people involved in service provision and management.

Similar efforts to the one described here are staff-intensive, at least initially. The easiest way to deploy a trial in some specific routes to test the effectiveness of the headway-based approach is based on street supervisors and a proper communication channel. There are opportunities to mitigate the staff needs with in-vehicle technology, such as specialized tablet-like communications systems that indicate the exact amount of holding time or changes in speed between bus stops (*15*). The deployment of a driver display unit, as in Stockholm and the Netherlands, will involve initial investment cost but then practically eliminate the operational costs associated with communicating this strategy. Moreover, the quality and frequency of the information provided will be considerably superior to those attained with street supervisors, enabling greater service improvements than those achieved in the experiment. Although rail services have been running autonomously using headway control strategies in many cities for years, autonomous headway control has not yet been applied in the more complex operating conditions of bus services. The real-world effect of headway management strategies such as that in use at WMATA will provide valuable experience as autonomous buses are deployed in the coming years. However, none of these will happen before everyone in the agency understands and supports headway management.

Acknowledgments

This research was supported by the FONDECYT project number 1150657 and the scholarship funded by CONICYT for Ph.D. studies (CONICYT-PCHA/Doctorado Nacional/2016).

Author Contributions

The authors confirm contribution to the paper as follows: study conception: YC, OC, CV; data analysis design: OC, JS-P; data collection: YC, CV; analysis and interpretation of results: OC, JS-P; draft manuscript preparation: OC, JS-P, CV. All authors reviewed the results and approved the final version of the manuscript.

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The Standing Committee on Transit Management and Performance (AP010) peer-reviewed this paper (19-00624).