EVALUATING THE PERFORMANCE AND BENEFITS OF BUS PRIORITY, OPERATION AND CONTROL MEASURES

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ABSTRACT

Preferential measures are designed and implemented to improve transit performance and level-of-service. The combination of priority, operational and control measures can contribute to improved bus services that are often coined buses with high level of service (BHLS). The performance and benefits of implementing such measures should be systematically evaluated in order to support transport planners and operators. We present an evaluation framework and a detail sequence of steps for quantifying the impacts of transit preferential measures. The effects of service performance on travel times and costs are assessed by accounting for relations between reliability and waiting times, crowding and perceived travel times, and vehicle scheduling and operational costs. The evaluation integrates the implications of reliability on generalized passenger travel costs and operational costs. A field experiment in Stockholm, Sweden, where a series of measures were implemented on the busiest bus line is used as a case study for applying the proposed evaluation framework. The results suggest that the societal benefits amount to 47 million Swedish crowns on an annual basis, predominantly attributed to passenger time savings. The overall assessment of the impacts of preferential measures enables the comparison of different implementations, assess their effectiveness, prioritize alternative measures and provide a sound basis for motivating investments.
1. INTRODUCTION

Policy makers and transport planners design and implement a large range of preferential measures aimed to make transit a more attractive travel alternative. These measures are designed to reduce travel times and improve service management and reliability. Reliability is crucial for both passengers and operators since a reliable transit service leads to operational efficiency gains, improves users’ satisfaction and their loyalty and potentially attracts new users (1). A synthesis of evidence from Europe, North America and Australasia by Currie and Wallis (2) concluded that the largest increase in ridership was related to preferential measures that targeted improving reliability.

A substantial introduction of bus priority measures will result with buses of high level of service (BHLS) which have shown an explosive growth in the last decade (3). Even though there is evidently a great interest in implementing transit preferential measures, there is lack of a systematic analysis framework of evaluating their impacts. Results of preferential measures are often reported in terms of ridership and speed changes aimed to promote the transfer of best practices. In a review of primarily European BHLS schemes, Finn et al. (4) stressed the importance of developing a structured impact analysis and post-implementation evaluation of the impacts of benefits of related measures. An overall assessment of their impacts will enable the comparison of different implementations, assess their effectiveness, prioritize alternative measures and provide a sound basis for motivating investments in such measures.

The primary objective of this study is to develop a systematic evaluation framework for quantifying the impacts of a combination of transit preferential measures which encompasses both operators and passengers’ benefits. Travel time savings, reliability benefits and operational costs are evaluated in detailed in this paper. The approach taken in this study is therefore to classify measures based on their consequences for vehicle time components. Preferential measures are designed to affect dwell time, running time or both. For example, changing the boarding procedure impacts dwell time whereas introducing bus lanes influences running time and applying a new real-time control strategy could affect both.

This paper empirically analyses the impacts of a package of preferential measures by estimating the implications of reliability on the costs associated with the fleet operations and passenger travel time savings. The analysis is based on automated data collection which facilitates detailed performance monitoring and post-implementation evaluation. Preferential measures can potentially influence several operators and passengers’ cost factors and hence result with non-trivial global effects.

The remaining of this paper is organized as follows: we first review previous studies that evaluated the impacts of measures to improve transit performance, focusing on their analysis method and performance indicators (Section 2). Then, the proposed framework for evaluating preferential measures is described in detail – from data through performance metrics to societal costs (Section 3). A case study of a field experiment concerning a trunk bus line in Stockholm, Sweden, is presented (Section 4), followed by the results of applying the analysis framework to evaluate the benefits of this pilot study (Section 5). We then conclude with an overall assessment of the proposed approach, its limitations and suggest venues for future research (Section 6).

2. LITERATURE REVIEW

The impacts of preferential measures are either analyzed by conducting a before-after comparison of transit performance indicators or by simulating transit operations and investigating the expected effects. Simulation studies were often used to study the effects of real-time control strategies such as transit signal priority (5), stop skipping (6), holding (7)
and short-turning (8). Performance indicators such as headway variability, passenger waiting times and on-board delays were compared for alternative set-ups and control strategy design based on simplified line representation. While simulation models allow testing and estimating the effects of a large number of scenarios, there is lack of empirical evidence on the impacts of control strategies, in particular when they are combined with other BHLS features.

Table 1 summarizes the analysis approach, preferential measures considered, performance indicators and main findings for empirical studies of bus preferential measures in the last fifteen years. It is evident that the impact of a large range of measures - including the introduction of bus lanes, transit signal prioritization, smart card fare collection, limited-stop operations, articulated buses – were examined in previous studies. With the exception of Diab and El-Geneidy (9), previous studies considered the impact of a single measure. Empirical studies were most commonly facilitated by AVL data, often supported by automatic passenger counts (APC) to gain information on dwell times or passenger demand.

Most of the studies considered only vehicle-related performance metrics with vehicle trip time metrics been most commonly used, whereas effects on passenger travel time received less attention in the literature (Table 1). Moreover, even when both vehicle and passenger travel times were investigated, changes in selected performance metrics were investigated rather than monetarizing the benefits associated with the implemented measures, preventing the overall assessment of BHLS-related investments. Adopting a multi-criteria approach, Cascajo and Monzon (10) performed an exhaustive assessment of BHLS-related measures, where the change in key performance indicators was aggregated based on normative judgment.

In line with previous studies that undertook an empirical post-implementation approach, this study develops an analytical framework that details a work process for evaluating the impacts of service improvement strategies. As described in the following section, the effects of service performance on travel times and costs are assessed by accounting for relations between reliability and waiting times, crowding and perceived travel times, and vehicle scheduling and operational costs.

**TABLE 1 Empirical studies that analyzed the impacts of preferential measures on bus performance**

<table>
<thead>
<tr>
<th>Study</th>
<th>Analysis method and data sources</th>
<th>Implemented measures</th>
<th>Vehicle metrics</th>
<th>Passenger metrics</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chira-Chavala, &amp; Coifman, 1996 (11)</td>
<td>Statistical analysis, Manual data</td>
<td>Smart card</td>
<td>Dwell time</td>
<td>Boarding time</td>
<td>Reduction in passenger boarding times and vehicle dwell times.</td>
</tr>
<tr>
<td>Strathman et al., 2002 (12)</td>
<td>Linear regression, Manual data + AVL, APC</td>
<td>Bus dispatching system</td>
<td>Trip time</td>
<td>Waiting time In-vehicle time</td>
<td>Passenger waiting and in-vehicle times decreased, passenger travel time reduced and operator trip time improved.</td>
</tr>
<tr>
<td>Kimpel et al., 2005 (13)</td>
<td>Linear regression, AVL, APC</td>
<td>Transit signal priority</td>
<td>Trip time, on-time performance</td>
<td>Excess waiting time</td>
<td>Changes in bus performance are not consistent across time periods.</td>
</tr>
</tbody>
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<tbody>
<tr>
<td>El-Geneidy et al., 2006 (14)</td>
<td>Linear regression AVL, APC</td>
<td>bus stop consolidation</td>
<td>Trip time</td>
<td>Headway</td>
<td>Bus trip times improved; no significant impact on trip time variation or headway variation.</td>
</tr>
<tr>
<td>Surprenant-Legault &amp; El-Geneidy, 2011 (15)</td>
<td>Linear regression + logit models AVL, APC</td>
<td>Reserved bus lanes</td>
<td>Trip time, on-time performance</td>
<td></td>
<td>Total trip time saving and improved on-time performance; decline in the variability of trip time and delay.</td>
</tr>
<tr>
<td>El-Geneidy &amp; Vijayakumar, 2011 (16)</td>
<td>Linear regression AVL, APC</td>
<td>Articulated buses</td>
<td>Trip time, Dwell time</td>
<td></td>
<td>Dwell time savings, increase in running time; overall increase in total trip time.</td>
</tr>
<tr>
<td>Diab and El-Geneidy, 2012 (9)</td>
<td>Linear regression AVL, APC</td>
<td>Smart card, limited-stop bus service, bus lanes, articulated buses, and transit signal priority</td>
<td>Trip time</td>
<td></td>
<td>Limited-stop bus service, reserved bus lane, and operation of TSP decrease trip time; smart card and articulated buses increase trip time.</td>
</tr>
</tbody>
</table>

3. EVALUATION FRAMEWORK

The proposed evaluation framework constitutes a systematic process to quantify and assess the impacts of preferential measures on service users and providers in monetary terms. This process comprises a sequence of steps as shown in Figure 1. First, the change in vehicle performance is investigated through analysing service speed and reliability metrics using AVL data. Second, the operator and passengers’ benefits are derived from the change in vehicle performance. Improvement in vehicle performance by delivering faster and more reliable service can potentially lead to a reduction in operational cost and passenger travel time. Quantifying the overall passengers’ time gain or loss requires information on passenger demand patterns. Then changes in passenger travel time are separately calculated for the waiting time and in-vehicle time by considering vehicle performance metrics and demand pattern. The nominal and perceived travel time components are cumulated to calculate the total and perceived passenger travel time, respectively. Third, both the operator and passengers’ benefits are converted into monetary terms by accounting for operational cost factors and passengers’ value of time. The combination of these cost components yields the overall societal benefits attributed to the introduction of the preferential measures.
In the following, the sequence of steps illustrated in Figure 1 is described in detail along with the mathematical formulation of service performance metrics. Let us consider a single bus line that is operated in two directions and each direction consists of an ordered set of stops, \( S = \{s_1, ..., s_{|S|} \} \), where \( s_i \) is the \( i \)-th stop. The data concerning each bus trip \( k \) in the AVL records consists of three data series: visited stops, arrival times and departure times. \( t_{k,s_i}^a \) and \( t_{k,s_i}^d \) denote the arrival and departure time of trip \( k \in K \) at/from stop \( s_i \in S \), respectively. \( K \) is the set of bus trips scheduled for the bus line under consideration.

### 3.1 Vehicle performance

#### 3.1.1 Vehicle running time and dwell time

Vehicle trip time consists of running time between successive stops and dwell time at stops, which together determine vehicle trajectory. The running time of trip \( k \) on a line segment connecting two successive stops, \( s_i \) and \( s_{i+1} \), is defined as

\[
t_{k,s_i}^{\text{running}} = t_{k,s_{i+1}}^a - t_{k,s_i}^d \tag{1}
\]

The dwell time for the same trip at stop \( s_i \) is

\[
t_{k,s_i}^{\text{dwell}} = t_{k,s_i}^d - t_{k,s_i}^a \tag{2}
\]
3.1.2 Reliability

Preferential measures are often designed to improve reliability which refers to the extent to which the service deviates from the planning. Since the focus of this study is on high-frequency services, reliability is measured in terms of regularity, the deviation from the planned headway. The observed headway between two consecutive buses is computed as

$$h_{k,s_i}^o = t_{k,s_i}^d - t_{k-1,s_i}^d$$ (3)

Various metrics of service reliability can be constructed based on the distribution of headways as described by Cats (17). Headway coefficient of variation at stop \(s_i\), \(CV(h_{s_i})\) – the ratio between the standard deviation and the mean value of observed headways at a certain stop - provides a sound and normalized measure of service regularity and is defined as

$$CV(h_{s_i}) = \sqrt{\frac{\sum_{k \in |K|} \frac{1}{|K|} \sum_{s_{i-1} \in |S|} h_{k,s_i}^o^2}{\left( \sum_{k \in |K|} h_{k,s_i}^o \right)^2}}$$ (4)

This indicator can be further aggregated by taking the average value over all stops along the route.

3.1.3 Demand patterns

Depending on the details of the APC and AFC available, passenger demand patterns can be either constructed or estimated. The on-board load profile is constructed by subtracting the accumulated number of alighting passengers from the accumulated number of boarding passengers:

$$l_{k,s_i} = \sum_{m=1}^{i} [b_{k,s_m} - a_{k,s_m}]$$ (5)

Where \(l_{k,s_i}\) denotes the number of on-board passengers between stops \(s_i\) and \(s_{i+1}\), and \(b_{k,s_m}\) and \(a_{k,s_m}\) are the number of passengers boarding and alighting trip \(k\) at stop \(s_m\), respectively. The demand matrix of each trip can be estimated by performing an iterative proportional fitting of the empirically logged total boarding and alighting margins per stop.

3.2 Travel time effects

3.2.1 Total vehicle trip time

From the operator’s perspective, the main determinant of line efficiency and operational costs is the time required to perform a trip and its predictability. Total vehicle trip time corresponds to the overall time that elapses between the origin terminal stop, \(s_1\), and the last stop, \(s_{|S|}\), calculated as follows

$$\overline{TT}^{s_1 \rightarrow s_{|S|}} = \frac{1}{|K|} \sum_{k \in |K|} \sum_{i=1}^{|S|-1} t_{k,s_i}^{dwell} + t_{k,s_i}^{running}$$ (6)

Similarly it is calculated for the other direction leading towards \(s_1\) denoted by \(\overline{TT}^{s_{|S|} \rightarrow s_1}\).

3.2.2 Passenger waiting time
For a high frequency line, passengers are assumed to arrive at stops without consulting the timetable. Passenger waiting time is therefore determined by the distribution of bus arrivals and can be approximated by its well-known relationship with service regularity – mean and variation of headways - which was established by Osuna and Newell (18). However, the idealized assumptions involved in their formulation can be substituted by the actual disaggregate data concerning vehicle headway and respective passenger volumes. The average passenger’s actual wait time (AWT) for trip set $K$ is thus estimated by

$$AWT = \frac{1}{\sum_{k \in K} \sum_{i=1}^{S} b_{k,s_i} \sum_{i=1}^{S-1} b_{k,s_i}} \cdot \frac{h_{k,s_i}^p - h_{k,s_i}^o}{2}$$  \hspace{1cm} (7)$$

Where $h_{k,s_i}^o$ denotes observed headway upon bus-trip $k$ arrives at stop $s_i$. $b_{k,s_i}$ is the number of passengers boarding trip $k$ at stop $s_i$ heading to downstream destinations.

AWT can be contrasted with the average waiting time that is expected in case of a perfectly regular service, scheduled wait time (SWT). The latter is calculated by plugging $h_{k,s_i}^o = h_{k,s_i}^p \forall k, s_i$ in Eq. 7, where $h_{k,s_i}^p$ is the planned headway upon bus-trip $k$ arrives at stop $s_i$. Better service regularity yields shorter passenger waiting times. This effect can be measured using the excess waiting time (EWT), the additional waiting time due to service irregularity, can then be defined as the difference between AWT and SWT:

$$EWT = \frac{1}{\sum_{k \in K} \sum_{i=1}^{S} b_{k,s_i} \sum_{i=1}^{S-1} b_{k,s_i}} \cdot \frac{h_{k,s_i}^p - h_{k,s_i}^o}{2}$$  \hspace{1cm} (8)$$

EWT is used by Transport for London (19) for monitoring service reliability as experienced by transit users.

### 3.2.3 Passenger in-vehicle time

The average passenger in-vehicle time (AIVT) between stop $s_i$ and a downstream stop $s_j$ measured for example in passenger-minutes can be obtained as follows

$$AIVT_{s_i,s_j} = \frac{1}{\sum_{k \in K} \sum_{m=1}^{S} q_{s_i,s_j,k}} \sum_{k \in K} q_{s_i,s_j,k} \cdot \left[ \sum_{m=1}^{j-1} t_{k,s_m}^{dwell} + t_{k,s_m}^{running} \right] s_i, s_j \in S, i < j$$  \hspace{1cm} (9)$$

Where $q_{s_i,s_j,k}$ is the number of passengers travelling on trip $k$ from stop $s_i$ to stop $s_j$. An aggregate measure at the route level can be calculated by the summation of the above equation for all relevant pairs of origin-destination stops.

### 3.2.4 Passenger travel time

The average nominal travel time (ATT) experienced by passengers along the line is obtained by summing the average actual waiting time and the average in-vehicle time

$$ATT = AWT + AIVT$$  \hspace{1cm} (10)$$

### 3.3 Monetary values

#### 3.3.1 Operator costs

From the point of view of the service provider, the deployment of preferential measures can potentially influence the costs associated with the line concerned due to its implications of fleet size requirements. The common practice among bus operators is to use a certain
percentile of the travel time distribution to determine the number of vehicles required to
operate the service. Assuming no interlining, the number of vehicles required for running a
certain line with a given planned headway, \( h^P \), can be approximated by

\[
z = \frac{p_\alpha(TT^{S_1 \to S_2}) + p_\alpha(TT^{S_2 \to S_3}) + \varepsilon}{h^P}
\]  

(11)

Where \( p_\alpha(TT^{S_1 \to S_2}) \) and \( p_\alpha(TT^{S_2 \to S_3}) \) are the \( \alpha \)th percentile of the vehicle total trip time
distribution for each line-direction, with typical values being \( \alpha = 85 \) or \( \alpha = 90 \) (20). \( \varepsilon \) is the
average recovery and layover time allocated in the terminal. The nominator in this equation is
known as the cycle time, the most important determinant of fleet size and hence the
operational costs.

The cost associated with operating a given fleet size comprises of depreciation cost of
vehicle purchasing, cost per vehicle-km and cost per vehicle-hour. The former is the
investment cost whereas the latter two constitute the variable cost which reflects fuel, labor
and maintenance costs. The total operation cost can thus be expressed as

\[
c^{\text{operator}} = \beta^{\text{fixed}} \cdot z + \tau \cdot \frac{3600}{h^P} \cdot [\beta^{\text{hr}} \cdot (\text{TT}^{S_1 \to S_2} + \text{TT}^{S_2 \to S_3} + \varepsilon) + \beta^{\text{km}} \cdot \text{TT}^{S_1 \to S_2} + \gamma^{S_2 \to S_3}] 
\]

(12)

Where \( \beta^{\text{fixed}} \), \( \beta^{\text{hr}} \) and \( \beta^{\text{km}} \) are the daily fixed, per vehicle-hour and per vehicle-kilometer
operation cost parameter. \( \tau \) denotes the number of operation hours per day and \( \text{TT}^{S_1 \to S_2} \) and
\( \gamma^{S_2 \to S_3} \) are the total line-direction length in kilometers.

### 3.3.2 Passenger costs

Changes in passenger travel times can be monetarized by considering the value-of-time
associated with each travel time component. An increase in on-board crowding levels
influences negatively passengers’ perception of travel experience. In-vehicle time multipliers
can be deployed to estimate the adverse effects experienced by passengers. The multipliers
suggested by Wardman and Whelan (21) based on a meta-analysis allow discriminating the
effect of on-board discomfort between sitting and standing passengers for a discrete set of
ratios between on-board load (\( l_{k,s_i} \)) and number of seats (\( v_k^{\text{seat}} \)), varying between 50% and
200%. The values provided in Wardman and Whelan (21) were regressed against the on-
board crowding level in order to assess the in-vehicle multipliers for sitting and standing
passengers for any intermediate level, resulting with

\[
\beta^{\text{sitting}}_{k,s_i} = 0.67 + 0.5 \cdot \gamma_{k,s_i}
\]

\[
\beta^{\text{standing}}_{k,s_i} = 0.85 + 0.9 \cdot \gamma_{k,s_i}, \text{ where } \gamma_{k,s_i} = l_{k,s_i}/v_k^{\text{seat}} \text{ is the load factor and } \beta^{\text{standing}}_{k,s_i}
\]

is relevant only in case \( \gamma_{k,s_i} > 1 \). The perceived in-vehicle time for passengers travelling
between stops \( s_i \) and \( s_{i+1} \) for trip \( k \) is then

\[
P^{\text{IVT}}_{k,s_i} = \min\left(\gamma_{k,s_i}, 1\right) \cdot v_k^{\text{seat}} \cdot \beta^{\text{sitting}}_{k,s_i} + \max\left(0, \left(\gamma_{k,s_i} - 1\right)\right) \cdot \left(l_{k,s_i} - v_k^{\text{seat}}\right) \cdot \beta^{\text{standing}}_{k,s_i}
\]

(13)

The total passenger cost, \( c^{\text{passengers}} \), in economic welfare terms is the sum over all the
generalized travel cost or the perceived average travel time for all passengers

\[
c^{\text{passengers}} = VOT \cdot \left(\beta^{\text{WT}} \cdot AWT + \frac{1}{\sum_{k \in K} \sum_{s_i=1}^{|S_i|-1} l_{k,s_i}} \cdot \sum_{k \in K} \sum_{s_i=1}^{|S_i|-1} P^{\text{IVT}}_{k,s_i} \cdot \sum_{s_i=1}^{|S_i|-1} b_{k,s_i}\right)
\]

(14)
Where $V_oT$ is the value of time used for project appraisal and $\beta^{WT}$ is the relative disutility associated with waiting as compared with in-vehicle time.

### 3.3.3 Societal costs

By adding the operator and passenger costs, the total societal costs are obtained

$$c_{societal} = c_{operator} + c_{passenger} \quad (15)$$

The effects - gains or losses – caused by the implementation of preferential measures can be assessed by comparing the before and after societal costs.

### 4. CASE STUDY

The evaluation framework described in the previous section was applied to the case study of a field experiment on trunk line 4 in Stockholm, Sweden. With more than 65,000 passengers per day and an average planned headway of 5 minutes, line 4 is the busiest and most frequent bus line in Sweden. The entire fleet comprises of low-floor articulated buses with 55 seats. The crescent-like route is 12 km long.

As part of its urban mobility strategy (22), Stockholm City aims to increase the average commercial speed of the trunk bus lines from the current level of 13 km/hr to 20 km/hr by 2030. This objective is part of its planning aim to increase the speed and reliability of high capacity means of transport. In order to attain this objective, a series of measures were designed and tested on line 4. A field experiment of priority, control and operational measures took place between March 17 and June 19 in spring 2014. This pilot study is a follow-up on previous field experiments that tested a real-time control strategy on other lines in Stockholm inner-city and concluded that additional measures can potentially supplement the proposed strategy (17). The pilot study is designed to improve regularity, provide faster boarding and alighting procedures and less crowded bus services. These improvements should thus contribute to an increase in service reliability and a decrease in travel times.
The evaluation of the pilot study was based on automated data collection. Automatic Vehicle Location (AVL) and Automatic Passenger Counts (APC) data were extracted for the trial period as well as the corresponding period in 2013 for all weekdays between 7 AM and 7 PM. The AVL database consists of more than 24,000 trip-records for each analysis period. These data include the time stamp of bus arrival and departure times from each stop along the route for each bus trip. Unlike AVL, a sample of 15% of the buses are equipped with APC in Stockholm. In the absence of complete information on passenger flows, the line origin-destination matrix was estimated based on the average numbers of boarding and alighting passengers at each stop using an iterative proportional fitting method. In this study, the effects of several measures that were implemented simultaneously are investigated by applying the evaluation framework for comparing the periods before and after implementation. The most important measures that were implemented by Stockholm City and the bus operator were:

- **Increase stop spacing** – four stops were cancelled on each direction (out of 30 and 31 stops in the northbound and southbound directions, respectively, Figure 2). This measure led to an increase in the average distance between stops from 413 to 479 meters, reaching the minimum level recommended in Finn et al. (4) for BHLS.

- **Changing passenger boarding procedure** - the boarding regime in Stockholm restricts to the front door and requires validating a prepaid ticket under driver’s inspection, while alighting is made from the rear doors. This regime was changed during the trial period to permit boarding from the third door where a conductor validated tickets upon boarding from this door. This measure is expected to ease dwell time by decreasing boarding time.

- **Introducing bus lanes** - a total of 3 km additional bus lanes on some line sections were introduced during the trial period (Figure 2). Reserved bus lanes are expected to shorten bus running time and reduce its variability.

- **Regularity-driven control and operations** – switching from schedule-based dispatching and holding control at a limited set of time point stops (TPS) to a continuous real-time headway-based scheme (17). This measure is designed to maintain regular headways and avoid bus bunching, one of the biggest problems in operating high-frequency services. Buses were dispatched from origin terminals based on the headways from the preceding bus and the headway from the successive bus. Drivers were instructed to monitor their relative position by adjusting their speed or holding at stops whenever needed based on a real-time indicator that was projected through the bus PC display.
The pilot study includes thus the implementation of link-related (introducing bus lanes), stop-related (changing passenger boarding procedure) and operation and control (increase stop spacing, regularity-driven control and operations) measures. In addition to the aforementioned measures, other minor preferential measures were implemented during the trial period, including: removing a number of parking spaces, redesigning cycle paths conflicting with bus traffic, revising traffic signal to better prioritize bus traffic, adding new stop prohibition area during peak periods and increased enforcement of illegally parked vehicles, all of which are link-related measures.

5. RESULTS

The analysis framework presented in Section 3 was applied to evaluate the implications of the measures that were implemented in the case study described in the previous section. Following the steps presented in Section 3, we first analyze vehicle performance (Section 5.1) in terms of speed and reliability, assessing vehicle and passenger time components (5.2) and finally evaluating the benefits of the field experiment by comparing the operational and travel costs.

5.1. Vehicle performance

The AVL data was first processed to analyze vehicle trajectories by calculating vehicle running and dwell times. Figure 3 illustrates the average vehicle trajectory using a time-space diagram for the before and after periods. Time point stops are marked in the figure. It is evident that vehicle travel times are constantly shorter in 2014 than in 2013. The reverse of slope values for line segments in Figure 3 correspond to the average vehicle speeds. There is a modest but clear increase in bus speeds along both line directions with the average speed increasing by 6-7%. The average (running) speed increased from 18.5 and 18.2 to 19.8 and 19.5 km/h for the northbound and southbound directions, respectively. A notable speed improvement of 27% occurred on segments where a bus lane or traffic signal priority adjustments was introduced. In contrast, no global trend could be observed for dwell time.
change when comparing the two periods. Overall, the average total dwell time per visited stop for a complete trip slightly increased in both directions. Changes in dwell times were further investigated by estimating alternative linear regression models with boarding and alighting counts as the independent variables. The estimation results suggest that while the service time per passenger decreased by approximately 10%, the constant time lost at stop increased by 20% for both line directions. While the decrease in passenger service time can be attributed to the additional boarding channel, the prolonged constant time is presumably caused by the particular implementation of the boarding regime where conductors stepped out of the bus to validate tickets as well as changes in the holding control.

FIGURE 3 Average vehicle time-space diagrams for before and after periods

Even though the planned headway almost uniformly equals five minutes throughout the analysis and period, the actual headway between consecutive trips varies considerably from one bus to the other. Histograms of all observed headways in 2013 and 2014 are presented in Figure 4. Headway distribution became narrower during the pilot study period indicating that the service became much more regular. The share of very short or very long headways — those that deviate by more than 50% from the average headway — decreased from 32% to 24%.
The coefficient of variation of the headway offers a global indicator of service regularity (Eq. 4). The average daily coefficient of variation of the headways declined on average by 15% from 0.80 and 0.70 for the north- and southbound directions, respectively, to 0.67 and 0.60. The results indicate that service regularity improved along the entire route in both directions with an ascending improvement in stops located in the middle and end of the routes.

5.2 Travel time effects

Total vehicle trip times were analyzed by plotting their distribution as shown in Figure 5. Two trends are clearly visible when comparing 2013 and 2014 – the distributions shifted to the left and became narrower, implying shorter and more reliable trip times. The mean and 90th percentile values are displayed in Figure 5. The average vehicle trip time became 6% shorter in both directions, yielding a reduction of 6:46 min in the average cycle time shorter in 2014 as compared to 2013. The smaller tail results with a decrease of 7% in the 90th percentile of both directions indicating that fewer trips are exceedingly long. The latter enables avoiding the propagation of delays from one trip to the other and thus delivering a more reliable service for passengers and yields a more reliable vehicle and crew scheduling.
We now turn to calculating passenger travel time. Given line 4 high frequency, passengers are assumed to arrive at stops without consulting the timetable. Passenger waiting time is therefore determined by the distribution of bus arrivals. More specifically, passenger average waiting time depends on the average headway and headway variability. The average headway remained unchanged between the two periods, whereas headway variability has decreased in the pilot study. Excess waiting time, $EWT$, was calculated based on the disaggregate headways at each stop. Overall, $EWT$ decreased by 25-27%. This stems from the fact the more passengers experience the long headways and therefore reducing the long tail of headway distribution results with waiting time gains. Moreover, the stops where great improvements in headway variations are obtained are also the stops with high passenger demand. This resulted with a 6-8% decrease in the average waiting time, $AWT$, for the northbound and southbound directions, respectively.
In addition to waiting times, in-vehicle times were calculated for each pair of stops along the line. After accounting for demand patterns based on the estimated OD matrix, the average in-vehicle time decreased during the trial period by 7.5% and 15% for the north- and southbound directions, respectively. Figure 6 illustrates the percentage difference in average passenger in-vehicle time between 2014 and 2013. Considerable in-vehicle time reductions were attained for most od-pairs, in particular for mid-range trips where the percentage-wise reduction is significant and high passenger volumes.

![Graph showing percentage change in in-vehicle times for origin-destination pairs, northbound direction](image)

**FIGURE 6** Percentage change in in-vehicle times for origin-destination pairs, northbound direction

The average nominal total passenger travel time, $ATT$, declined from 22:37 and 14:19 to 20:58 and 12:25 minutes for the north- and southbound directions, respectively. In-vehicle time savings account for more than 80% of these time gains.

5.3 Monetary values

First, the operational costs are calculated by examining the effects of the pilot study on fleet size. In order to determine the fleet size required to operate the case study line with the required planned headway, the 90th percentile of the total vehicle trip time and a layover time of 10 minutes were assigned to Eq. 11 ($\alpha = 90\%$; $\epsilon = 10\text{min}$). This approximation yields 28 buses in 2013 which can be reduced to 26 buses based on the performance attained during the field experiment. Alternatively, the same fleet could be using for offering a higher frequency.

The cost associated with operating estimated fleet sizes for the before and after periods can then be calculated. The operation cost parameters in Eq. 12 depend on vehicle type and service area. The values of $\beta^{\text{fixed}}$, $\beta^{\text{hr}}$ and $\beta^{\text{km}}$ are 1,970 SEK/day (SEK – Swedish crowns; exchange rate €1 = SEK 9.22), 480 SEK/km and 9.5 SEK/hour, respectively, for low floor articulated buses operating in urban areas in Sweden (23). The before-after difference in operational cost is 11,716 SEK per day which amount to approximately 3.5 million SEK per year.
Second, passenger perceived in-vehicle time is computed according to Eq. 14 by considering the sitting and standing multiplier functions. The perceived passenger travel time is obtained by adding the perceived average in-vehicle time to the weighted average waiting time by $b^W_T = 2$. The output is multiplied by the value of time in order to express passenger costs in monetary terms (Eq. 14). Passenger perceived travel time saving attributed to introduction of the preferential measures yields 2.8 SEK saving per boarding based on the value of time recommended by the Stockholm County council of 69 SEK per hour. This is equivalent to almost 43.5 million SEK time saving per year only for 7AM to 7PM operations on weekdays.

Finally, the summation of the operator and passenger cost saving results with the total societal benefits. The implementation of the measures included in the field experiment lead to societal benefits that worth 47 million SEK on an annual basis.

6. Conclusion

Different preferential measures have been extensively implemented in transit systems around the world to improve system performance and level of service. However, there is lack of a systematic evaluation of their impacts. The planning, operations and real-time management of transit systems requires a comprehensive evaluation on deployed measures in order to compare the effectiveness of different implementations, prioritize alternative measures and provide a sound basis for motivating investments in such measures. This paper presents a systematic evaluation framework and a detail sequence of steps for quantifying the impacts of a combination of transit preferential measures. The evaluation encompasses both passenger and operators benefits. In contrast to previous studies, the approach taken in this study seeks to integrate all the trips components that are influenced by the deployed measures and assess their implications on operators and passengers’ costs. The proposed framework is based on automated and passive data collection which facilitates detailed performance monitoring and post-implementation evaluation without imposing any additional data collection requirements.

The proposed evaluation framework was applied for analyzing the effects of a combination of preferential measures that were introduced to increase the speed and reliability of bus line 4 in Stockholm. The measures resulted with a faster and more regular service, yielding shorter waiting time and in-vehicle times for most passenger origin-destinations. Moreover, the improvement in service performance led to a shorter scheduled trip time and hence smaller fleet size requirements. We estimate that the societal benefit associated with the introduced measures amounts to 47 million SEK per year (approximately 5.1 million euro) only for 7AM to 7PM operations on weekdays. The vast majority of these benefits (92.5%) are attributed to passenger travel time savings. The passenger-based performance metrics used in this study could be further enhanced if detailed APC or smartcard transaction data are available.

The case study evaluation contributed to a more evidence-based planning and public debate in Stockholm by providing an estimate of the benefits which can be compared with investment costs and alternative investments (e.g. converting trunk line 4 into a light rail train). The simultaneous introduction of several preferential measures did not allow to empirically assess the contribution of each measure to the overall impact. Future studies could simulate each measure and combination of measures separately in order to estimate their individual as well as synergy effects.

The evaluation of BHLS-related measures was restricted in this study to their primary and secondary implications on passenger travel times and operational costs for the line under consideration. A network-level assessment may consider also induced demand to the improved line due to route choice or modal choice effects as well as changes in accessibility.
due to changes in stopping patterns. Even non-users might also be influenced, for example prolonged travel times due to the prioritization of transit services.

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