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Evaluating the Impacts and Benefits of Public Transport Design and Operational Measures

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Abstract

Design and operational measures are designed and implemented to improve public transport performance and level-of-service. In the case of urban bus systems, priority, operational and control measures are aimed to elevate bus services to buses with high level of service (BHLS). Even though there is an explosive growth in design and operational measures implementation and growing research interest in investigating their impact on performance indicators, there is lack of a systematic evaluation of their benefits. We present an evaluation framework and a detail sequence of steps for quantifying the impacts of public transport design and operational 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. We deploy the proposed evaluation framework to a field experiment in Stockholm where a series of measures were implemented on the busiest bus line. The results suggest that the total passenger and operator benefits amount to 36.8 million Swedish crowns on an annual basis. The overall assessment of the impacts of design and operational measures enables the comparison of different implementations, assess their effectiveness, prioritize alternative measures and provide a sound basis for motivating investments.

Keywords: Design and Operational Measures, Service Reliability, Empirical Evaluation ,Bus with High Level of Service

1. Introduction

Policy makers and transport planners design and implement a large range of design and operational measures aimed to make public transport a more attractive travel alternative. These measures are designed to reduce travel times and improve service reliability. Reliability is crucial for both passengers and operators since a reliable public transport service leads to operational efficiency gains, improves users' satisfaction and their loyalty and potentially attracts new users (Perk et al. 2008). A synthesis of evidence from Europe, North America and Australasia by Currie and Wallis (2008) concluded that the largest increase in ridership was related to design and operational 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 (Hidalgo and Gutierrez 2013). BHLS often serve a function between regular urban bus and light rail train in European cities in terms of their position in network hierarchy, right-of-way, capacity and the cost associated with their construction and operations. The Transit Capacity and Quality of Service Manual (TCRP 2003) provides guidelines for estimating the expected performance impacts of public transport design factors. While these guidelines are useful for substantiating design choices and benchmarking system performance, they do not allow estimating the overall benefits associated with design and operational measures.

Even though there is evidently a great interest in implementing public transport design and operational measures, there is lack of a systematic analysis framework of performing an ex-ante evaluation of their impacts. Results of design and operational 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. (2011) 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 public transport design and operational 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 goes beyond measuring the improvements in vehicle and service performance by quantifying and monetarizing the operational and travel time savings associated with the implemented measures.

This paper empirically analyses the impacts of a package of design and operational 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. Design and operational measures can potentially influence several operators and passengers' cost factors and hence result with non-trivial global effects. For example, holding at stops prolongs dwell times for vehicle and on-board delay for passengers whilst potentially increasing service reliability and hence reduce passenger waiting time. The implications of such measures on vehicle scheduling and consequently operational costs often remain unknown because of the contradictory effects of mean vehicle trip time and its variability. A comprehensive analysis is thus needed to consider operators and passengers' perspective in order to evaluate the deployment of design and operational measures.

The remaining of this paper is organized as follows: we first review previous studies that evaluated the impacts of measures to improve public transport performance, focusing on their analysis method and performance indicators (Section 2). Then, the proposed framework for evaluating design and operational measures is described in detail – from data through performance metrics to 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 growing availability of automated data collection techniques and in particular automatic vehicle location (AVL) data enable researchers to analyze public transport operations and the determinants of service performance. Most commonly, the explanatory variable of vehicle trip times were analyzed in order to measure the importance of route attributes such as length, number of stops, passenger activity at stops and bus stop spacing (e.g. Berkow et al. 2009, Li and Bertini 2009,). The effect of driver heterogeneity on running times at the route-level was studied by Strathman et al. (2002) and Mishalani et al. (2008). Mazloumi et al. (2010) analyzed vehicle trip time variability and its relation to schedule adherence. While these studies shed light on the main determinants of public transport vehicle travel time, they do not allow assessing the impacts of design and operational measures.

The impacts of design and operational measures are either analyzed by conducting a before-after comparison of public transport performance indicators or by simulating public transport operations and investigating the expected effects. Simulation studies were often used to study the effects of real-time control strategies such as public transport signal priority (Chandrasekar et al. 2002), stop skipping (Sun and Hickman, 2005), holding (Cats et al. 2011) and short-turning (Tirachini et al., 2011). 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, design and operational measures considered, performance indicators and main findings for empirical studies of bus design and operational measures in the last fifteen years. It is evident that the impact of a large range of measures - including the introduction of bus lanes, public transport signal prioritization, smart card fare collection, limited-stop operations, articulated buses – were examined in previous studies. With the exception of Diab and El-Geneidy (2013), 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) or automatic fare collection (AFC) 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. While Tirachini (2013) monetarized the benefits of better fare collection on passengers time, operation cost and air pollution, he evaluated a single measure and travel times were estimated rather than deduced from automated data. Adopting a multi-criteria approach, Cascajo and Monzon (2014) 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 design and operational measures on bus performance

Study	**Analysis method and data sources**	**Implemented measures**	**Vehicle metrics**	**Passenger metrics**	**Main findings**
Chira-Chavala, & Coifman, 1996	Statistical analysis Manual data	Smart card (instead of fare box)	Dwell time	Boarding time	Reduction in passenger boarding times and vehicle dwell times.
Strathman et al., 2002	Linear regression Manual data + AVL, APC	Bus dispatching system	Trip time	Waiting time In-vehicle time	Passenger waiting and in-vehicle times decreased, passenger travel time reduced and operator trip time improved.
Dueker et al., 2004	Linear regression AVL, APC	Low floor buses	Dwell time		Reduction in vehicle dwell times.
Kimpel et al., 2005	Linear regression AVL, APC	Transit signal priority	Trip time, on-time performance	Excess waiting time	Changes in bus performance are not consistent across time periods.
El-Geneidy et al., 2006	Linear regression AVL, APC	Bus stop consolidation	Trip time Headway		Bus trip times improved; no significant impact on trip time variation or headway variation.
Milkovits, 2008	Linear regression AVL, APC	Smart cards (instead magnetic stripe fare tickets)	Dwell time		Smart card improve dwell time, but only in uncrowded situations.
van Oort and van Nes (2009)	Statistical analysis Data not specified	Foreword-headway holding control	On-time performance	Travel time	Mean and variation of passenger travel times decreased and punctuality and regularity improved.

Study	Analysis method and data sources	Implemented measures	Vehicle metrics	Passenger metrics	Main findings
Surprenant-Legault & El-Geneidy, 2011	Linear regression + logit models AVL, APC	Reserved bus lanes	Trip time, on-time performance		Total trip time saving and improved on-time performance; decline in the variability of trip time and delay.
El-Geneidy & Vijayakumar, 2011	Linear regression AVL, APC	Articulated buses	Trip time, Dwell time		Dwell time savings, increase in running time; overall increase in total trip time.
Diab and El-Geneidy, 2013	Linear regression AVL, APC	Smart card, limited-stop bus service, bus lanes, articulated buses, and transit signal priority	Trip time and Trip time deviation		Limited-stop bus service, reserved bus lane, and operation of TSP decrease trip time; smart card and articulated buses increase trip time. Smart card, reserved bus lane, and articulated buses increase trip time deviation from schedules; limited-stop bus service, and operation of TSP have no significant effect on trip time variation.
Cats (2014)	Statistical analysis AVL	Even-headway holding control	Trip time, Dwell time	Waiting time	Dwell time and passenger waiting times improved. Bus trip time variability decreased; no significant change in mean trip time.
Gibson et al. 2015	Linear regression AVL, AFC, and signal settings	Median reserved bus lanes		Access time In-vehicle time	In-vehicle time improved , increase in access time

3. Evaluation Framework

The proposed evaluation framework constitutes a systematic process to quantify and assess the impacts of design and operational 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 analyzing service speed and reliability metrics using AVL data. Design and operational measures are classified based on their consequences for vehicle time components: link-related (e.g. bus lanes, signal priority, elevated crossing), stop-related (e.g. docking guidance, boarding procedure) and operations and control (e.g. stopping pattern, holding strategy). These classes of measures are expected to impact running time between stops, dwell time at stops or both time components, respectively. 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. This information can be retrieved from either APC or smart card data. Information on access and egress walking times can be retrieved from a travel survey or mobile phone data if available. 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 perceived In-vehicle time is calculated by taking the crowding effect into account (i.e. multipliers for sitting and standing passengers at different crowding level).The perceived travel time components are cumulated by considering their corresponding weights to calculate the perceived passenger travel time. The operational benefits are computed based on the change in cycle time by considering fixed and variable cost components. Third, both the operator and passengers' benefits are converted into monetary terms by accounting for operational cost factors and passengers' value of travel time saving (VTTS). The combination of these cost components yields the overall benefits attributed to the introduction of the design and operational measures.

The contribution of the proposed framework lies in providing a sound procedure for monetarizing the operational and travel time savings of public transport design and operational measures. While vehicle running and dwell times and passenger volumes (Step 1) are commonly used for monitoring service performance, their interaction and variations need to be considered in order to assess their implications on passenger waiting time and perceived in-vehicle time, as well as vehicle layover and recovery times (Step 2). As discussed in the literature review, previous empirical and simulation studies that evaluated the impacts of design and operational measures considered some of the travel time effects that are included in Step 2 but none of them integrated and monetarized their effects by accounting for fleet size consideration, operational costs, crowding and reliability effects (Step 3). The outcome of this framework allows comparing and prioritizing alternative interventions and can thus support planners and policy makers in selecting and designing the most effective measures. The evaluation framework relies solely on data collected for the service under consideration. It is therefore limited to effects constrained to the specific service (i.e. excluding mode and route choice effects).

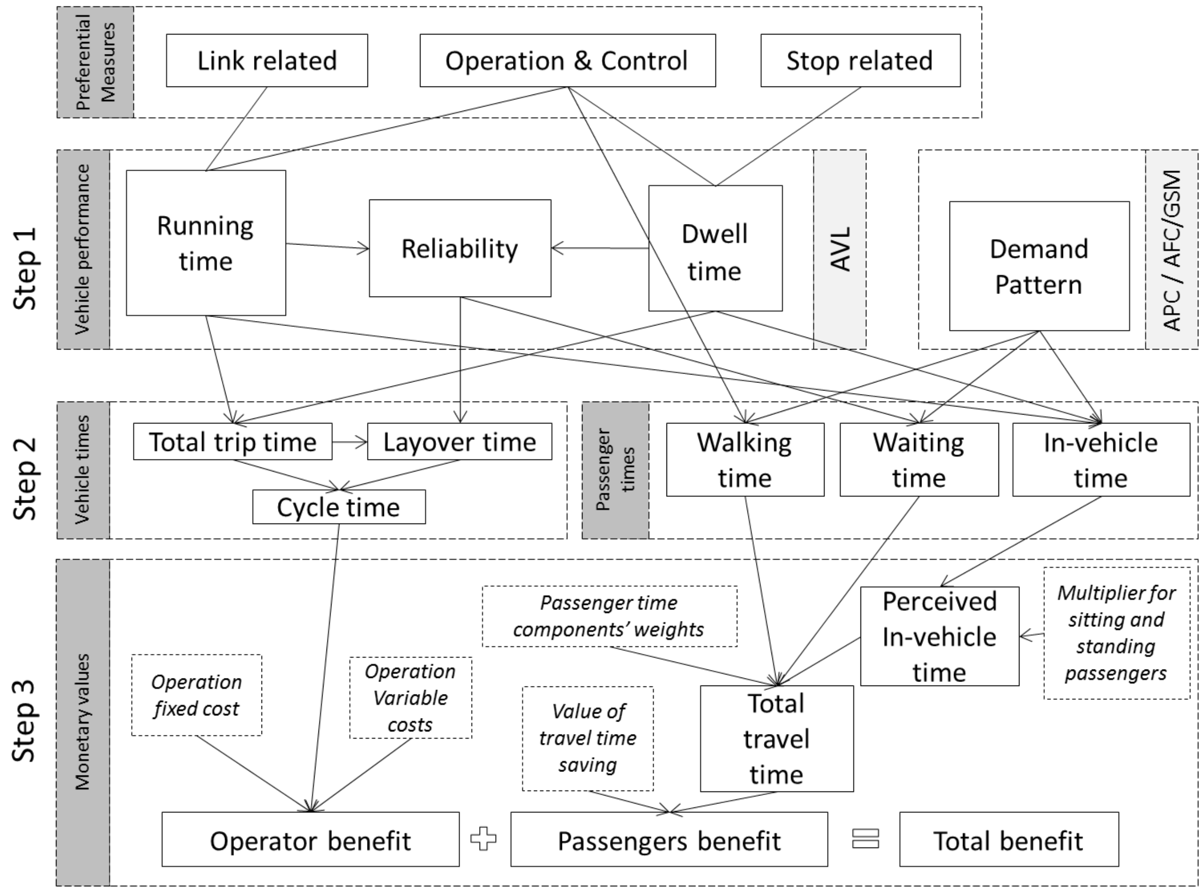

Figure 1: Workflow of the evaluation framework

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, $S = \{s_1, \dots, s_{|S|}\}$, 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^a_{k,s_i} and t^d_{k,s_i} 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 Performance metrics

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 former consists of bus riding time and intersection delays. The latter includes door opening and closing times, service time to allow passenger boarding and alighting activities, and possibly additional time due to holding control. Design and operational 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.

Running time and dwell time are the fundamental elements of vehicle performance and are thus analyzed at the first step of the evaluation scheme. Depending on the AVL system used, vehicle travel time values can be either approximated based on vehicle probes or can be directly retrieved. The running time of trip k on a line segment connecting two successive stops, s_i and s_{i+1}, is defined as

$$t_{k,s_i}^{running} = t_{k,s_{i+1}}^{a} - t_{k,s_i}^{d} \quad (1)$$

The dwell time for the same trip at stop s_i is

$$t_{k,s_i}^{dwell} = t_{k,s_i}^{d} - t_{k,s_i}^{a} \quad (2)$$

The mean and variance of vehicle running time and dwell times determine service speed and reliability, as explained in the following section.

3.1.2 Reliability

Design and operational measures are often designed to improve reliability which refers to the extent to which the service deviates from the planning. Depending on service frequency, reliability is conceived in terms of either punctuality or regularity. The former is relevant in case of low-frequency services where service providers operate their service based on a timetable, apply schedule-based control and passengers coordinate their arrival at the stop with the planned vehicle arrival time. Hence, reliability should then be measured in terms of deviation from the schedule such as on-time performance indicators. In contrast, in the case of high-frequency services, dispatching and control is based on headways between consecutive buses and passengers arrive at random at stops without consulting the timetable which often specifics only the planned headway.

Since the focus of this study is on high-frequency services, reliability is measured in terms of regularity, the deviation from the planned headway. In this case, vehicles are planned to be equally spaced along the line causing even intervals between successive bus arrivals, the observed headway however varies considerably from one bus to the other. As stressed by Finn et al. (2011), a good regularity is a prerequisite for system capability to realize its capacity. The observed headway between two consecutive buses is computed as

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

Various metrics of service reliability can be constructed based on the distribution of headways as described by Cats (2014). 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

$$CV(h_{s_i}) = \frac{\sqrt{\frac{\sum_{k\in K}(h^o_{k,s_i} - \frac{\sum_{k\in K} h^o_{k,s_i}}{|K|})^2}{|K|}}}{\frac{\sum_{k\in K} h^o_{k,s_i}}{|K|}} \quad (4)$$

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, stop-to-stop passenger demand patterns can be either constructed or estimated. Additional mobility data such as mobile phone probes may enable deducing passenger origins and destinations beyond the public transport system boundaries. The on-board load profile is constructed by subtracting the accumulated number of alighting passengers from the accumulated number of boarding passengers:

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

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.

Most performance indicators can be calculated based on the boarding, alighting and on-board passenger volumes. In case that the analysis of waiting time or in-vehicle time effects for a specific origin-destination pair are of interest, further information on the origin-destination passenger demand matrix is required. 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. Using this method, $q_{s_i,s_j,k}$, the number of passengers travelling on trip k from stop s_i to any downstream stop s_j $(i \prec j)$ can be estimated, such that the following conditions are satisfied:

$$\sum_{s_j\in S} q_{s_i,s_j,k} = b_{k,s_i} \quad \forall s_i \in S, \forall k \quad (6)$$

$$\sum_{s_i\in S} q_{s_i,s_j,k} = a_{k,s_j} \quad \forall s_j \in S, \forall k \quad (7)$$

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, $s_{|S|}$. The average total trip time is computed for each bus line direction, calculated as follows

$$\overline{\mathrm{TT}}^{s_1 \rightarrow s_{|S|}} = \frac{1}{|K|} \sum_{k \in K} \sum_{i=1}^{|S|-1} t_{k,s_i}^{dwell} + t_{k,s_i}^{running} \tag{8}$$

Similarly it is calculated for the other direction leading towards s_1 denoted by $\overline{TT}^{s_{|S|} \rightarrow s_1}$. Total trip time distribution and its variation are investigated in order to evaluate operational reliability.

3.2.2 Layover and recovery times

Bus trip time is an operational factor which is highly influenced by inherent uncertainty sources such as congestion and demand variation. To reduce the negative effects of uncertainty in trip times, scheduled layover and recovery times are introduced between consecutive bus trips to allow the service to recover in case of delays. The amount of layover time allotted is hence highly dependent on trip time variability. Assuming $\mathrm{TT}_p^{s_1 \rightarrow s_{|S|}}$ and $\mathrm{TT}_p^{s_{|S|} \rightarrow s_1}$ are the average planned trip time for both line-directions, the scheduled layover time, ε, is

$$\varepsilon = \left(TT_p^{s_1 \rightarrow s_{|S|}} + TT_p^{s_{|S|} \rightarrow s_1}\right) - \left(\mathrm{p}_\alpha(\mathrm{TT}^{s_1 \rightarrow s_{|S|}}) + p_\alpha(TT^{s_{|S|} \rightarrow s_1})\right) \tag{9}$$

Where $\mathrm{p}_\alpha(\mathrm{TT}^{s_1 \rightarrow s_{|S|}})$ and $p_\alpha(TT^{s_{|S|} \rightarrow s_1})$ are the αth percentile of the vehicle total trip time distribution for each line-direction. More reliable vehicle trip times are therefore expected to allow planning for shorter non-revenue times at terminals. Although the layover time is often pre-scheduled by operators, this potential secondary effect of design and operational measures implementation can be assessed.

3.2.3 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 (1972). 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

$$AWT = \frac{1}{\sum_{k \in K} \sum_{i=1}^{|S|-1} b_{k,s_i}} \sum_{k \in K} \sum_{i=1}^{|S|-1} b_{k,s_i} \cdot \frac{h_{k,s_i}^o}{2} \tag{10}$$

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. 10, where h^{p}_{k,s_i} 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 (Furth and Muller 2006), can then be defined as the difference between AWT and SWT:

$$EWT = \frac{1}{\sum_{k\in K}\sum_{i=1}^{|S|-1} b_{k,s_i}} \sum_{k\in K}\sum_{i=1}^{|S|-1} b_{k,s_i} \cdot \left[\frac{h^{o}_{k,s_i}}{2} - \frac{h^{p}_{k,s_i}}{2}\right]. \qquad (11)$$

EWT can be calculated separately for each stop to analyze how service reliability evolves along the route. EWT is used by Transport for London (2012) for monitoring service reliability as experienced by public transport users.

3.2.4 Passenger in-vehicle time

Unlike passenger waiting time, the in-vehicle time is directly observable by relating passenger volumes and vehicle travel times. 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

$$AIVT_{s_i,s_j} = \frac{1}{\sum_{k\in K}\sum_{m=i}^{j-1} q_{s_i,s_j,k}} \sum_{k\in K} q_{s_i,s_j,k} \cdot \left(\sum_{m=i}^{j-1}\left[t^{dwell}_{k,s_m} + t^{running}_{k,s_m}\right]\right) \qquad s_i, s_j \in S, i \prec j \qquad (12)$$

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. The aggregation enables however to neglect the inferred origin-destination relations by relying on observed passenger loads (which are the result of super-positioning passenger o-d flows):

$$AIVT = \sum_{m=1}^{|S|-1}\sum_{n=m+1}^{|S|} AIVT_{s_m,s_n} = \frac{1}{\sum_{k\in K}\sum_{i=1}^{|S|-1} l_{k,s_i}} \sum_{k\in K}\sum_{m=1}^{|S|-1} l_{k,s_m} * \left[t^{dwell}_{k,s_m} + t^{running}_{k,s_m}\right] \qquad (13)$$

3.2.5 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

$$ATT = AWT + AIVT \qquad (14)$$

In the event that data about passenger walking times is available, it can be included in the ATT by calculating the average access and egress walking times per passenger.

3.3 Monetary values

In the third step of our framework (Figure 1), both operator and passengers' benefits are converted into monetary terms by accounting for operational cost factors and passengers' VTTS. The latter is a function of individual attributes such as income, trip purpose and trip distance. This function is usually estimated based on data from stated choice experiments (Börjesson and Eliasson 2014). The combination of these cost components yields the overall benefits attributed to the introduction of the design and operational measures.

3.3.1 Operator costs

From the point of view of the service provider, the deployment of design and operational 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, z, for running a certain line with a given planned headway, h^p, can be approximated by

$$z = \left\lceil \frac{\mathrm{p}_\alpha(\mathrm{TT}^{s_1 \rightarrow s_{|S|}}) + p_\alpha(TT^{s_{|S|} \rightarrow s_1}) + \varepsilon}{h^p} \right\rceil \tag{15}$$

Where the typical values for α are 85 or 90 (TCRP, 2000). 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

$$c^{operator} = \beta^{fixed} \cdot z + \tau \cdot \frac{3600}{h^p} \cdot [\beta^{hr} \cdot (\overline{TT}^{s_1 \rightarrow s_{|S|}} + \overline{TT}^{s_{|S|} \rightarrow s_1} + \varepsilon) + \beta^{km} \cdot (r^{s_1 \rightarrow s_{|S|}} + r^{s_{|S|} \rightarrow s_1})] \tag{16}$$

Where β^{fixed}, β^{hr} and β^{km} are the daily fixed, per vehicle-hour and per vehicle-kilometer operation cost parameter. τ denotes the number of operation hours per day and $r^{s_1 \rightarrow s_{|S|}}$ and $r^{s_{|S|} \rightarrow s_1}$ are the total line-direction length in kilometers. More detailed estimation of cost parameters can potentially be embedded in Eq. 16 if available (e.g. fuel consumption as a function of running speed). Finally, the operational cost saving, $\Delta c^{operator}$, is obtained by subtracting the operational cost after implementation of design and operational measures by the operational cost before the implementation.

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. The disutility associated with waiting and on-board sitting and standing time components needs to be first normalized relatively to the in-vehicle time. 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 (Li and

Hensher, 2011). The multipliers suggested by Björklund and Swärdh (2015) , using data from an stated-preference study, allow discriminating the effect of on-board discomfort between sitting and standing passengers for a discrete set of standing passenger density per square meter, ranging between 0 and 8. The values provided in Björklund and Swärdh (2015) 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 $\beta_{k,s_i}^{sitting} = 0.973 + 0.0652 \cdot \gamma_{k,s_i}$ and $\beta_{k,s_i}^{standing} = 1.565 + 0.0685 \cdot \gamma_{k,s_i}$, where $\gamma_{k,s_i} = max(0,(l_{k,s_i} - v_k^{seat}))/\lambda_k^{area}$ is the standing passenger density factor (passenger/m^2) and λ_k^{area} denotes the standing area. $\beta_{k,s_i}^{standing}$ is relevant only in case $\gamma_{k,s_i} > 0$. The perceived in-vehicle time for passengers travelling between stops s_i and s_{i+1} for trip k is then

$$PIVT_{k,s_i} = \left[\min\left(l_{k,s_i}, v_k^{seat}\right) * \beta_{k,s_i}^{sitting} + \max\left(0,(l_{k,s_i} - v_k^{seat})\right) * \beta_{k,s_i}^{standing}\right] \cdot \left[t_{k,s_i}^{dwell} + t_{k,s_i}^{running}\right] \quad (17)$$

The first term corresponds to the weighted passenger-in-vehicle time multiplier for a given trip-link and the second term is the respective vehicle travel time. It is assumed that passengers will sit as long as there is residual seat capacity and thus standing disutility is applied in case the load exceeds the number of seats for the excessive number of passengers. Aggregated to an entire line, the perceived average passenger in-vehicle time ($PAIVT$) is

$$PAIVT = \frac{1}{\sum_{k\in K}\sum_{i=1}^{|S|-1} l_{k,s_i}} \sum_{k\in K}\sum_{i=1}^{|S|-1} PIVT_{k,s_i} \quad (18)$$

The total passenger cost saving, $\Delta c^{passengers}$, in economic welfare terms is the sum over all the generalized travel cost or the perceived average travel time for all passengers. The total passenger cost saving can thus be calculated as the product of the monetary gain per passenger and the number of affected passengers as follows

$$\Delta c^{passengers} = \beta^{VTTS} \cdot \left(\beta^{WT} \cdot (AWT^{after} - AWT^{before}) + (PAIVT^{after} - PAIVT^{before})\right) \cdot \sum_{k\in K}\sum_{i=1}^{|S|-1} b_{k,s_i}^{after} \quad (19)$$

Where β^{VTTS} is the value of travel time saving used for project appraisal and β^{WT} is the relative disutility associated with waiting as compared with in-vehicle time. In case information on individual or user group value of travel time saving is available, β^{VTTS} can be specified accordingly.

3.3.3 Total passenger and operator benefits

By adding the operator and passenger cost savings, the total cost saving is obtained

$$\Delta c^{total} = \Delta c^{operator} + \Delta c^{passenger} \quad (20)$$

Δc^{total} denotes the effects - gains or losses – caused by the implementation of design and operational measures .

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 and traverses the main urban arterials of the inner-city and connects its southern (Södermalm) and western (Kungsholmen) islands with the central (Vasastan) and eastern (Östermalm) districts (Figure 2). Moreover, it connects main transportation hubs with interchanges to metro lines, commuter and local trains.

As part of its urban mobility strategy (Stockholm City 2012), 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 (hereafter referred to as 'after period'). 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 (Cats, 2014). 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. The AVL and APC data were extracted for the trial period as well as the corresponding period in 2013 (March 17 - June 19) for all weekdays between 7 AM and 7 PM (hereafter called 'before period'). The data was provided by SLL, Stockholm County public transport authority. 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 and these devices are circulated over buses to ensure high coverage and statistical soundness. APC records include data on the number of passengers boarding and alighting the bus at each stop along the route. No data cleaning procedures were required prior to data analysis. 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 the absence of information on passenger access and egress legs, passenger walking times are not included in this analysis. 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). These stops were selected for cancellation because of their low passenger demand level and short distances to stops in the area. 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. (2011) for BHLS. While compromising accessibility, this measure could reduce bus travel times (Levinson 1983, Tirachini, 2014). The effect of stops consolidation on passenger travel time and operational performance has been investigated by El-Geneidy et al. (2006). Their empirical results show that the vehicle travel times have improved and offset the passengers' accessibility reduction effect.
- *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. Previous studies demonstrated that boarding regimes and fare payment techniques have a significant effect on dwell time (Fletcher and El-Geneidy, 2013 and Tirachini, 2013).
- *Introducing bus lanes* - a total of 3 km additional bus lanes on some line sections were introduced during the trial period (Figure 2). Shalaby (1999) showed the average vehicle trip time has improved following the introduction of reserved lanes on urban arterial. 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 (Cats, 2014). 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.
- *Improving transit signal priority* –Signal priority programs have been introduced or revised (i.e. conditional priority)in a number of signalized intersections along the bus route.

Dion et al. (2004) showed that an efficient transit signal priority program can significantly decrease travel time, delay, stops, and fuel consumption.

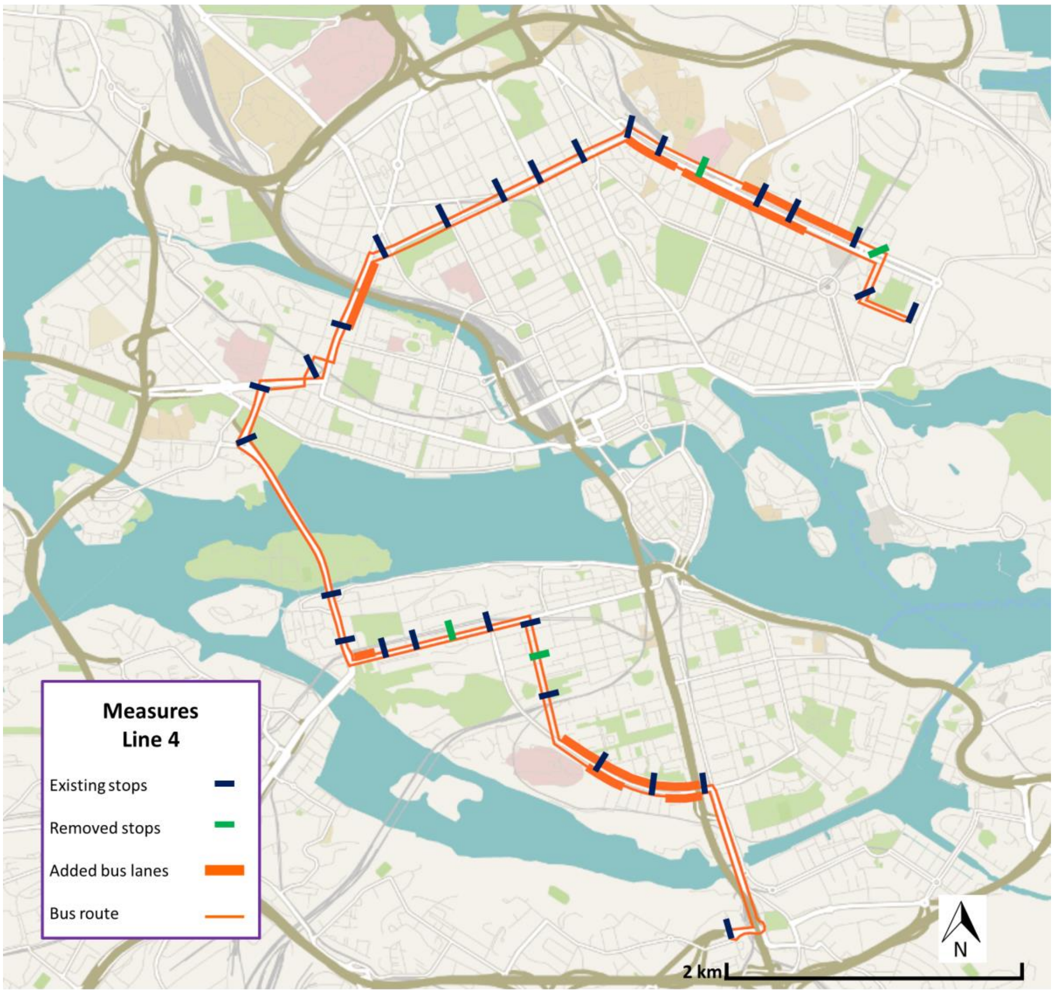

Figure 2: Physical measures that were implemented during the trial period

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 design and operational 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 (5.3).

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 during the experiment period. 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. This failure is attributed to two factors. Firstly, not all passengers were aware of the possibility of boarding through the rear door. Secondly, the requirement of a ticket inspector for allowing boarding through the rear door made the boarding possibility uncertain for the passengers. 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 occasionally stepped out of the bus to validate tickets as well as changes in the holding control.

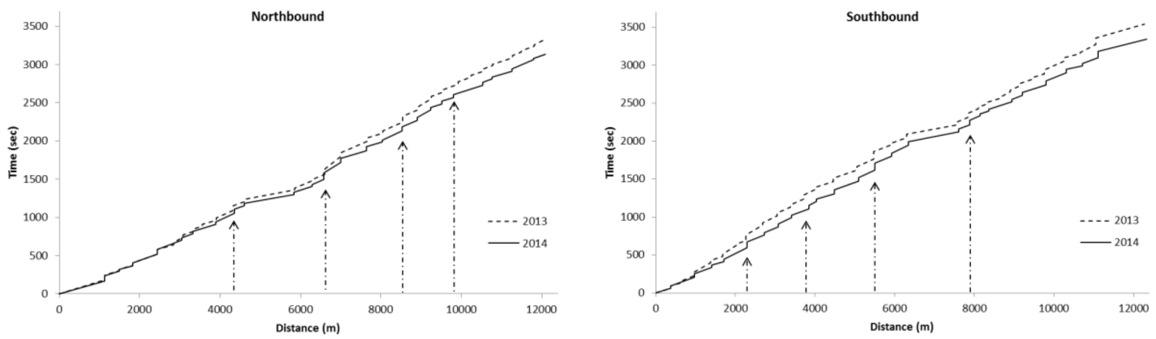

Figure 3: Average vehicle time-space diagrams for before and after periods

Even though the planned headway almost uniformly equals five minutes throughout the analysis period, the actual headway between consecutive trips varies considerably from one bus to the other. Histograms of all observed headways in before and after periods are presented in Figure 4. Headway distribution became narrower during the pilot study period indicating that the service became 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%. In order to quantify the change in headway regularity with better granularity, the coefficient of variation of the headway should be investigated. 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 longer layover time attained by shorter vehicle trip time may partially contribute to more even dispatching from terminals.

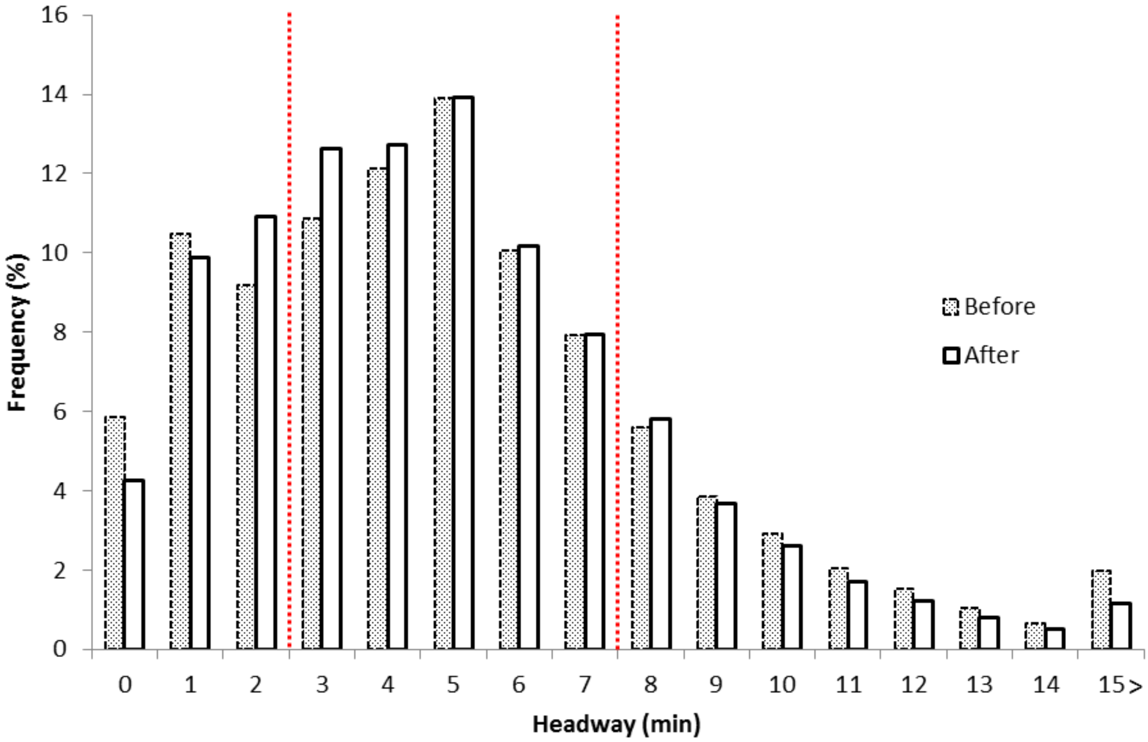

Figure 4: Observed headway histogram along the line for the before and after periods; dashed lines mark the range of headways that deviate by up to 50% from the average headway

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 before and after design and operational measures implementation periods – the distributions shifted to the left and became narrower, implying shorter and more reliable trip times. Road construction works on a segment along the southbound direction led to a lesser improvement for this direction. 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 during the experiment period as compared to the before period. The smaller tail results with a decrease of 7% in the 90^{th} 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.

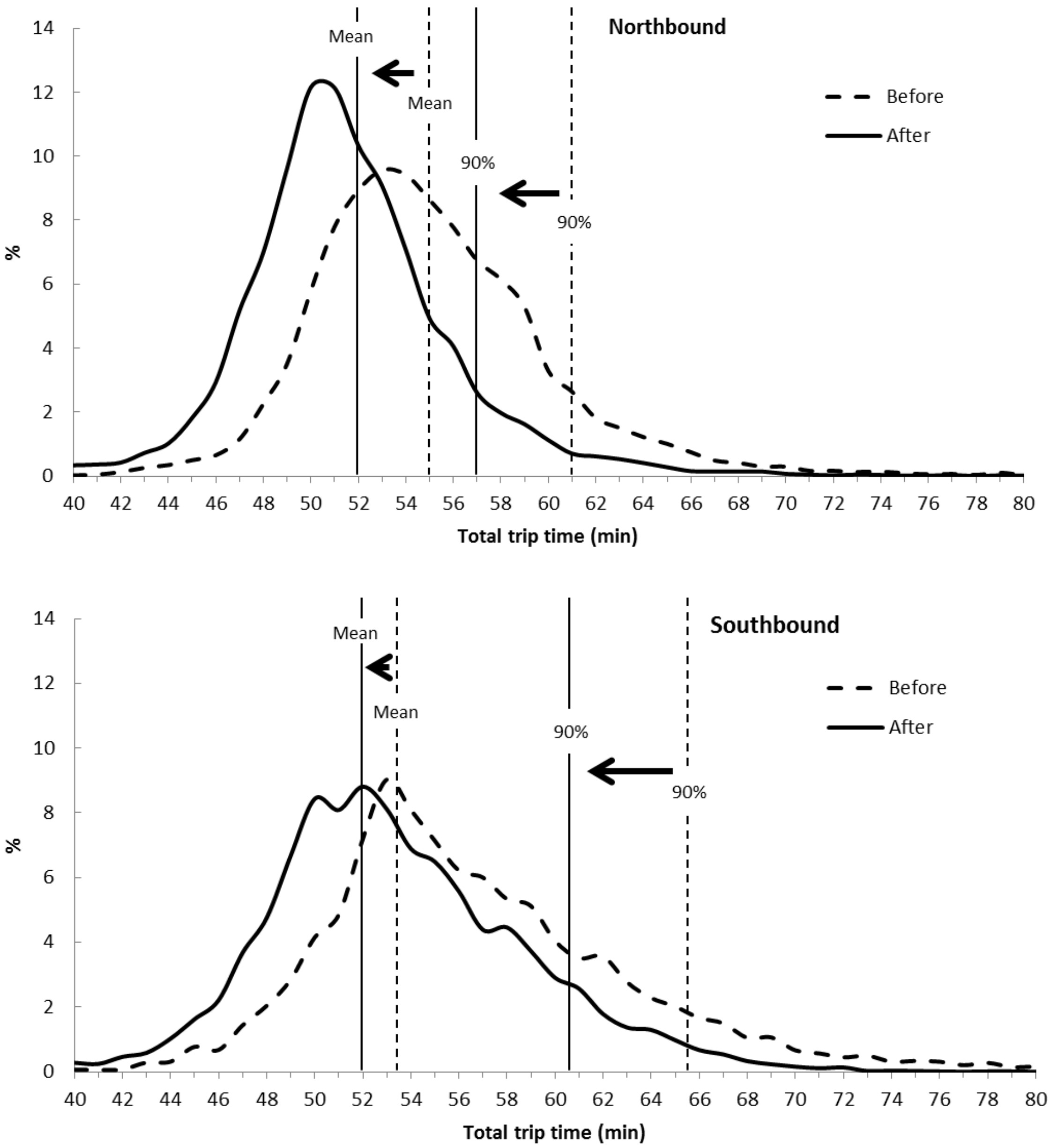

Figure 5: Total vehicle trip time histogram for the before and after periods towards northbound (above) and southbound (below)

We now turn to calculating passenger travel time. No significant trend is observed in ridership between before and after periods. It can be attributed to combination of measures with antithetical effects. 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 and is presented in Figure 6 for both line directions. Reflecting the increasing trend in regularity along the line, passengers boarding further downstream will experience EWT of up to three times greater than those waiting at the beginning of the line. 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. In addition, a pronounced improvement in *EWT* occurs directly after TPS (marked with circles in Figure 6), especially prior to the implementation period where holding control was restricted to these stops. This resulted with a 6-8% decrease in the average waiting time, AWT, for the northbound and southbound directions, respectively.

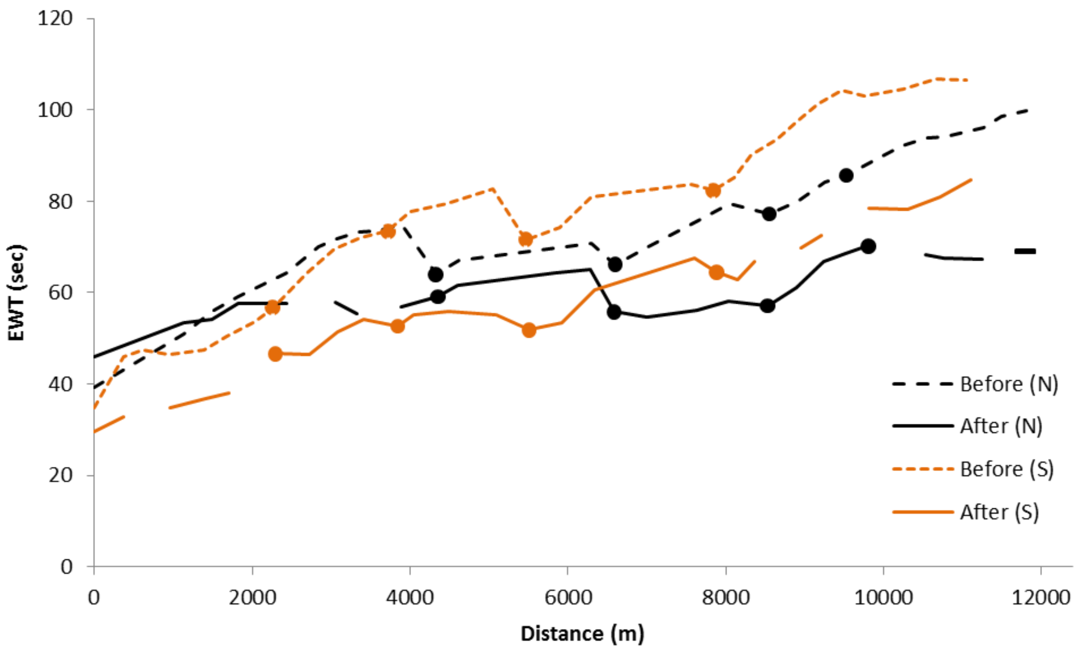

Figure 6: Excess waiting time for the before and after periods towards northbound (N) and southbound (S)

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 7 illustrates the percentage difference in average passenger in-vehicle time between after and before implementation periods. 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.

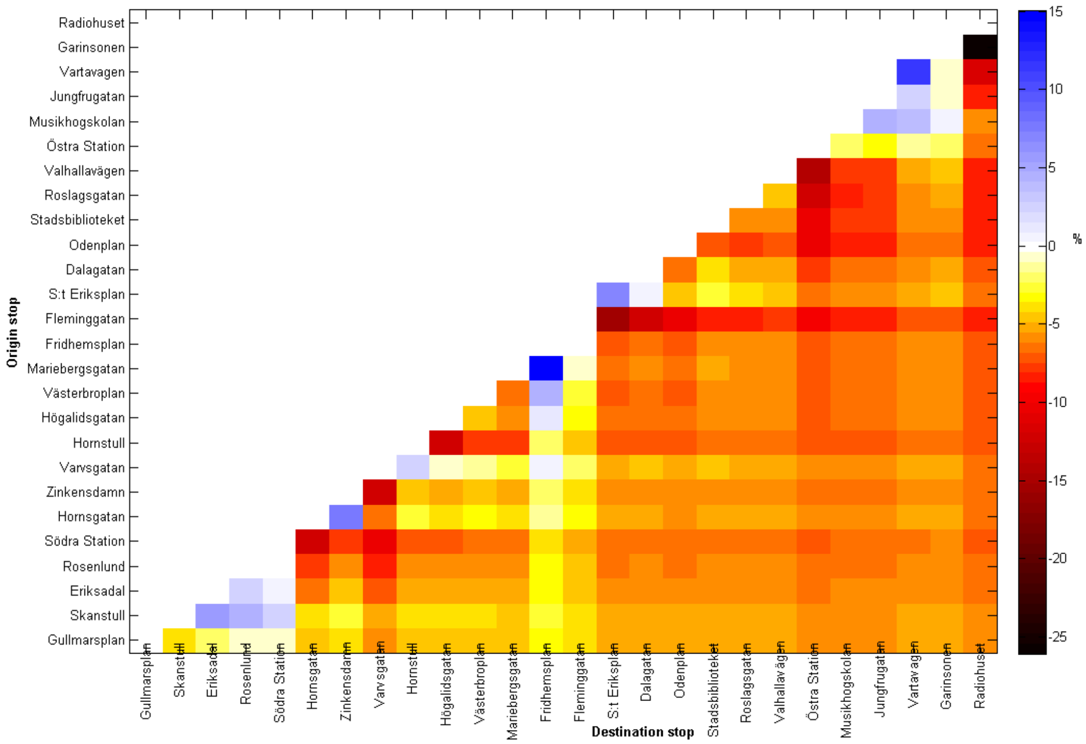

Figure 7: Percentage change in in-vehicle times for origin-destination pairs, northbound direction

Table 2 presents a summary of various travel time component for the before and after periods. The reported values have been aggregated for both directions and include the mean and standard deviation of bus trip time, *EWT* and *IVT*. Travel time for both buses and passengers are shorter and more reliable following the design and operational measures.

Table 2 Summary of different travel time component working days 7:00 to 19:00

	Bus trip time [min]		*EWT* [min]		*IVT* [min]	
	Mean	STD	Mean	STD	Mean	STD
Before	56.1	6.2	1.2	2.1	14.5	11.4
After	52.7	5.7	0.9	1.7	13.0	10.4
Change (%)	-6,0	-8,9	-24,4	-15,7	-10,0	-8,4

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. 15 ($\alpha = 90\%$; $\varepsilon = 10$min). This approximation yields 28 buses in the before period which can be reduced to 26 buses based on the performance attained during the field experiment. Alternatively, the same fleet could be used 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. 16 depend on vehicle type and service area. The values of β^{fixed}, $\beta^{hr}$and β^{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 (Trafikverket 2015). The benefits of bus lanes are presumably underestimated since the operational cost per bus-km decreases with increasing speeds. The before-after difference in operational cost is 11,716 SEK per day.

Second, passenger perceived in-vehicle time is computed according to Eq. 17 and 18 by considering the sitting and standing multiplier functions. The change in perceived passenger travel time is obtained by adding $\Delta PAIVT$ (i.e. $PAIVT^{after} - PAIVT^{before}$) to the weighted ΔAWT (i.e. $AWT^{after} - AWT^{before}$) by $\beta^{WT} = 2$. Table 3 presents the summary of nominal and perceived passengers' travel time saving factors for both directions. Waiting time saving accounts for 14% and 26% of the nominal and weighted passenger time savings, respectively.

Table 3: Passengers travel time saving (hour/day)-working days 7:00 to 19:00

Waiting time				In-vehicle time			
Nominal		Perceived ($\beta^{WT} = 2$)		Nominal		Perceived (Crowding)	
North-B	South-B	North-B	South-B	North-B	South-B	North-B	South-B
88.6	145.7	177.3	291.4	665.1	764.8	560.9	767.5

The output is multiplied by the value of travel time saving in order to express passenger costs saving in monetary terms (Eq. 19). Although there are several factors that might affect VTTS according to the literature (Börjesson and Eliasson 2014), information on passenger-specific attributes was not available for this study. While there are studies on how VTTS varies over different travel time and distance, they do not differentiate VTTS for trips shorter than 100 kilometers. The VTTS recommended by the Stockholm County council of 69 SEK per hour is therefore applied uniformly.

Passenger perceived travel time saving attributed to introduction of the design and operational measures yields 2.5 SEK saving per boarding. This is equivalent to almost 130,000 SEK time saving per day only for 7AM to 7PM operations on weekdays.

Finally, the summation of the operator and passenger cost saving results with the total benefits. The implementation of the measures included in the field experiment lead to benefits that worth 141,381 SEK per day.

6. Conclusion

Different design and operational 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. This paper presents a systematic evaluation framework and a detail sequence of steps for quantifying the impacts of a combination of public transport design and operational 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 design and operational 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 passenger and operator benefit associated with the introduced measures amounts to 141,381 SEK per day (approximately 15,300 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 overall assessment of impacts attributed to the implemented design and operational measures supports the comparison of different implementations, assess their effectiveness, prioritize alternative measures and provide a sound basis for motivating investments in such measures. 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). Future studies may extend the proposed evaluation framework by including the fixed and variable costs associated with the design and operational measures.

The simultaneous introduction of several design and operational 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 public transport. Other directions for future research include the inclusion of indirect and long-term effects such as economic activity, externalities and land-use development (Weisbrod and Reno 2009) in the evaluation framework.

Acknowledgments

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