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# An empirical evaluation of measures to improve bus service reliability: Performance metrics and a case study in Stockholm

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**Abstract** This paper evaluates the effects of implementation of a range of physical and operational measures during a pilot study on the busiest and most frequent trunk bus line in Stockholm, Sweden. Vehicle positioning and passenger counts data were analysed to evaluate the impact of the field experiment. The study has proven that the bus service performance has been improved from both passengers and operator perspectives. These measures resulted with a service that is 7% faster on average yielding a 10% decrease in passenger in-vehicle times. The faster service leads to 8 minutes shorter cycle time which could potentially cut the fleet size by 2 buses. The results demonstrate that improved regularity and less bunching leading to a 25% reduction in passengers' waiting times due to irregularity. However, no apparent change in dwell times has been observed. We estimate that each passenger saved 2 minutes which is 10% of journey time. These time savings amount to 9 million Swedish Crowns (1.1 million USD) per year for weekday afternoon peak periods only.

**Keywords:** Preferential measures · Service Performance · Bus priority

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# 1 Introduction

Service reliability is one of the main concerns for both passengers and operators due to its implications on level-of-service, system performance and efficiency. Running times between stops and dwell times at stops constitute bus travel times (Sun et al., 2014) and passengers' in-vehicle time. Abkowitz (1978) distinguished between three categories of methods to improve transit service reliability by altering the aforementioned factors: priority, control, and operational.

Priority methods are the specific action to prioritize transit vehicles movement over general vehicular traffic by means of introducing bus lanes or transit signal prioritization. Operational methods involve such methods as schedule modification, route restructuring, and driver training that usually requires a longer implementation period. Control methods are applied in real-time and include vehicle holding, short-turning, stop skipping, and speed modification.

A series of priority, control and operational measures were implemented on trunk bus line 4 in Stockholm, Sweden, as part of a pilot study. This study is a follow-up on 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 and less crowded bus services. In addition, it is expected to increase service reliability and decrease total travel time. In this study, the effects of several coordinated measures on aforementioned targeted service indicators have been evaluated.

With more than 65,000 passengers per day and 4 minute planned headway in the peak period, Line 4 is the busiest and most frequent bus line in Stockholm. SLL, the regional public transport agency, conducted the pilot study from 17-03-2014 to 19-06-2014. The most important physical and operational measures that were implemented by Stockholm City and the bus operator were:

1. Cancelling four stops on each direction out of 30 and 31 stops in northbound and southbound directions respectively.
2. Allowing boarding from the third door (in addition to the front door)
3. Introducing bus lanes on some line sections, a total of 3 additional km
4. Real-time headway-based holding strategy
5. Some parking spaces were removed along the bus line
6. Increasing monitoring of illegally parked vehicles

The removal of four bus stops results with an increase in the average distance between stops from 413 to 479 meters. While compromising accessibility, this measure aims to reduce bus travel times (Levinson 1983, Tirachini, 2014). The effect of number of stops on bus travel time has been investigated by Strathman et al., (2002) and Bertini and El-Geneidy (2004). Bertini and El-Geneidy modelled the bus running time and empirically shown each stop adds 26 seconds to the trip time regardless of number of boarding and alighting, while Strathman et al.'s model estimates 8 seconds additional time per stop.

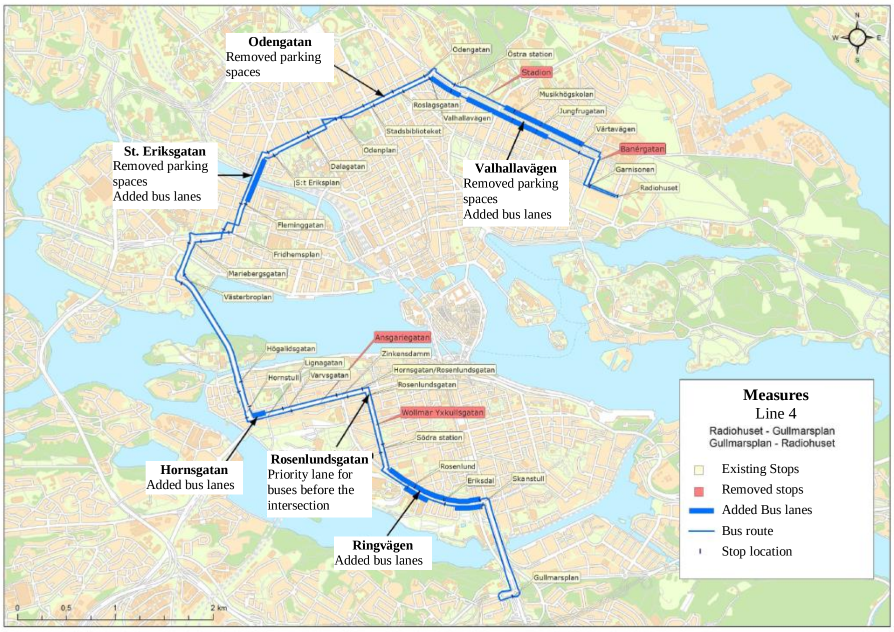


**Fig. 1** Physical measures that were implemented during the trial period

Boarding regimes and fare payment techniques have a significant effect on dwell time (Fletcher and El-Geneidy, 2013 and Tirachini, 2013). The boarding regime in Stockholm allows passengers boarding through the front door and validating their prepaid ticket under driver's inspection and alighting is made from the rear doors. This regime was changed during the trial period to permit boarding from the third door while a conductor validates tickets upon boarding from this door.

This paper analyses empirically the impacts of the priority, control and operational measures on both operator and passengers' performance metrics by conducting a before-after comparison. A comprehensive evaluation of service reliability and its implications on passengers' travel times was performed. In the following sections we present the service metrics and report alongside the respective results. We then conclude with an overall assessment of the pilot study and the effectiveness of the implemented measures.

## 2 Data

In this study Automatic Vehicle Location (AVL) and Automatic Passenger Counts (APC) data were extracted for the trial period (March 17-June 19, 2014) and the corresponding period in 2013 for weekdays and 7:00-19:00 time period. These data were then processed in order to filter the relevant data and estimate the travel time distributions and origin-destination matrices for each line directions in the analysis periods. The AVL database consists of more than 24,000 trip-records for each analysis period. These data provide the time of bus arrival and departure times from each stop along the line.

## 3 Measuring Quality of Service

The before-after empirical analysis enables to evaluate the impacts of the overall set of measures on performance. The evaluation consists of vehicle-based and passenger-based key performance indicators (KPIs). First, bus travel time is decomposed into running time between stops (and the corresponding speeds) and dwell times at stops. Second, the total bus trip time and its implications on fleet size and timetable design are investigated. Third, the reliability of the service as measured in terms of service regularity is analyzed. The headway between consecutive bus arrivals was measured at each stop as well as its overall distribution and the share of buses that are bunched. Fourth, passengers waiting times were computed based on the distribution of headways per stop and the respective number of boarding passengers. Fifth, passengers' in-vehicle times were calculated by constructing a matrix of travel times between each pair of stops along the line and multiplying it with the estimated passenger demand matrix. Finally, the total passenger travel times was calculated by summing for each origin-destination the waiting time and in-vehicle times and deriving from this the total passenger travel time savings and their monetary value.

### 3.1 Vehicle-Based Performance measures

#### 3.1.1 Speed

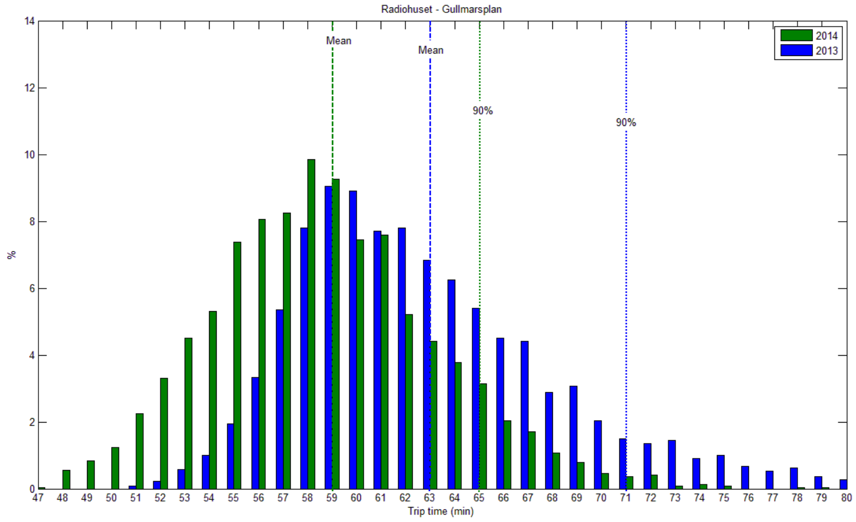
The calculated speed profile on the road segments connecting stops along both directions of line 4 demonstrates pronounced variations with average speed ranging from 5 to 40 km/hr for specific line segments. There is a modest but clear increase in bus speeds along both line directions with the average speed increasing by 6-9%. The average speed increased from 18.1 and 16.2 to 19.3 and 17.6 km/h for the northbound and southbound directions, respectively. Introducing new bus lanes has probably contributed to the improvement in speed.

#### 3.1.2 Dwell time

Dwell time in this study corresponds to door opening times. The AVL data does not allow distinguishing between passenger service and additional (holding, door opening) time components. No global trend could be observed when comparing the two periods. Overall, the average total dwell time per visited stop for a complete trip increased by 30 and 16 seconds in the northbound and southbound directions, respectively. In order to assess the overall trend of dwell time, alternative linear regression models were estimated based on passenger counts. The estimation results suggest that while the service time per passenger decreased by approximately 10%, the constant time lost at stop increased by 15-25% for both line directions. The decrease in passenger service time is presumably due to the additional boarding channel, while the prolonged constant time could be attributed to changes in the boarding regime and holding control.

### 3.1.3 Total Bus Trip Time

Total trip time and its variability are the most important determinants of fleet size and hence the operational costs associated with running a given service frequency. Figure 2 presents the average and 90th percentile of the trip time distributions for both directions. This is clearly evident trip travel time distribution became more reliable as they express less variation for both directions. The mean values and the 90th percentiles are marked for the before and after periods. The total trip time shifts to the left and becomes narrower with a smaller tail. Fewer trips are exceedingly long, avoiding the propagation of delays from one trip to the other and enabling more reliable service for passengers and more reliable scheduling for operator and drivers.



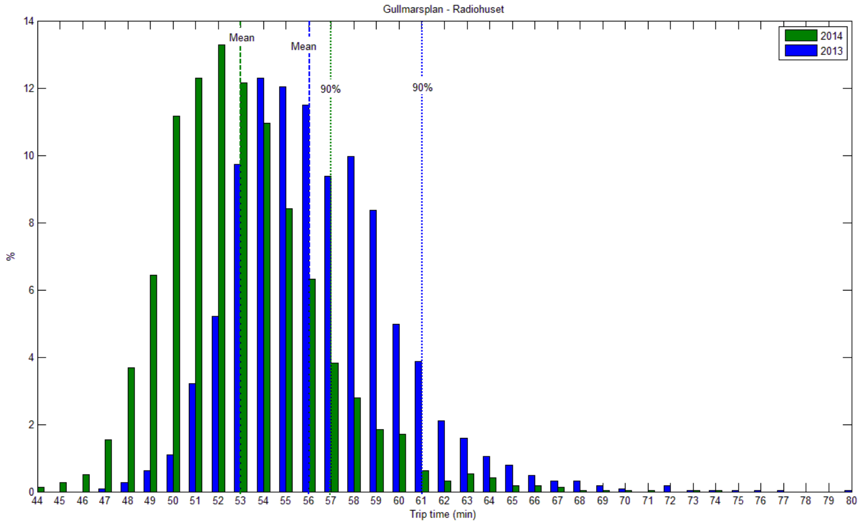


**Fig. 2** Trip travel time histogram for the afternoon peak period on the northbound (above) and southbound (below) directions

### 3.1.4 Service Regularity

The overall headway distribution is presented in Figure 3 for all observed headway throughout the line for the afternoon peak period. Headway variability decreased significantly and the service became much more regular. Headway distribution became narrower during the pilot study period with a large decrease in cases of extremely short or extremely long headways. The share of headways close to the average planned headway of 5 minutes increased.

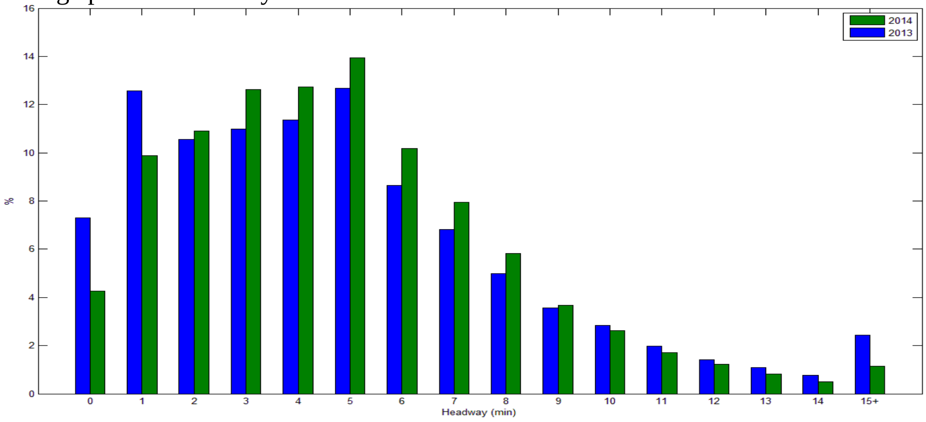


**Fig. 3** Headway distribution for the afternoon peak period (15:00-18:00).

## 3.2 Passenger-Based Performance measures

The measures undertaken in this pilot study are ultimately designed to improve passenger level-of-service. While the changes in vehicle-focused indicators suggest that service performance has improved, further analysis is required in order to assess and quantify the effects that the field experiment had on passengers' experience.

Line 4 is operated in two directions and each direction consists of an ordered set of stops, $S = \{s_{1,}, \ldots, s_g\}$, where $s_i$ is the i-th stop and $s_g$ is the last stop. The information 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 $s_i \in S$. A set of bus trips denoted by $K$ is assigned to run on line 4.

### 3.2.1 Waiting time

Given line 4 high frequency, passengers are assumed to arrive at stops without consulting the timetable. Passengers' waiting time is therefore determined by the distribution of bus arrivals (Strathman et al., 2002). Passenger's average waiting time for trip set $K$ given by

$$AWT = \frac{1}{\sum_{k \in K} \sum_{s_i \in S} B_{k,s_i}} \sum_{k \in K} \sum_{s_i \in S} B_{k,s_i} * \frac{h^{o}_{k,s_i}}{2} \qquad (1)$$

Where $\mathrm{h}^{\mathrm{o}}_{\mathrm{k},s_i}$ denotes observed headway upon bus-trip k arrives at stop $s_i$. $B_{k,s_i}$ represents passenger demand at stop $s_i$ for trip $k$ regardless of their destinations. Since we do not have access to detailed passenger demand for each trip, the average value obtained from sampled APC data $\overline{B_s}$ replaces $B_{k,s}$. Passengers' waiting time is therefore determined by the distribution of bus arrivals. More specifically, passenger's average waiting time is determined by: (1) the mean headway and, (2) headway variability. Excess waiting time (EWT) is the additional waiting time due to service irregularity; hence, better service regularity yields shorter passenger waiting times. Excess waiting time is used by Transport for London (2012) is the difference between Actual Wait Time (AWT) and Scheduled Wait Time (SWT).

$$EWT = \frac{1}{\sum_{k \in K} \sum_{s_i \in S} \bar{B}_{s_i}} \sum_{k \in K} \sum_{s_i \in S} \bar{B}_{s_i} * \left[\frac{h^{o}_{k,s_i}}{2} - \frac{h^{p}_{k,s_i}}{2}\right] \qquad (2)$$

Where $\mathrm{h}^{\mathrm{p}}_{\mathrm{k},s_i}$ is the scheduled headway upon bus-trip k arrives at stop $s_i$. Excess waiting time (EWT) was calculated based on the disaggregate headways at each stop and presented in figure 4 for the afternoon peak period and on both line directions. Overall, there is a decrease in excess waiting time by 27-29%. This improvement tends to increase at further downstream stops.

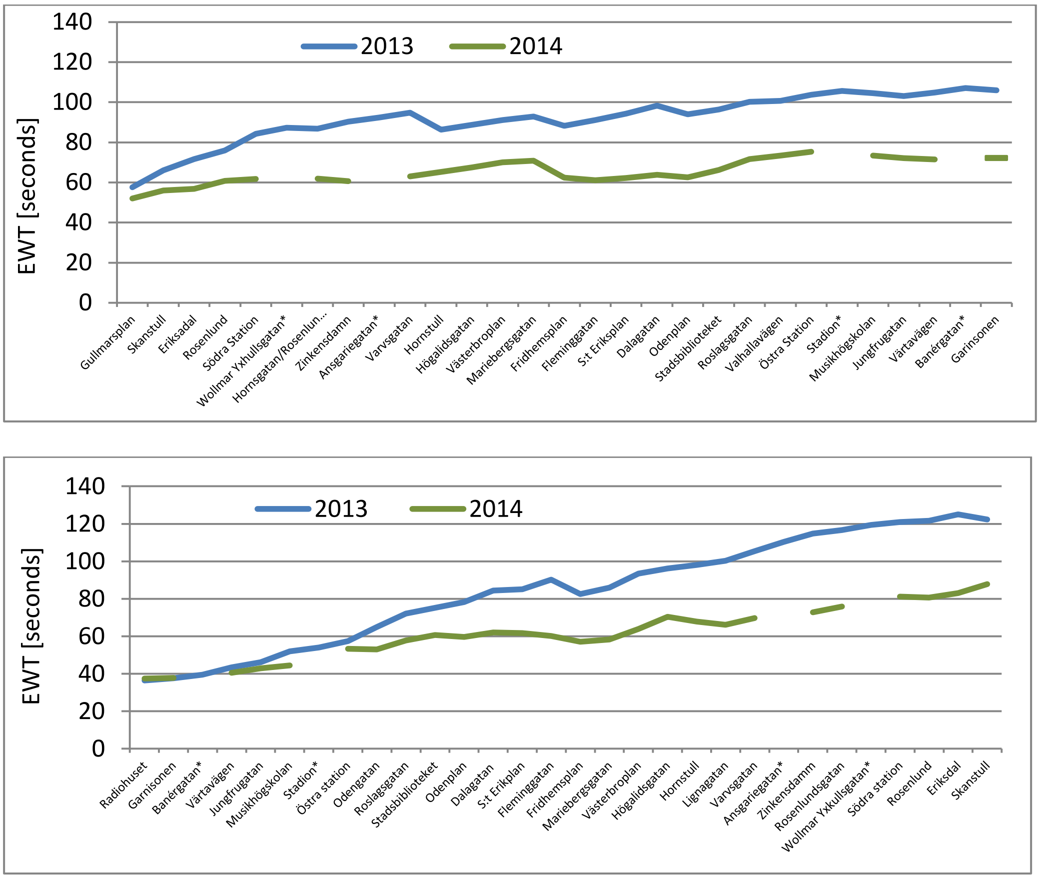


**Fig. 4** Excess waiting time for the afternoon peak period (15:00-18:00) along the route on the northbound (above) and southbound (below) directions.

### 3.2.2 In-Vehicle Time

In-vehicle time is the time that passengers spend on-board from the origin stop $s^-$ to the destination stop $s^+$. The average In-vehicle time was computed for each possible combination of origin and destination stops along the line and the results presents in a matrix format $\Pi^{\text{In-vehicle}}$. $\Pi_{s^-,s^+}^{In-vehicle}$ represents the average time that a passenger spends in vehicle from stop $s^-$ to arrive at stop $s^+$ and given by

$$\Pi_{s^-,s^+}^{In-vehicle} = \frac{1}{|K|} \sum_{k \subset K} t_{k,s^+}^{a} - t_{k,s^-}^{d} \tag{3}$$

Where $t_{k,s^+}^{a}$ and $t_{k,s^-}^{d}$ represent arrival time and departure time for trip k at/from stop $s^+$ and $s^-$, respectively. Each component of this matrix represents average of travel time for all connecting road segment plus average dwell times of the stops between corresponding origin and destination of the route.

Since only 10% of vehicles operating in line 4 are equipped with APC devices, the average boarding and alighting numbers are considered for the entire fleet. Then the origin-destination stops of passengers travelling with this line were estimated based on the average numbers of boarding and alighting passengers at each stop using iterative proportional fitting method.

Based on the passenger demand matrix that was constructed for this line from APC data, the corresponding average number of passengers travelling between each pair of stops is available. The product of the OD-matrix for the current bus line users in 2014 and average in-vehicle time saving matrix provides the in-vehicle time saving in person*minute unit.

$$TIVS = \sum_{s_i=s_1}^{s_g} \sum_{s_j=s_{i+1}}^{s_g} \bar{C}_{s_i,s_j}^{2014} * \left[\Pi_{s_i,s_j}^{In-vehicle,2014} - \Pi_{s_i,s_j}^{In-vehicle,2013}\right] \tag{4}$$

where $\bar{C}_{s_i,s_j}^{2014}$ notes average number of passengers traveling from $s_i$ to $s_j$ per vehicle. The average passenger in-vehicle time was reduced by 7% and 15% for the northbound and southbound directions, respectively.

### 3.2.3 Total Passenger Trip Time

For each pair of stops along line 4 the average waiting time and the average in-vehicle time were summed to obtain the total passenger trip time. Then the total travel time per passenger was computed for the before and after periods. The average percentile passenger travel time saving per passenger is presented in figure 5. In most cases in northbound direction, the passenger travel time change implies a time saving of up to 19%. Whereas in the southbound direction, for trips that involved travelling through Mariebergsgatan – Västerbroplan, travel time got worse due to the construction works in this area.

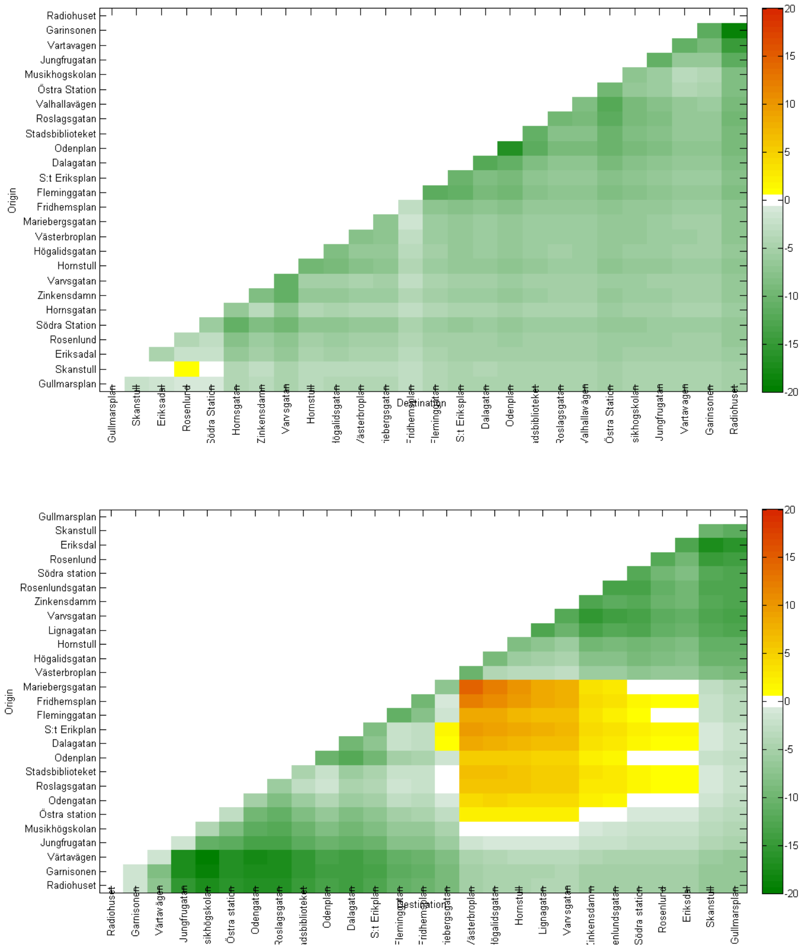


**Fig. 5** OD travel time saving for the afternoon peak period (15:00-18:00) along the route on the northbound (above) and southbound (below) directions.

For each pair of stops along line 4 the average waiting time and the average in-vehicle time were summed to obtain the total passenger trip time. Then the total travel time per passenger was computed for the before and after periods. Table 1 summarizes the travel time components per passenger by displaying the value for 2014 and the absolute and percentage change from 2013. The average passenger trip time decreased by 7% for the direction towards Radiohuset and by 14% for the direction towards Gullmarsplan. Overall, the average passenger trip time decreased by 10% from 19.5 minutes to 17.5, saving 2 minutes per passenger. 82% of the time savings were obtained through shorter in-vehicle times, while the remaining reduction is attributed to shorter excess waiting times.

**Table 1** summarized travel time components per passenger by displaying the value for 2014 and the absolute and percentage change from 2013.

| | **Southbound** | **Northbound** | **Line 4 both directions** |
|---|---|---|---|
| Total waiting time | 207 sec (2014)<br>-20 seconds/-9% | 206 sec (2014)<br>-21 seconds/-9% | 206 sec (2014)<br>-20 seconds/-9% |
| Total in-vehicle time | 1090 sec (2014)<br>-80 seconds/-7% | 609 sec (2014)<br>-110 seconds/-15% | 850 sec (2014)<br>-95 seconds/-10% |
| Total journey time | 1297 sec (2014)<br>-100 seconds/-7% | 815 sec (2014)<br>-131 seconds/-14% | 1056 sec (2014)<br>-116 seconds/-10% |

The perceived travel time savings amount to 550 pass-hours in a single afternoon peak period. In the perceived travel time calculation, waiting time and in-vehicle time are weighted 2 and 1.17. Given that the value-of time is 69 Swedish Crowns per hour, these time savings correspond to saving 38,000 Swedish Crowns per afternoon.

## 4 Conclusions

This study investigates the impact of combination of measures implemented in a pilot study along bus line 4 in Stockholm, Sweden. The results prove that the deployed measures have been effective to improving trunk line 4 performance. The analysis indicates that these measures resulted with a service that is 7% faster on average yielding a 10% decrease in passenger in-vehicle times. The faster service leads to shorter cycle time (-8min) and 10 minutes shorter for the 90th percentile value. This reduction could potentially help the operator to cut the fleet size by 2 buses, from 27 to 25 buses. This calculation is based on maintaining the current planned headway. Alternatively, the same fleet could be using for offering a higher frequency.

The results demonstrate that improved regularity and less bunching leading to a 25% reduction in passengers' waiting times due to irregularity. However, no apparent change in dwell times has been observed, while a truly open-doors boarding regime will presumably have a significant impact. We estimate that each passenger saved 2 minutes in average which is 10% of average journey time. These time saving amounts to 9 million Swedish Crowns (1.1 million USD) per year for afternoon peak periods only weekdays. These remarkable benefits were obtained with inexpensive measures.

Many of the measures, particularly improvements in signal priority, headway-based control and the changes in the boarding regime, implemented in this pilot study are directly applicable to other high-demand lines in Stockholm and other trunk lines in big cities around the world. The trunk lines and in particular the inner-city trunk-lines already have a distinctive image and it is therefore advisable to implement a common policy for these lines.

The impacts of public transport preferential measures were assessed in this study by performing a before-after empirical analysis of vehicle positioning and passenger counts data. The passive collection of data in the public transport industry facilitates the systematic evaluation of policy and operational measures. In particular, the development and deployment of passenger-based performance measures allows quantifying passenger time savings and consequently derive the monetary value of these savings. The latter is instrumental in supporting decision makers in selecting and designing measures to improve public transport service. The passenger-based performance measures used in this study could be further enhanced if detailed APC or smartcard transaction data are available.

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