Research in Transportation Economics 100 (2023) 101327

Contents lists available at ScienceDirect

Research in Transportation Economics

journal homepage: www.elsevier.com/locate/retrec

Research paper

Effects on operating costs of adjusting bus departure times during peak-hour traffic in Sweden

Eva-Lena Eriksson [a,b,*], Helene Lidestam [a,b,c], Lena Winslott Hiselius [b,d]

[a] Department of Management and Engineering, Linköping University, SE-581 83, Linköping, Sweden
[b] K2 – The Swedish Knowledge Centre for Public Transport, Bruksgatan 8, SE-222 36, Lund, Sweden
[c] Swedish National Road and Transport Research Institute (VTI), SE-581 95, Linköping, Sweden
[d] Department of Technology and Society, Lund University Faculty of Engineering, Box 118, SE-221 00, Lund, Sweden

ARTICLE INFO

JEL classification:
R410
R480
R500

Keywords:
Public transport
Peak hour traffic
Optimisation
Cost efficiency
Timetable adjustment
Vehicle scheduling

ABSTRACT

The cost of public transport has increased more than the supply in recent years in Sweden. One of the main cost drivers identified is peak-hour traffic. The major operating cost factors are the need for a large bus fleet for short periods during mornings and afternoons and the scheduling of drivers for shorter periods than the minimum working hour restriction. The objective of this paper is to study the effect of the number of buses needed (and hence the operating cost) during peak hours when adjusting the bus departure times. The study also analyses the increase in public transport supply and the number of boarding passengers if the cost reduction is re-invested. The analysis is based on case studies and simulated scenarios of possible adjustments in departure times for buses. The results show that by marginally adjusting the departure times, fewer buses are needed which leads to decreased operating costs. Further, the results show that the reduction in costs can be used to improve public transport in the area by expanding the supply of public transport in the long run.

1. Introduction

Traffic flow is unevenly distributed over the day. This is because the general travel pattern in society is mainly constricted by working hours for schools and workplaces. Generally, the demand is highest around 7–9.15 a.m. and 4–7.30 p.m. (Hale & Charles, 2009). There are some variations between countries though. In Sweden, the typical starting time for schools and office work is 8 a.m. and the travel demand is highest around 7–8 a.m. and 3.30–5 p.m. This concentration in travel demand is called peak-hour traffic. For public transport, during the peak hours, there is crowding and a higher number of passengers per hour compared to other hours of the day.

In recent years in Sweden, the cost of public transport has increased more than the supply (Eriksson et al., 2017; Swedish Association of Local Authorities and Regions, 2017). One of the main cost drivers identified is the peak-hour traffic (Camén & Lidestam, 2016; Lidestam et al., 2018) since the total number of drivers and buses in a traffic area is dimensioned after the high demand during the short morning peak (Camén & Lidestam, 2016; Vigren, 2016). There is also an interest from society and public authorities to increase the market share of public transport as a sustainable transport measure (e.g., Stjernborg & Mattisson, 2016), which potentially will add more passengers to the peak hours. The main cost drivers identified for the peak-hour traffic are bus driver's working time regulations (in Sweden the drivers have to be scheduled for a minimum of 3 h, which is longer than the main peak period), that the vehicles are dimensioned to carry more passengers than the average route demand, and that the large bus fleet is not fully utilised outside peak hours (Camén & Lidestam, 2016; Lidestam et al., 2018). The increase in costs for the bus operators leads to increased contract costs for the public transport authorities (PTAs) (Camén & Lidestam, 2016). The large bus fleet also has a negative impact on the environment, e.g., the emissions per passenger can be reduced with buses dimensioned after average demand.

In connection to discussions of introducing measures to spread out the peak-hour travel demand the question usually arises regarding the cost effectiveness. The effects and costs concern both the traveller in terms of adjustments such as changed waiting time but also effects for the operator in the number of busses etc.

Previous research regarding lowering public transport costs by optimising timetables by adjusting departure times is commonly focused on model development. For example, Zhang et al. (2021) developed a model that slightly adjusts bus departure times intending to reduce

* Corresponding author. Department of Management and Engineering, Linköping University, SE-581 83, Linköping, Sweden.
E-mail addresses: eva-lena.eriksson@liu.se (E.-L. Eriksson), helene.lidestam@liu.se (H. Lidestam), lena.hiselius@tft.lth.se (L. Winslott Hiselius).

https://doi.org/10.1016/j.retrec.2023.101327
Received 30 November 2022; Received in revised form 26 June 2023; Accepted 5 July 2023
Available online 8 July 2023

passenger travel time, Gao et al. (2019) optimised the bus timetable by allowing uneven headway that reduces operation costs, Tang et al. (2021) developed a model with the aim to optimise the bus timetable with regards to the number of departure times and passengers waiting time, Schmid and Ehmke (2015) modelled an increase in departure time flexibility to minimise costs of operation, and Shang and Liu (2019) developed a vehicle scheduling model intending to improve the match between the number of vehicles needed and passenger's waiting time.

Cost of operation is essential (and increasingly so) for the public transport system in times of tougher economic constraints (e.g., increases in fuel prices and salaries). Though the research carried out so far concerning the effects of adjusted departure times there is still a lack of studies analysing the effects on operation costs based on marginal changes in the timetable. This type of research could serve as an illustration for public transport operators and public transport authorities and serve as a base for future discussions on peak hour measures.

Thus, the purpose of this study is to analyse the impact on operator costs if the departure time of buses were to be adjusted marginally. This empirical contribution is done by studying whether the number of vehicles needed, and hence the costs, can be reduced by adjusting the scheduled bus timetable. Through scenario simulations in a bus planning system, the bus departure times are adjusted marginally. Adjusting the departure times makes it possible to utilise the vehicle fleet more effectively and reduce the number of vehicles needed. This study evaluates the effects of the proposed adjustment of bus departure times from two economic perspectives; partly how the change affects the costs for the bus operator when fewer vehicles are needed and drivers can be scheduled more effectively, and partly how the PTA can use the cost reduction to potentially increase the overall public transport supply. This study is conducted through two case studies in Sweden with information and help from a bus operator and a regional PTA based in the studied traffic areas. Due to business secrecy, the cases are not geographically identified in this paper. In order to gain further insights, the result of the study was presented and discussed with representatives from the regional PTA and the bus operator.

In the study, the following research questions are answered:

1. What are the effects on the operating costs of adjusting the bus departure times by up to between 2 and 30 min?
2. What is the potential increase in the overall public transport supply and the number of boarding passengers if the identified cost reduction were to be re-invested in the public transport system?

The Swedish regional public transport system consists of 21 regional PTAs, governed by politicians, which are responsible for the public transport within the region. The traffic is most commonly publicly procured and is run by a public transport operator. Traffic planning, regarding vehicle type, vehicle circulation, and frequency, is usually regulated through the contract. Although this study is related to Swedish conditions, the results could be of interest to local, regional, or national governments and operators with similar problem definitions and travel patterns. The problem of high costs due to peak-hour traffic is relevant to other regions and countries, as well as the possibility to lower the costs by adjusting departure times marginally. It is important to emphasize that only operational costs regarding bus drivers and buses are considered in this study. Other socio-economical costs like costs for delays, individual behavioural change or increased crowding on the bus are not considered. The study is conducted to show the potential of adjusting bus departure times, not to generate a full cost assessment. To be effective the adjusting of bus departure times must be combined with an implemented effort to cut the demand in peak hours, such as staggering school hours.

To be able to adjust the departure times there is a need to spread out the travel demand during peak hours. For instance, in Sweden, measures to spread out the peak demand can be implemented by the PTA themselves or in collaboration with actors such as bus operators or municipalities. Previously conducted research proposes a series of measures in this area. Globally, the need to spread out the travel demand is mainly due to capacity and crowding problems (e.g., Currie, 2010; Halvorsen et al., 2016; Tang et al., 2020). Regardless of the origin of the problem, the same type of solutions can be effectively used. Various measures for reducing travel demand during peak hours have previously been identified, such as ticket price differentiation based on the time of day you are travelling, increase in parking fees in cities, as well as, spreading out working hours for schools and workplaces (e.g., Kamel et al., 2020; Ljungberg, 2009; Noordegraaf & Annema, 2012; Qian & Rajagopal, 2015).

This paper is organised as follows. Section 2 shortly describes the central concepts used in the study. Section 3 describes the methodology used for the two case studies, for the calculations of the potential to use the cost reduction to increase the overall supply and the number of boarding passengers, and for the interviews with public transport actors. In Section 4 the results are presented. Section 5 discusses the results and finally, conclusions are drawn in Section 6.

2. Central concepts

2.1. Bus runs and public transport planning optimisation

The bus run is the daily assignment for a specific bus, which routes it will take and when. Fig. 1 illustrates examples of different bus runs during a traffic day, where some buses run during the whole day and some just during the morning and afternoon peaks. Bus run number 3 is an example of the latter and consists of two work blocks, one in the morning between 7 and 8 a.m. and one in the afternoon between 2 and 7 p.m. The peak hour demand is specifically relevant for the regional traffic, with a high ratio of students travelling to school, resulting in many routes having a similar departure time.

A bus line is defined as the planned route between two geographical locations on which passengers can travel, with a number of bus stops in between. A bus trip is a one-way journey on a bus line when the bus goes from one end stop to the other. In this study, a school bus is defined as a bus line paid for by the municipality on which only pupils are allowed to travel. A school bus is only run in the morning and in the afternoon, going to and from school. If the pupils live close to a bus line, they are usually given a public transport ticket and get to travel with the regular public transport to and from school.

Fig. 2a and b illustrate an example of the potential of adjusting the departure times and how this affects the number of buses needed. In Fig. 2a, there is an overlap between two bus trips in location D, which results in the need for two bus runs. By adjusting the departure times slightly, as illustrated in Fig. 2b, only one bus run is required to cover the two trips. In total, fewer buses are needed and the planning can be done more effectively.

The schedule for the bus runs and the drivers is optimised regarding different cost factors and preferences, usually by using a public transport planning software. For the bus runs the factors include how different routes should connect, type of vehicle, length of a run for a specific vehicle type, dwell time (time spent at each stop), and layover time (time in between two trips). The optimisation process aims to reduce unproductive time and kilometres (i.e., when the vehicle is not used on a bus line).

2.2. Increase in passengers when there is an increase in public transport supply

Resources saved by adjusting departure times may be used as reinvestments in the public transport system, i.e., to increase public transport supply. The Mohring effect (Mohring, 1972) states that an increase in public transport supply due to an increase in public transport demand will lead to a further increase in the demand since the increase in frequency (and hence reduction in waiting time) reduces the total

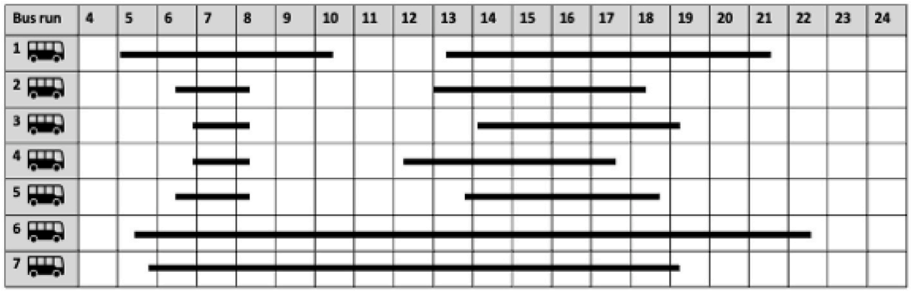

Fig. 1. Examples of bus runs during a traffic day (4 a.m. to midnight), with one row representing a specific numbered bus run (1, 2, 3, etc.). The time of day is along the horizontal axis and the numbered bus runs are on the vertical axis.

travel cost for the passengers. Further research has shown that the Mohring effect is more significant for buses and off-peak travel, compared to rail and subway and peak hours, respectively (Silva, 2021). Another study supporting the Mohring effect is Balcombe et al. (2004, p. 246) showing that changes in supply will lead to a change in demand. It may, however, take several years for the market to reach a new equilibrium state.

The relationship between changes in the number of passengers and the public transport supply can also be described using elasticities. The concept of elasticity is used to describe how a change in a factor affects the demand, e.g., the ratio between a percentage change in the supply of public transport and the corresponding percentage change of boarding passengers. The supply elasticity formula is:

$$\varepsilon_s = \frac{\%\Delta N}{\%\Delta S} \tag{1}$$

Where ε_s is the supply elasticity, $\%\Delta N$ is the percentage change of the number of boarding passengers, and $\%\Delta S$ is the percentage change of the public transport supply. For example, a supply elasticity of 0.4 means that if the supply of public transport increases by 10% the number of boarding passengers will increase by 4%. The public transport supply elasticity is usually measured with regards to either vehicle kilometres, bus frequency, or total travel time (Dickinson & Wretstrand, 2015) and will vary with respect to e.g., peak or off-peak travel, the existing level of service, and if the effect is measured in the short or long run (Balcombe et al., 2004). A review of elasticity studies mainly made in Great Britain concludes that the elasticity of bus demand with respect to total vehicle kilometres is 0.38 in the short run and 0.66 in the long run (Balcombe et al., 2004). A selection of other studies concludes a supply elasticity of 0.4–0.7 depending on vehicle kilometres or frequency (Dickinson & Wretstrand, 2015), 0.38–0.45 with regards to traffic supply in a Norwegian and Swedish context (Nilsson et al., 2017), 0.2–0.3 for traffic supply per urban area in Sweden during the years 1985–2004 (Tegnér et al., 2006), and 0.17–0.67 in the short and long run, respectively, in a review of Swedish studies (K2 et al., 2017). A recent Swedish case study concludes that an increase in off-peak frequency for rural public transport results in substantial growth in passengers, mostly during peak hours, with long-term supply elasticities for the studied cases being higher than 1 (Hansson et al., 2022).

3. Method

The study was divided into three steps. First, scenario simulations were made regarding the possibility to adjust the departure times for buses within two case studies (separate traffic areas located in Sweden). Different scenarios were simulated and optimised with information from and with the help of a bus operator and a regional public transport authority (PTA). Based on these results, the cost reduction, and the potential bus fleet efficiency (defined in Section 3.1) were calculated. Second, based on the bus fleet efficiency documented in the two case studies, calculations were made regarding the potential increase in the overall supply of public transport and the yearly number of boarding passengers if the cost reduction is re-invested. These calculations were applied to a larger traffic area in order to illustrate the potential of a full-scale implementation of adjusting peak-hour traffic.

The traffic areas used for the simulations were chosen together with the bus operator and the PTA. Initially, in the first case study a small traffic area, one simulation scenario, and one evaluation parameter (number of vehicles) were chosen. In the second case study, the simulation was expanded to a larger traffic area with six scenarios simulated and including more parameters for evaluation. The two case study areas complemented each other in size.

In the final step, through interviews, the results of the study were discussed with and validated by persons with expert knowledge from a bus operator and a regional PTA based in the studied traffic areas.

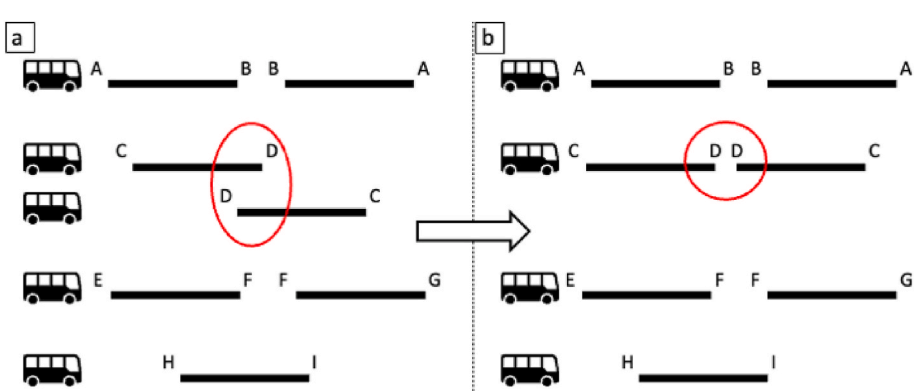

Fig. 2a, b. An illustration of the potential of marginally adjusting the departure times with respect to the number of bus runs needed. The capital letters (A, B, C, etc) represent geographical locations, the buses represent a bus run, and the horizontal lines represent a one-way trip on a bus line.

3.1. Simulations of adjusted departure times for buses

The public transport planning software Hastus (Giro, n.d.) was used to simulate different scenarios of adjustments in bus departure times. The software is based on optimisation modules which run based on preferences and constraints fed in by the planner. Blais and Rousseau (1988) and Blais et al. (1990) present an overview of Hastus. The software is one of the main planning tools on the market and is used by authorities and operators around the world. In research, the software has for example been used in a study by Salicrú et al. (2011). The number of vehicles needed and the cost for working time and distance are included as base parameters in a scenario simulation and weighed against each other. The objective function aims to minimise unproductive kilometres and time (e.g., deadhead and layover time) and the number of vehicles needed. Parameters that are taken into consideration when running the optimisation are for example the type of vehicle needed on a specific bus line, the length of a bus run, layover time, and constraints connected to working hours.

The effect of adjusting the bus departure times was studied through different scenarios. The base scenario is the timetable and bus runs of the traffic running in the area during the time the simulations were made. The simulation was made with traffic data from a weekday since peak hour traffic occurs on weekdays and the traffic flow during a weekday is used to dimension the size of the bus fleet. In the simulated scenarios, all factors and conditions were kept the same as the base scenario except for the possibility for the software to adjust the departure times. Hourly, distance-based, and yearly operating costs (e.g., salary, maintenance costs, and cost of capital) used in the study are the same as the bus operator use in their daily planning. Increasing the degree of freedom for the software regarding the departure times resulted in a change in frequency and headway. In this case, having a set timetable was not prioritised, i.e., there was no penalty imposed in the optimisation process with regards to the software's possibility to adjust a departure time with respect to keeping a set headway. The main goal of the simulations was to reduce costs, by using fewer buses, and keep or increase the effectiveness. The different scenarios contributed to the evaluation of how many fewer buses could be used during peak hours, based on different degrees of freedom for adjusting departure times.

The results from the simulations regarding the reduction in the number of vehicles needed, hence the reduction in costs, were translated into a percentage for possible bus fleet efficiency. This relates to the operational costs for the bus operator by for example needing fewer buses and a smaller depot, consequently lowering the costs for the PTA. The possible bus fleet efficiency *BFE* was set to be the ratio between the number of buses in the simulated scenario and the number of buses in the base scenario.

$$BFE = 1 - \frac{\text{Number of buses in simulated scenario}}{\text{Number of buses in base scenario}} \tag{2}$$

The number of buses needed reflects all the vehicles needed to cover all the bus runs in the area. This includes meeting all set conditions, for example, the type of vehicle, departure time, and layover time.

In future studies, a larger traffic area could be included to be able to investigate how the effects can be implemented when scaled up.

3.1.1. Case study 1

The first case study is set in an urban area with approximately 7 000 inhabitants. Close to the urban area lies a city with approximately 110 000 inhabitants (in a Swedish context a large city). Regional and school buses serve the traffic area. There are two lines which on a weekday are served by nine buses. Approximately 1 100 boarding passengers travel with public transport on a weekday, of which 30% board during the morning peak hour (7–8 a.m.). During the morning peak hour, the share of students among the passengers is 55%. On the two lines, the headway is on average 30 min.

The simulations were made on timetable data and passenger information from the year 2018. The focus of this case study is the possible reduction in the number of vehicles needed.

3.1.2. Case study 2

The second case study is set in a mid-sized municipality, including a few neighbouring urban areas, with a total of approximately 50 000 inhabitants. The municipality has twelve urban areas, and the traffic area is served by local, regional, and school buses. Within the traffic area, there are 50 bus lines which are served by 75 buses on a weekday. Many of the lines are only trafficked to and from schools in the area, hence only have departures in the morning and the afternoon. Some lines are more frequently run with a headway of 10 min.

The chosen traffic day for the case study was a Monday. The simulations were made on timetable data and passenger information from the year 2018. The focus of this case study is on the possible reduction in the number of vehicles needed and on the number of driver's shifts that are shorter than 3 h.

3.2. Increased number of boarding passengers

The results from the simulations made in the two case studies were utilised in the calculations of the potential effects of re-investing the identified cost reduction. The re-investment results in an increase in public transport supply, leading to an increase in the number of boarding passengers (according to the Mohring effect and previous research regarding supply elasticity, see Section 2). An increase in the number of boarding passengers further results in an increase in fare revenues, which also can be re-invested to increase the supply of public transport and additional increase the number of passengers.

Since the two case study areas are small, the calculations were performed on a larger traffic area by using passenger numbers, fare revenues, and traffic costs from the bus traffic from this area. In this traffic area, the number of boarding passengers was approximately 11.1 million people, the fare revenue was 105.5 million SEK, and the cost for the traffic was 232.9 million SEK in 2017. Resulting in a cost recovery rate (CRR) of 45.3% (the ratio of fare revenue to total operating costs) in this larger area. In Sweden, the average cost recovery rate is 50% (Trafikanalys, 2019). The cost recovery rate was assumed to be fixed over the years. When the PTA's budget for public transport is increased (due to an increase in fare revenue), there is a possibility to increase the supply further in the coming year, thus keeping the ratio of fare revenue to total operating costs the same. It is assumed that the increase in passengers and fare revenue occurs during the following year to be able to instantly add the increase in the number of passengers to the calculations of the possible increase in supply the following year.

The bus fleet efficiency *BFE* was utilised to make re-investment in the public transport system, hence increasing the supply by the same order of magnitude. The supply elasticity ε_s was set to 0.4 since the literature review (Section 2.2) suggests that it is a commonly used value for effects occurring in the short run. The chosen elasticity represents the general increase of departures during the traffic day as the supply is assumed to increase throughout the day. Furthermore, a sensitivity analysis was performed where the supply elasticity was set to 0.15 and 0.7, respectively, also including in the study values in the lower and upper part of the range concluded in the literature review. With the supply elasticity set to 0.4, there is an increase in the percentage of boarding passengers by:

$$\alpha_0 = BFE \bullet \varepsilon_s = BFE \bullet 0.4 \tag{3}$$

Where α_n equals the percentage increase in the number of boarding passengers of year n. The number of passengers increases to:

$$N_1 = N_0 \bullet (\alpha_0 + 1) \tag{4}$$

Where N_n equals the number of boarding passengers year n after the first bus fleet efficiency and re-investment. An increase in passengers leads to an increase in fare revenue to:

$$R_1 = R_0 + (N_1 - N_0) \bullet R_t \tag{5}$$

Where R_n equals the fare revenue of year n, and R_t is the average ticket revenue from an adult boarding a bus in the traffic area. In the calculations, it is assumed that the increase in passengers will be mostly adults. Ticket sales data shows that the average ticket revenue from an adult boarding public transport in the traffic area is 11.43 SEK (R_t).

For the cost recovery rate to remain the same there is a need for the PTA to increase the budget. This leads to a total traffic cost, or traffic budget, of:

$$C_1 = C_0 + \frac{(R_1 - R_0)}{CRR} \tag{6}$$

Where C_n equals the traffic cost of year n, and CRR equals the cost recovery rate. The increase in traffic costs is translated into a percentage increase in the supply of:

$$S_1 = \frac{C_1 - C_0}{C_0} \tag{7}$$

Where S_n equals the percentage supply increase of year n. The increase in public transport supply leads to a percentage increase in the boarding passengers by:

$$\alpha_1 = S_1 \bullet \varepsilon_s \tag{8}$$

In the second year of increase in supply, the number of passengers increases to:

$$N_2 = N_0 \bullet \alpha_1 + N_1 \tag{9}$$

The yearly increase in passengers is related to the number of passengers in year zero. This is done with the motivation to keep the calculations and the potential increase in the number of passengers as conservative as possible. Continued calculations of the increase in the number of passengers are conducted iteratively.

3.3. Interviews with public transport actors

In order to seek insights and opinions from experts in public transport planning based on their experience, knowledge and understanding of the subject, representatives from the regional public transport authority (PTA) and the bus operator were interviewed, one from each organisation. The aim of the interviews was to discuss the results of the study and to have the credibility of the calculations and the realism of the estimated effects assessed.

The person interviewed from the PTA works with the strategic development of regional public transport. The person interviewed representing the bus operator works as a senior traffic planner. The interviews took place in June 2022 and lasted an hour each.

The interviews were unstructured with open-ended questions to encourage an informal conversation where the interviewees had the opportunity to expand their answers. The unstructured interview method was chosen to be able to understand the challenges and opportunities the two actors see regarding this study's approach to reducing the cost of public transport during peak hours. Starting the interview sessions, the background, method, results, and conclusions of the study were presented to the interviewees. The questions regarded among others general comments on the results, the feasibility of adjusting the departure times, consequences, barriers and opportunities connected to the adjustment, if the calculated increase in the number of passengers is probable, and if the size of the increase in passengers is a notable effect.

4. Results

4.1. Case study 1: Reduction in the number of buses needed

In the first case study, one scenario was simulated. The degree of freedom for adjusting the departure times was set to up to 30 min. The bus runs for the morning peak hours are illustrated in Fig. 3, with Fig. 3a showing the bus runs for the base scenario and Fig. 3b showing the result from the simulation. The two bus lines are indicated in blue and red, and the dashed green line is the bus driving back to the first bus stop of the line (either in traffic or as a deadhead trip). In the base scenario, there are two departure times on the red line (07.05 and 07.28 a.m.) that are operated by three and two buses, respectively. The result from the simulation evens out the departure time during the peak hours and increases the number of departures to choose from (eleven departures in the base scenario and fourteen departures in the simulated scenario) and there is an increase in frequency. Furthermore, fewer vehicles are needed. In the base scenario, nine bus runs were needed, and the simulated scenario uses seven bus runs.

4.2. Case study 2: Reduction in the number of buses and short driver shifts needed

In the second case study, six scenarios were simulated. In the scenarios, it was possible to adjust the departure times by up to 2, 5, 15, 20, 25, and 30 min respectively. The results are presented in Table 1. For the base scenario and all six simulated scenarios, the planned operating time (number of hours in traffic) is 496.35 h, the planned operating distance (distance in traffic) is 17 937.8 km, and the total number of one-way trips is 788.

The two main outcomes of the scenario simulations are the number of buses needed for all runs during a day in the traffic area and how many of the driver's shifts are shorter than 3 h. The reduction in the number of buses needed is used to determine the bus fleet efficiency of the proposed adjustment of departure times.

Allowing departure times to be adjusted by up to 2 min resulted in an adjustment of five bus trips divided on to five different bus lines. This resulted in an infrequent timetable rather than a change in headway and the need for one less bus. When allowing departure times to be adjusted up to 5 min the majority of the adjusted departure times occurred on two bus lines and during the morning peak. There was a reduction of five buses needed and one shift shorter than 3 h.

When simulating an adjustment of departure times up to 15 min there were changes made also during the afternoon peak. When allowing adjustments shorter than 15 min the morning peak was dimensioning, however with a 15-min adjustment in departure time trips during the afternoon peak also needed to be adjusted to avoid the afternoon peak getting dimensioning. In total, 14 of the 88 changed departure times got adjusted the maximum allowed 15 min, which affects the headway. If the frequency is low to start with this can have a big effect and in extreme cases lead to a longer gap between departing buses. Nevertheless, in most instances, the headway during peak hours is kept fairly straight and the adjustment in departure times in some instances leads to a gap when changing timetable headway. The change in the number of vehicles needed is shown in Fig. 4 for the three scenarios where the departure time is adjusted by up to 2, 5, and 15 min.

In the scenarios above 15 min (where the departure times are allowed to adjust up to 20, 25, and 30 min), there is a decline in the possibility to reduce the number of vehicles needed in comparison to other cost factors. Adjusting the departure times by up to 20 and 25 min results in that one more bus being needed compared to the 15-min scenario, but there is an increase of ten percentage points with regards to time effectiveness (ratio of planned operating time and total working time). This increase in effectiveness might compensate for the cost of an extra bus. The difference between the scenarios of adjusting the departure times by up to 20 or 25 min is that in the latter, fewer departure

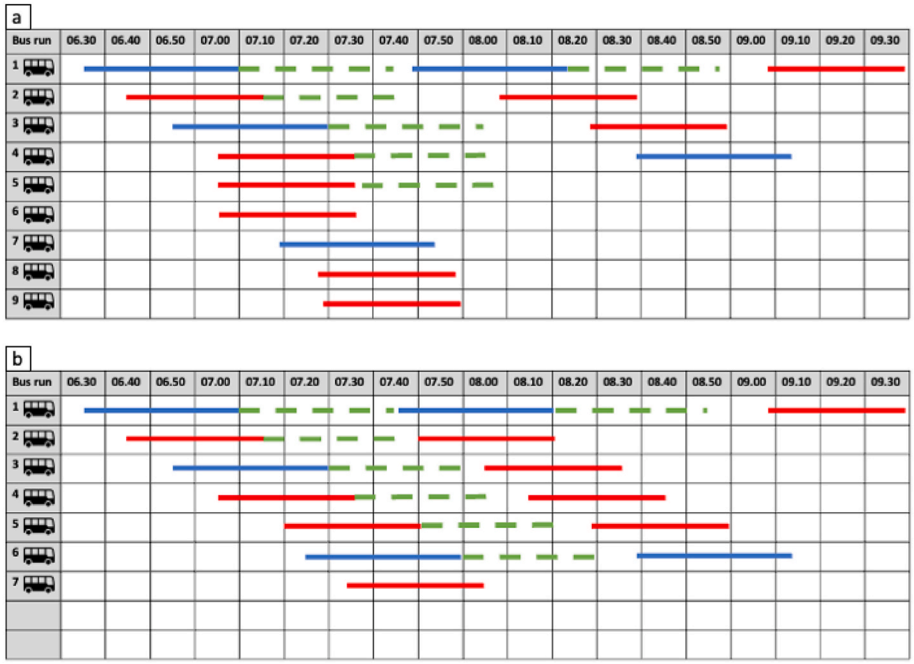

Fig. 3. a, b. Illustration of the two bus lines in the traffic area, represented by blue and red lines. The dashed, green line is the bus driving back to the first bus stop. Fig. 3a shows the base scenario and Fig. 3b shows the simulated scenario. Departure times were allowed to be adjusted up to 30 min.

Table 1
Result from running the six scenario simulations. Departure times on a one-way trip were allowed to be adjusted by up to 2, 5, 15, 20, 25, and 30 min respectively.

	Base scenario	Adjust 0–2 min	Adjust 0–5 min	Adjust 0–15 min	Adjust 0–20 min	Adjust 0–25 min	Adjust 0–30 min
Total working time – Include operating, deadhead, and layover time (h)	636.45	636.75	632.80	622.35	552.78	557.62	550.80
Time effectiveness – Ratio of planned operating time and total working time (%)	77.99	77.95	78.44	79.75	89.79	89.01	90.11
The number of vehicles needed	**75**	**74**	**70**	**67**	**68**	**68**	**67**
The number of one-way trips adjusted	–	5	48	88	72	40	70
Total time/average time per one-way trip changed when adjusting departures (min)	-/-	8/1.6	126/2.6	417/4.7	367/5.1	182/4.6	430/6.1
The number of shifts shorter than 3 h	**61**	**64**	**60**	**47**	**44**	**54**	**43**
The average length of shifts shorter than 3 h (min)	106	103	110	108	108	112	112

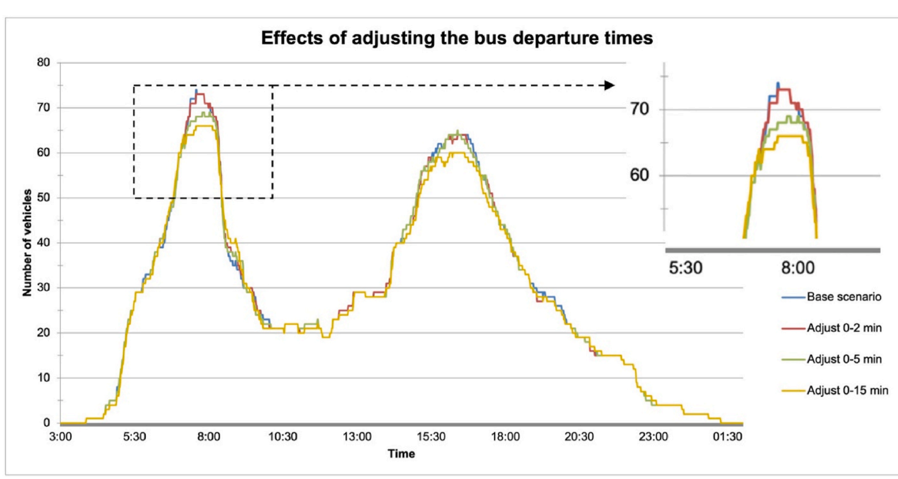

Fig. 4. The effect with regards to the number of vehicles needed when adjusting the departure times by up to 2, 5, and 15 min. The highest peak is reduced, and the curve is slightly flattened.

times are adjusted and additional shifts are shorter than 3 h. In the scenario when the departure time is allowed to be adjusted by up to 30 min there are 67 buses needed, the same number as when adjusting the departure times by up to 15 min, and a further increase in time effectiveness. When the optimisation process no longer can reduce the number of buses needed there is instead a focus on reducing the total working time and distance, thus increasing the time effectiveness.

The result indicates that the increase in effect is small, for example, when comparing the number of vehicles needed in the different scenarios. Adjusting the departure time by up to 15 min results in the reduction of the highest peak demand. When adjusting departure times by more than 15 min the peak-hour traffic starts to have the same headway as the off-peak traffic and that would require a decrease in demand to be possible to implement.

4.3. Increased overall public transport supply

The reduction in the number of buses needed in the second case study and the scenario of adjusting bus departures up to 15 min was chosen as a base for the calculation of increased overall public transport supply and the number of boarding passengers. The second case study is conducted in a larger traffic area than case study 1 and is operated by a larger bus fleet. The chosen scenario is assumed to be easier to implement because the frequency was kept mainly the same as in the base scenario.

In case study 2 the simulations of adjusting the departure times by up to 15 min resulted in a reduction in the number of vehicles needed from 75 to 67. This is translated into a bus fleet efficiency *BFE* of:

$$BFE = 1 - \frac{67}{75} = 10.7\% \tag{10}$$

The bus fleet efficiency *BFE* was then assumed to be utilised as reinvestment in the public transport system, hence increasing the supply, increasing the percentage of boarding passengers by:

$$\alpha_0 = BFE \bullet \varepsilon_s = 0.107 \bullet 0.4 = 4.3\% \tag{11}$$

The number of boarding passengers increases to:

$$N_1 = N_0 \bullet (\alpha_0 + 1) = 11\ 100\ 000 \bullet 1.043 = 11\ 573\ 600 \text{ passengers} \tag{12}$$

The increase in boarding passengers leads to an increase in fare revenue to:

$$R_1 = R_0 + (N_1 - N_0) \bullet R_t = 105\ 500\ 000 + (11\ 573\ 600 - 11\ 100\ 000) \bullet 11.43 = 110\ 913\ 248 \text{ SEK} \tag{13}$$

For the cost recovery rate to remain the same the total traffic cost, or traffic budget, should increase to:

$$C_1 = C_0 + \frac{(R_1 - R_0)}{CRR} = 232\ 900\ 000 + \frac{(110\ 913\ 248 - 105\ 500\ 000)}{0.453} = 244\ 850\ 194 \text{ SEK} \tag{14}$$

The increase in traffic cost is translated into a percentage increase in the supply by:

$$S_1 = \frac{C_1 - C_0}{C_0} = \frac{244\ 850\ 194 - 232\ 900\ 000}{232\ 900\ 000} = 5.1\% \tag{15}$$

The increase in public transport supply leads to a percentage increase in the boarding passengers by:

$$\alpha_1 = S_1 \bullet \varepsilon_s = 5.1 \bullet 0.4 = 2.1\% \tag{16}$$

In the second year of increase in supply the number of passengers increases to:

$$N_2 = N_0 \bullet \alpha_1 + N_1 = 11\ 100\ 000 \bullet 1.02 + 11\ 573\ 600 = 11\ 801\ 418 \text{ passengers} \tag{17}$$

Continued calculations of the increase in the number of passengers are conducted iteratively. There will be a declining trend in the increase in the number of passengers since the supply elasticity is 0.4, and the iteration was continued until year six. The resulting number of boarding passengers per year is presented in Fig. 5. In total over six years, there is an increase of approximately 900 000 boarding passengers (+8.1%). There is a total increase in fare revenue of approximately 10.3 million SEK (+9.8%) and the traffic cost increases by approximately 22.7 million SEK (+9.8%). Furthermore, the PTA must increase the budget by 12.4 million SEK in tax funding to be able to maintain the cost recovery rate at the same level as the base scenario (year zero).

4.3.1. Sensitivity analysis

In the sensitivity analysis, the supply elasticity ε_s was set to 0.15 and 0.7, respectively, also including in the study values in the lower and upper part of the range concluded in the literature review (Section 2.2). The calculations were performed in the same manner and with the same input values as in Section 4.3

With a supply elasticity of 0.15, there is a smaller increase in the number of boarding passengers, compared to the calculations in Section 4.3, resulting in a less increase in the traffic budget and a smaller increase in the public transport supply in the upcoming year. Already in year 2 the increase in the number of boarding passengers comes to a halt. The resulting number of boarding passengers per year is presented in Fig. 6. In total over six years, there is an increase of approximately 220 000 boarding passengers (+1.95%). There is a total increase in fare revenue of approximately 2.5 million SEK (+2.35%) and the traffic cost increases by approximately 5.5 million SEK (+2.35%). Furthermore, the PTA must increase the budget by 3.0 million SEK in tax funding to be able to maintain the cost recovery rate at the same level as the base scenario (year zero).

With a supply elasticity of 0.7, there is a larger increase in the number of boarding passengers, compared to the calculations in Section 4.3, resulting in a greater increase in the traffic budget and a larger increase in the public transport supply in the upcoming year. In year 6 the increase in passengers is still ongoing. The resulting number of boarding passengers per year is presented in Fig. 7. In total over six years, there is an increase of approximately 3 370 000 boarding passengers (+30.4%). There is a total increase in fare revenue of approximately 38.6 million SEK (+36.6%) and the traffic cost increases by approximately 85.2 million SEK (+36.6%). Furthermore, the PTA must increase the budget by 346.6 million SEK in tax funding to be able to maintain the cost recovery rate at the same level as the base scenario (year zero).

4.4. Interviews with public transport actors

The results of the study and the feasibility of the proposed adjustments in bus departure times were discussed with representatives from a bus operator and a regional PTA. The interviewed persons deemed, based on their expertise, that adjustments of the departure times up to 15 min are feasible regarding vehicle scheduling, tender process, current contracts (bus operator), finances, budgeting, and decision process (PTA). If the departure times are adjusted up to 5 min it is assumed that

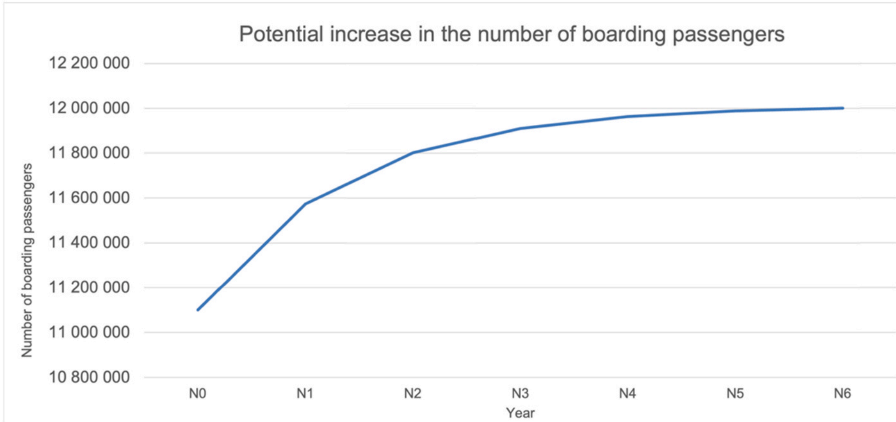

Fig. 5. The potential increase in the number of boarding passengers, when re-investing the bus fleet efficiency gained if being able to adjust bus departure times up to 15 min.

no major travel behavioural change is needed. However, to be able to make bigger changes in the timetable there is a need for the passengers to change their departure times to even out the peak demand, which likely makes such a change in the timetable more difficult to carry through. Measures to spread out the travel demand have been previously implemented by the bus operator, however, the measures were small in scale and resulted in limited behavioural changes. Furthermore, the experience is that it is difficult to change the passenger's peak-hour departure times which are restricted by working hours. The interviewees underline that the size of the traffic area affects the possibility to adjust the departure times. A larger traffic area with many departures, frequent headway, and a certain number of bus lines result in a higher degree of flexibility. However, if a certain headway is to be maintained the possibility of adjustments in the timetable is reduced.

The interviewees emphasized different aspects of the effect of adjusting departure times up to 5 min (small bus fleet efficiency improvements) in contrast to being able to adjust them for a longer period of time. The interviewee from the bus operator underlined that adjusting

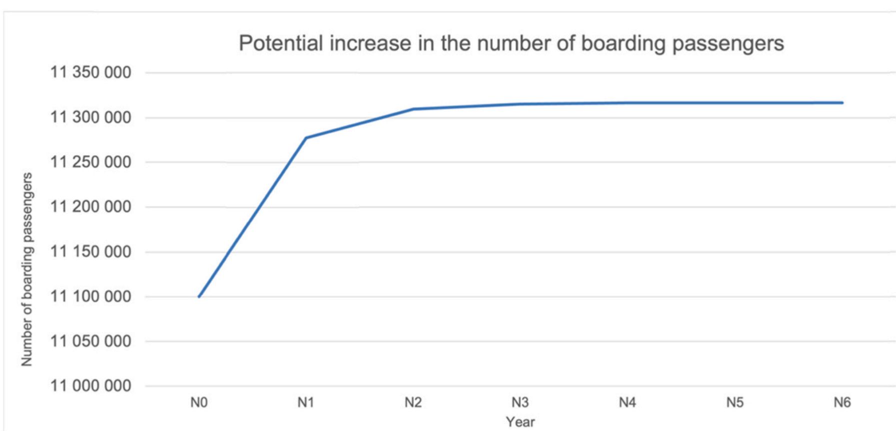

Fig. 6. The potential increase in the number of boarding passengers when the supply elasticity is set to 0.15.

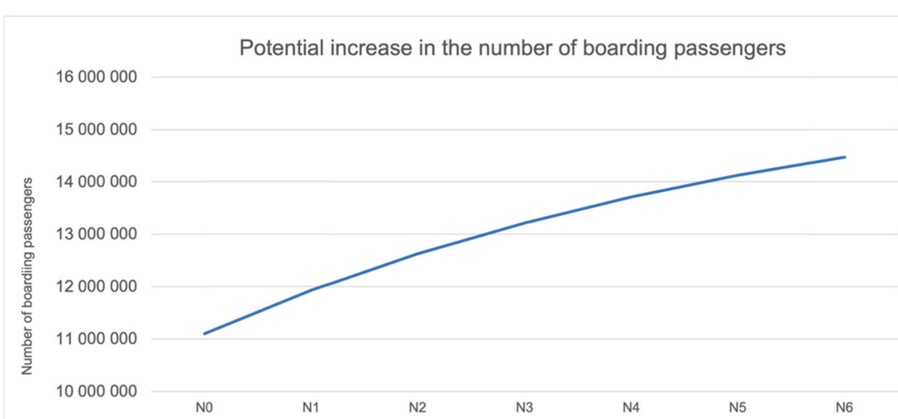

Fig. 7. The potential increase in the number of boarding passengers when the supply elasticity is set to 0.7.

the departure times by up to 5 min is easily executed and results in the sharpest peak being cut. Additionally, a larger change in bus departure times during peak hours has a greater impact and usually involves communication with more actors, such as schools and the municipality. The PTA interviewee reasoned that larger adjustments are a political question and are outside the scope of what is possible to mandate a bus operator to be responsible for. Changes in the public transport supply and travel time are acknowledged as the two most important parameters within traffic planning regarding impacting the number of boarding passengers.

Both interviewees point out that additional actors need to be included if adjustments over a few minutes are to be implemented. This includes especially municipalities and schools since pupils travelling with the buses will be affected. A large share of the passengers during peak hours are pupils, resulting in governmental actors having significant power over the possibility to spread out the peak demand. The experience is that these actors are difficult to get involved because they do not see the whole picture of the larger traffic system and its costs, instead, they focus on their departmental costs and planning. A small number of municipalities actively work with staggered school starting hours as a way to enable an adjusted bus timetable where fewer vehicles are needed.

Both interviewees agreed with the results regarding the possibility to reduce the number of buses needed and that if reinvesting saved resources an increase in boarding passengers is a probable effect. The interviewee from the bus operator indicates that the increase in passengers results in a high effect in relation to the input. However, both interviewees did express a concern regarding how easy it is to translate the bus fleet efficiency into an increase in supply. The level of generalizability is dependent on the traffic area and demographics, with the need for a certain lowest level of base traffic.

5. Discussion

The purpose of this study was to analyse the impact on operating costs if the departure times of buses were to be adjusted up to 30 min. The effects of the proposed changes were evaluated from two economic perspectives: resulting bus fleet efficiency and how re-investing it can lead to an increase in the number of boarding passengers. The study demonstrates a possible reduction in the number of vehicles needed if the bus departure times can be adjusted marginally. Resulting in a reduction in the cost of operations. Furthermore, if the cost reduction is re-invested to increase the public transport supply there will be an increase in the number of boarding passengers. The results indicate that even small changes in departure times within a limited area can result in cost reductions. Moreover, the assumption is made that the result can be extrapolated to larger traffic areas, such as whole regions and countries.

There are several challenges linked to being able to marginally adjust the bus departure times. The largest issue is assumed to be the need to spread out the peak travel demand. Furthermore, there is a challenge in making sure that the sharpest peak demand is spread out and just not moved in time, to be able to reduce the number of vehicles needed in a traffic area. When trying to create a more even traffic flow with less difference between peak and off-peak hour traffic, for both car traffic and public transport, there is a need to consider the big picture. An even traffic flow contributes to more optimal use of vehicles and working schedules that are more convenient for bus drivers.

The high demand during peak hours is partly related to students travelling to school. The interviewees mentioned the school starting hours several times as a reason for the travel demand being so high during peak hours and that departure times are adapted to fit the school schedule. The school buses are ordered by the municipality, which does not consider the whole traffic system but only focuses on the school starting hours. However, since the municipality decides the school hours it is perceived as easier to affect than the hours at private workplaces. Staggered school starting hours can contribute to cutting the peaks in traffic and levelling out the use of buses during the day (Ljungberg, 2009). A study by Ljungberg (2009) concludes that a change in school starting hours of 15 min can result in an increase in social welfare (with respect to buses not needed, cost of public funds, and costs for the pupils). Several attempts to change the school starting hours have been implemented in Sweden, however, most of them were interrupted or terminated after a while (Swedish Association of Local Authorities and Regions, 2019). More communication between different actors has been requested to support these initiatives as well as additional evidence regarding the effects of the costs for small adjustments in time. Furthermore, a change in school hours can affect office hours and change people's travel behaviour and patterns in the long run. Moreover, the Covid-19 pandemic has actualized the question of changing school starting hours, as well as the starting times at workplaces. For example, bus operators in the Netherlands successfully implemented staggered school starting hours in 2020 and 2021 (Keolis, 2022). By increasing the general understanding and awareness of the high costs related to high and sharp travel demand peaks, measures to change the behaviour of the individual passenger can be further motivated.

A reduction in travel demand during peak hours for all travel modes can increase accessibility, leading to reduced travel time for both public transport and cars. Changing people's travel patterns also creates a demand for the new departures generated when re-investing the bus fleet efficiency. Further studies should include which challenges and possibilities the municipalities and school principals see with staggering the school starting hours. Furthermore, how a change in school working hours affects the overall use of the school facilities, personnel, activities for students after school, and staff meetings.

A drawback with adjusting the departure times a few minutes is the risk of losing a set headway. This can be perceived as negative by the passengers since it can be harder to keep track of the departure times when it is not a rolling timetable. This can be partly helped by that most timetables today are accessible digitally and passengers can check the departure times through an app. Digital access to a timetable might lead to that a set headway is not as important in the future, since there is no need to learn the timetable by heart. If the buses depart with a high frequency, there is also less need for a set timetable since the passengers just head to the bus stop and wait for the next bus to arrive.

In this study, the calculated bus fleet efficiency is 10.7%, with regards to the reduction of the number of buses needed when being able to adjust the departure times up to 15 min. Similar studies have found a cost reduction of 4.54–12.84% when optimising a bus timetable (Gao et al., 2019), or a reduction of the total cost of passenger waiting time and vehicle operation (number of vehicles) by 16.90% (Shang & Liu, 2019). In comparison to these two studies, the calculated bus fleet efficiency seems probable. The fully allocated cost model defined by Fielding (1987) also includes peak vehicle costs that relate to the fleet size and its associated infrastructure (e.g., depot size) and general administration. Savage (1989) describes and compares two bus costing methodologies: the British National Bus Company model and the Australian Adelaide model. Both models point to a higher than the mean production cost for peak hour traffic, related to the number of vehicles needed and overhead costs related to the fleet size. Taking these cost models into account might result in an even higher possible bus fleet efficiency for this study. The interviewee from the bus operator discussed the results regarding the ongoing introduction of electric vehicles in the bus fleet, resulting in a reduction of the variable costs and an increase in the set costs. This might affect the results of this type of study within a decade.

The calculated potential increase in the number of boarding passengers and ticket revenues is dependent on the chosen value of the supply elasticity. The value of the supply elasticity depends on several factors, e.g., change in frequency and headway, if the increase in supply has a corresponding demand, and how large the increase in supply is compared to the base scenario. The performed sensitivity analysis provides a range of potential increases in the number of boarding passengers. Furthermore, the reduction in peak demand might not be equal to or larger than the increase in off-peak demand.

6. Conclusions

The results from the study showed that by adjusting the bus departure times by up to 15 min, fewer buses are needed and the peaks in traffic can be cut. Even adjusting the departure times up to 5 min leads to a decrease in operating costs. The reduction in costs mainly originates from a reduction in the number of vehicles and drivers needed, and more effective use of the resources. The operating cost reduction can be translated into a bus fleet efficiency, which potentially can be used to improve public transport in the area by expanding the supply in the long run. The scenario simulations made in the two case studies include local traffic areas, however, the results indicate the possible reductions in cost for regional public transport systems by adjusting the departure times by a few minutes. To be able to implement an adjustment of bus departure times it is necessary to spread out the travel demand during peak hours, for example by staggering school start hours. These results should be studied further regarding the design of the public procurement process and the effects of built-in flexibility in contracts.

The use of fewer vehicles also has positive environmental effects since fewer buses must be manufactured and the buses are used more effectively. Furthermore, the need for fewer buses leads to less space needed for a bus depot. When the cost reduction can be utilised to increase the overall supply of public transport, the increase in passengers leads to a higher passenger ratio of the bus and a reduction in environmental impact per passenger.

CRediT authorship contribution statement

Eva-Lena Eriksson: Methodology, Formal analysis, Writing – original draft, Visualization. **Helene Lidestam:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Lena Winslott Hiselius:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

Declarations of interest: none.

Acknowledgements

This research was supported by the Swedish Energy Agency [project number 51089-1]. The study was conducted with the help of and with information from Stefan Jonsson, Nobina, Sofia Malander, Östgötatrafiken, and Jakob Klasander, Östgötatrafiken. The authors wish to thank the reviewers for the valuable comments that have been made to this paper.

References

Balcombe, R., Mackett, R., Paulley, N., Preston, J., Shires, J., Titheridge, H., Wardman, M., & White, P. (2004). *The demand for public transport: A practical guide (trk report TRL593*.

Blais, J.-Y., Lamont, J., & Rousseau, M. (1990). The HASTUS Vehicle and Manpower Scheduling System at the Société de transport de la Communauté urbaine de Montréal. *INFORMS Journal on Applied Analytics, 20*(1), 26–42. https://doi.org/10.1287/inte.20.1.26

Blais, J.-Y., & Rousseau, J.-M. (1988). Overview of HASTUS current and future versions. In J. R. Daduna, & A. Wren (Eds.), *Computer-aided transit scheduling* (pp. 175–187). Springer. https://doi.org/10.1007/978-3-642-85966-3_15.

Camén, C., & Lidestam, H. (2016). Dominating factors contributing to the high(er) costs for public bus transports in Sweden. *Research in Transportation Economics, 59*, 292–296. https://doi.org/10.1016/j.retrec.2016.07.021

Currie, G. (2010). Quick and effective solution to rail overcrowding: Free early bird ticket experience in melbourne, Australia. *Transportation Research Record, 2146*(1), 35–42. https://doi.org/10.3141/2146-05

Dickinson, J., & Wretstrand, A. (2015). Att styra mot ökad kollektivtrafikandel—en kunskapsöversikt. *K2 Research, 2015*(2), 105. K2.

Eriksson, T., Betanzo, M., Johansson, M., & Norheim, B. (2017). *Hur får vi mer kollektivtrafik för pengarna? Ekonomisk analys av perioden 2000–2015 av svensk upphandlad kollektivtrafik* (No. 118/2017). UrbanetAnalyse. https://s3.eu-west-1.amazonaws.com/rr-urbanet/Filer-Dokumenter/UA_rapport_1182017_Kollektivtrafikens-kostnadsutveckling_slutlig_2017_06_30_version10.pdf.

Fielding, G. J. (1987). *Managing public transit strategically: A comprehensive approach to strengthening service and monitoring performance* (1st ed.). Jossey-Bass Publishers http://catdir.loc.gov/catdir/toc/wiley023/87045497.html.

Gao, P., Zuo, X., Bian, Q., & Zhao, X. (2019). A memetic algorithm to optimize bus timetable with unequal time intervals. *Proceedings of the Genetic and Evolutionary Computation Conference Companion*, 1336–1344. https://doi.org/10.1145/3319619.3326844

Giro. HASTUS software (n.d.)Retrieved 17 May 2022, from https://www.giro.ca/en-ca/our-solutions/hastus-software/.

Hale, C., & Charles, P. (2009). Managing peak demand for passenger rail: A literature review. *Australasian Transport Research Forum, 32*, 15. https://australasiantransportresearchforum.org.au/managing-peak-demand-for-passenger-rail-a-literature-review/.

Halvorsen, A., Koutsopoulos, H. N., Lau, S., Au, T., & Zhao, J. (2016). Reducing subway crowding: Analysis of an off-peak discount experiment in Hong Kong. *Transportation Research Record, 2544*(1), 38–46. https://doi.org/10.3141/2544-05

Hansson, J., Pettersson-Löfstedt, F., Svensson, H., & Wretstrand, A. (2022). Patronage effects of off-peak service improvements in regional public transport. *European Transport Research Review, 14*(1), 19. https://doi.org/10.1186/s12544-022-00543-4

K2, Statens vegvesen, & Urbanet Analyse. (2017). *Kollektivtrafik—Utmaningar, möjligheter och lösningar för tätorter* (Fourth edition). https://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/kollektivtrafik_utmaningar_mojligheter_och_losningar_for_tatorter.pdf.

Kamel, I., Shalaby, A., & Abdulhai, B. (2020). A modelling platform for optimizing time-dependent transit fares in large-scale multimodal networks. *Transport Policy, 92*, 38–54. https://doi.org/10.1016/j.tranpol.2020.04.002

Keolis. (2022). *Easing rush hour crowding in the Netherlands' public transportation*. https://innovation.keolis.com/en/projects-news-insights/easing-rush-hour-public-transit-crowding-in-the-netherlands-by-reaching-out-to-stakeholders-in-education/.

Lidestam, H., Camén, C., & Lidestam, B. (2018). Evaluation of cost drivers within public bus transports in Sweden. *Research in Transportation Economics, 69*, 157–164. https://doi.org/10.1016/j.retrec.2018.05.009

Ljungberg, A. (2009). Staggered school hours to spread peak demand for public transport. Benefits and costs. *International Journal of Transport Economics, 36*(1), 141–160.

Mohring, H. (1972). Optimization and scale economies in urban bus transportation. *The American Economic Review, 62*(4), 591–604.

Nilsson, D., Stjernborg, V., & Fredriksson, L. (2017). *Effekter av kollektivtrafiksatsningar—En kunskaps- och forskningsöversikt* (K2 Working Papers 2017:4). https://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/effekter_av_kollektivtrafiksatsningar_k2_working_paper_2017_4.pdf.

Noordegraaf, D. M. V., & Annema, J. A. (2012). Employer attitudes towards peak hour avoidance. *European Journal of Transport and Infrastructure Research, 12*(4). https://doi.org/10.18757/ejtir.2012.12.4.2975. Article 4.

Qian, Z., & Rajagopal, R. (2015). Optimal dynamic pricing for morning commute parking. *Transportmetrica a-Transport Science, 11*(4), 291–316. https://doi.org/10.1080/23249935.2014.986671

Salicrú, M., Fleurent, C., & Armengol, J. M. (2011). Timetable-based operation in urban transport: Run-time optimisation and improvements in the operating process. *Transportation Research Part A: Policy and Practice, 45*(8), 721–740. https://doi.org/10.1016/j.tra.2011.04.013

Savage, I. (1989). The analysis of bus costs and revenues by time period: II. Methodology review. *Transport Reviews, 9*(1), 1–17.

Schmid, V., & Ehmke, J. F. (2015). Integrated timetabling and vehicle scheduling with balanced departure times. *OR Spectrum, 37*(4), 903–928. https://doi.org/10.1007/s00291-015-0398-7

Shang, H., & Liu, Y. (2019). An extended vehicle scheduling model considering interests of both passengers and bus operators. *2019 Chinese control conference (CCC)*, 1995–2000. https://doi.org/10.23919/ChiCC.2019.8865735.

Silva, H. E. (2021). The mohring effect. In *International encyclopedia of transportation* (pp. 263–266). Elsevier. https://doi.org/10.1016/B978-0-08-102671-7.10050-8.

Stjernborg, V., & Mattisson, O. (2016). The role of public transport in society—a case study of general policy documents in Sweden. *Sustainability, 8*(11). https://doi.org/10.3390/su8111120. Article 11.

Swedish Association of Local Authorities and Regions. (2017). Kollektivtrafikens kostnadsutveckling – en överblick. Vad förklarar utvecklingen 2011-2015. https://skr.se/download/18.45167e4317e2b341b24adfc0/1642687744526/7585-529-5.pdf.

Swedish Association of Local Authorities and Regions. (2019). *Peaktider i kollektivtrafiken* [Idéskrift]. Avdelningen för tillväxt och samhällsbyggnad. https://skr.se/skr/tjanster/rapporterochskrifter/publikationer/peaktiderikollektivtrafiken.65349.html.

Tang, J., Yang, Y., Hao, W., Liu, F., & Wang, Y. (2021). A data-driven timetable optimization of urban bus line based on multi-objective genetic algorithm. *IEEE Transactions on Intelligent Transportation Systems, 22*(4), 2417–2429. https://doi.org/10.1109/TITS.2020.3025031

Tang, Y., Yang, H., Wang, B., Huang, J., & Bai, Y. (2020). A Pareto-improving and revenue-neutral scheme to manage mass transit congestion with heterogeneous commuters. *Transportation Research Part C: Emerging Technologies, 113*, 245–259. https://doi.org/10.1016/j.trc.2019.05.016

Tegnér, G., Henningsson, J., Gaudry, M., Nordell, O., & Lundblad, G. (2006). *Kollektivtrafikens marknadsutveckling –tendenser och samband: Bearbetning av SLTF-statistiken (rapport 2006:43)*. Transek AB. https://doi.org/10.13140/2.1.2480.4649

Trafikanalys. (2019). *Regional linjetrafik 2018* (trafikanalys statistik 2019:22). Trafikanalys. https://www.trafa.se/globalassets/statistik/kollektivtrafik/kollektivtrafik/2018/regional-linjetrafik-2018–statistikblad.pdf.

Vigren, A. (2016). Cost efficiency in Swedish public transport. *Research in Transportation Economics, 59*, 123–132. https://doi.org/10.1016/j.retrec.2016.05.009

Zhang, W., Xia, D., Liu, T., Fu, Y., & Ma, J. (2021). Optimization of single-line bus timetables considering time-dependent travel times: A case study of beijing, China. *Computers & Industrial Engineering, 158*, Article 107444. https://doi.org/10.1016/j.cie.2021.107444