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Cycling tolls and optimal number of bus stops – the importance of congestion and crowding

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Abstract
This paper optimises the number of bus stops, and prices for car, bus and cycling in the busiest inner city corridor in Stockholm. We find that the number of bus stops is already close to optimal. Welfare would increase if the peak frequency was increased, the bus fares were differentiated such that short trips paid less than the current rate, and that the toll for longer car trips was increased. The optimal toll for cyclists, and the welfare benefit from it, is small and does not compensate the transaction costs. The distributional effects of bus fare changes and higher car tolls are small because on one hand, high income groups place more value on travel time gains, but on the other hand, low income groups travel less frequently by car. Surprisingly, we find that in the welfare optimum, the bus service generates a surplus due to congestion in the bus lane, crowding in the buses, and extra boarding and alighting time per passenger. The Mohring effect is limited because the demand, and thereby the baseline frequency, is already high.

Keywords: Public transport, cycling, bus stops, congestion, optimal pricing of urban transport.

JEL Codes: R41, R48.

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1 INTRODUCTION

It appears that cycling has received increasing attention from planners and decision makers in the US and Europe in the past decades (CEMT, 2005). The EU commission's Green Paper (European Commission, 2001) states that "More attention should be paid to the development of adequate [bicycle] infrastructure". Since the 1990s, cycling has also been increasing in inner cities in America, Canada and Australia (Pucher & Buehler, 2012). In Stockholm, Copenhagen (City of Copenhagen, 2011), London (Transport for London, 2015) and various Dutch cities (Ministry of Transport Netherlands, 2009), cycling is increasing in the dense city core (but not further out in the counties). This increases the interaction between cyclists and other modes. Still, the large literature on optimal welfare pricing and allocation of road lanes (Basso & Silva, 2014; Parry & Small, 2009) has so far neglected cycling.

In this paper, we extend previous analysis on welfare optimal pricing and public transport design to include cycling. When considering the interaction between cyclists and other transport modes, the number of bus stops becomes a key policy variable depending on street design. In many cities the bicycle lane often disappears at the bus stop, forcing cyclists to divert into the car lane. Typically, cyclists either have to wait for the bus to leave the bus stop, or overtake it by diverting into the car lane, which in turn slows the cars down.

In the seminal work by Mohring (1972), the optimal number of bus stops is a trade-off between access cost on one hand, and in-vehicle travel time and operation costs on the other. In our model we add a much less studied second element which influences the optimal number of bus stops: the interaction between buses and other traffic at the bus stop including cyclists. We focus on the efficiency aspects assuming full control of the supply side by the planner and leave the procurement dimension of bus supply aside. We define a formal model, linking demand and supply, for an inner city corridor and calibrate the model for Stockholm. The model takes into account the interaction between different modes, enabling us to model the effect of different policy instruments. We derive the optimal pricing of cars, buses and cyclists in the corridor. The optimal pricing of cyclists depends on the extent to which they create congestion in the street in a direct way, and to what extent it slows other modes at the bus stop. If use of buses and cars is not priced correctly, the pricing and investments for cyclists also takes into account the possible substitution effects. The model also optimises bus frequency and number of bus stops. We also explore how the optimal number of bus stops, prices and frequencies depend on the design of the bus stops.

Given the strong political objective to increase cycling in many cities, we admit that it might be difficult to launch a toll for cyclists. The increased promotion by policy makers is not at all surprising, given the advantage of bicycling in dense cities - its space efficiency when used and parked, low travel time, reliability, low price, quietness, and cleanness. What is surprising, however, is that cycling is rarely seen as one travel mode among others, with its merits and demerits; it is usually motivated by its indirect effects: zero emissions and health benefits. By exploring a toll for cyclists we acknowledge that cycling also gives rise to congestion.

The correlation between cycling and health is well established, and for this reason, some authors have claimed that health benefits add major external benefits of cycle investments (Sælensminde (2004); Krag (2005); WHO (2011)). Health benefits include the the value assigned to human injuries and deaths, but also the costs for the social

security system and production losses. However, the value of human injuries and death constitue 75-85% of the health benefits of generated cyclist (Swedish Environmental Protection Agency, 2005).

Now, the traditional view in economics literature is that personal health is primarily an individual responsibility and benefit (except the cost for the social security system and the external part of the production losses), and thereby internalised in the travelers' choice to cycle. There is also supporting evidence that health benefits are to a large extent internalised in travellers' decisions and that cyclist to a large extent replace other exercise with cycling (Börjesson & Eliasson, 2012b). For this reason we assume in this paper that the health benefits are internal: the awareness of health benefits increases cycling volumes, reduces the values of time for cyclists and is thus already considered in our analysis. Apart from external health benefits of cycling, we also view accident risks of cycling as being internalised by cyclists.

The assumption that buses are more intensively used by lower income groups is often used as an argument in favour of reducing bus fares. Moreover, low-income groups have also traditionally cycled more, all other things being equal. However this is no longer true at least for Stockholm (Börjesson & Eliasson, 2012a). For this reason, we also explore the income redistribution of the policy instruments under study.

Stockholm differs from most other cities in that congestion charges are levied on the corridors leading into the city. Due to the extensive monitoring program that was put in place when the charges were first introduced in 2006, data regarding traffic flows, elasticities and cross-elasticities are also well documented in Stockholm.

The paper is organised as follows. Section 2 briefly discusses the literature. Section 3 presents the model components. Section 4 derives optimal pricing, frequency and optimal bus stop rules. Section 5 presents the study area and the calibration data. Section 6 presents numerical results and section 7 documents the sensitivity analyses. Section 8 concludes with some caveats.

2 LITERATURE AND OUR CONTRIBUTION

There are two strands of research that are useful for our purpose. There is the general theory on public transport pricing and organisation, and there is the specific research on bus services, including the number of stops.

Optimal pricing and frequency principles for public transport have been developed by Mohring (1972) as well as Jansson (1980, 1984), Viton (1980), Kraus (1991), Jara-Díaz and Gschwender (2003), Monchambert and de Palma (2014), de Palma, Kilani, and Proost (2015) and De Borger and Proost (2015). The optimal pricing and frequency rules have been illustrated for metropolitan areas by Parry and Small (2009), Basso and Silva (2014), Kilani et al. (2014) and Tirachini et al. (2014b). The principles put forward are that i) for given frequencies, first best prices for bus use should internalise the external crowding costs and ii) first best frequencies need to balance the costs of an extra bus with the decrease in waiting time costs (Mohring, 1972) and decreased crowding costs (de Palma et al, 2015) for the users as well as the increased congestion in the bus lane.

In his seminal work, Mohring (1972) explicitly models the optimal number of bus stops as a trade-off between the operators' costs and in-vehicle travel time versus access time. Jansson (1980, 1984) simplifies this model by assuming that the number of bus

stops is constant, implying that it does not influence access time. On the other hand, Jansson considers peak and off-peak periods, and the differences in demand across them. He concludes that, in general, it would be optimal to run approximately the same frequency in peak and off peak. Börjesson et al. (2017), however, find that the optimal bus frequency is substantially higher in the peak compared to the off-peak in a commuting corridor in Stockholm, and that current bus frequency is lower than optimal in the peak and higher than optimal in the off-peak. They also find that reducing the off-peak frequency increases welfare more than optimising fares. This difference in conclusions comes from Jansson's assumption that drivers cannot be employed only in the peak hours[3] and from Börjesson et al. considering crowding in the bus. Moreover, S. R. Jara-Díaz and A. Gschwender (2003) show that when the frequency and the density of the bus service are jointly optimised, the optimal frequency is lower than when the density is considered to be fixed.

Tirachini et al. (2014a) find that travel time variability and crowding discomfort leads to higher optimal bus sizes. The results of Tirachini et al. (2013) underscores the importance of taking crowding costs into account when estimating the demand for buses.

Moreover, Tirachini et al. (2014b) find that the optimal frequency is sensitive to the cost of crowding and the congestion on the bus lane. We find the same and also that the optimal profit/deficit is sensitive to these parameters. In addition, Tirachini and Hensher (2011) find that, in most cases investment in an off-board fare payment system to reduce boarding time is cost effective. van Nes and Bovy (2000) find that the optimal number of bus stops is smaller when maximising the bus operator's profit than when maximising welfare. Tirachini (2014) also finds that the optimal number of bus stops increases with demand, such that when demand increases, the distance between stops in the CBD decreases from 370 to 260 m and from 600 to 470 m in the suburbs. When considering the trade-off between the operators' costs and in-vehicle travel time versus access time, both Furth and Rahbee (2000) (for a bus route in Boston) and Li and Bertini (2009) (for a bus route in Portland) find an optimal spacing of bus stops of approximately 400 m. This is more than the current spacing of bus stops in the inner city corridor under study in this paper.

We make contributions to the literature in four aspects: First we add cycling as one travel mode among the others in the formal model. Second, we study the effect of adjusting the number of bus stops, bus frequency and pricing of different modes on the optimal subsidies. Third, we study the distributional effects of bus pricing, stops and frequencies. Cycling is on the rise in many cities, and both cycling and increased public transport patronage are often argued as a main solution to combat congestion. We are able to analyse this issue for the busiest bus service in Stockholm, where we have good data on supply and demand for all travel modes (including cycling).

This paper also contributes to the literature on the optimal street design around bus stop. Unless the street space and public transport system are designed efficiently, Gosse and Clarens (2013) show that increased cycling increases congestion and accidents due to interaction with motor traffic. For this reason many cities have, or are introducing, bicycle lanes. Typically the bicycle lane runs between the curb or parked cars and the bus lane, but disappears at the bus stop because the bus has to reach the curb (Figure 1). The cyclists are thus forced to divert into the car lane to overtake the bus or to wait for the bus to leave the stop. In many Asian countries (China, Malaysia, Vietnam,

[3] The presence of union may restrict the bus companies to pay drivers for the whole shift, instead of for a few hours in the peak period only.

Cambodia) the bus stops are often located in the non-motorised lane. So when there is a bus at the bus stop, bicycles divert into the car lane. The result is a temporary conflict between bicycles, buses and cars which reduces road capacity and reduces traffic safety. In Copenhagen and in Dutch cities, on the other hand, the bicycle paths are adjacent to the curb at the bus stop (Figure 2). So when bus passengers have to cross the bicycle path to reach the bus stop, the risk of accidents increases and comfort and speed for cyclists decrease (Snizek et al., 2013). The bicycle path can also be completely separated from the rest of the road traffic (Figure 3). Hence, in many cities, the interaction of cyclists with other traffic is important when considering frequencies, fares and the number of bus stops as well as road user charges and allocation and design of the street space. Our study finds that the optimal pricing, bus frequency, number of bus stops and subsidy is virtually independent from street design, due to the small externalities created by cycling. They might, however, play a role for the comfort and safety for the cyclists, but the effect is embedded in the calibration.

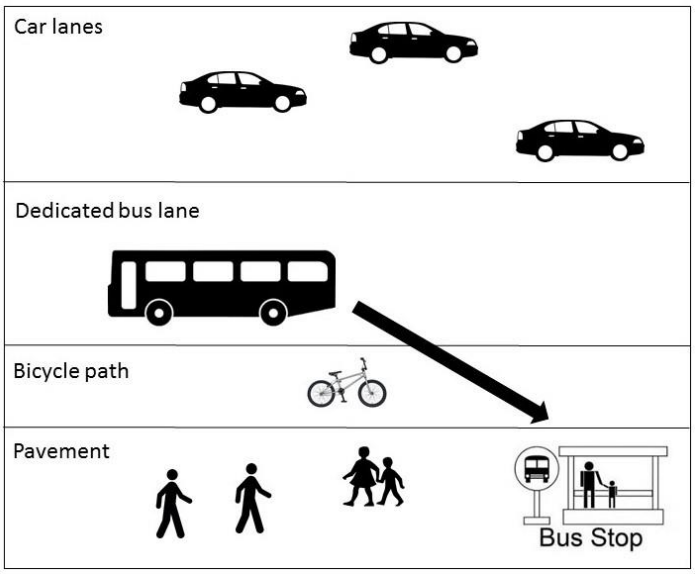

Figure 1: Bus stop design in our model

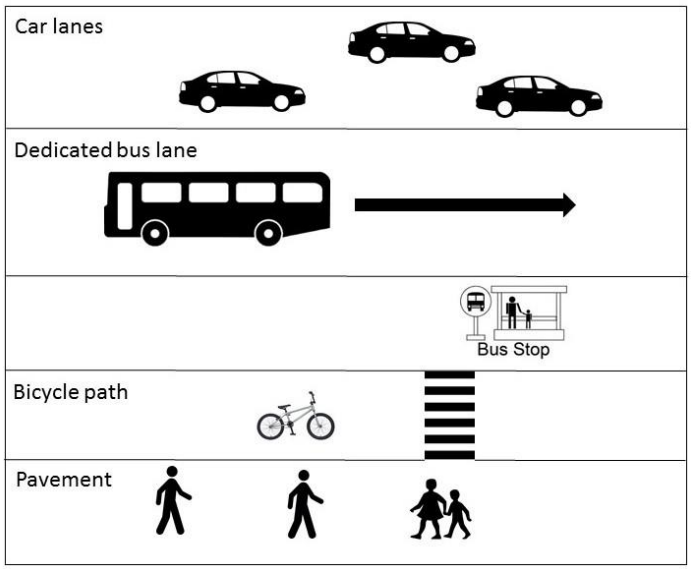

Figure 2: Alternative bus stop design (Design (i) in sensitivity analysis)

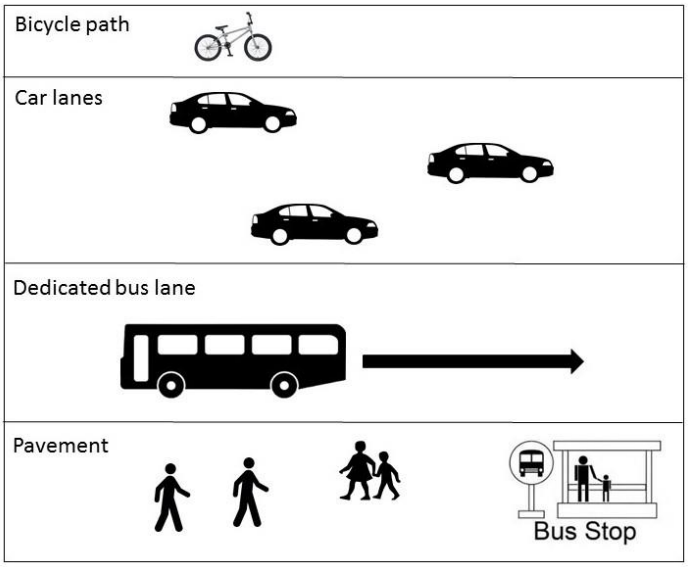

Figure 3: Alternative bus stop design (Design (ii) in sensitivity analysis)

3 THE MODEL

We formally define an aggregate model for an urban area around a given bus corridor. Population is homogenously spread along the corridor. We use four different user groups, distinguished by income and preference for cycling, indexed by k= 1,2,3,4 (high, mid, low income, and no-bicycle). The travellers' preferences differ by user group, but are assumed to be homogenous within the user group. Hence, each user group can be treated as a representative individual. The number of trips by income group is a continuous variable.

Travellers in the first three user groups are distinguished by income level, and have therefore different values of time. The fourth group has no access to cycling. The first three user groups can demand two different goods: long and short trips (j= short [s], long [l]). For short and long trips, the travellers can choose between three modes: h: car (c), bus (b) and bicycle (v). The fourth user group, no-bicycle, is assumed to have the same values of time as the mid-income group. The travellers in this user group do not want to/cannot choose to cycle (disability, age, heavy luggage, trips longer than 12 km etc.), and cycling is therefore not included in their choice set. The no-bicycle user group makes only long trips (j= long [l]) and only car (c) and bus (b).

The users' marginal costs of travelling consist of the monetary cost and time cost for different travel time components. The marginal user cost of a car trip varies in function of travel time cost (the level of road congestion) and on the marginal monetary cost of driving the car. The travel cost of bicycling depends on travel time and perceived comfort and safety and hence, on the quality of the bicycle network. The user costs of a bus trip include the in-vehicle time cost, the waiting time at bus stops, and the access cost to bus stops. Since an additional element in this model is the interaction between modes at bus stops, which affects the trip time for all, the frequency of buses and number of bus stops influence the user cost.

We include the marginal cost of bus supply. It depends on frequency offered and the number of bus stops. More bus stops increases supply cost because each bus stop has an investment and maintenance cost.

We also take into account the urban-rural differences of external costs caused by accidents involving cars or buses and emissions. These external costs are partly internalised in fuel taxes[4].

For the formal presentation of the model, we need to specify the preferences, travel time and cost by mode, as well as the cost of public transport supply in greater detail. We make two simplifications: First, we limit our analysis to one corridor rather than a full network; second, we consider the peak period only (two hours in the morning 7-9 and two hours in the afternoon (15.30-17.30) on a representative workday).

3.1 Preferences

We assume residents to be fixed. The travellers' preferences are represented by a quasi-linear quadratic utility function *U*. Utility is the sum of utility derived from non-transport goods (money *m*) and the sub-utility functions $B^{s,k}$ and $B^{l,k}$ for all transport goods. We assume that the demand for short and long trips is independent.

Utility function for a representative user in group *k* is given by

$$U^k(m^k, q_c^{s,k}, q_b^{s,k}, q_v^{s,k}, q_c^{l,k}, q_b^{l,k}, q_v^{l,k}) = m^k + B^{s,k}(q_c^{s,k}, q_b^{s,k}, q_v^{s,k}) + B^{l,k}(q_c^{l,k}, q_b^{l,k}, q_v^{l,k}), \tag{0}$$

where *m* is the utility from goods other than transportation. The quasi-linear function removes the income effect[5] justified by the limited share of the household costs allocated to transport. The quadratic sub-utility function for short and long trips has the form

$$\begin{aligned} B^{j,k}(q_c^{j,k}, q_b^{j,k}, q_v^{j,k}) = {} & a_c^{j,k} q_c^{j,k} + a_b^{j,k} q_b^{j,k} + a_v^{j,k} q_v^{j,k} \\ & - 0.5 b_c^{j,k} \left(q_c^{j,k}\right)^2 - 0.5 b_b^{j,k} \left(q_b^{j,k}\right)^2 - 0.5 b_v^{j,k} \left(q_v^{j,k}\right)^2, \\ & - i_{cb}^{j,k} q_c^{j,k} q_b^{j,k} - i_{cv}^{j,k} q_c^{j,k} q_v^{j,k} - i_{bv}^{j,k} q_b^{j,k} q_v^{j,k} \end{aligned} \tag{1}$$

where *q* is the number of trips by the representative individual. The parameters *i*, *a* and *b* are the parameters in the sub-utility function *B*, where *i* indicates the relationship between modes. In our setting, different modes are substitutes so $i > 0$ ($i < 0$ if they are complements). The superscripts *k* and *j* stand for user group and trip length respectively. The subscripts *c*, *b* and *v* represent the car, the bus, and cycling, respectively.

[4] The current level of fuel tax in Sweden is 664 euros per 1000L (petrol) and 573 euros per 1000L (diesel) (Source: current road fuel excise duty in Sweden). Taking fuel efficiency of 6.5L per 100km implies a fuel tax per vkm of 4.4 eurocents for gasoline cars. The external air pollution and noise costs are 4.3 eurocents per vkm (cars), 21.4 eurocents per vkm (bus); the external accident cost is 0.1-0.3 eurocents per vkm (European Commission – DG Mobility and Transport, 2014).This means the gasoline tax internalises the external costs for rural car use. In this paper, we study an inner city area with higher external costs so these external costs are partly internalised only. For diesel cars, an even smaller part of the external costs are internalised as they pay less taxes per km, but this requires a policy correction at the level of vehicle purchase taxes. For buses, around 4.5 times of fuel for car use is consumed, so 19.6 eurocents per vkm is internalised by fuel tax. See Section 3.4 for more details.

[5] This is justified by two factors. First we calibrate a utility function for each user group so that the effect of income differences is already taken into account in the calibration. Second, we consider only price variations of transport goods that are only a small share of total expenditures so that the income effect of price variations is small. For instance, an increase of 20% of the cost of trips (that counts for 10% of the total budget) means that there will be an income effect of 2% only.

Then we can derive the willingness to pay by user group, trip length and transport mode as linear inverse demand functions:

$$\begin{aligned}\frac{\partial B^{j,k}}{\partial q_c^{j,k}} &= a_c^{j,k} - b_c^{j,k} q_c^{j,k} - i_{cb}^{j,k} q_b^{j,k} - i_{cv}^{j,k} q_v^{j,k} \\ \frac{\partial B^{j,k}}{\partial q_b^{j,k}} &= a_b^{j,k} - b_b^{j,k} q_b^{j,k} - i_{cb}^{j,k} q_c^{j,k} - i_{bv}^{j,k} q_v^{j,k} \\ \frac{\partial B^{j,k}}{\partial q_v^{j,k}} &= a_v^{j,k} - b_v^{j,k} q_v^{j,k} - i_{cv}^{j,k} q_c^{j,k} - i_{bv}^{j,k} q_b^{j,k} \\ \text{for} \quad j &= s,l \quad k = 1,2,3,4\end{aligned} \tag{2}$$

By definition the willingness to pay equals the user cost (including tolls and fares) in equilibrium. We analyse the user costs in the next subsection.

3.2 User cost

Here we define the user cost by mode, excluding the tolls and fares. The user cost for cyclists is

$$uc_v^{j,k} = dis^j c_v + dis^j VOT_v^k TT_v, \tag{3}$$

where c_v is the fixed monetary cost for cycling per km, dis stands for distance in km, VOT_v^k stands for the value of cycling time, which is group specific. And the travel time per km TT_v is given by

$$TT_v = \alpha_v + \beta_v \frac{q_v^l + \lambda q_v^s}{n_h cap_v} + \gamma_v n_s P_b P_c \ , \tag{4}$$

where α_v is the free-flow cycling time. The second term refers to cycling time which depends on the number of bicycles on the road. β_v is the congestion parameter and the fraction represents the occupancy of the road. The numerator gives the total number of cyclists during the peak period with q_v^l denoting the number of long trips, q_v^s for short trips, and λ as the relative distance of short trips to long trips. The denominator is the total capacity during the peak period, with n_h as the number of hours in peak period and cap_v is the number of bicycle lanes. The third term is the additional travel time for bicycles which is caused by the interactions with other modes. This additional travel time is only imposed when there is a car in the car lane and a bus at the bus stop at the same time, forcing the cyclist to wait. γ_v is the additional travel imposed on a cyclist who encounters a bus at the bus stop. n_s is the average number of bus stops per km, P_c is the probability that there is a car in the car lane (when the cyclists divert into the car lane), and P_b is the probability that there is a bus at the bus stop (when the cyclists pass it).

The user cost for drivers is

$$uc_c^{j,k} = dis^j c_c + dis^j VOT_c^{inv,k} \left[\alpha_c + \beta_c \frac{q_c^l + \lambda q_c^s}{n_h cap_c} + \gamma_c n_s P_b P_v \right], \tag{5}$$

which is of a similar structure as user costs for cyclists. It consists of the monetary cost c_c and the time cost (the second term on the right hand side). Again, the last term in the brackets, which represents the delay caused by interaction with other modes at bus stops, is non-zero only when there is a bus at the bus stop so the passing cyclist has to divert into the car lane, imposing a cost on drivers.

The user cost for bus passengers includes the cost of the waiting time at the bus stop, the access cost to the bus stops, and the cost of in-vehicle time,

$$uc_b^{j,k} = VOT_b^{w,k}\frac{60}{2f} + VOT_b^{ac,k}\frac{L}{2n_s v_w} + dis^j VOT_b^{inv,k}\cdot TT_b^{inv}\cdot DisCom \quad (6)$$

The value of time is different for waiting time at the bus stop $VOT_b^{w,k}$, access time to the bus stops $VOT_b^{ac,k}$ and in-vehicle time $VOT_b^{inv,k}$. The waiting time at the bus stop is defined in minutes (*60/(2f)*, where *f* is the frequency of buses per hour), and buses are assumed to arrive uniformly.[6] The access time equals the walking distance (length of the bus route L divided by $2n_s$, assuming uniform distribution of passengers along the route) divided by the walking speed v_w. The in-vehicle time takes the same form as in the previous user costs except that it is augmented by a discomfort multiplier.

The total in-vehicle time is defined as

$$TT_b^{inv} = \alpha_b + \beta_b\frac{\sigma(V_b)f}{cap_b} + \gamma_b n_s P_v + TS_b, \quad (7)$$

where α_b is the free-flow bus travel time. The second term is the additional travel time for the bus arising from interaction with other buses. It depends on the bus frequency and the vehicle equivalent of a bus (σ), which in turn depends on the number of seats on the buses (V_b) and the number of bus lanes (cap_b). The third term, γ_b is the delay arising from interaction with bicycles at the bus stop. The last term is the time spent by buses at bus stops, TS_b, which is defined as

$$TS_b = n_s\left[t_s + \zeta(q_b^l + q_b^s)/(fn_h n_s)\right]. \quad (8)$$

It includes a fixed time cost t_s (per stop) for the bus entering and leaving the stop, and a variable cost depending on the number of passengers boarding and alighting at each stop. ζ is the time needed for a passenger to board and alight, which is then multiplied by the average number of passengers who board and alight per stop.

The discomfort/crowding multiplier has the form of

$$DisCom = dc_b^{n_{on}/V_b}, \quad (9)$$

which is a nonlinear increasing function. It is equal to one when the bus is empty, and is equal to dc_b when the number of passengers on board n_{on} reaches the seating capacity of bus V_b, and continues to increase afterwards. The number of passengers on board at a certain point of time is

$$n_{on} = r_{on}\cdot(q_b^l + \lambda q_b^s)/(fn_h), \quad (10)$$

which is given by an on-board ratio r_{on} multiplied by the average number of passenger trips per bus. Note that $r_{on} < 1$ because not all bus passengers travel the route throughout.

[6] It is a reasonable assumption that bus passengers arrive randomly and do not plan their trip according to the time table when the frequency is as high as in the corridor under study.

Finally, the probability that a bus/car/bicycle is at (or pass) a bus stop is:

$$\begin{aligned} P_b &= \max\left[TS_b \cdot f\ /3600, 1\right] \\ P_c &= \max\left[TS_c \cdot \left(q_c^l + \lambda q_c^s\right)/(3600 \cdot n_h), 1\right], \\ P_v &= \max\left[TS_v \cdot \left(q_v^l + \lambda q_v^s\right)/(3600 \cdot n_h), 1\right] \end{aligned} \tag{11}$$

where TS_b is the time that buses spent at the bus stops. We assume that bicycles and cars spend two seconds passing each bus stop $(TS_c = TS_v = 2\,\text{sec})$. These probabilities take the maximum value of one when the time that all buses/ cars / bicycles spend at the bus stop exceeds the length of the peak period.[7]

Table 1 explains how the externalities associated with the three modes influence user costs by mode.

Table 1: How externalities influence user costs by mode

Cause \ Effect	Bicycle user cost	Bus user cost	Car user cost
Bicycle volume	Delay other bicyclists	When the bicycle lane is not fully separated from bus stops: Delay buses at bus stops; buses do not have priority	When the bicycle lane is not fully separated from bus stops: Delay car users when they have to avoid a bus already at a bus stop
Bus frequency	When the bicycle lane is not fully separated from bus stops: Delay bicyclists only when a car happens to be passing the bus stop	Less discomfort for existing bus users; less delay by boarding/alighting; delay other buses	When the bicycle lane is not fully separated from bus stops: Delay cars when bicyclists have to avoid the bus already at a bus stop
Car volume	When the bicycle lane is not fully separated from bus stops: Delay bicyclists when there is a bus at the	None	Delay other car users

[7] Theoretically, we need this upper bound but this is just a hypothetical situation that we have not encountered in the area under study. For example, when there are more than 1800 bicycles per hour passing the bus stop, stopping time is over one hour in total so the probability of a bicycle passing the bus stop is one, meaning that there are always bicycles passing the bus stop and buses cannot get in or leave the bus stop.

	bus stop		

3.3 Cost of public transport supply

The supply cost of buses is

$$C_b = n_s \cdot c_s + n_h \cdot f \cdot k\,, \tag{12}$$

where c_s is the capital and maintenance cost of one bus stop, and k is the operation cost per bus service in peak hours (hence this is the cost per kilometre times the distance of the bus route).

Table 2 summarises the marginal welfare effects of the two policy variables bus frequency and the number of bus stops.

Table 2: Marginal welfare effects of an extra bus or bus stop

	Welfare gain (positive)	Welfare cost (negative)
Extra bus	Reduced crowding in buses, reduced waiting times, reduced delay caused by boarding/alighting	Cost of bus and congestion on bus lane + more likely for cars and bicycles to be delayed at bus stops
Extra stop	Reduced access costs	Equipment cost of bus stop + longer in-vehicle time for bus users + more conflicts with bicycles that lead to more car congestion + more likely for bicycles to be delayed at bus stops

3.4 External costs

Table 3 summarises our assumptions on external costs in this model. In addition to the part of external costs (noise, emissions and automobile accidents) that are internalised in the current fuel tax, we include additional urban external costs for short car trips, long car trips and additional bus frequencies respectively e_c^s, e_c^l, e_b.

Moreover, we assume that the accident costs for cyclists[8] and the health benefits achieved from cycling are internalised in the traveller's choice to cycle. The main reason for assuming that the risk of accidents are internalized is that the lion part of accidents (eighth of ten cyclists (Niska och Eriksson, 2013)) involve the injured cyclists only. Moreover, since our analysis focuses on the delay caused by interactions between modes at bus stops, we assume the accident cost is internalised in cyclists' choice.

[8] The accident risk for cyclists is significant: according to the Transport Administrations a cycling accident cost is on average 0.6 million SEK (2014 price level). The average risk of an accident is 2.5 per million bicycle kilometers, based on an assessment made of cycling accident from the STRADA (Swedish Traffic Accident Data Acquisition) database statistics and total cycling distance in Sweden assessed from Swedish NTS data. These imply an accident cost of 1.5 SEK (0.15 euro) per bicycle kilometer.

As we optimise explicitly fares and frequency, the external costs of a bus (air pollution, congestion, accident costs) are taken into account when the frequency is decided. The external cost of a passenger (for given number of buses) equals the additional crowding cost and additional delay for the passengers already in the bus.

Mode	Accident interaction within mode	Accident interaction with other modes	Other external costs
Bicycle	Average risk of bicycle – bicycle accidents probably constant. Expected cost is internalized except for public subsidies health services and loss of life not covered by insurance.	Average risk of bicycle-bus and bicycle-car accidents could increase but this is largely internalized by cyclist.	Health benefits of biking are internalized by cyclist.
Bus on bus lane	Average risk of bus - bus accidents may be constant or increase but this is internalized by the bus company.	Average risk of bus-bicycle accident increases but bus company largely internalizes this cost via experience rating of insurance.	Air pollution, climate damage and noise are partly internalized via fuel tax.
Car	Average risk of car - car accidents may be constant, increase or decrease but this is internalized by experience rating of car insurance.	Average risk of car-bicycle accidents is constant, increases or decreases. This cost is internalized via experience rating of insurance.	Air pollution, climate damage and noise are partly internalized via fuel tax.

Table 3: Assumptions on external costs in the model.

Source: Mayeres et al. (1996).

4 THE WELFARE OPTIMUM

Our welfare function, Ω, equals the user surplus and the producer surplus minus total external cost other than congestion (as long as we can assume that the taxes collected to finance possible deficits for the producer are non-distortive[9])

$$\Omega = \sum_{j,k} B^{j,k}(..,q_h^{j,k},..) - \sum_{j,k,h} q_h^{j,k} uc_h^{j,k} - C_b - e_c^l q_c^l - e_c^s q_c^s - e_b\, fn_h\,. \tag{13}$$

We eliminate the bus fare from the user cost and revenues from the producer surplus since this is only a transfer.

In user equilibrium the user cost (including fares and tolls τ) equals the willingness to pay

[9] Taxes are often distortive because they move economic activities away from their optimal allocation. For instance, a tax on labour income may decrease incentive to work and thus labour supply. This issue has been widely discussed in optimal taxation literature.

$$uc_h^{j,k} + \tau_h^j = \frac{dB^{j,k}}{dq_h^{j,k}}, \ \forall \ j,k,h \ . \tag{14}$$

We first derive the optimal tolls, fare, bus frequency, and number of bus stops. Differentiating the welfare function with respect to demand for the three modes and trip lengths, setting each derivative to zero, and plugging in the user equilibrium condition, we get the optimal fare or toll by trip length

$$\begin{aligned}
\tau_v^j &= \sum_h \sum_k \sum_j q_h^{j,k} \frac{\partial uc_h^{j,k}}{\partial q_v^j} \\
\tau_b^j &= \sum_h \sum_k \sum_j q_h^{j,k} \frac{\partial uc_h^{j,k}}{\partial q_b^j} \\
\tau_c^j &= \sum_{h=c,v} \sum_k \sum_j q_h^{j,k} \frac{\partial uc_h^{j,k}}{\partial q_c^j} + e_c^j
\end{aligned} \quad . \tag{15}$$

These equations demonstrate that the optimal toll or fare of a trip equals the marginal external costs. In our model we have a rather complex interaction between modes which are influencing the externalities and therefore reflected in the pricing structure. For instance, the optimal toll for a car trip is the sum of the congestion cost accruing to other drivers, the delay for cyclists at bus stops, and other externalities. The effect on the user cost of the delayed drivers and cyclists depends on their values of time (that differ by user groups and by trip length). Therefore, the external costs are summed across user groups $(k = 1,2,3,4)$ and trip length $j = s,l$.

We move on to derive the explicit expressions of the optimal tolls and fares, given the bus frequency, and number of bus stops. To do this we first notice that when the bus frequency is fixed we have that

$$\frac{\partial uc_b}{\partial q_c} = 0, \frac{\partial C_b}{\partial q_c} = \frac{\partial C_b}{\partial q_b} = \frac{\partial C_b}{\partial q_v} = 0 \, . \tag{16}$$

Then we have the optimal tolls for short and long car trips

$$\begin{aligned}
\tau_c^s &= \sum_{j,k} \frac{dis^j \cdot VOT_c^{inv,k} \cdot \beta_c \cdot \lambda}{n_h cap_c} \cdot q_c^{j,k} + \sum_{j,k} \frac{dis^j \cdot VOT_v^{inv,k} \cdot \gamma_v n_s P_b TS_c \cdot \lambda}{60 n_h} \cdot q_v^{j,k} + e_c^s \\
\tau_c^l &= \sum_{j,k} \frac{dis^j \cdot VOT_c^{inv,k} \cdot \beta_c}{n_h cap_c} \cdot q_c^{j,k} + \sum_{j,k} \frac{dis^j \cdot VOT_v^{inv,k} \cdot \gamma_v n_s P_b TS_c}{60 n_h} \cdot q_v^{j,k} + e_c^l
\end{aligned} \quad , \tag{17}$$

where the first term is the congestion caused by the extra car trip on other drivers, the second term is the delay caused by cars at bus stops on bicyclists, and the last term is the external cost of emissions from one car trip. All these terms are proportional to trip distance.

For bus users, we have instead

$$\tau_b^s = \sum_{j,k} dis^j VOT_b^{inv,k} \cdot DisCom \cdot \left[\frac{\zeta}{fn_h} + TT_b^{inv} \frac{\ln(dc_b) \cdot r_{on} \cdot \lambda}{V_b fn_h} \right] q_b^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_v^k \cdot \gamma_v n_s P_c \cdot \zeta}{60 n_h} \cdot q_v^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_c^{inv,k} \cdot \gamma_c n_s P_v \cdot \zeta}{60 n_h} \cdot q_c^{j,k}$$
$$\tau_b^l = \sum_{j,k} dis^j VOT_b^{inv,k} \cdot DisCom \cdot \left[\frac{\zeta}{fn_h} + TT_b^{inv} \frac{\ln(dc_b) \cdot r_{on}}{V_b fn_h} \right] q_b^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_v^k \cdot \gamma_v n_s P_c \cdot \zeta}{60 n_h} \cdot q_v^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_c^{inv,k} \cdot \gamma_c n_s P_v \cdot \zeta}{60 n_h} \cdot q_c^{j,k} \quad , \qquad (18)$$

where two terms (in the square brackets) in the first line correspond to the external cost of one extra bus user arising from longer boarding/alighting time and on-bus crowding, respectively. The second (third) row is the delay on other bicycles (cars) at bus stop, caused by an extra bus trip.

For bicycle trips, we have

$$\tau_v^s = \sum_{j,k} \frac{dis^j VOT_v^k \cdot \beta_v \cdot \lambda}{n_h cap_v} \cdot q_v^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_c^{inv,k} \cdot \gamma_c n_s P_b \cdot TS_v \cdot \lambda}{60 n_h} \cdot q_c^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_b^{inv,k} \cdot DisCom \cdot n_s \cdot \gamma_b \cdot TS_v \cdot \lambda}{60 n_h} \cdot q_b^{j,k}$$
$$\tau_v^l = \sum_{j,k} \frac{dis^j VOT_v^k \cdot \beta_v}{n_h cap_v} \cdot q_v^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_c^{inv,k} \cdot \gamma_c n_s P_b \cdot TS_v}{60 n_h} \cdot q_c^{j,k}$$
$$+ \sum_{j,k} \frac{dis^j VOT_b^{inv,k} \cdot DisCom \cdot n_s \cdot \gamma_b \cdot TS_v}{60 n_h} \cdot q_b^{j,k} \quad , \qquad (19)$$

where the first term represents the marginal cost of increased congestion for other bicyclists. The second term includes the probability that there is a bus at the stop when a cyclist passes it, and therefore has to divert into the car lane and slow the car traffic down. The third term corresponds to the delay of buses caused by one more bicyclist passing the bus stops. All three terms are proportional to trip distance.

The optimal pricing rule needs to be adapted when the bicycle lane is fully separated from the car and bus lanes at the bus stop (typical for Copenhagen and Dutch cities). All the terms involving interactions at bus stops then drop out. For car trips we then have

$$\tau_c^s = \sum_{j,k} \frac{dis^j \cdot VOT_c^{inv,k} \cdot \beta_c \cdot \lambda}{n_h cap_c} \cdot q_c^{j,k} + e_c^s$$
$$\tau_c^l = \sum_{j,k} \frac{dis^j \cdot VOT_c^{inv,k} \cdot \beta_c}{n_h cap_c} \cdot q_c^{j,k} + e_c^l \quad (20)$$

For bus users we have

$$\tau_b^s = \sum_{j,k} dis^j VOT_b^{inv,k} \cdot DisCom \cdot \left[\frac{\zeta}{fn_h} + TT_b^{inv} \frac{\ln(dc_b) \cdot r_{on} \cdot \lambda}{V_b fn_h} \right] q_b^{j,k}$$
$$\tau_b^l = \sum_{j,k} dis^j VOT_b^{inv,k} \cdot DisCom \cdot \left[\frac{\zeta}{fn_h} + TT_b^{inv} \frac{\ln(dc_b) \cdot r_{on}}{V_b fn_h} \right] q_b^{j,k} \quad (21)$$

For bicycles we have

$$\tau_v^s = \sum_{j,k} \frac{dis^j VOT_v^k \cdot \beta_v \cdot \lambda}{n_h cap_v} \cdot q_v^{j,k}$$
$$\tau_v^l = \sum_{j,k} \frac{dis^j VOT_v^k \cdot \beta_v}{n_h cap_v} \cdot q_v^{j,k} \quad (22)$$

So far the derived fares and tolls give the optimal prices for a given number of bus stops and bus frequency To determine the optimal frequency, we take the derivative of welfare function with respect to the bus frequency, and set it to zero. We simultaneously optimise prices of the three modes by plugging in the optimal pricing conditions, since this strongly simplifies the optimal capacity rules. Then we have

$$\sum_{j,k,h} q_h^{j,k} \frac{\partial uc_h^{j,k}}{\partial f} = -n_h \cdot k - e_b$$
$$\frac{\partial uc_v^{j,k}}{\partial f} = dis^j VOT_v^k \cdot \gamma_v n_s P_c \cdot \frac{n_s t_s}{60}$$
$$\frac{\partial uc_b^{j,k}}{\partial f} = -VOT_b^w \frac{60}{2f^2}$$
$$+dis^j VOT_b^{inv,k} \cdot DisCom \cdot \left(\beta_b \frac{\sigma(V_b)}{cap_b} - \frac{\zeta \cdot \sum_{j,k} q_b^{j,k}}{n_h f^2} - TT_b^{inv} \frac{\ln(dc_b) \cdot r_{on} \cdot \left(q_b^l + \lambda q_b^s \right)}{V_b n_h f^2} \right)$$
$$\frac{\partial uc_c^{j,k}}{\partial f} = dis^j VOT_c^{inv,k} \cdot \gamma_c n_s P_v \cdot \frac{n_s t_s}{60} \quad (23)$$

The expression of $\frac{\partial uc_b^{j,k}}{\partial f}$ tells us how the user cost for bus trips changes with frequency. The first term shows that an increase in bus frequency decreases waiting time. The second term shows that the passengers' marginal user cost is determined by the in-vehicle travel time which increases with more congestion in the bus lane, but goes down with higher frequency. Moreover, it shows that the value of in-vehicle travel time increases with more crowding on the bus.

The expressions of $\frac{\partial uc_c^{j,k}}{\partial f}$ and $\frac{\partial uc_v^{j,k}}{\partial f}$ tell us that more buses delay the bicycle and car traffic at bus stops.

For optimal number of bus stops, we differentiate the welfare function with respect to n_s, plug in the optimal pricing conditions, and set the expression equal to zero

$$\begin{aligned}
&\sum_{j,k,h} q_h^{j,k} \frac{\partial uc_h^{j,k}}{\partial n_s} = -c_s \\
&\frac{\partial uc_v^{j,k}}{\partial n_s} = dis^j VOT_v^k \cdot \gamma_v P_c \cdot \left(\frac{2f \cdot n_s t_s}{60} + \frac{\zeta \cdot \sum_{j,k} q_b^{j,k}}{60 n_h} \right) \\
&\frac{\partial uc_b^{j,k}}{\partial n_s} = -VOT_b^{ac,k} \frac{L}{2 v_w n_s^2} + dis^j VOT_b^{inv,k} \cdot DisCom \cdot \left(\gamma_b \cdot P_v + t_s \right) \\
&\frac{\partial uc_c^{j,k}}{\partial n_s} = dis^j VOT_c^{inv,k} \cdot \gamma_c P_v \cdot \left(\frac{2f \cdot n_s t_s}{60} + \frac{\zeta \cdot \sum_{j,k} q_b^{j,k}}{60 n_h} \right)
\end{aligned} \quad . \tag{24}$$

This shows that the cost of increasing the number of bus stops (the investments and maintenance cost for the additional bus stop) is balanced with the benefit of lower access costs for bus passengers and also with longer in-vehicle time cost for existing bus users. For both drivers and cyclists, the user cost increases because they are delayed at bus stops.

5 STUDY AREA AND MODEL CALIBRATION

This section provides some background information and describes how the model is calibrated. All the data sources and calculations are documented in Appendices A to D.

5.1 Study Area

Bus service No.4 connects Gullmarsplan and Radiohuset and has currently 31 stops (Figure 4). This route is 12 km long and serves 65,000 passengers per day. During a representative day of a 4-hour peak period considered in this paper (7-9 in the morning and 3-5 in the afternoon), 38,845 passengers are served.[10] The fleet serving this route consists of 84-seat buses. More values of parameters are reported in Appendix A.

[10] Source: Public Transport Stockholm (SLL).

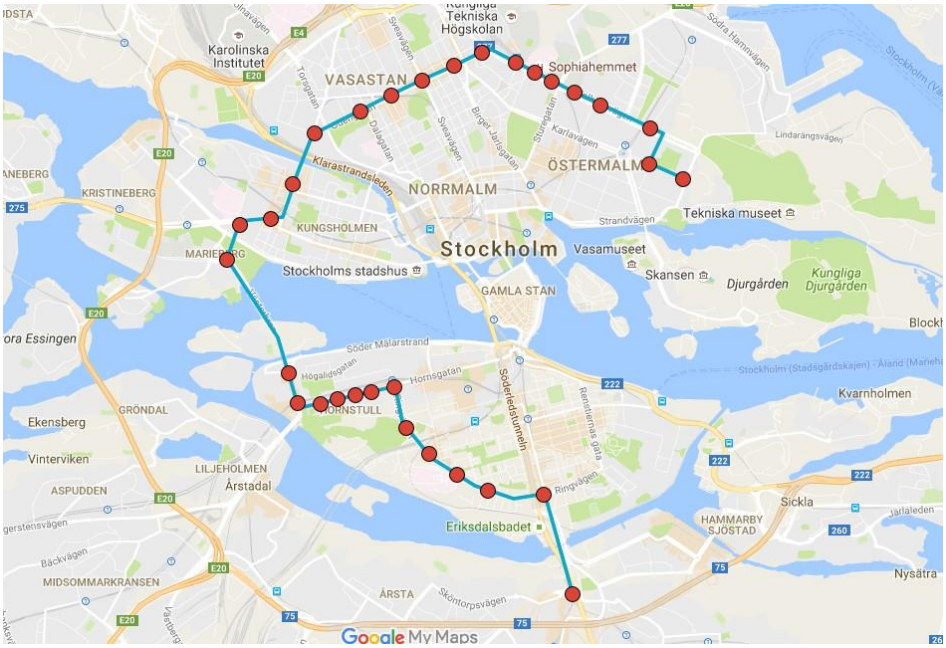

Figure 4: Route of Bus No.4 with location of bus stops.

In the model, we assume that bus is the only public transport mode that is available. In some of the relevant Origin Destination (OD) pairs, there is however a limited overlap with Metro.[11]

The baseline scenario is calibrated for the year 2014. At that time, the average car toll in the peak was €1.8 per trip (it was time varying between €1.5 and 2 in the peak). In 2016 the toll was increased to €3.5 per trip[12]. In this paper the monetary values in Swedish Krona (SEK) are converted to Euro using an exchange rate of 1 SEK = 0.1 €.

The cost functions for buses (see Appendix B) are based on data from Public Transport Stockholm (SLL), taking into account the capital and operating costs of buses (cost of drivers, fuel, and maintenance).

5.2 Calibration

We calibrate the parameters *a*, *b* and *i* in our model for the baseline situation for which we have 4 types of data: a) observed trip quantities by mode and user group, observed money costs and travel times; b) the values of time; c) the price and cross-price elasticities; and d) speed-flow functions.

The number of travellers by mode, user group and trip length is observed from car traffic counts, bus automatic passenger counts (APC) [13] and travel surveys, see Table 4. The APC reports the number of passengers boarding and alighting for all bus stops. From this we can compute the average passenger volume per bus between all bus stops. Then we use the travel survey to divide the total bus demand into user groups and trip lengths.

The car traffic volume by user groups and trip lengths is taken from the travel survey, and validated against the traffic count data. The two sources matched well, and we

[11] Four parts of the bus line overlap with Metro lines, with a total length of 3.8 km.
[12] Source: Swedish Transport Administration (Trafikverket): http://www.trafikverket.se/.
[13] For the period 2014-3-17 to 2014-6-19. Source: Public Transport Stockholm (SLL).

therefore used the traffic volume from the travel survey in the baseline scenario. For cycling, the traffic volume by user group and trip lengths is also taken from the travel survey and validated against the bicycle count data collected by the city of Stockholm. The bicycle counts and the travel survey matched well. Table 4 shows the traffic volume by mode and user group used in the baseline, including long and short trips. Mode shares are in brackets.[14]

Table 4 also shows the in-vehicle value of time (VTT) for bus by user group. They are calculated from the Swedish national travel survey applying the income elasticity of 0.7 (Börjesson & Eliasson, 2014). The values of time for all other travel time components and modes (for the mid-income group) are taken from and computed for all user groups using the same income elasticity as for the in-vehicle value of time. These values are reported in Appendix C.

Table 4: Number of trips in both directions by user group and mode, and the bus in-vehicle VTT by user group.

	car	bus	bicycle	Total	VTT In-vehicle, Bus
High-income	9837 (49%)	6632 (33%)	3716 (18%)	20186 (100%)	9.7
Mid-income	12228 (41%)	12138 (41%)	5133 (17%)	29499 (100%)	7.2
Low-income	4483 (29%)	8502 (54%)	2716 (17%)	15701 (100%)	4.4
No bicycle	15489 (57%)	11572 (43%)	0	27062 (100%)	7.2
Total	42037 (45%)	38845 (42%)	11565 (13%)	92448 (100%)	

Apart from the number of trips by trip length and mode, the pecuniary travel cost (tolls, fares and operation costs of cars and bicycles) are shown in Table 5. Table 5 also reports in-vehicle travel times per trip. For bus they are taken from the official timetable of SLL. For car the travel time is computed from the speed flow relationship described below, and a free-flow travel time is taken by assuming the official speed-limit of 40 km/h on average. To compute the cycling travel time we assume a speed of 12 km/h. The values of time (VTT) for different parts of the trip for the mid-income group are reported.

Table 5: Number of trips in both directions by trip length and mode, and VTTs of the mid-income group.

	Bus	bicycle	Car
Short trips (0-4 km)			
Volume/day	6129	5964	6432
User operation cost per trip [€]	0	0.0025	0.5
Tolls or Fare [€]	2	0	1.8
In-vehicle travel time [min]	14.8	15.3	11.7
Long trips (4-12 km)			
Volume/day	32716	5601	35605
User operation cost per trip	0	0.01	2.1

[14] Multiple mode trips are negligible in central Stockholm.

[€]			
Tolls or Fare [€]	2	0	1.8
In-vehicle travel time [min]	59.2	61.3	46.8
Short and long trips			
In-vehicle VTT mid-income [€/h]	9.7	10.5	12.0
VTT Wait, Mid-income [€/h]	12.2	-	-
VTT Access, Mid-income [€/h]	10.2	-	-

Cross-price elasticities between bus and car trips, and own elasticities for car are computed for Stockholm using data from the congestion charging trial (Börjesson et al., 2017). For public transport we assume an own-price elasticity of -0.4. This is what is found in many studies (Litman, 2004) and in the national transport model (Börjesson & Eliasson, 2014). The cross-time elasticity for number of cycling trips, with respect to bus in-vehicle travel time of a bus trip, is taken from the national transport model. The cross-price elasticity for increased car driving cost on the number of cycling trips is also taken from the national transport model. All price and time elasticities are summarised in Table 6. We apply the same money price elasticities for all user groups.

For all user groups and trip distances, the price elasticities are converted to generalised price elasticities by multiplying the ratios of full user cost of a trip to pecuniary cost of a trip. As a result, we have higher generalized price elasticities for longer trips and for higher-income groups. Similarly, the cross-time elasticity for cycling is converted to generalised price elasticities by multiplying the ratios of total user cost of a trip to time cost of the trip.

Table 6: Money price elasticities[15]

Money price elasticities	Notation	Value
Own elasticity, bus	ε_b	-0.4
Own elasticity, car	ε_v	-0.54
Own elasticity, bicycle	ε_c	-0.8
Cross-price elasticity, the effect of a price increase of car trip on the demand for bus trip	ε_{cb}	0.13
Cross-price elasticity, the effect of a price change of bus trip on the demand for cycling	ε_{bv}	0.067
Cross-price elasticity, the effect of a price increase of car trip on the demand for cycling	ε_{cv}	0.081

Table 7 shows the parameters of all the speed-flow relationship (α and β) and the parameters related to bus stops. The β parameters are observed for Stockholm

[15] These are average elasticities for Sweden. In the Stockholm corridor under study, however, the market share for bus is higher than the average for Sweden (50% compared to 18% for Sweden) and the market share for car is lower (about 34% compared to 80% for Sweden). For this reason the cross-elasticity for bus-cycling should be adjusted upward to 0.19. The cross-elasticity for car-cycling should be adjusted downward to 0.014. The model results are however not sensitive to these elasticities because the effect on the market share for and pricing of cycling is still small. The results are included in Section 7 Sensitivity Analysis (scenario xi). We have therefore kept the averages for Sweden for the baseline.

(Börjesson et al., 2017). For the rest of the parameters, we describe how we arrive at these values from literature and observation in Appendix D. In Section 7, we also conduct sensitivity analysis on these values.

Table 7: Speed-flow and bus stop related parameters

Parameter	Notation	Value
Free-flow time in min/trip, car	α_c	28
Free-flow time in min/trip, bus	α_b	34
Free-flow time in min/trip, bicycle	α_v	50
Additional time needed for one more vehicle, car (min per vehicle)	β_c	0.006
Additional time needed for one more vehicle, bus (min per vehicle)	β_b	0.01
Additional time needed for one more vehicle, bicycle (min per vehicle)	β_v	0.001
Car trips slowing down at bus stops, if interacting with bicycle and bus (min per vehicle)	γ_c	0.02
Bus delay at bus stops, if interacting with a bicycle (min per vehicle)	γ_b	0.02
Delay for bicycles at bus stops, if interacting with car and bus (min per vehicle)	γ_v	0.02
Minimum stop time at a bus stop (sec)	t_s	10
Boarding and alighting time per passenger (sec/passenger)	ζ	1.8

The following parameters are also used: The vehicle equivalent of the buses (σ) is 5 and the capacity (number of lanes) parameters cap_c is 1.5 (50% of the distance has one car lane and 50% has two lanes). The parameters cap_b and cap_v equal to one.

In Sweden, external costs of rural road traffic (car) are internalised by fuel taxes (0.044 Euro/vehicle km). For inner city Stockholm, the external costs are higher. Therefore, we have the following values to account for the additional urban externalities[16]: 0.048 Euro/vehicle km for private cars and 0.504 Euro/vehicle km for city buses.

6 RESULTS

We have eight policy variables in total: the pricing of the six types of trips, and the bus frequency as well as the number of bus stops. Any combination of bus fares, bus frequencies, number of bus stops, car tolls, and bicycle pricing leads to an equilibrium on the urban transport market. Bus subsidies are simply defined as bus operating cost

[16] For cars, the sum of external costs is 0.092 euro/vehicle km (=0.02 (noise) + 0.024 (accidents) +0.048 (emissions)) in inner city Stockholm, so the external costs that are not internalised by fuel tax is 0.048 euro/vehicle km (=0.092-0.044 euro/vehicle km). For buses, the sum of external costs is 0.7 euro/vehicle km (=0.1+0.504+0.095) in inner city Stockholm. Assuming that a bus consumes 4.5 times of fuel for a car, 0.196 euro/vehicle km is internalised in fuel tax. So the external costs that are not internalised by fuel tax are 0.504 euro/vehicle km. [Source: *Method of analysis and economic values for the transport sector*, *ASEK* (*Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn*, *ASEK*), prepared by the Swedish Transport Administration (Trafikverket). http://www.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/11_luftfororeningar_a60_160906.pdf]

minus fare revenue. We start with the current design of bus stops: there is a bicycle lane that disappears at the bus stops. Next we explore some alternative designs of bus stops in the sensitivity analysis.

We start by analyzing the ideal situation where all policy variables can be optimised. This ideal situation may not be possible for political reasons, but it is a good benchmark. Indeed, we know from Section 4 that the full optimisation produces tolls and fares such that the user cost (including tolls and fares) equal the marginal social cost (MSC). The optimal frequency and number of bus stops are achieved when the producer cost equals the benefit of an extension. Note that in all the optimization scenarios, no distributive objective is considered explicitly because the welfare function is the (unweighted) sum of welfare changes (equivalent variations) of different income and user groups.

6.1 Direction of marginal changes

Table 8 reports the baseline tolls and fares and compares them to the external marginal social costs (MSC) by mode and trip length, given the baseline frequency and number of bus stops. Our example demonstrates that with the baseline frequency and number of bus stops, the external MSC for the bus users is slightly lower than the bus fare, especially for short trips. For long car trips the baseline toll is less than half of the external MSC. For short car trips, however, the toll is higher than the external MSC. The reason is that the baseline congestion toll is uniform (distance-independent). Bicycling trips cause, as expected, a small external cost due to congestion on the bicycle lane and interaction with the other modes on the bus stops. But the cost of collecting the toll for cycling is probably larger than the welfare benefit of launching and enforcing it, and the implementation of cycling tolls might not be worthwhile.

Table 8: External cost compared with tolls and fares in baseline.

	Short bus trips	Long bus trips	Short car trips	Long car trips	Short bicycle trips	Long bicycle trips
Baseline toll/fare	2	2	1.8	1.8	0	0
Baseline external MSC	1.5	1.9	1.1	4.4	0.1	0.5
Change needed to reach optimum	-	-	-	++	+	+

6.2 Optimal policy

Table 9 reports the welfare effects resulting from five different policy scenarios, each of which optimises welfare with respect to a set of policy variables.

Table 10 reports the prices and fares by mode for the two scenarios which involve optimising prices. Table 11 reports the resulting number of trips by mode and by trip length for all scenarios.

Table 9: Comparison of baseline and policy scenarios (in terms of welfare effects and subsidies)

Policy scenario	Welfare gain €/day	Number of stops	Frequency /hour	Supply cost €/day	Subsidy €/day	Total number of bus trips / day

Baseline	0	31	12	21264	-56426	38845
1. All prices + frequency +stops	19032	**29**	**18**	30814	-35543	45904
2. All prices only	9138	31	12	21264	-55530	40489
3. Frequency only	8236	31	**17**	29636	-52624	41130
4. Bus stops only	304	**28**	12	21118	-56582	38849
5. Frequency +stops	8399	25	17	28393	-53515	40954

Table 10: Fares and tolls in the optimal pricing scenarios

Policy scenario	Short bus trips	Long bus trips	Short car trips	Long car trips	Short bicycle trips	Long bicycle trips
Baseline	2	2	1.8	1.8	0	0
1. All prices + freq +stops	1.2	1.5	0.9	3.8	0.2	0.5
2. All prices only	1.6	2.0	1.0	3.8	0.1	0.5

Table 11: Number of trips (in thousands) in baseline and policy scenarios

Policy scenario	Short bus trips	Long bus trips	All bus trips	Short car trips	Long car trips	All car trips	Short bicycle trips	Long bicycle trips	All bicycle trips
Baseline	6.1	32.7	38.8	6.4	35.6	42.0	6.0	5.6	11.6
1. All prices + freq +stops	7.1	38.8	45.9	7.2	28.7	35.9	5.3	5.1	10.4
2. All prices only	6.4	34.1	40.5	7.3	29.1	36.4	5.5	5.3	10.9
3. Frequency only	6.4	34.8	41.1	6.4	35.4	41.8	5.9	5.5	11.5
4. Bus stops only	6.1	32.8	38.8	6.4	35.6	42.0	6.0	5.6	11.6
5. Frequency +stops	6.2	34.7	41.0	6.4	35.4	41.8	6.0	5.5	11.5

In the baseline scenario there are 31 bus stops, a frequency of 12 buses per peak hour, a total supply cost for buses of 21,264 €/day. A profit of 56,426 €/day is generated (see Section 6.4 for a further discussion on the negative subsidy or surplus).

Scenario 1, optimising all policy variables, produces a welfare gain of 19,032 Euro (0.2 Euro per trip). The second scenario, optimising fares and tolls only, produces approximately half of that welfare gain. This is similar to the welfare gain generated by scenario 3, which optimises frequency only. Hence, optimising tolls and fares only, or bus frequency only, has the same contribution to total welfare. The benefit from

optimising the number of bus stops is marginal, and the baseline number of bus stops is close to the optimal number.

The high welfare gain generated from optimising the frequency demonstrates the high disutility of crowding on buses: when frequency increases, the occupancy level falls. Only a small share of car and cycling trips are diverted to bus when frequency increases. But new bus trips are generated by higher frequency and thereby lower crowding levels on the buses, and they increase welfare.

The high welfare gain generated from optimising tolls demonstrates the welfare improvement of differentiating tolls with respect to trip lengths and mode, in function of external MSC. The welfare improvement is mainly generated by differentiating the car tolls with respect to trip length[17], because for bus and bicycle, the optimal fares and tolls are close to the ones in the baseline. The optimal fare is only slightly lower than in the baseline scenario for short trips. In passing we note that optimising cycling tolls only generates a welfare gain of 192.4 Euros/day, and hence underscores the problem that the cost of collecting and enforcing the toll would be larger than the benefit of collecting it.

For scenarios with optimal tolls (scenarios 1 and 2), the number of long car trips is reduced by 18-19% and the number of short car trips decreases by 14-15%. In scenario 1, car trips are to a large extent diverted to buses (due to lower crowding levels on the buses), whereas in scenario 2, many of the car trips priced off the road just disappear. This demonstrates that optimal tolling coupled with attractive public transport does not necessarily reduce mobility. However, optimal tolling without more capacity in the public transport might do, but it is still effective in reducing congestion.

In all scenarios except for the fourth, the number of cycling trips decrease. Scenario 2 shows this is largely due to the tolling of cyclists, but to some extent also because some cyclists are diverted to buses when occupancy levels reduce due to higher bus frequency.

When optimising welfare with respect to the number of bus stops only, the optimal number of bus stops is 28, which is just slightly lower than the number of bus stops in scenario 1 (29), optimising all policy variables, and lower than the number in the baseline (31). Removing one bus stop increases the user cost for long bus trips (0.07-0.08% depending on income group) less than for the user cost for short trips (0.7-1%). This is because the increase in access cost is the same for short and long trips, but for short trips this is a larger share of the user cost. In addition, reducing the number of bus stops benefits drivers and cyclists by decreasing the interactions with buses at the bus stops. But, again, these effects are small. Moreover, the optimisation of the number of bus stops does not affect the overall modal share.

In scenario 5, we have the baseline prices and optimise only the number of bus stops and the frequency. This has a marginal effect on the optimal frequency (compared to scenario 1) but reduces the number of bus stops. The lower number of bus stops is a result of more long bus trips and more cycling trips with baseline tolls and fares.

[17] The gain is mainly from pricing long car trips correctly. We will see in Section 6.5 that 67% of this welfare gain can still be attained under second-best pricing, when both long and short car trips are charged the same toll.

6.3 Distributional impact

We proceed by exploring how the changes in the consumer surplus (CS) are distributed across trip lengths and user groups in the five policy scenarios. In the distributional analysis we disregard the fact that the distribution of the net benefit depends also on how profits are used or how deficits are financed. Mayeres and Proost (2001) showed that this is crucial to determine the ultimate impact of the price reform. Table 12 shows the percentage change in consumer surplus (CS) by user group and trip distance.

In the scenarios optimising tolls and fares (scenarios 1 and 2), welfare is reduced for long trips. This reduction is driven mainly by the high tolls for long car trips (more than double of the baseline toll). For short trips welfare increases with optimal prices because they are lower (than baseline prices), except for cycling (which is zero in the baseline). In the scenario optimising the frequency, welfare increases most for long trips, because they benefit most from the reduced crowding on the buses.

Focusing instead on user groups, we see that in the scenario "optimising frequency" (scenario 3), high-income and no-bicycle travellers benefit most. The high-income group benefits most because they place the highest value on waiting time savings and less crowding (and they have the highest generalised price elasticities). The no-bicycle group benefits because the share of long bus trips is largest in this group.

In the scenario optimising all fares and tolls (scenario 2) the no-bicycle group loses most, due to the high share of (long) car trips (see Table 4). Low income users lose least due to the low share of car trips. In scenario 1 (combination of scenarios 2 + 3), the effects of scenarios 2 and 3 cancel out so that consumer surplus barely changes for any income group. For the no-bicycle user group, however, the CS reduces by 9%. For this user group the benefit of more buses does not make up for the loss of the higher car toll for long trips.

The number of bus stops has barely any effect on the CS for any of the income groups because the changes in number of bus stops in these scenarios are small.

To summarise, optimal pricing generates the largest differences across user groups and trip lengths. Optimal pricing hurts high-income groups and travellers making long trips the most.

Table 12: CS changes in %, by trip length and user groups

Policy scenario	High-income group	Mid-income group	Low-income group	No-bicycle group	Users taking short trips	Users taking long trips
1. All prices + freq +stops	1%	0%	3%	-9%	15%	-6%
2. All prices only	-7%	-8%	-5%	-19%	10%	-16%
3. Frequency	4%	3%	2%	4%	1%	4%
4. Bus stops	0%	0%	0%	0%	0%	0%
5.	3%	3%	2%	4%	1%	4%

Baseline tolls + frequency + stops						

6.4 The surplus of the bus operator

We have noticed that the subsidy for bus No. 4 is negative in several scenarios, which means the operator could actually generate a surplus from operating this line. This needs some explanation because subsidies to public transport are a well-known and frequent example of a second-best policy.

We know from economic theory that bus transport does not have strong scale economies, so the main justifications for a net subsidy can be a strong Mohring effect, under-priced competing modes (car, bicycle), or distributive motives (as the low-income group are often users of public transport). On the other hand, there are also justifications for a surplus, namely external costs of bus use (due to crowding or boarding and alighting, interaction with other modes of increase infrequency), or a high cost of public funds. In our case, the Mohring effect is limited because the demand, and thereby the baseline frequency, is already so high. This means that the reduction in waiting time of increased frequency is relatively small. From the sensitivity analysis in Section 7, we know that a major reason for the surplus is congestion on the bus lanes, as well as crowding in the buses and extra boarding and alighting time per passenger at the bus stop. The congestion in the bus lane increases the marginal cost of more buses, and reduces thereby the optimal frequency and total supply cost. Crowding in the buses and extra boarding and alighting time both increase with lower frequency, which in turn increases the optimal fares, and thereby further increase the size of the budget surplus. We do not consider the cost of cost of public funds in this paper.

Consider now the results of the different scenarios as reported in Table 9. The baseline has non-optimised prices and frequencies; all we can observe is that revenues are higher than costs. Consider then the scenario where, starting from the baseline, only the frequency is optimised. As frequency is the main cost driver, a higher frequency decreases the surplus from 56,426 to 52,624 €/day despite the increase in bus patronage.

When only the number of bus stops is optimised, the smaller number of bus stops reduces costs slightly but the surplus barely changes because bus patronage is almost the same as in the baseline.

Next, consider the scenario where only the prices are optimised. The optimal bus fare for short trips is smaller than in the baseline. However, the toll for car trips is higher and this increases the number of bus users. The slightly lower bus fare and the slightly higher bus use cancel out and lead to a surplus that is close to the one in the baseline.

Finally, consider the scenario where all prices, frequency and number of bus stops are optimised. As optimal frequency is larger, the crowding externality is smaller and the optimal bus fares have to be lower. The high frequency and the low fares result in a surplus that is much smaller than in all other scenarios. The main reason for why there is still a surplus is the remaining scarcity of road space that cannot be solved in our policy framework with a fixed number of lanes. This scarcity means that even under the optimal policies that we consider there will be congestion externalities within the bus corridor and interactions with bicycles and cars at bus stops, and crowding on the buses increasing bus fares.

6.5 Second-best pricing

We have seen that differentiating car tolls increases welfare substantially. However, in reality it has proven to be difficult to implement distance based car tolls. For this reason, the two first rows of Table 13 show how the results of scenarios 1 and 2 change if the tolls and fares are constrained to be uniform across trip lengths. These tolls and fares are shown in Table 14.

The welfare gains are lower when pricing instruments are constrained to be uniform. The welfare gain is 36% lower for scenario 2, that optimises prices only, and 11% lower for scenario 1 where all policy variables were optimised. Two inefficiencies arise from pricing different trip lengths uniformly. First, short trips are over-priced (in particular short car trips) while long trips are under-priced. Second, mode shares are inefficient because more drivers making short trips are diverted to buses, increasing crowding, while long car trips become too attractive, and increase, which increases congestion.

Scenario 1 shows that the optimal number of bus stops decreases with uniform prices, but there are only marginal effects on optimal frequency, supply cost and subsidy.

The third row in Table 13 (and Table 14) shows how scenario 1 changes when constraining the bicycle toll to zero, scenario 1-c. This is relevant because it might be very difficult to push a bicycle toll for political reasons, and also because of cost of collecting and enforcing a bicycle toll. The tolling of bicycling trips, however, only has a marginal effect on welfare despite the difficulties in implementation.

Table 13: Comparison of second-best pricing scenarios with uniform tolls

Second-best pricing	Welfare gain €/day	Number of stops	Frequency /hour	Supply cost €/day	Subsidy €/day	Total number of bus trips /day
Baseline	0	31	12	21264	-56426	38845
(1-b)All prices + freq +stops	16929	**27**	**18**	30944	-35044	46166
(2-b)All prices only	5892	31	12	21264	-57351	40589
(1-c) Bus fares and car tolls + freq +stops + No bicycle toll	16584	**27**	**18**	30932	-33254	46189

Table 14: Fares and tolls under second-best pricing

Second-best pricing	Short bus trips	Long bus trips	Short car trips	Long car trips	Short bicycle trips	Long bicycle trips
Baseline	2	2	1.8	1.8	0	0
(1-b)All prices + freq + stops	**1.4**	**1.4**	**3.3**	**3.3**	**0.5**	**0.5**
(2-b)All prices only	**1.9**	**1.9**	**3.3**	**3.3**	**1.2**	**1.2**
(1-c) Bus fares and car tolls + freq +stops +No bicycle toll	**1.4**	**1.4**	**3.3**	**3.3**	0.0	0.0

7 SENSITIVITY ANALYSIS

In this section we perform sensitivity analyses on a number of parameters. We start this section by exploring how the results change if we assume a different design of the bus stops. In the rest of the sensitivity analysis we look at the sensitivity of crowding disutilities, cross-elasticities between bus and car trips, boarding and alighting time, the minimum stop time for buses at the bus stops, the congestion in the bus lane, the emissions of buses, and cross-elasticities involving cycling trips.

The implication of having a different design of the bus stops is that the cyclists do not interact with buses or cars as explained in Section 2. We do this in two steps: first we assume we have a bus stop where the bicycle paths are between the curb and the bus stop, such that bus passengers have to cross the bicycle path to reach the bus stop (Figure 2). This means that the cyclists are still delayed at the bus stop because pedestrians have priority, the buses and cars are not delayed. In a second step we assume that the bicycle lane is in the middle of the street (Figure 3), such that not even the cyclists are delayed at the bus stop.

More specifically, the sensitivity analysis includes the following:

i) Assume a different design of the bus stops (no interaction with cyclists at the bus stop) ($\gamma_c = 0; \gamma_b = 0$).
ii) Assume a different design of the bus stops (no interaction with cyclists at the bus stop) ($\gamma_c = \gamma_v = \gamma_b = 0$).
iii) Increase the crowding multiplier, dc_b, from 1.1 to 1.5.
iv) Decrease the crowding multiplier, dc_b, to 1 (no crowding discomfort).
v) Double the cross-elasticity ε_{cb} from 0.13 to 0.26.
vi) Half the cross-elasticity ε_{cb} from 0.13 to 0.065.
vii) Reduce the boarding and alighting time per passenger, ζ from 1.8 sec to 1.5 sec.
viii) Reduce minimum bus stop time at the bus stop t_s, from 10 sec/stop to 5 sec/stop.
ix) Assume no congestion in the bus lane ($\beta_b = 0$) .
x) Assume the use of electric buses (no emissions) ($e_b = 0$) .
xi) Adjust cross –elasticity involving cycling (from $\varepsilon_{cv} = 0.081, \varepsilon_{bv} = 0.067$ to $\varepsilon_{cv} = 0.014, \varepsilon_{bv} = 0.19$)

The results of these analyses are shown in Table 15 and Table 16. Tests *i* and *ii* show that the design of the bus stops has marginal effects on all policy variables in optimum, including number of bus stops, simply because the externalities from cyclists at the bus stops are so small. It is not meaningful to compare the welfare levels in the sensitivity test, because the baseline is recalibrated in all scenarios.

From the other tests, a key observation is that the optimal bus frequency is sensitive to the congestion in the bus lane and the crowding in the buses. When putting congestion in the bus lane to zero the optimal frequency almost doubles. The optimal frequency also increases substantially when the crowding disutility is doubled.

The sensitivity analysis also further supports our explanation for the bus surplus in our main analysis. In test i*x,* where the congestion in a bus lane is zero, we need a subsidy in the optimum because a) the supply cost is higher due to a much higher frequency (in turn because of the lower external cost of more buses); b) there are lower fares due to less crowding in the buses and c) lower fares due to shorter boarding and alighting

time per passenger. In addition, in test *iv*, where the crowding on the bus is set to zero, and in test *viii*, where the boarding and alighting is halved, the surplus is smaller compared to the main analysis because the fares are lower due to lower marginal cost of more bus passengers. In test *iv*, however, the supply cost is also smaller than in the main analysis, resulting from a slightly lower frequency which is caused by a lack of crowding in the buses.

The bottom line is that the surplus is sensitive to the congestion on the bus lane, the crowding in the bus, the marginal boarding and alighting time per passenger.

Apart from this, the conclusions drawn in the main analysis are robust. In particular, the doubled or halved price-elasticity for bus-car (the effect on the demand for bus trips of a price increase of car trips) has no effect on frequency, but results in slightly fewer bus stops. The effects on the prices and subsidy are also small, but when halving the elasticity, the optimal tolls increase marginally. Adjusting the cross-elasticities involving cycling trips according to the mode shares in inner city Stockholm (from Swedish averages) does not really change the results because the market shares for cycling are still low. Nonetheless, this sensitivity test is still essential because there are, in existing literature, barely any data on these cross-elasticities involving cycling trips.

Table 15: Sensitivity analysis.

Scenarios	Number of stops	Frequency /hour	Supply cost €/day	Subsidy €/day	Subsidy (%)	Total number of bus trips /day
Baseline	31	12	21264	-56426	-265%	38845
1. All variables optimised	29	18	30814	-35543	-115%	45905
i)$\gamma_c = 0; \gamma_b = 0$	29	18	30977	-34638	-112%	46127
ii)$\gamma_c = \gamma_v = \gamma_b = 0$	29	18	31054	-34254	-110%	46206
iii)$dc_b = 1.5$	26	24	40006	-61777	-154%	45982
iv)$dc_b = 1$	29	16	28217	-24566	-87%	47204
v) ε_{cb} doubled	28	18	31115	-36932	-119%	46686
vi) ε_{cb} halved	28	17	28975	-47190	-163%	43228
vii) Reduced ζ	28	17	29557	-32088	-109%	46120
viii) t_s halved	37	18	32159	-28018	-87%	47081
ix)$\beta_b = 0$	28	35	59233	9365	16%	57873
x)$e_b = 0$	28	18	30977	-35009	-113%	45987
xi)$\varepsilon_{cv} = 0.014, \varepsilon_{bv} = 0.19$	28	18	30886	-35471	-115%	46117

Table 16: Sensitivity analysis (optimal prices).

Scenarios	τ_{b^s}	τ_{b^l}	τ_{c^s}	τ_{c^l}	τ_{v^s}	τ_{v^l}

Baseline	2	2	1.8	1.8	0	0
1. All variable optimised	1.2	1.5	0.9	3.8	0.2	0.5
i)$\gamma_c = 0; \gamma_b = 0$	1.2	1.5	0.9	3.8	0.0	0.2
ii)$\gamma_c = \gamma_v = \gamma_b = 0$	1.2	1.5	0.9	3.7	0.0	0.2
iii)$dc_b = 1.5$	1.3	2.4	0.9	3.8	0.1	0.5
iv)$dc_b = 1$	1.1	1.1	1.3	3.7	0.3	0.4
v) ε_{cb} doubled	1.2	1.5	0.9	3.7	0.1	0.5
vi) ε_{cb} halved	1.5	1.8	1.2	3.9	0.3	0.5
vii) Reduced ζ	0.8	1.4	0.7	3.7	0.0	1.0
viii) t_s halved	0.7	1.4	0.5	3.7	0.0	0.6
ix)$\beta_b = 0$	0.7	0.9	0.9	3.7	0.1	0.6
x)$e_b = 0$	1.2	1.5	0.9	3.8	0.1	0.5
xi)$\varepsilon_{cv} = 0.014, \varepsilon_{bv} = 0.19$	1,2	1,5	0,9	3,8	0,1	0,5

8 CONCLUSION

We developed a stylised model that analyses the role of the number of bus stops, frequencies and prices (car tolls, bus fares and bicycle tolls) for a corridor where buses, bicycles and cars compete to produce short and long urban trips. We do this for the busiest bus line, no 4, in Stockholm, where we have good data on supply and demand by income group for all travel modes (including cycling).

We find that the producer generates a surplus in the baseline and that the current frequency is lower than optimal. However, as with the optimal frequency and prices, the size of the surplus is similar as to the baseline. This is surprising given that public transport subsidies are a well-known second-best policy. There are several reasons for the surplus in the busy inner city bus corridor: there are no strong scale economies of a bus system (as opposed to rail), and in our case there is only a limited Mohring effect because the baseline frequency is already high. Moreover, the high marginal social cost of one more bus is high due to congestion in the bus lane, which reduces the optimal frequency and thereby the total supply cost. Finally, crowding on the buses and extra boarding and alighting time per passenger at the bus stops increase the marginal cost of more buses and bus passengers, and thus increases the optimal fares.

The optimal tolls for cyclists in Stockholm are low irrespective of how the bus stops are designed due to the low externalities caused by cycling trips. Given the operation cost of a system, collecting and enforcing bicycle tolls is probably not efficient. This might, however, be different in cities with substantially higher cycling levels (like Copenhagen and some Dutch cities).

Distributional effects between income groups are small in the optimal scenarios due to two opposing effects: Low-income users lose least from higher optimal tolls for drivers, due to the low share of car trips. On the other hand, high-income travellers benefit most from the higher optimal frequency, since they have a higher value of reduced waiting time and increased comfort.

Our results suggest higher tolls for long car trips. Higher tolls, matching the optimal toll in our findings, were also implemented in Stockholm in 2016.

Appendix A Values of parameters

Values of other parameters are listed here.

Parameter	Notation	Value
Length of bus line	L	12 km
Number of operation hours per day	n_h	4 hours
Number of bus stops	n_s	31
Monetary cost for car trips	c_c	2.1 euro
Monetary cost for bus trips	c_b	2 euro
Monetary cost for bicycle trips	c_v	0.01 euro
Ratio of distance between short and long trips	λ	1/4
Walking speed	v_w	0.06 km/min
Number of seats on bus	V_b	84
Discomfort coefficient for bus trip	dc_b	1.1
Equivalent size of bus to cars	$\sigma(V_b)$	5
On-board ratio	r_{on}	0.17

Appendix B Cost functions for buses

The following table presents data on capital and operating cost of buses and bus stops.

Bus cost functions	
Seats in the bus	84
Bus purchasing cost, euro	600 000
Depot cost per bus per year, euro	9 000
Life years of bus	12
Discount rate	0.04
Days of year	250
Number of trips per bus in the peak	4
Capital cost per year per bus, euro	63 931+9000=72 931
Capital cost per peak trip, euro	72 931/(4*250)=72.93
Marginal cost for maintenance and fuel, euro/km	1
Marginal cost for drivers, euro/km	1.5
Marginal cost per trip (maintenance, fuel, drivers), euro	(1+1.5)*12=30
Marginal cost per peak trip, euro	72.93+30=102.93
Bus stops	
Installation, euro	15 000
Life years of bus shelter	10
Capital cost per bus shelter per year, euro	1 500
Operating cost per bus shelter per year, euro	1 500
Marginal cost on bus shelter per day, euro	3 000/250=12

These costs are multiplied by a factor of 2 in our calculations because costs are higher in the inner city area.

Appendix C Value of time for all user groups

This appendix lists the value of time of different modes for all user groups. The mid-income group is the reference group and the values of time of the low-income group and the high-income group are obtained by making use of income differences of -55% and +50% respectively. An income elasticity of values of time of 0.7 is adopted.

VOT	Short trips, low-income group	Long trips, low-income group	Short trips, mid-income group	Long trips, mid-income group	Short trips, high-income group	Long trips, high-income group	No-bicycle group
Car, in-vehicle	0.123	0.123	0.2	0.2	0.27	0.27	0.2
Bus, waiting	0.12546	0.12546	0.204	0.204	0.2754	0.2754	0.204
Bus, access	0.10455	0.10455	0.17	0.17	0.2295	0.2295	0.17
Bus, in-vehicle	0.0738	0.0738	0.12	0.12	0.162	0.162	0.12
Bicycle , in-vehicle	0.107625	0.107625	0.175	0.175	0.23625	0.23625	--

Appendix D Description of bus-related parameters

From Google map and the bus time table from SLL, the free flow travel time is 35 min and peak hour travel time is 55-60 min for the bus trip we consider in this study. The difference between these two values (20-25 min) consists of these four components (parameters shown in Table 7):

1. Congestion on the bus lane. It leads to an addition of 6.6 min of travel time in the baseline.
2. Boarding and alighting. If we take the value of 2.5 sec/person from Basso and Silva (2014), it will lead to a 16-min increase in travel time. As observed at one bus stop of No 4, we have more efficient boarding and alighting in Stockholm, which is 1.8 sec/person, leading to only a 12-min increase in travel time in the baseline. The reason for this higher efficiency might be the higher demand for this bus line: the more passengers boarding at the same stop, the lower the average boarding and alighting time per person is.
3. Fixed stopping time for bus. We take the value of 10 sec/stop (which leads to a 5.2-min increase in travel time in the baseline), instead of 15 sec/stop from Basso and Silva (2014). This lower value is observed at bus stops in Stockholm.
4. Interactions at bus stops with cars and bicycles take the value of 0.27 min.

The sum of these four components gives a total increase in travel time of 24.07 min, which aligns with the difference between the observed baseline travel time and the free flow trip time. In section 7, we also conduct sensitivity analyses on these parameters.

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