forskningsprogrammet TRANSPORTEKONOMI

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Working Papers in Transport Economics 2019:2

Abstract

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Congestion charges, Parking, Pricing, Demand, Optimization, Urban, Welfare

JEL Codes

R41, R48, R10

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Optimal pricing of car use in a small city – A case study of Uppsala

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ABSTRACT
Studies of cities which successfully have shifted mode choice from car to more sustainable modes, suggest that coordinated packages of mutually reinforcing policy instruments are needed. Congestion charges and parking fees can be important parts of such packages. This paper aims to examine the introduction of welfare optimal congestion charges and parking fees in a model calibrated to Uppsala, a small city in Sweden. The results suggest that welfare optimal congestion charges in Uppsala are as high as EUR 3.0 in the peak hours and EUR 1.5 in the off-peak. In a rough cost-benefit analysis it is shown that the introduction of congestion charges in Uppsala are welfare improving if operating costs of congestion charges are proportional to city population size (compared to Gothenburg). The model can be used to assess when it is worthwhile to introduce congestion pricing.

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1 INTRODUCTION

There has been a long-standing hope that building smarter cities can reduce car use substantially, reducing carbon emissions and making the city more attractive. Predominantly North American studies (e.g. Ewing and Cervero 2010 or Stevens 2017) have focused on building cities more compact and studying how such development could reduce car use. They found that the "magnitude of that reduction is generally small" (Stevens 2017, p 15). McIntosh et al. (2014) and Buehler et al. (2017) on the contrary, argued that some European cities have been successful in de-coupling growth from increased car use, leading to reduced shares of trips, by implementing combinations of policy instruments. Buehler et al. (2017) showed that the share of car trips has been reduced in five large German speaking cities and provided an in-depth description of a wide range of policies, to which these effects may be attributable. They emphasized that "coordinated packages of mutually reinforcing transport and land use policies" are important to achieve these effects and that parking policies and parking management is likely to have been the most important of the car-restrictive policies for reducing the share of car trips (p. 4). Examples of such parking management measures are reduction of on-street parking spaces and construction of off-street parking garages, parking time limitations for street parking and increase in per hour parking prices. Keeping in mind that congestion charges, parking fees and improved public transport supply are only parts of such coordinated packages, it is nevertheless important to try to understand the relative merits of individual policy instruments and the possible synergies between them. Early contributions are Vickrey (1963) launching the pricing instrument to curb congestion and not much later (Kulash, 1974) proposed using parking pricing as a means to do so. Button (1995) noted that parking is a complement to road use and asserted that parking policy "has obviously been widely used in many cities as a control over excessive congestion" (p. 43), using a proposal in Los Angeles as an example. In line with this idea we will study the role of parking fees as a substitute or complement to congestion charges.

From an economic welfare perspective, however, road pricing is likely to be superior to parking fees to reduce the externalities created by car use, i.e. congestion charges is a first-best policy and increased parking fees a second best policy in this respect. A problem when using parking fees as substitute for congestion is that they may have adverse effects on the composition of traffic, i.e. it will in excess penalize stops and may encourage through traffic (Button 1995). These nuances will not be address in the present study. Also, subsidies to public transport may be a possible (second-best) substitute to congestion charges (Button, 1995), and this potential will also be explored in the present study. Although a parking tax is often mentioned in the theoretic literature as a sound policy tool and applied by some US cities[1] it is rarely applied in Europe (Mingardo et al. 2015).

The aim of this paper is to estimate the short-term consequences of the introduction of welfare optimal congestion charges and parking fees in Uppsala, a small[2] city in Sweden. The consequences are evaluated for social welfare, mode shares, congestion and CO_2-emissions. The welfare optimization will lead to consideration of various uncorrected market failures; congestion, the alternative cost of parking space, the travel times as well as crowding in public transport. The paper examines the relative merits of congestion charges and parking fees for increasing welfare.

The contribution of this paper is primarily modelling of both congestion charges and parking fees calibrated to rich data from a small city, with a simple model that is relatively easy to apply to other small cities. As discussed below many earlier papers have done extensive modeling of congestion policies in large cities while fewer have studied effects of parking on congestion in empirical models and small cities. Börjesson and Kristoffersson (2018), advised against introducing congestion charging in small cities. "For smaller cities, with less congestion, strong arguments against introducing congestion charges are system costs, the risk of inefficient spending of revenue, and negative distribution effects in cities with low public transport usage" (p. 49). Even so few attempts appear to have been done to quantify the effects of a potential congestion charge in small cities. This study can therefore be used to assess when it is worthwhile to introduce congestion pricing. The example of a small Swedish city is interesting as a case in this context, since Sweden has already introduced congestion charges in the two largest cities, and hence there exist a lot of high-quality data from these earlier experiences. This study also analyzes the possible need to optimally adapt public transport to complement the car use instruments.

Although Uppsala being the fourth largest city in Sweden, in 2016 it had the second most severe congestion problem in Sweden in terms of mean delay, with almost the same delay as the most congested city, Stockholm (Tomtom, 2019). One obvious reason is that the two largest cities at this time had reduced their congestion problems by implementing congestion charges.

Berglund and Canella (2015) and Pyddoke et al. (2017) utilized demand modeling to identify policy packages for more sustainable development of the transport system in Uppsala. A conclusion from Berglund and Canella (2015) was that large increases in parking fees and an introduction of a national kilometer tax would be needed to achieve the goals. Pyddoke et al. (2017) indicated that there was a substantial potential for both parking charges and for increasing the population density of the inner zone of Uppsala to shift transport from car to

[1] E.g., in 2007 the City of Seattle implemented a commercial parking tax levied on motorists who pay to park a motor vehicle within Seattle city limits. The rate was 5% from the start and has been increased successively to 12.5% 2019. (Litman et al., 2010, Seattle.gov, 2019).

[2] We use the OECD classification (OECD, 2019) of size of urban areas throughout the paper. Urban areas are classified as small if population is between 50 000 and 200 000. We use the shorter term city instead of urban area.

public transport and walking and cycling. However, none of these studies were based on welfare optimization and they did not estimate the welfare effects of policies.

Political actors are frequently reluctant to price externalities, when doing so is perceived to harm strong interest groups. A solution has been to use alternative policy instruments that can reduce externalities without raising the cost of these interest groups. Subsidizing public transport is such an alternative to pricing congestion. However, increasing public transport supply without examining costs and benefits, risks leading to an oversupply of public transport. Asplund and Pyddoke (2018), found a substantial oversupply in Uppsala, using the so-called BUPOV[3] model. They modeled welfare optimal bus pricing and frequency in Uppsala considering variability in occupancy and using detailed data on origin and destination incorporating modal choice[4] and local external effects. In this paper we extend this analysis by also optimizing parking pricing and by introducing congestion charges into the BUPOV-model.

BUPOV represents traffic demand and is calibrated to variations between peak and off-peak, in inner and outer parts of the city. Total welfare is optimized with respect to congestion charges for passing a cordon limiting the inner zone, parking fees in the inner zone in both periods. As for the scope, we attempt to capture the major short run welfare effects of trips beginning or ending in Uppsala, but only the parts of trips occurring within city boundaries. That is, possible non-internalized external effects arising outside Uppsala (e.g., congestion effects in Stockholm) resulting from trips beginning or ending in Uppsala are outside the scope of this study. Also, social preferences for redistribution between income groups are outside the scope of the formal analysis. In the long run more adaptation may occur due to changes in choice of destinations, location of residence and workplace, and in private supply of parking spaces etc.

In the present study the welfare effects from reduced externalities are about a tenth of the size of the revenues from either optimal parking fees or optimal congestion charges. In this paper we use recommended marginal cost of public funds (MCPF) factor from the official cost benefit guidelines in Sweden of 1.3 (Swedish Transport Administration, 2016a), as did Eliasson (2009). Effects of reduced labor market efficiency from reduced accessibility for commuters are also factored into the evaluation.

The analysis has three important limitations. First, the knowledge about investment and operating costs for congestion charging systems and shadow cost of alternative use of parking facilities is scarce. Second, the higher costs for car drivers after reforms of road and parking prices are likely to lead to long term adaptions in terms of changes in the choice of destination, mode, car type et cetera. The long-term effects are likely to be larger than the short-term effects

[3] From Swedish *Bussutbud- och prissättning—optimeringsverktyg* (bus supply and pricing—optimization tool).
[4] From the National Travel Survey and the national demand model.

and are not analyzed here. Third, health effects of increased walking and cycling and the general niceness effect of calmer streets are not included in the analysis[5].

Congestion charges have previously been introduced in the two largest cities in Sweden, Stockholm and Gothenburg. Gothenburg provides the closest comparison object, since Gothenburg is smaller than Stockholm and the introduction was later (in 2013, which is close to the years for which we have data for Uppsala in BUPOV). Therefore, the price elasticity and costs of technical system has been taken from the Gothenburg case.

The central results indicate that even in small cities like Uppsala there can be substantial welfare benefits from increasing the price of car use. The results suggest that welfare optimal congestion charges in Uppsala are as high as EUR 3.0 in the peak hours and EUR 1.5 in the off-peak (converting 10 SEK to 1 EUR). In a rough cost-benefit analysis it is shown that if congestion charge operating costs are proportional in city population size (compared to Gothenburg) then introduction of congestion charges in Uppsala seem to be welfare improving.

The remainder of the paper is organized as follows. Section 2 reviews the literature on parking policies and congestion charges. The model is presented in Section 3. In Section 4, the data used are presented and Uppsala is described. Simulation results are presented in Section 5 and, finally, findings and limitations are discussed in Section 6.

2 LITERATURE

The literature on road pricing in general is extensive; Tsekeris and Voß (2009) reviewed about 400 papers on the subject. Several papers have developed models to optimize congestion charges and public transport fares and frequencies for large cities. Examples include London and Brussels (Proost and Dender, 2008), Washington, DC, Los Angeles and London (Parry and Small, 2009), Paris (Kilani et al., 2014), Sydney (Tirachini et al., 2014), London and Santiago de Chile (Basso and Silva, 2014) and Stockholm (Börjesson et al., 2017). Armelius and Hultkrantz (2006) simulated the effects of road pricing in Stockholm but did not optimize. West and Börjesson (2018) studied the congestion charges in Gothenburg, the second largest city in Sweden, with only about half the population compared to Stockholm. Comparing the effects of congestion charges in Stockholm and Gothenburg, the authors noted that the city in Gothenburg is more dispersed in form. Furthermore, in Gothenburg the mode share of public transport is smaller and the share of low-income earners using cars is larger. Therefore Eliasson (2016) found that low income earners pay a substantially larger share of their income on congestion charges in Gothenburg than in Stockholm. West and Börjesson (2018) showed that net social benefits were positive although redistribution from car users to the government were considerably larger than the net benefit. The welfare effects of this redistribution are regressive. All these

[5] The effect of irritation from dense traffic is included for car drivers only, not for other travelers (cyclist and pedestrians) or the effect on restaurants etc.

papers have studied large cities with substantial congestion, the importance of congestion problems smaller cities is therefore less known. We have not been able to find any relevant studies on system costs for the congestion charging.

The literature on parking pricing is smaller than the literature on congestion charges but growing. Much of it analyzes pricing as a means to reduce congestion and was published in the 90's. Higgins (1992) evaluated the pros and cons of implementing parking pricing to reduce traffic through parking taxes. Several studies have explored parking prices as a second-best strategy to mitigate congestion. Arnott et al. (1991) showed that spatially differentiated parking fees may rival with time-differentiated congestion fees. Glazer and Niskanen (1992) noted that increasing the fixed price per parking would reduce congestion, while increasing the time varying component (i.e. the per hour price) would not have that effect. Verhoef et al. (1995) had a theoretic focus and examined weather physical restrictions on parking or parking fee would be the best policy instrument to curb congestion, and parking fee was found to be superior in this respect. These three studies provide valuable insights although they use highly stylized models.

Calthrop et al. (2000) showed that pricing of parking and road use, need to be simultaneously determined. In their simulation model (of a hypothetic city) they also showed that the second-best pricing of all parking spaces produced higher welfare gains than the use of a single ring cordon scheme, though marginally lower than the combination of a cordon charge with resource-cost pricing[6] of parking spots. Fosgerau and de Palma (2013) studied optimal parking fees for commuters and its effects on congestion. They focused on the timing of the car trip and hence the arrival to and departure from the parking spot. Optimal parking fees were found to reduce but not remove congestion.

Kuppam et al. (1998) performed a stated response analysis of the effectiveness of parking pricing strategies for Transportation Control in the Washington, D.C., metropolitan area. The conclusion was that parking pricing–based strategies had the potential to serve as effective transportation control measures. A similar approach was adopted by Hensher and King (2001), who studied the Sydney central business district.

Optimal parking policy integrated with public transport policy has to our knowledge previously only been estimated in a few studies. Voith (1998) constructed a general equilibrium model to study parking, transit, and employment in a central business district. He derived conditions under which parking taxes can be levied and used to subsidize transit and to increase a central business districts size and land values. Cavadas and Antunes (2018) studied a midsize city in Portugal, one motivation for the study was public deficits. The objective function was not to maximize welfare, but to minimize the joint operating deficit of both the transit and the parking systems given a minimum mobility requirement. Migliore et al. (2014) optimized welfare (including revenue from public transport) in Palermo subject to parking prices, given the

[6] I.e. the price needed to cover building costs, but exluding external effects

constraint that 30% of parking spaces should be vacant, in order to minimize search traffic.

In an alternative approach Calthrop and Proost (2006) modeled the interaction between on-street and off-street parking markets but disregarded the congestion externalities. The main result was that if there are enough private suppliers of parking so that the market is sufficiently competitive, the parking price for on street parking should be set equal to the resource cost for off-street parking at optimal quantity. Later studies Kobus et al. (2013) and Gragera and Albalate (2016) find that parkers are willing to pay a premium to park on-street, indicating that an optimal policy involves charging a premium for on-street parking. This premium was found to range from EUR 0.35 to EUR 0.6.

3 MODEL OVERVIEW

Our analysis is built on the assumption of one social planner that manages all publicly owned assets, such as streets and a share of the parking facilities. That is, we do not make a distinction of between various sections and levels of governance, in reality, these parties may partly have different objectives. Hence any potential political economic games between various public actors are out of the scope of the present analysis. We assume that the social planner is a Stackelberg leader, and the individuals and private owners of parking facilities react in their self-interest on actions of the social planners. That is, if the social planner affects the local market for parking, by for example reducing supply and increasing parking fees, this will create an opportunity for private parking owners to increase revenue in the short term by also increasing parking fees, and in the long run possibly by expanding supply. However, while our model of the individual responses is on a quantitative level, our model of the parking firms is on a qualitative, reasoning, level only, based on basic economic theory. When we refer to welfare optimality, this term refers to optimality of what a hypothetical social planner that manages all publicly owned assets to maximize the welfare of the citizens, and that is a Stackelberg leader, would find optimal.

The model (BUPOV) presented here is intended to represent the effects of transport policies on mode choice, trip timing, and welfare in a small city with one public transport mode (bus only). BUPOV has a nested structure, involving two optimization steps. A social planner is a Stackelberg leader and optimizes welfare, given that she anticipates what the travel demand responses will be. That is, she optimizes welfare by a set of policy variables, given the user equilibrium that will be the result of such policy changes.

The model is based on a radial spatial representation of a city with two zones — the city center (inner zone) and the outer city (outer zone). The analysis is restricted to workday traffic, divided into two time-period categories: peak and off-peak (OP). This representation makes it possible to analyze fares and frequencies differentiated in time and space. Since the studied policy measures are evaluated at the zone level with trips aggregated, route choices within each zone are assumed to be unaffected, so route choice is not modeled. This approach implies a limitation, as the rebound effect of reduced congestion in the city center is not fully accounted for, since some traffic travelling around the city to avoid crowding may switch routes to going through the city center. Such changes are not represented.

BUPOV is based on detailed data on current travel behavior in terms of origin–destination (OD) matrixes; it implicitly represents the current population density but does not represent changes in population or place of residence. Travelers can choose between three modes of transportation: car, bus, and walk/cycle. The choice of travel alternative depends on monetary cost, road congestion, crowding in buses, and time gains and losses due to changes in bus frequencies. In addition to the effects of policies on producers and consumers, there are effects on the time cost of freight traffic, effects on health (e.g., of noise and air pollution), and environmental effects primarily in terms of carbon dioxide emissions. The changes in the public transport authority's financial results are evaluated using a MCPF-factor. In optimum, this should correspond both to the marginal welfare costs of raising one additional unit of tax revenue or to the marginal valuation of one additional unit of public funds used for alternative purposes, for example health care. But we also multiply the consumer benefits with a wider economic benefit (WEB)-factor, i.e. accounting for better functioning of labor market from increased accessibility, counteracting the effect from the MCPF factor. The WEB-factor is calculated by "removing" the MCPF-factor from commuting trips, by also multiplying the consumer surplus by the MCPF-factor for the fraction of trips that are commuting trips. This simple approach gives the same WEB-factor as calculated by a sophisticated model for the total plan of transport investment projects in Sweden (Anderstig et al., 2018), 12% extra benefits from increased generalized accessibility, i.e. consumer surplus.

We model three types of OD pairs: within the inner zone ("inner"), between zones in any direction[7] ("inter"), and within the outer zone ("outer"). Each OD pair constitutes a separate (isolated) demand system, interlinked by sharing space, both inside the buses and on the streets. The demand for a travel alternative (mode m and time period t, for a trip for an OD pair) is modeled as a change from the demand in the reference situation as follows:

$$\Delta D_{m,t,OD} = \Delta D_{m,t,OD}(p, f, o, \delta | \varepsilon), \tag{1}$$

where p is price, f is bus frequency, o is level of occupancy in buses, δ is traffic delay (for buses and cars), and ε is a matrix of demand elasticities.

[7] Not modeling the direction of trips (i.e., towards and away from the city center) in morning versus afternoon peak hours is a simplification that may lead to the underestimation of crowding, as we assume that passengers are evenly spread between the two directions of each line. A sensitivity analysis in this respect is performed in Appendix J, where we test the extreme alternative assumption that all passengers travel in the same direction, that is half of the busses run empty and the passengers experience double the crowding compared to in the reference model. The welfare gains from optimization seems reasonably robust to this alternative model specification.

Route choices within each mode are not assumed to be affected on an aggregate level by the variables in eq. (1).[8] In Asplund and Pyddoke (2018), the total travel demand for each OD pair was assumed to be constant in terms of number of starts and destinations (destination choice is not assumed to be affected). This assumption is relaxed in the present analysis, using data from the introduction of congestion charges in Stockholm on how large proportion of trips that disappeared completely. The choice of mode and the timing choice for each trip are flexible. This implies that when the demand decreases for a mode in a time period, these trips are allocated among the other time periods and modes, proportionally to the initial demand for each other mode and time period and vice versa for demand increases.

Adjustment to a new user equilibrium caused by a change in a policy variable (e.g., frequency) is done by successively iterating the demand calculations of consumer travel choices, congestion, and in-vehicle crowding in buses. In the baseline case, demand is assumed to be in a steady state, but if a policy reform is introduced, a new steady state is approached through iteration. The levels of congestion and crowding affect the generalized cost of each travel alternative, meaning that some travelers adjust their travel choices when these levels change, so congestion and crowding will again be updated. This iteration process continues until the model reaches a new steady state.

It is assumed that the walk/cycle mode does not interact with car congestion. That is, walkers and cyclists do not experience road congestion and do not contribute to congestion for other modes. The costs associated with walking and cycling are therefore independent of the level of motorized traffic, which obviously is a simplification.

The congestion charge is introduced for crossing the border between the outer and the inner zone in the model Figure 1. The parking fee is modelled as a proportional increase in the current fees in the inner zone. These hypothetical reforms are modelled to give welfare gains in the form of revenue to the public sector reducing the need for other taxes with higher welfare losses, less congestion, and less environmental externalities.

A formal presentation of the central equations in Appendix A, and a complete specification of the original BUPOV model is found in Asplund and Pyddoke (2018).

4 DATA

Uppsala lies 70 kilometers north of Stockholm (Sweden's capital) and has Sweden's oldest university. In 2010, it had 155,000 inhabitants and its urban area covered 51 square kilometers. Figure 1 shows a stylized map of Uppsala.

[8] The network and routing are not included in the model, which is based on mean travel distances and times for each mode and OD pair from a separate routing model.

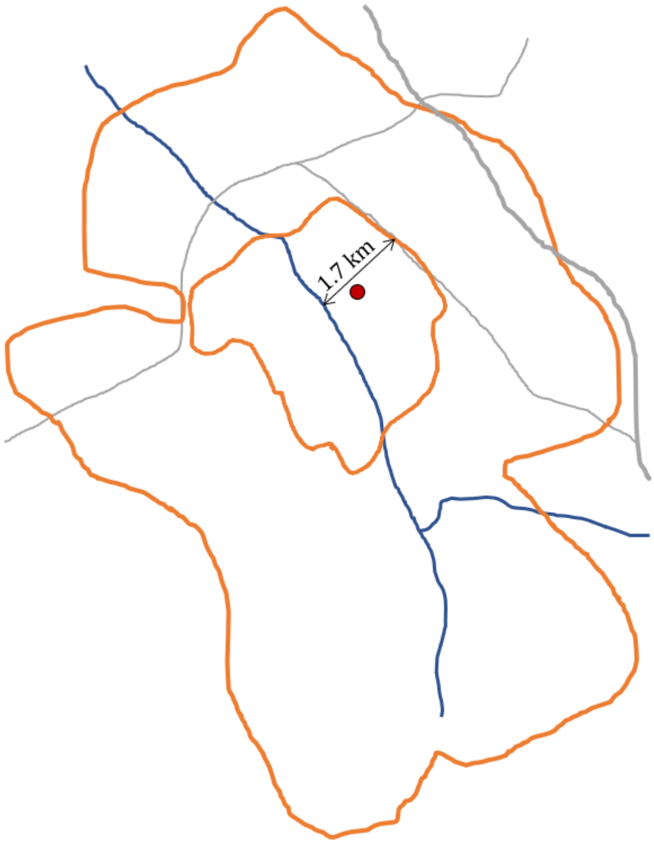

Figure 1
Stylized map of Uppsala. Orange shapes represent the edges of each zone. Blue and gray lines represent rivers (Fyrisån) and mayor roads respectively. The red dot represents Uppsala central station.

The BUPOV model is calibrated using travel data from the national travel surveys and from the Swedish national passenger demand model, and with boarding data from the public transport authority. An earlier version of BUPOV (Asplund and Pyddoke 2018) is extended by a more resolved and accurate representation of parking fees.

One difference from the travel survey is that this study concerns workdays only. Another is that we have made adjustment to account for trips with an origin or destination outside of Uppsala (see Appendix C: Demand calibration). In this study, the distribution of trips across modes, OD pairs, and time periods is taken from the Swedish national travel demand model, SAMPERS for 2010.[9] [10] This model is regularly updated for the purpose of national infrastructure planning. Two peaks of five hours per day in total (7:00-9:00 and 15:00-18:00) is based on SAMPERS documentation. Because the absolute numbers in the SAMPERS data do not coincide with those from the municipality's travel survey for 2015 (Uppsala Municipality, 2016) and boarding data from 2014 (UL, 2015), the

[9] The use of SAMPERS data, the data aggregation, and the representation of congestion and crowding in PT were inspired by the HUT model used by Pyddoke et al. (2017).
[10] Our dataset was provided by Urbanet Analys AB.

SAMPERS demand predictions have been scaled to fit those data[11]. Table B1 in Appendix B reports other SAMPERS data that have been used. Table B2 in Appendix B summarize other important data.

Table 1 reports the estimated mode shares for Uppsala.

Table 1
Mode shares and total no. of trips in Uppsala

		RVU[12] 2010	RVU 2015	Present study*
Mode shares	Car	42 %	37 %	45%
	Bus	12 %	13 %	14%
	Walk/cycle	44 %	47 %	41%
	Other	3 %	2 %	0%
Tot no. of trips			370,480	357,117

Source: Travel Survey Uppsala (Uppsala Municipality, 2015).
* Refers to workday averages of peak and OP values, including trips with origins or destinations outside Uppsala.

BUPOV uses (own) generalized cost elasticities, calibrated to match empirical responses from relevant peer reviewed literature. Public transport elasticities are from a literature review of Balcome (2004), and in the present study car elasticities have been updated to match the responses from introduction of congestion charges in Gothenburg, according to Börjesson and Kristoffersson (2015)[13]. The resulting elasticities in peak and off-peak (OP) are close; the monetary cost elasticity is about -0.7, and the generalized cost elasticity is about -0.9. This translates to a fuel cost elasticity[14] that varies between -0.04 and -0.09 for inner zone and interzonal trips. These elasticities can be compared to rough averages for fuel price elasticities in urban areas in Sweden estimated in Pyddoke and Swärdh (2008) -0.2 for short run and -0.5 in long run. Where it may be reasonable to find higher elasticities for Stockholm with higher availability of substitutes to car travel than as an average for all urban areas (down to 3000 inhabitants).

Two observations can be made here. Our short run elasticities are comparable to the literature and the long run elasticity of demand for car use with respect to driving costs is higher than the short run elasticities. This implies that the long-term effects from car restrictive policies may be larger than calculated here with the BUPOV model.

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[11] PT demand has been scaled by 1.26 to match boarding data and car, walking and cycling has been scaled to match RVU 2015 (by about 1.02).
[12] RVU = Resvaneundersökning = Travel habit survey.
[13] In Gothenburg, congestion charges were about 1.5 EUR in peak hours and about 0.8 EUR in the OP, and the response was a decline in affected car trips by 12.5% in peak and 12% in the OP. In this study, generalized cost elasticities of car trips in Uppsala have been calibrated to give the same percentage responses to introduction of the same congestion charges in Gothenburg. In an earlier version of BUPOV, elasticities were instead based on price elasticities from introduction of congestion charges in Stockholm.
[14] This is a distance-based cost elasticity based on a km-cost of 0.15 EUR from Börjesson et al. 2017.

BUPOV uses a quadratic volume delay function (VDF), calibrated with publicly available data on delays in Uppsala from Tomtom (2017), see Appendix D. Although this is a rough representation of congestion consequences from changes in traffic flows, we know of no currently available method to assess at the delay effects from decreased traffic in Uppsala on an aggregate level.

In the present study, the number of persons per car has been updated from a national figure of 1.53 pers./car to an Uppsala specific figure of 1.2 (from RVU, 2015) and a new, more accurate estimation of the number of car trips in baseline has been performed[15]. After that a recalibration of the volume delay function has been performed, resulting in the following volume delay function. The total percental delay per trip compared with free-flow conditions in each zone and time period is:

$$\delta_{z,TP} = 7.52 \cdot 10^{-7} \cdot {Q_{z,TP}^{v}}^{2}, \qquad (2)$$

where $Q_{z,TP}^{v}$ is the total vehicle-equivalent flow per area and hour in each zone and time period is:

$$Q_{z,TP}^{v} = \left(Q_{z,TP}^{v,PT} + Q_{z,TP}^{v.freght}\right) \cdot 2.5 + Q_{z,TP}^{v,car}, \qquad (3)$$

where $Q_{z,TP}^{v,freght}$ is the relevant flow of trucks for freight purposes (static demand) and 2.5 (from Börjesson et al., 2017) indicates how much congestion a bus or truck generates compared to a car.

Costs of crowding and congestion, and the marginal cost of public funds are taken from the Swedish national guidelines on the welfare economics of infrastructure investments, ASEK 6 (Swedish Transport Administration, 2016). According to ASEK 6, the in-vehicle value of time varies with the crowding level, as implemented in BUPOV through the following equation:

$$VoT_{z,TP}^{ivt,car} = \left(1 + 0.33 \cdot \delta_{z,TP}\right) \cdot VoT_{free}^{ivt,car}, \qquad (4)$$

where 0.33 is a parameter indicating how VoT increases with increased congestion[16] and $VoT_{free}^{ivt,car}$ is the free-flow (in-vehicle) value of time.

The marginal external effects of traffic safety, emissions, and noise from cars and buses (including internalization) are calculated for Uppsala based on a combination of ASEK 6, Nilsson and Johansson (2014), Swedish Transport

[15] The largest change compared to in Asplund and Pyddoke (2018) is by increasing the number of trips in the outer zone by including trips with an origin or destination outside of Uppsala.

[16] This figure is based on interpretation of Wardman and Ibáñez (2012), the underlying study to ASEK 6.

Administration (2015), and ASEK 3 (SIKA, 2005).[17] According to these calculations, car trips in Uppsala have internalization rates (for all calculable externalities except congestion) of slightly more than 100%, while emissions from buses are only internalized by about 50% (see Table 2). This means that there will be a small welfare gain from an increased number of car trips, since the extra tax collected is worth more than the costs of all other externalities including the emission caused, and vice versa for buses.

Table 2
Internalization rate of emissions and other external effects reported in 2014.

	Car	Bus
Inner	104%	50%
Outer	119%	55%

Sources: See footnote 15.

Since pricing of car use is the focus in the present study, parking fees in BUPOV has been updated with more accurate data on parking fees in Uppsala compared to in Asplund and Pyddoke (2018)[18], see Table 3. These figures are based on extensive data on parking fees, travel patterns and trip purposes in Uppsala, see Appendix E. We have no information on the extent of the private supply of parking, e.g. by employers. We have therefore assumed that all car trips with destinations in the inner city are associated with parking charges payable for the individual car user.

Table 3
Parking fees (EUR) in the inner zone per one-way trip in present study

Type of trip	**Peak**	**OP**
Inner zone	4.8	1.7
Interzonal trips*	2.4	0.9

*The assumption is that half of the interzonal trips originates from a residence in inner zone with a trip purpose in the outer zone, meaning that only for half of them it is needed to pay parking fees in the inner zone. Also, the shadow cost of parking space has been crudely estimated in the present study. In Asplund and Pyddoke (2018) the assumption was that the

[17] In Samkost (Nilsson and Johansson, 2014), total externality per vehicle-km was EUR 0.022 for cars and EUR 0.164 for heavy vehicles (e.g., buses) on average in Sweden; however, the authors used a somewhat lower CO_2 emission value than the official one (ASEK 6). Because this figure is both difficult to estimate and controversial, we have chosen the official figure and have adjusted the Samkost values in this respect. We have also adjusted for local conditions in Uppsala compared with the national averages for noise (data from Samkost), NOX, and particulate matter emissions (emission factors from the Swedish Transport Administration, 2015; Uppsala-specific valuations from ASEK 3). These adjustments increased the total externality per vehicle-km to EUR 0.038 for cars in the outer zone, EUR 0.043 for cars in the inner zone, in Uppsala. The total tax (from Samkost) is EUR 0.045 for cars.

[18] In the previous version of BUPOV only crude estimation of parking fees was done, and there was no distinction between interzonal trips and trips in the inner zone only. These old estimates were 60 SEK/ one-way trip in the peak and 3.0 EUR / one-way trip in the OP, that is substantially higher than the new estimates.

shadow cost of parking was equal to the price. This assumption largely was confirmed in the present analysis, see Appendix E.

Table 4 displays income distributions for the travelers in Uppsala as estimated from travel survey data. The income distribution profile among car users in this estimation is similar to the general population.[19] The implication is that for any policy that redistributes resources from car users to public sector in Uppsala, the distributional effects will to a large extent depend on how the additional revenues are used.

Table 4
Income distribution in Uppsala (in EUR/year)

Income class	Min income	Max income	All modes	Car
Missing			24%	19%
Low	0	14,233	27%	20%
Middle low	14,233	24,284	28%	36%
Middle high	24,285	34,675	14%	16%
High	34,675		7%	8%
Sum			100%	100%

Source: SIKA (2007)

5 RESULTS

This section presents the optimization results for the three different policy scenarios; optimization of parking fees, optimization of congestion charges, optimization of both parking fees and congestion charges, and a cost-benefit comparison of alternative policies to reduce car use and sensitivity analyses of key parameters. Table 5 displays optimal policy levels for these scenarios, and the resulting changes in trips. In Table F.1 (in Appendix F) the corresponding figures are displayed when parking fees and congestion charges are optimized simultaneously with public transport (PT) pricing[20].

Table 5
Optimal policy and changes in number of trips

Optimization variables	**Policy scenarios**			
	Base-line	Parking	Congestion charges	Both
Public transport	0	0	0	0
Parking fee	0	1	0	1
Congestion charges	0	0	1	1

[19] Car use is somewhat less common among low income earners, but somewhat more common among the group middle low. If the groups “Low” and “Middle low” are merged, these make up 73 % of the total answers, 70% of the answers among car users.
[20] In Asplund and Pyddoke (2018) optimal public transport supply was found to be robust. In the present study, simulations indicate that result still holds when including car pricing. Also, optimal car pricing seems robust with respect to optimal supply, so the relationship is not very interesting to explore in further detail and hence has been excluded from the main analysis.

Parameter		Parameter level in optimal scenario			
Parking fee*	Inner, Day	4.8	8.0	4.8	4.8
	Inner, Hour	2.4	4.3	2.4	1.8
Congestion charges (EUR)	Inter, Peak	0	0	3.0	3.0
	Inter, OP	0	0	1.5	1.7
Mode		**Changes in number of trips**			
Car		160,778	-8%	-10%	-10%
Public transport		50,920	3%	5%	5%
Walk/cycle		145,418	2%	2%	2%
Total		357,117	-2%	-3%	-3%

*Per on-way trip in the inner zone. For interzonal trips, the cost per trip is about half, since by assumption half of them originates from a residence in the inner zone and have a trip purpose outside the inner zone.

Optimal parking fees imply a substantial increase compared to current levels. The optimal congestion charges are also large, and within the range of current Stockholm levels (EUR 1.1 to EUR 3.5). The simulated decrease in number of trips across the cordon is similar to the actual decrease following the introduction of congestion charges in Stockholm, a reduction of somewhat[21] more than 20% in both cases (Eliasson et al. 2009). The optimal congestion charges are almost twice as high as the Gothenburg charges (in Börjesson and Kristofferson (2015), even though Gothenburg is an about four times larger city.

Table 6 shows that implementing jointly optimized policies does little to increase welfare from the results for optimal congestion charges. This implies that optimization of parking fees and congestion charges are substitute policies, and hence largely confirm the observation from Calthrop et al (2000), that pricing of parking and road use need to be determined simultaneously. Optimal parking fees are highly sensitive to the first best policy of congestion charges, while the opposite relationship does not hold. The reduction in number of car trips are similar across policies, and in all three scenarios the decreases in delay due to decreased congestion in the inner zone is about the same. In peak hours the delay (compared to free flow travel time) decreases from 89% in baseline to 61-65%, and in the OP the delay decreases from 39% in baseline to 28-32%.

Table 6
Welfare results, excluding operating costs of welfare optimal congestion charging (CC) technical system

Welfare effect (EUR/weekday)	Parking fee	Congestion charges	Both
Consumer surplus	-84,618	-111,078	-106,075
Of which congestion benefits	*+9,067*	*+11,035*	*+10,731*
Of which dead weight loss	*-6,844*	*-11,941*	*-12,073*
WEB (0.30*CS_commute)	-10,529	-13,821	-13,198

[21] In Uppsala 26% in peak and 23% in OP. Note that the difference compared to Table 5, is that number of trips in in Table 5 refers to all trips in Uppsala, to only across the cordon.

Producer surplus, public transport	+5,939	+7,883	+7,691
Congestion tax revenues	0	+109 728	+116,663
Producer surplus parking, public	+43,354	0	-6,162
Producer surplus parking, private	+43,354	0	-6,162
MCPF (0.30*PS_public)	+14,788	+35,283	+35,458
Congestion benefits for trucks	+395	+499	+482
Net of other external effects	-172	-339	-335
Of which CO2 benefits	*+724*	*+1,249*	*+1,217*
Net social benefits	**+12,512**	**+28,155**	**+28,362**

The most important components of the welfare net calculations are; the time savings of travelers and burdens of switching to a less preferred travel mode, increased revenues to the regional public transport agency, the marginal cost of public funds, and the wider economic benefits (costs) from decreasing (increasing) costs of trips, while other effects such as e.g. environmental effects are small. Observe that the congestion benefits are about a tenth of the total congestion tax revenues, while the net of further externalities is small. The largest welfare gain comes from the additional benefits from using the increased tax revenue. The total net benefit is less than a third of the total revenue. Comparing the numbers for the parking fee; the magnitude of the congestion benefits are similar but the benefits from using the increased public revenue are smaller then for congestion charges.

Table 7
Cost-benefit analysis of introduction of welfare optimal congestion charges (EUR)

Comparison policy	Do-nothing	Optimize parking fees
Welfare gain per weekday from introducing CC	+28,155	+15,642
Welfare gain per year*	+7,038,684	+3,910,598
Net welfare gain per year, assuming Gothenburg operating costs= 11,700,000**	-4,661,316	-7,789,402
Net welfare gain per year, assuming Gothenburg operating costs divided by 3.7***	+3,904,509	+776,423
Payback time in years, assuming Gothenburg investment cost = 30,000,000 EUR**	8	39
Payback time in years, assuming Gothenburg investment cost divided by 3.7***	2	10

*Multiplying the daily gain by 250
** Source: Göteborgs stad (2015)
*** The assumption is instead that operating costs are proportional to city size, so the Gothenburg costs are divided by 3.7 = 599,011/160,462, which corresponds to the ratio between city inhabitants in 2018.

Table 7 displays a rough cost-benefit analysis of introduction of congestion charges. Introduction of congestion charges are compared to two policies; doing nothing, and optimizing parking fees. The results indicate that a yearly welfare surplus is sensitive to the operating cost of the system. If operating costs are proportional to city population size, the payback time of investment (in terms of welfare) is 2-39 years, depending if investment costs also follow city size and whether or not optimization of parking fees is a viable option.

In Sweden there is a political goal to decrease domestic CO_2 emissions by 70% to 2030. Therefore, in Table 8, various policies to approach this goal for Uppsala, by decreasing the number of car trips in the city by 10% are explored. The column public transport supply indicates that trying to achieve this by only changing public transport supply is both extremely costly and counterproductive, since it implies increasing public transport supply to a level so high that it becomes a serious environmental problem. In the second column, policy is to provide public transport free of charge. This only achieves a 5% reduction in car trips. In the third column, both frequencies and fares are adjusted to reach a 10% reduction of car trips. In the last two columns, parking fees and congestion charges respectively are optimized. Of these two, congestion charges give the largest welfare gain and the largest CO2 reductions. Welfare optimal congestion charges also give higher tax revenues than welfare optimal parking charges. The results imply, that if politicians truly want to reduce CO2 emissions by reducing the numbers of car trips, it is necessary to increase pricing of car trips.

Table 8

Alternative policies to achieve a reduction in car trips by 10%

Policy scenario		**PT^ supply**	**PT price***	**PT**	**Parking fees**	**CC**
PT supply level		1198%	100%	446%	100%	100%
PT fare level	I-I, Peak	100%	0%	0%	100%	100%
	I-I, OP	100%	0%	0%	100%	100%
	I-O, Peak	100%	0%	0%	100%	100%
	I-O, OP	100%	0%	0%	100%	100%
	O-O, Peak	100%	0%	0%	100%	100%
	O-O, OP	100%	0%	0%	100%	100%
Parking fee	Inner, Day	100%	100%	100%	179%	100%
	Inner, Hour	100%	100%	100%	209%	100%
Congestion charges (EUR)	Inter, Peak	0	0	0	0	34
	Inter, OP	0	0	0	0	13
Welfare effects (EUR)		**-22,956,437**	**+90,516**	**-5,460,853**	**+120,903**	**+280,348**
Congestions benefits (EUR)		-683,281	+36,811	-136,984	+108,322	+108,307
CO2 benefits (EUR)		-7,255	+580	-1,499	+950	1,214
Consumer surplus (EUR)		-456,359	+725,545	+1,097,873	-1,051,842	-1,086,639

^PT: public transport

*Only using the PT price instrument is not enough to achieve a 10% reduction in car trip, since free PT achieves only 5%.

Table 9 below presents sensitivity analyses with respect to different levels of the share of public ownership of parking, marginal costs of public funds and valuations of CO2 emissions.

Table 9
Sensitivity analysis on key parameters

Optimization variables		**Sensitivity parameter**			
		Share public parking*	MCPF **	CO2 ***	Elasticity ****
Public transport		0	0	0	0
Parking fee		1	0	0	0
Congestion charges		0	1	1	1
Parameter		**Parameter level in optimal scenario**			
Parking fee	Inner, Day	7.3	4.8	4.8	4.8
	Inner, Hour	3.6	2.4	2.4	2.4
Congestion charges (EUR)	Inter, Peak	0	2.1	3.3	3.7
	Inter, OP	0	0.9	1.8	1.5
Mode		**Changes in number of trips**			
Car		-5%	-6%	-12%	-11%
Public transport		2%	3%	5%	5%
Walk/cycle		2%	1%	3%	3%
Total		-2%	-2%	-4%	-3%
Welfare effects (EUR)		**6,387**	**8,036**	**35,599**	**29,101**
Congestions benefits (EUR)		7,126	7,717	12,045	11,058
Consumer surplus (EUR		-63,131	-73,575	-122,961	-122,393

*Decreasing the assumed share in baseline from 0.5 to 0.25.
**Decreasing the MCPF-factor from 1.3 to 1.
*** Increasing the CO2 valuation from 0.114 to 0.7 EUR per kg/CO2 relating to ASEK 6 and ASEK 7 (forthcoming) respectively.
**** Using own price elasticities from Stockholm instead of Gothenburg.[22]

The first column demonstrates the effect of a smaller share of public ownership of parking on parking fees. Reducing the share from 0.5 to 0.25 reduces the welfare gain from optimal parking fees from almost EUR 12,500 per workday to EUR 6,400, and car trips are reduced by 5 % instead of 8 %. The second column represents the effects of a lower MCPF, 1 instead of 1.3, optimal congestion charges. This reduces the burden of and the value of tax revenue. In this case the optimal congestion charges in peak are reduced from 3.0 to 2.1 in peak and from 1.5 to 0.9 in off-peak. The third column represents the effects of an increased valuation of CO2 emissions from EUR 0.114 to EUR 0.7. This increases the congestion charge in peak from EUR 3.0 to EUR 3.3 and in off-peak from EUR 1.5 to EUR 1.8. The last column indicates that core results are not very sensitive to the elasticity of demand.

6 DISCUSSION AND CONCLUSION

[22] Own price elasticities for car in the baseline model has been calibrated to match responses from introduction of Gothenburg congestion charges. Börjesson et al. (2017) estimated price elasticities from the introduction of congestion charges in Stockholm, which have been used in the sensitivity analysis, changing the peak elasticity from -0.72 to -0.54 and the OP elasticity from -0.71 to -0.85.

The aim of this study is to estimate the short-term consequences of the introduction of welfare optimal congestion charges and parking fees in Uppsala, a small city in Sweden. The consequences are evaluated for social welfare, mode shares, congestion and CO_2-emissions. The most important finding is that even a small city may benefit from introducing congestion charges. In a rough cost-benefit analysis it is shown that if congestion charge operating costs are proportional in city population size (compared to Gothenburg) then introduction of congestion charges in Uppsala seem to be welfare improving. These crude estimates indicated that it would worthwhile to do a detailed analysis of the in introduction of congestion charges in Uppsala, and the related operational costs.

The study supports the notion that congestion charges and increases of parking fees are to a large extent substitutes. If implementing congestion charges, there is little benefit from also implementing increased parking fees. An advantage of parking fees is that, in contrast to congestion charges, they do not require any further system costs. A disadvantage of using parking fees is that if this policy is implemented, the share of public ownership of parking lots will most likely decrease over time, meaning, that this strategy will only be effective for a certain time period, and after that congestion charges will be needed. Also, it is currently probably not legal to use parking fees for generating revenue to the municipality. A recent appeal suggests that some current practices in parking charging may not be permitted in Swedish legislation (Stockholmdirekt, 2019). Introduction of a parking tax may provide a way out of these dilemmas.

For both optimal congestion charges and optimal parking fees the increased revenues are much larger than net welfare gains. For congestion charges the revenue (i.e. the redistribution) is more than three times larger than the total welfare gain. The strongest reason for introducing optimal congestion charges or increased parking fees are therefore fiscal, in that they provide a means to tax the citizens without distorting incentives as much as marginal increase in labor taxes would. This relates to a larger discussion about double dividend from taxing external effects. E.g. Jacobs and de Mooij (2015) indicated that in a completely optimized tax system (including distributional goals) the MCPF-factor would be equal to unity. A correct consideration of the total general equilibrium effects of taxation is complicated and we have limited our analysis to the partial equilibrium effects using the standard marginal cost of public funds approach is used to value the increase in public revenue and by using a WEB-factor to account for the effect increased cost of commuting on the labor market. However, the result of a fiscal net gain from introducing congestion charges are in line with the conclusions from Parry and Bento (2001). From a simple general equilibrium model, they concluded that congestion charges theoretically imply a double dividend.

The redistribution of welfare from car users to the public sector resulting from the payments of charges and fees respectively are however large and their distributional effects will to a large extent depend on how the additional revenues are used. In Stockholm (Eliasson, 2016) and Gothenburg (West and Börjesson, 2019) for the introduction of congestion charges regressive distributional effects were found. If public parking owners increase their prices (and reduce supply) this will mean an opportunity for private parking owners to follow, and hence reap oligopolistic rents, implying a redistribution from travelers to private parking owners, and this redistribution may be regressive, if ownership of parking facilities is concentrated to the wealthiest decile.

There are some important qualifications to the analysis presented in this paper. Both optimal parking fees and congestion charges will decrease the demand for parking. The first qualification is that, the welfare gains of these policies are also dependent on the assumption that parking space can be converted to other valuable use at low costs (for example as bus or bike lanes). A second qualification is the uncertainty about the share of car trips that are associated with a payment of parking fees. We have no indications of there being a substantial supply of free employer supplied parking in central Uppsala. In the current model it is therefore assumed that there is no such free parking in central Uppsala. High shares of employer supplied free parking is likely to reduce the effects of higher parking fees. A third qualification that is worth mention are the health benefits from more exercise if there is more walking and cycling and if the city becomes more attractive with less car traffic are not analyzed. The availability of such cost-benefit values is discussed by van Wee and Börjesson (2015). They argued that reliable such values were not available at that time and that values for health effects did not take full account for the fact that only parts of health effects are external. Given the lack of good data on these three qualifications, caution is called for. Nevertheless, there seem to robust policy advice from modestly adjusting the parking policy. In Uppsala the official policy states that the city aims at most 85% occupancy in street parking. This policy appears to be adopted from Shoup (referenced by Inci (2015, p. 58). A robust strategy could therefore be to consider increasing the parking fees in places where occupancy is higher than 85%, and to consider transforming parking spaces to other valuable uses such as improving cycling possibilities in places where occupancy is considerably lower than 85%. However, in locations where occupancy is low and no other use is feasible, it may be welfare improving to reduce the parking fees.

Turning back to the discussion in the introduction on the relative merits of single policy instruments or policy packages in influencing car dependence we note the following. Our simulation (Table 8) suggest that the total welfare costs for using increased frequencies of public transport are much larger than for using car pricing[23]. Furthermore, results indicate that there are negative synergies between congestion charges and parking fees.

Finally, the following paths for further research are noted. Better estimates of the costs and ownership of parking could clearly improve the above calculations. Furthermore, using long-term elasticities some-long term adaptions could be forecasted.

[23] Car pricing implies a welfare gain instead of a cost.

ACKNOWLEDGEMENTS

This study has been funded by Swedish Transport Administration and Vinnova, Sweden's innovation agency. We thank our colleague at VTI, Chengxi Liu, for preparation of income data. We are most grateful for important comments by Prof. Lars Hultkrantz, Prof. Stef Proost, Prof. Maria Börjesson and Adj. Prof. Karin Brundell-Freij. We thank Lisa Svanberg for proofreading. The paper was reviewed by Lars Hultkrantz at a seminar held at VTI 2019-09-23.

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APPENDIX A: CENTRAL EQUATIONS IN BUPOV

The generalized consumer cost per car trip in each OD pair, time period (TP), and iteration (i) is:

$$GC^{car}_{OD,TP,i} = \frac{DC \cdot d_{OD} + p^{car}_{OD,TP}}{o_{car}} + \sum_z \left(VoT^{ivt,car}_{z,TP,i} \cdot t^{ivt,car}_{OD,z,TP,i}\right), \tag{A.1}$$

where DC is the distance cost per car (comprising cost of capital, fuel, and wear and tear) and $p^{car}_{OD,TP}$ is the mean parking fee paid per car, OD pair, and time period.

The generalized consumer cost per public transport trip in each zone, time period, and iteration is:

$$GC^{PT}_{OD,TP,i} = p^{PT}_{OD,TP} + \sum_{j=wait,walk,ch} \left(VoT^{j,PT}_{TP} \cdot t^{j}_{OD,PT,TP}\right) + + \sum_z \left(VoT^{ivt,PT}_{z,TP,i} \cdot t^{ivt}_{OD,z,PT,TP,i}\right), \tag{A.2}$$

where $p^{PT}_{OD,TP}$ is the fare per OD pair and time period, j denotes trip components other than in-vehicle time, $wait$ denotes the waiting time, $walk$ walking time to reach bus stops, and ch changing time between bus lines for each trip.

The change in number of trips per mode, OD pair, and time period due to a policy reform is (in iteration i):

$$\Delta D^{tot}_{OD,m,TP,i} = \Delta\widetilde{D}_{OD,m,TP,i} + \sum_{\widehat{m},\widehat{TP}} \left(-\Delta\widetilde{D}_{OD,\widehat{m},\widehat{TP},i} \cdot \theta^{OD,m,TP}_{\widehat{m},\widehat{TP}}\right) \tag{A.3}$$

where

$$\Delta\widetilde{D}_{OD,m,TP,i} = \Delta GC^{m}_{OD,TP,i} \cdot \varepsilon_{m,TP} \tag{A.4}$$

is the partial change in demand resulting from changes in the own generalized cost of each travel alternative (m, TP).

$$\Delta GC^{m}_{OD,TP,i} = GC^{m}_{OD,TP,i} - GC^{m}_{OD,TP,0} \tag{A.5}$$

$\varepsilon_{m,TP}$ is the own generalized cost elasticity, derived from the own price elasticity.[24]

$\theta^{OD,m,TP}_{\widehat{m},\widehat{TP}}$ is the share of changes in trips in one alternative (m, TP) resulting from changes in the generalized cost of another alternative $(\widehat{m}, \widehat{TP})$. For the closest travel alternatives, this is proportional to travel demand in iteration 0, while for other travel alternatives, this parameter is zero. That is, the distribution of moves of trips to the three closest alternatives is proportional to the number of trips in each of these three alternatives in the baseline scenario.

As a last step, the total number of trips for each travel alternative within each OD pair is updated as:

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[24] $\varepsilon_{m,TP} = \varepsilon^{price}_{m,TP} \cdot \frac{\sum_{OD}\left(GC^{m}_{OD,TP,i} \cdot D_{OD,m,TP,0}\right)}{\sum_{OD}\left(p^{m}_{OD,TP,i} \cdot D_{OD,m,TP,0}\right)}$

$$D_{OD,m,TP,i+1} = D_{OD,m,TP,i} + \Delta D^{tot}_{OD,m,TP,i}. \qquad \text{(A.6)}$$

Eqs. (A.1–A.6) are run in a recursive loop (in which i is increased by 1 for each iteration) until the system reaches the user equilibrium; that is, the first iteration when there is no substantial difference between any variable versus in the previous iteration.

Calculating the consumer surplus with simultaneous cost changes for multiple goods (i.e. travel alternatives) is not straight forward. The correct way of doing this is to assume a (arbitrary) sequence of cost changes, and then shift the demand curve for each good after each change, and after each cost change use the rule of one-half on own-price changes only. In the current version of BUPOV this is implemented as following for each OD-pair. First the rule of one-half is applied to peak car trips, based on the baseline demand. Next, the demand curve for the other travel alternatives is shifted by adding switches of travel alternative due to changes in the generalized cost of the peak car alternative. These new artificial "baseline" demands will constitute new bases for the for calculation of the CS for the other travel alternatives. E.g., next the rule of one-half is applied to OP car trips, using the updated "baseline" demand, the after that the baseline demands for the bus alternatives are updated, and so forth.

The change in consumer surplus (due to a policy change) compared with baseline is defined by the rule of one-half, for each mode,[25] time period, and OD pair (in iteration i), as:

$$CS_{OD,m,TP,i} = -\Delta GC^{m}_{OD,TP,i} \cdot \widetilde{D_{OD,m,TP,i*}} \left(1 + \frac{\Delta GC^{m}_{OD,TP,i} \cdot \varepsilon_{m,TP}}{2}\right), \qquad \text{(A.7)}$$

where $\widetilde{D_{OD,m,TP,i*}}$ is the artificial "baseline" demand, only used for CS calculation, dependent on the (arbitrary) order of travel alternatives in applying the rule of one-half.

Note that (A.7) has been updated compared to in Asplund and Pyddoke (2018).[26]

The total welfare effect of a given policy change is:

$$\Delta W_i = (1+\mu) \cdot \Delta CS_i + (1+\tau) \cdot (\Delta PS_i +) + \Delta PR_i + \Delta CT_i + \Delta E_i, \qquad \text{(A.8)}$$

where $1+\mu$ is the WEB factor, $1+\tau$ is the MCPF factor, ΔPS_i denotes changes in producer surplus for publicly owned transport services (public transport, parking and congestion charges revenues), ΔPR_i the total net benefit of changes in parking revenues from privately owned parking lots, ΔCT_i congestion benefits

[25] However, there is no change in the generalized costs of walk/cycle, so in practice this calculation is performed for car and bus transport only.

[26] Prof. Stef Proost in September 2019 reviewed our work and noted the previous version of (A.7) was on a non-preferred form that could result in errors. A sensitivity analysis on (A.7) has been performed, indicating that the error was not important when optimizing bus policy, but is important when optimizing car pricing. The reason is that that deadweight losses are small from changing the bus system, but large when optimizing car pricing in Uppsala.

for trucks, and ΔE_i the net social cost of other external effects, all compared with the baseline.

The welfare optima given different restrictions are defined as:

$$\max(\Delta W_{i*}|\Psi), \tag{A.9}$$

where Ψ is a set of restrictions ($\Psi \in \emptyset$ defines the welfare optimum), and $i*$ denotes the user equilibrium[27].

[27] Note that eq. (37) implies that the policy maker is a Stackelberg leader, setting policy in anticipation of the future total response (in the last iteration only). That is, policy is set once only and not in every iteration *i*.

APPENDIX B: DATA

Table B1 summarizes the SAMPERS data used

Table B1
SAMPERS data used

OD pair	Walking time, PT* (min)	No. of bus changes	IVT, PT (min)	IVT, Car (min)	Distance, mean (km)	Distance, car (km)	Distance, PT (km)
I-I	7.2	0.13	4.0	4.1	2.1	2.2	2.4
I-O	9.7	0.35	13.6	7.6	4.8	5.1	5.4
O-O	11.8	0.71	19.6	7.8	4.9	6.0	7.2

*PT: public transport

Table B2 reports additional data used.

Table B2
Other parameter values and utilized data

Source	Parameter/data	Value
National travel survey for Uppsala (RVU, 2015)	Occupancy car (pers. per car)	1.2
	Share of commuting trips for car trips in Uppsala[28]	41.5%
Reported 2010 statistics for Uppsala	Bus fare	EUR 1.12
SKL (2014)	Mean point occupancy per bus in the baseline	8.5
ASEK 6 (Swedish Transport Administration, 2016a, regional trips 2014)	Marginal cost of public funds (factor)	1.3
	VoT car on empty street[29]	EUR 9.30 /h
	Increased VoT car for a doubling of travel time[30]	+1/3
	VoT trucks[31]	EUR 31.2
	VoT bus in empty vehicle	EUR 3.70
	Yearly capital cost per car (assuming average value of cars is half the price of a new one)	EUR 1,242
Combination of Trafikanalys (2016) and Swedish Transport Administration (2016b)	Proportion trucks (of cars)	2.6%
Börjesson et al. (2017)	Km-cost for car	EUR 0.15
	Bus equivalent to the number of cars in causing congestion	2.5
	Number of workdays a year	250
Jennervall (2016)	Yearly insurance cost per car in Uppsala	EUR 425

[28] Taken as the mean to two estimation methods based on table E.1, in Appendix E. The first method is simply to assume that each trip to work generates on return trip on a one-to-one basis, i.e. the share commuting trips is 46.6%. The other method is to exclude trips back to home and take the commute trips as the share trips to work in the new sample, i.e. 36.3%.
[29] Based on the shares of commute trips, business trips, and other trips in Uppsala 2015 (RVU, 2015)
[30] Estimated in present study to match ASEK recommendations, based on visual interpretation of figure in underling study (i.e., Wardman and Ibáñez, 2010).
[31] Based on the crude assumption that VoT of trucks is the same as for business trips.

APPENDIX C: DEMAND CALIBRATION

Trips with a starting point or destination outside the city center of Uppsala versus with a destination or starting point in Uppsala are analyzed using different methods, depending on the assumptions on how they interact with traffic. For public transport travelers who come from outside the analyzed zones, they are all assumed to arrive by train or regional bus at Uppsala's main station, from which they proceed to their respective destinations by bus or walking, according to the distribution of these two modes for the respective zone type (i.e., inner/inter). This part of the trip is then added to the total travel by bus/walking for the respective zone (i.e., inner/inter). This is because these travelers are likely to consider bus/walking/taxi if the cost picture changes. Even though the elasticities probably differ somewhat from those of other travelers (especially for the car option), because these trips are relatively few, this assumption is not likely to affect the results much.

Walking and bicycle trips going from Uppsala to outside of Uppsala are assumed to be unaffected by changes in the inner zone; therefore, they are excluded from the analysis, as are all. Cars traveling between outside Uppsala and the inner parts of Uppsala both experience and induce congestion and should therefore be included in the congestion and welfare calculations. For simplicity, these car trips are added to the inter trips, although their true individual elasticities differ from those of trips going the shorter distance between the inner and outer zones within Uppsala (due to different generalized costs per trip). This means that the own price elasticities for car inter trips may be somewhat overestimated. In the same way, car journeys from outside Uppsala to the outer zone of Uppsala are simply added to car journeys within the outer zone.

The travel distances differ among modes in the baseline (not much in the inner zone but walking/bicycling trips are substantially shorter in the outer zone than are car and public transport trips). Because of this, some adjustments of the model are needed with regard to travel distance. A first step is to recognize that the mean travel distances hide considerable within-mode heterogeneity. A reasonable assumption is that the walkers and cyclists who are most likely to switch to another mode are the ones who have a trip length in the upper part of the distribution of trip lengths among walkers and cyclists, that is, closer to the average trip lengths of public transport and car trips. At the same time, the public transport and car users who are most likely to switch mode to walking/bicycling are the ones who have trip lengths shorter than the average trip lengths of car and public transport users, that is, closer to the average trip lengths of walkers and cyclists. Because of this, in combination with the tractability of simplicity, all switchers of mode or of time period are assumed to have a trip length that is the same across modes (i.e., the sample mean). Therefore, for each iteration, total vehicle distance is updated (from baseline) by adding/subtracting the distance from the trip switching according to this principle. However, the distance also shows up in the calculation of the generalized cost of the car alternative (eq. (17)). Because elasticities are based on the costs of the whole sample, not just the switchers, distances in eq. (17) are based on mean distances for car users only.

This is also important when calculating the summed-up welfare effects of decreased congestion.

It is assumed that the parts of the inter journeys that are in the inner zone are approximately as long as the lengths of trips within the inner zone, i.e., about 2 km. Based the assumptions for Figs. 1 and 2, the distance to the point of B (the inner/outer zone boundary) is calculated to be 16 percent of the distance from C to T.

APPENDIX D: VOLUME DELAY FUNCTION CALIBRATION

Calibration of the volume delay function is done as following. We have used data for mean delays in Uppsala for 2015, from Tomtom (2017). However, Tomtom does not provide figures for the OP, only for the peaks and in total (23% extra time). Therefore, the OP delay needs to be estimated, see Table D.1

Table D1

Estimation of mean delay in each time period

Time period (TP)	Peak	OP
Share of car trips	0.35	0.65
Delay, δ_{TP}	36.2%*	15.9%**

* Mean (morning_peak; afternoon_peak)

**(Mean_delay_in_Uppsala - Share_peak*Delay_peak)/Share_OP

Table D2

Traffic flows in each zone and time period

	Area (km2)	Vehicle_equivalent_km/km²/h, $Q^{v}_{z,TP}$	
		Peak	OP
Inner	12	1 088	722
Outer	86	493	324

Table D.2 displays the traffic flows in each time period and zone in BUPOV. The data in tables D.1 and D.2 are combined to estimate the VDF as percent delay as a function of Vehicle_equivalent_km/km²/h. Since the Tomtom data is not presented for various zones, this is not straight forward. We have the following equation system:

For each time period and zone:

$\delta_{z,TP}$ = VDF($Q^{v}_{z,TP}$)

For each time period:

δ_{TP} = Share_inner · $\delta_{inner,TP}$ + (1-Share_inner) · $\delta_{outer,TP}$

This equation system has been solved manually (by iteration) by assuming a quadratic form of the VDF, with the linear argument and intercept equal to zero[32]. The resulting VDF is:

$$\delta_{z,TP} = 7.52 \cdot 10^{-7} \cdot {Q^{v}_{z,TP}}^{2},$$

[32] In Asplund and Pyddoke (2018) the linear argument was showed contribute very little to total delay.

APPENDIX E: PARKING

Price data and calibration

Table E1 displays calculations of number of parking hours per trip.

Table E1
Calculation of number parking hours per car-trip, for peak and OP-trips respectively. Trip purpose shares are from the travel survey for Uppsala from 2015 (Uppsala municipality, 2016, Bilaga 1, Tabell 12a).

Assumed time-period of trip	Trip purpose	Share per car (%)	Assumed no. of parking hours per trip
Peak	Work	23.3	8
	School	1.3	8
	Mean peak		**8**
OP	Transport of kids	8.0	0
	Food shopping	6.4	0
	Other shopping	4.4	2
	Leisure	12.3	3
	Service	1.7	1
	Other	2.0	2
	Business	4.7	3
	Mean OP		**1.7**
Excluded	Return to home	35.9	

An extensive scan of market prices of parking at various locations in the inner zone of Uppsala was performed in 2019, were all prices available online were compiled. There were also information about the number of parking lots at each location, and this information was utilized to weight the average parking prices in each zone. There were three types of fees; fee per hour, fee per day, and fee per month. For peak and OP trips respectively, for each location the cheapest available prices was chosen based on assumptions. It was assumed that only hour prices was relevant for the OP trips, since this is so much cheaper when parking only 1.7 hours. For peak trips it was assumed that 20 identical trips per car per month were made, implying that monthly fee was often the cheapest price, when available. The resulting parking prices per peak and OP trip are presented in Table 3.

The social cost of parking space

Policies that affect transport demand, does typically also affect the demand for parking. Hence, for complete welfare analysis, the availability and social cost of parking space need to be considered. However, to analyses these issues is a rather demanding task, as will be illustrated below. In the simplest case, when conversion to other purposes is costless and the price of real estate is constant over time a simple formula for the social cost of parking space can be established as:

$$C = \text{operating cost} + \text{opportunity cost of space} \qquad \text{(E.1)}$$

The operating cost includes the quantity dependent costs of the ticket system and enforcing, e.g. patrolling and supervision. The alternative rent here refers to the potential rent or use value if the land would be dedicated to purposes other than parking. The operating cost is comparatively easy to estimate, while the location specific rent is harder to estimate. The rent on office floors could serve as an upper bound for alternative use of garage buildings, since there would be a substantial cost for converting garages to office buildings.

Consider this basic micro economic model of supply/pricing equilibrium of a specific product (a stationary version of eq. 7.1 in Hanley et al., 2007):

$$\frac{v}{p} = r - \gamma, \qquad \text{(E.2)}$$

where v is yearly profit per unit of capital (e.g. square meter of land), p is the current price of one unit of capital, r is the interest rate and γ yearly (percental) price increase of capital. This model could be translated to the problem of a social planner owning capital in the form of parking lots. The v and r are no longer market values but reflect social values, i.e., v corresponds to the required social profit from each parking lot, i.e. the revenue minus the social cost, and r now corresponds to the social discount rate.

The actual marginal social profit of each parking lot outside the welfare optimum is then:

$$v^* = R - C - v = R - C + (\gamma - r) \cdot p \qquad \text{(E.3)}$$

where R is revenue and C is operating cost and shadow rent. γ is easy to estimate while r and p are somewhat harder.

The current official real discount rate for Swedish infrastructure investments in Sweden is 3.5%/y. The same discount rate was estimated by Asplund (2018) to 5.1%, with a reasonable range of 2.2-9.1% (according to Table 2). According to official Swedish data (Statistics Sweden, 2019a) real estate prices has increased by 5.67% per year and the consumer prices has increased by 2.95% per year (Statistics Sweden, 2019b) between 1981-2018, meaning that the real price increase has been 2.7%. Since this number is within the range of reasonable social discount rates in Sweden, the assumption here has been that γ and r are not significantly different and therefore (E.3) can be simplified by approximating the last term to 0:

$$v^* = R - C = R - (\text{operating cost } + \text{ opportunity cost of space }) \quad \text{(E.4)}$$

The alternative rent has been estimated by compiling a small dataset of rents (exclusive of heating and hot water) for commercial buildings in the inner zone of Uppsala, from adds during the period 2019-03-12 – 2019-03-14 (Objektvision, 2019), see Table E.2. The conversion cost has been estimated[33] to 282 EUR/parking lot/month from Boverket (2009), by assuming that the conversion cost is the same as the cost of building from scratch.

Table E.2
Commercial rents in Uppsala 2019 in EUR

Address	Size (m2)	Monthly rent	No. of parking lots*	Monthly rent per lot	Monthly shadow rent**
S:t Johannesgatan 2	58	895	2.3	454	171
Eldkvarnsgatan 5	90	1,350	3.6	441	158
Skyttelgatan 15	42	630	1.7	441	158
Vattholmavägen 10	131	1,965	5.2	441	158
Åkaregatan 5	315	3,300	12.6	308	253

*Assuming 25 m2/parking lot
**Subtracting conversion cost (from parking building to commercial use) of 282

The mean value of the monthly shadow rent in Table E.2 is 134 EUR. Adding the operation cost of 30 EUR/month from Jernberg and Örnfeldt (2009), means that the total shadow cost of parking is about 164 EUR in the inner zone of Uppsala (for garages). The monthly parking price offered by a large commercial garage operator, Q-park, in the inner zone of Uppsala in 2019 was 238 EUR[34]. Considering that Q-park has considerable vacancies in their garages, a mean revenue of about 160 EUR/parking lot does not seem unreasonable. For simplicity, it has therefor been assumed that $v^* \approx 0$. It should be noted that the public sector only manages one garage in the inner zone of Uppsala, but a lot of on-street parking. The public sector owns further parking spaces, these are however managed by private operators responsible for the pricing decision. For simplicity it has been assumed that the $v^* \approx 0$ also holds for on-street parking.

A further implication of the (large) conversion cost between garages other commercial use, is that private supply is somewhat inflexible in the short run. $v^* \approx 0$ is likely to hold also for private parking owners, if their required rate of return is similar to the social discount rate. Then the figures above suggest that

[33] The total building cost in Linköping, as similar city, in 2009 was 1532 EUR/m2. Using a discount rate of 5.1% from Asplund (2018) and 25 m2/parking lot, and 40-year calculation period this translates to a shadow cost of 282 EUR/parking lot/moth.

[34] The mean of the cheapest monthly fee at 8 locations in the inner zone of Uppsala by Q-park https://www.q-park.se/sv-se/?l=Uppsala C, Uppsala, Sverige.

if parking revenues decreases as consequence of public intervention, it may be profitable to convert parking facilities to other use. However, the opposite does not hold in the short run. Parking prices must probably increase severalfold to motivate conversion from other commercial use to parking facilities in the short run. An implication of this is that owners of parking lots possess some market power, that may be utilized to set prices higher than their run marginal cost of parking short run. Our short run model of private parking owners is that supply is fixed, and that they set prices equal to the ones set by the public owner. However, in the long run, higher prices may stop possible conversion of private parking facilities to other use, meaning that in the long run private parking supply is likely to be at least somewhat flexible.

One implication of the above model is that if public parking owners increase prices and reduce supply, then in the short run this will imply large monetary transfers from car travelers to not only the public, but also to private parking owners, and this may be viewed as problematic. If ownership of parking (possibly through ownership of parking firms) is more concentrated to the wealthy end of the income distribution than car use in Uppsala, this would have regressive consequences.

APPENDIX F: RESULTS

Optimal policy and changes in number of trips with and without public transport optimization

Table F.1
Policy scenarios (percent are compared to baseline prices) and resulting changes in number of trips

Optimization variables		**Policy scenarios**					
		Parking fee		Congestion charges		Both	
Public transport		0	1	0	1	0	1
Parking fee		1	1	0	0	1	1
Congestion charges		0	0	1	1	1	1
Parameter		**Parameter level in optimal scenario**					
PT fare level	I-I, Peak	100%	77%	100%	28%	100%	20%
	I-I, OP	100%	0%	100%	0%	100%	0%
	I-O, Peak	100%	77%	100%	205%	100%	206%
	I-O, OP	100%	55%	100%	155%	100%	156%
	O-O, Peak	100%	77%	100%	0%	100%	0%
	O-O, OP	100%	55%	100%	0%	100%	0%
Parking fee	Inner, Day	167%	159%	100%	100%	99%	90%
	Inner, Hour	179%	152%	100%	100%	77%	54%
Congestion charges (EUR)	Inter, Peak	0	0	30	37	30	39
	Inter, OP	0	0	15	19	17	23
Mode		**Changes in number of trips**					
Car		-8%	-8%	-10%	-12%	-10%	-10%
Public transport		3%	18%	5%	2%	5%	2%
Walk/cycle		2%	-1%	2%	3%	2%	3%
Total transport demand		-2%	-1%	-3%	-4%	-3%	-3%

Table F.2
Welfare results (EUR)

	Parking fee		Congestion charges		Both	
PT opti.?	0	1	0	1	0	1
CS tot	-84 618	-36 847	-111 078	-138 395	-106 075	-125 807
CS time	*9 067*	*8 939*	*11 035*	*11 662*	*10 731*	*10 873*
DWL	*-6 844*	*-6 192*	*-11 941*	*-7 894*	*-12 073*	*-7 813*
WEB	-10 529	-4 585	-13 821	-17 220	-13 198	-15 653
PS, PT	5 939	-15 435	7 883	14 610	7 691	14 033
PS, CC	0	0	109 728	134 254	116 663	152 015
PS, PF1	43 354	34 256	0	0	-6 162	-15 446
PS, PF2	43 354	34 256	0	0	-6 162	-15 446
MCPF	14 788	5 646	35 283	44 659	35 458	45 180
Trucks	395	389	499	536	482	493
EE tot	-172	-200	-339	-370	-335	-361
of CO2	*724*	*791*	*1 249*	*1 369*	*1 217*	*1 297*
NSB	**12 512**	**17 481**	**28 155**	**38 074**	**28 362**	**39 008**

CS = Consumer surplus
DWL = Dead weight loss
WEB = 0.3*CS*Share_commute
PS = Producer surplus
MCPF = Marginal cost of public funds = 0.3*PS
PT = Public transport
CC = Congestion charges
PF = Parking fees
EE = External effects, including CO2
CO2 = Benefits from carbon dioxide reductions
NSB = Net social benefits, including MCPF and wider economic benefits
PF1 = Publicly owned parking
PF2 = Privately owned parking