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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 that have successfully shifted demand from cars 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 examines the introduction of welfare-optimal congestion charges and parking fees in a model calibrated to Uppsala, a small city in Sweden. These effects are modeled with a simple transport demand model for the welfare optimization of parking fees, congestion charges, and public transport provision. The results suggest that welfare-optimal congestion charges in Uppsala are as high as EUR 2.8 in peak hours and EUR 1.4 in off-peak hours. A rough cost–benefit analysis shows that the introduction of congestion charges in Uppsala is welfare improving if the operating costs of congestion charges are proportional to city population size. In the main scenarios, optimal congestion charges and parking fees reduce the number of car trips by 10% and 7%, respectively. The model can be used to assess when it is worthwhile to introduce congestion pricing.

1. Introduction

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[1] city in Sweden. The consequences are evaluated in terms of social welfare, mode shares, congestion, and CO_2 emissions. Welfare optimization will lead to consideration of various uncorrected market failures: congestion, alternative costs of parking space, and crowding in public transport. The paper examines the relative merits of congestion charges and parking fees for increasing welfare.

This paper considers these policies in a setting with current levels of car use and congestion. Assessment of the need for these policies should, however, be considered from the perspective of ongoing trends of urbanization, increased incomes, and increased market shares of electric vehicles, all leading to a potential increase in demand for car use. In addition, these demand increases may be expected to be reinforced by the oncoming introduction of self-driving vehicles (Wadud, 2017). Such increased car use will result in considerable congestion problems, which will reduce the livability of cities unless the trend is counteracted by policy. The post-covid-19 responses adds to the uncertainty about future demand patterns, possibly leading to e.g. more remote work, longer commute distances and reduced public transport demand, compared to pre-covid-19 conditions (which data in the present study is based on). If congestion problems increase, the potential for adopting car use pricing may be large in small cities, where 13% of the OECD population lives (OECD, 2019).

The primary contribution of this paper is to model 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 the effects of parking on congestion in empirical models and small cities. Börjesson and Kristoffersson (2018) advised against introducing congestion charges 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 made to quantify the potential effects of congestion charges in small cities. This study can therefore be used to assess under what circumstances it may be worthwhile to consider congestion charges and make detailed city specific assessment of such policy. The example of a small Swedish city is interesting as a case in this context, since Sweden has already introduced congestion charges in its two largest cities, so there are a lot of high-quality data from these earlier

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

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experiences. There are many small cities (in the OECD sense) in Europe.[2] Some French cities in this group, e.g. Grenoble, have contemplated charges similar to congestion charges. The present study gives a hint about the size of welfare optimal congestion charges in cities with similar size, level of congestion and value of travel time. This study also analyzes the possible need to optimally adapt public transport to complement car-use instruments.

Although Uppsala is 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 already reduced their congestion problems by implementing congestion charges.

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 to these interest groups. Subsidizing public transport is one such alternative to pricing congestion. However, increasing public transport supply without examining the costs and benefits risks leading to an oversupply of public transport. Asplund and Pyddoke (2020) found a substantial oversupply of public transport 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 the BUPOV model to include parking pricing and congestion charges.

BUPOV represents traffic demand and is calibrated to variations between peak and off-peak (OP) times, 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, and with respect to parking fees in the inner zone (in each time period). As for the scope, we attempt to capture the major short-term welfare effects of trips beginning or ending in Uppsala, but only those parts of trips occurring within city boundaries. That is, possible non-internalized external effects arising outside Uppsala (e.g., congestion effects in other urban areas) 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 term, more adaptation may occur due to changes in destination choice, residential and workplace location, private supply of parking spaces, etc.

In this study, the welfare effects of reduced congestion are estimated at about one tenth of the revenues from implementing either optimal parking fees or optimal congestion charges. We use the recommended marginal cost of public funds (MCPF) factor of 1.3 from the official Swedish cost–benefit guidelines (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, knowledge of the investment and operating costs of congestion charging systems and the shadow cost of alternative use of parking facilities is scarce. Second, the higher costs for car drivers after road and parking price reforms are likely to lead to long-term adaptations in terms of changes in the choice of destination, mode, car type, etc. The long-term effects are likely to exceed the short-term effects and are not analyzed here. Third, the 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, i.e., Stockholm and Gothenburg. Gothenburg provides the closest object of comparison, since Gothenburg is smaller than Stockholm and the introduction was later there (in 2013, close to the years for which we have data for Uppsala in BUPOV). Therefore, the price elasticity and technical system cost have 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 2.8 in peak hours and EUR 1.4 in OP hours (converting SEK 10 to EUR 1). A rough cost–benefit analysis shows that if congestion charge operating costs are proportional to city population size (relative to Gothenburg), then the introduction of congestion charges in Uppsala seems 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, the study's findings and limitations are discussed in Section 6.

2. Literature

There has been a long-standing hope that building smarter cities can substantially reduce car use, reducing carbon emissions and making cities more attractive. Predominantly North American studies (e.g., Ewing and Cervero, 2010; Stevens, 2017) have focused on building more compact cities and studying how such development could reduce car use. They found that the "magnitude of that reduction is generally small" (Stevens, 2017, p. 15). However, McIntosh et al. (2014) and Buehler et al. (2017) argued that some European cities have successfully decoupled growth from increased car use, leading to reduced shares of car trips, by implementing combinations of policy instruments. These instruments include parking management measures such as reduction of on-street parking spaces, construction of off-street parking garages, parking time limitations for street parking, and increased hourly parking charges. In this study, we will focus on optimal parking prices and congestion charges to curb congestion and examine the effects on mode shares. Keeping in mind that these policies may ideally only be parts of broader combinations of policies, it is nevertheless important to understand the relative merits of individual policy instruments and the possible synergies between them.

The literature on road pricing in general is extensive, and Tsekeris and Voß (2009) reviewed about 400 papers on the subject. Early contributions were made by Vickrey (1963), who launched the pricing instrument to curb congestion, and Kulash (1974), who later proposed using parking pricing as a means to do so. Button (1995) noted that parking complements road use and asserted that parking policy "has obviously been widely used in many cities as a control over excessive congestion" (p. 43), citing a proposal in Los Angeles as an example.

Several papers have developed models to optimize congestion charges and public transport fares and frequencies for large cities, for example, London and Brussels (Proost and van 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 the model. All these papers

[2] The European mayors list of Europe's 500 largest cities ranked by population City Mayors: The 500 largest European cities (1–100) contains 151 cities from Norilsk with 149,000 inhabitants to Split with 200,000.

[3] From Swedish *Bussutbud-och prissättning—optimeringsverktyg* (bus supply and pricing—optimization tool).

[4] From the National Travel Survey and the national demand model.

[5] The effect of irritation from dense traffic is included for car drivers only, not for other travelers (e.g., cyclists and pedestrians) or, for example, users of restaurants.

have studied large cities with substantial congestion, so the importance of congestion problems in smaller cities is less understood. West and Börjesson (2020) studied the congestion charges in Gothenburg, with only about half the population of Stockholm. Comparing the effects of congestion charges in Stockholm and Gothenburg, the authors noted that 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 in congestion charges in Gothenburg than in Stockholm. West and Börjesson (2020) showed that net social benefits were positive, although redistribution from car users to the government was considerably larger than the net benefit. The welfare effects of this redistribution were found to be regressive. We have not been able to find any relevant studies of the costs for the system for observing cars passing the cordon and for collecting the charges.

The literature on parking pricing is smaller than that on congestion charges, but is growing. Several studies have explored parking prices as a second-best strategy to mitigate congestion and many of these were published in the 1990s. Higgins (1992) evaluated the pros and cons of implementing parking pricing to reduce traffic through parking taxes. Arnott et al. (1991) showed that spatially differentiated parking fees may rival time-differentiated congestion fees. Glazer and Niskanen (1992) noted that increasing the fixed price per parking occasion 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 theoretical focus and examined whether physical restrictions on parking or parking fees would be the best policy instrument to curb congestion, finding that parking fees were superior in this respect. These three studies provide valuable insights although they use highly stylized models.

Calthrop et al. (2000) showed that the pricing of parking and road use need to be simultaneously determined. In their simulation model of a hypothetical city, they also showed that the second-best pricing of all parking spaces produced higher welfare gains than did the use of a single ring cordon scheme, though the gains were marginally lower than those of the combination of a cordon charge and the resource-cost pricing[6] of parking spots. Fosgerau and de Palma (2013) studied optimal parking fees for commuters and their effects on congestion. They focused on the timing of the car trip and hence the arrival at and departure from the parking spot, finding that optimal parking reduced but did not eliminate congestion. Nourinejad and Roorda (2017) theoretically and numerically examined the properties of time-varying parking fees on traffic demand, showing that higher per-hour parking fees lead to more traffic if dwell times are elastic.

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

Optimal parking policy integrated with public transport policy has to our knowledge previously only rarely been estimated. Voith (1998) constructed a general equilibrium model to study parking, transit, and employment in a CBD. He derived conditions under which parking taxes can be levied and used to subsidize transit and increase a CBD's size and land values. Cavadas and Antunes (2018) studied a medium-sized city in Portugal, one motivation for the study being public deficits. The objective function was not to maximize welfare, but to minimize the joint operating deficit of both the transit and 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 constraint that 30% of parking spaces should be vacant 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 to equal the resource cost of off-street parking in optimal quantity. In later studies, Kobus et al. (2013) and Gragera and Albalate (2016) found 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.

In the case city of Uppsala the following studies has been conducted. 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. Berglund and Canella (2015) concluded that large increases in parking fees and introduction of a national kilometer tax would be needed to achieve the goals. Pyddoke et al. (2017) indicated that both parking charges and increasing the population density of the inner zone of Uppsala have substantial potential to shift demand from car to public transport, walking, and cycling. However, none of these studies was based on welfare optimization and they did not estimate the welfare effects of policies.

3. Model overview

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 optimizes welfare, given that she anticipates what the private responses will be. That is, she optimizes welfare via a set of policy variables, given the user equilibrium that will result from such policy changes. Our analysis is based on the assumption of only one social planner, who manages all publicly owned assets, such as streets and a share of the parking facilities. That is, we do not distinguish between various sections and levels of governance, which, in reality, may have partly different objectives. Hence, any potential political economic games between various public actors are beyond the scope of this analysis. We assume that the individuals and private owners of parking facilities react in their self-interest to the actions of the social planner. That is, if the social planner affects the local market for parking, for example, by 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 term possibly by expanding supply. However, while our model of the individual responses is quantitative, our model of the parking firms is on a qualitative, reasoning level only, based on fundamental economic theory. When we refer to welfare optimality, this refers to the optimality that a hypothetical social planner who manages all publicly owned assets to maximize the welfare of citizens and firms, would find optimal.

BUPOV 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 optimal prices 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 traveling around the city to avoid

[6] That is, the price needed to cover building costs, but excluding external effects.

crowding may switch routes and instead go 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 walking/cycling. The choice of travel alternative depends on monetary cost, road congestion, bus crowding, 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 CO_2 emissions. The changes in the public transport authority's financial results are evaluated using an MCPF factor. In optimum, this should correspond both to the marginal welfare costs of raising one additional unit of tax revenue and to the marginal valuation of one additional unit of public funds used for alternative purposes, for example, health care. We also multiply the consumer benefits by a wider economic benefit (WEB) factor, i.e., accounting for better functioning of the labor market from increased accessibility, counteracting the effect of 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 investment plan of transport projects in Sweden (Anderstig et al., 2018), that is, 12% more 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 on the streets and inside the buses. 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.

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 (2020), the total travel demand for each OD pair was assumed to be constant in terms of the 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 a proportion of trips disappeared completely. The mode and timing choices 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.

The congestion charge is introduced for crossing the boundary between the outer and the inner zones of the model (Fig. 1). The parking fee is modeled as a proportional increase in the current fees in the inner zone, including both on-street parking and garages. These hypothetical reforms are modeled 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 fewer environmental externalities. In BUPOV, the dwell time of parking is assumed to be inelastic, a weakness that will lead to overestimation of the effect of per-hour parking fees on reduced traffic. However, this overestimation will be most important for non-commuting trips, i.e., mostly affecting OP traffic when congestion is low. A further model simplification is that the costs associated with walking and cycling are therefore independent of the level of motorized traffic.

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 (2020).

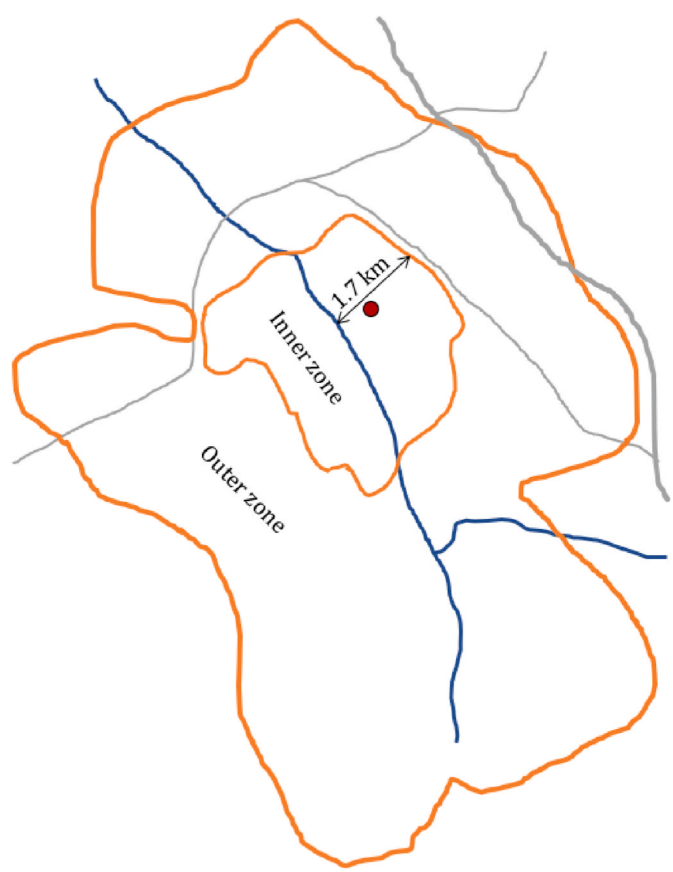

Fig. 1. Stylized map of Uppsala. Orange lines represent the boundaries of each zone. Blue and gray lines represent rivers and major roads, respectively. The red dot represents Uppsala central station. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

[7] Not modeling the direction of trips (i.e., towards and away from the city center) in the morning versus afternoon peak hours is a simplification that may lead to the underestimation of crowding, as we assume that passengers are evenly distributed 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 buses run empty and the passengers experience double the crowding versus the reference model. The welfare gains from optimization seem reasonably robust to this alternative model specification.

[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.

4. Data

Uppsala lies 70 km 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. Fig. 1 shows a stylized map of Uppsala.

The BUPOV model is calibrated using travel data from the National Travel Survey and from the Swedish national passenger demand model, and uses boarding data from the public transport authority. An earlier version of BUPOV (Asplund and Pyddoke, 2020) has been extended by a more resolved and accurate representation of parking fees.

One difference from the National Travel Survey is that BUPOV represents workdays only. Another is that we have made an adjustment to account for trips with origins or destinations outside of Uppsala (see Appendix C: Demand calibration). In BUPOV, 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 5 h per day in total (7:00–9:00 and 15:00–18:00) are 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 from boarding data from 2014 (UL, 2015), the 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 summarizes other important data.

Table 1 reports the estimated mode shares for Uppsala.

BUPOV uses its own generalized cost elasticities, calibrated to match empirical responses from the relevant literature. Public transport elasticities are from a literature review by Balcome (2004), and in the present study car elasticities have been updated to match the responses from the introduction of congestion charges in Gothenburg, according to Börjesson and Kristoffersson (2015).[13] The resulting elasticities in peak and OP hours 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 the rough averages for fuel price elasticities in urban areas in Sweden estimated by Pyddoke and Swärdh (2015), i.e., −0.2 in the short term and −0.5 in the long term. Two observations can be made here. Our short-term elasticities are comparable to those in the literature and the long-term elasticity of demand for car use with respect to driving costs is higher than the short-term elasticities. This implies that the long-term effects of car-restrictive policies may be substantially larger than those calculated here with the BUPOV model.

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 the delay effects of decreased traffic in Uppsala on an aggregate level.

In this study, the number of persons per car has been updated from a national figure of 1.53 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, the volume delay function was recalibrated, resulting in the following volume delay function. The total percent delay per trip compared with free-flow conditions in each zone and time period is:

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

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

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

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

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

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

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

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 Administration (2015), and ASEK 3 (SIKA, 2005).[17] According to these calculations, taxes on car trips in Uppsala in

Table 1
Mode shares and total number of trips in Uppsala.

		RVU[12] 2010	RVU 2015	Present study*
Mode shares	Car	42%	37%	45%
	Bus	12%	13%	14%
	Walking/cycling	44%	47%	41%
	Other	3%	2%	0%
Total number of trips			370,480	357,117

*Refers to workday average peak and OP values, including trips with origins or destinations outside Uppsala.
Source: Travel Survey Uppsala (Uppsala Municipality, 2016).

[9] The use of SAMPERS data, the data aggregation, and the representation of congestion and crowding in public transport were inspired by the HUT model used by Pyddoke et al. (2017).
[10] Our dataset was provided by Urbanet Analys AB.
[11] Public transport demand has been scaled by 1.26 to match boarding data, while car travel, walking, and cycling have been scaled to match RVU 2015 (by about 1.02).
[12] RVU = Resvaneundersökning = Travel habit survey.
[13] In Gothenburg, congestion charges were about EUR 1.5 in peak hours and about EUR 0.8 in OP hours, and the response was a decline in affected car trips by 12.5% in peak and 12% in OP hours. In this study, generalized cost elasticities of car trips in Uppsala have been calibrated to give the same percentage responses to the introduction of the same congestion charges in Gothenburg. In an earlier version of BUPOV, elasticities were instead based on price elasticities from the introduction of congestion charges in Stockholm.
[14] This is a distance-based cost elasticity based on a per-km cost of EUR 0.15 from Börjesson et al. (2017).
[15] The largest change compared with Asplund and Pyddoke (2020) was to increase the number of trips in the outer zone by including trips with origins or destinations outside of Uppsala.
[16] This figure is based on interpretation of Wardman and Ibáñez (2012), the study underlying ASEK 6.
[17] In Samkost (Nilsson and Johansson, 2014), the 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 values from ASEK 3). These adjustments increased the total externality per vehicle-km to EUR 0.038 for cars in the outer zone and to EUR 0.043 for cars in the inner zone, in Uppsala. The total tax (from Samkost) is EUR 0.045 for cars.

Table 2
Internalization rates for emissions and other external effects, excluding congestion costs reported in 2014.

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

Sources: See footnote 15.

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

Type of trip	Peak	OP
Inner zone	4.8	1.7
Interzonal trips[a]	2.4	0.9

[a] The assumption is that half of the interzonal trips originate from residences in the inner zone with a trip purpose in the outer zone, meaning that only half of them incur parking fees in the inner zone. Also, the shadow cost of parking space has been crudely estimated in this study. Asplund and Pyddoke (2020) assumed that the shadow cost of parking was equal to the price. This assumption was largely confirmed in the present analysis (see Appendix E).

2014 was roughly in line with the external effects from those trips, congestion excluded, see Table 2. For bus trips however, the corresponding external effects were only internalized to about 50%. This means that when congestions costs are substantial, the internalization rates in Uppsala will be considerably lower than indicated in Table 2. I. e., existing taxation implies a degree of internalization of total external effects, and when assessing the optimal levels of further policy instruments, it is useful to know this initial degree of internalization. However, one additional implication is that if congestion reducing policies would be introduced, there would not be additional net benefits from reduced emissions etc. from cars, but only from buses, which may seem counterintuitive.

Since car use pricing is the focus in this study, parking fees in BUPOV have been updated with more accurate data on parking fees in Uppsala than the data in Asplund and Pyddoke (2020[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, for example, by employers. We have therefore assumed that all car trips with destinations in the inner city are associated with parking charges payable by the individual car user.

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

5. Results

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

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).

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
Parameter		**Parameter level in optimal scenario**			
Parking fee[a]	Inner, Day	4.8	7.9	4.8	4.8
	Inner, Hour	2.4	4.1	2.4	1.8
Congestion charges (EUR)	Inter, Peak	0	0	2.8	2.8
	Inter, OP	0	0	1.4	1.6
Mode		**Changes in number of trips**			
Car		160,778	−7%	−10%	−9%
Public transport		50,920	+3%	+4%	+4%
Walking/cycling		145,418	+2%	+2%	+2%
Total		357,117	−2%	−3%	−3%

[a] Per one-way trip in the inner zone. For interzonal trips, the cost per trip is about half, since half of them are assumed to originate from residences in the inner zone and to have trip purposes outside the inner zone.

Optimal parking fees imply a substantial increase from current levels. The optimal congestion charges are also high, and within the range of current Stockholm levels (EUR 1.1–3.5). 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 (see Börjesson and Kristoffersson, 2015), even though Gothenburg is about four times larger than Uppsala.

Table 6 presents the marginal cost of an extra vehicle passing through the city center in four cases: the baseline scenario, with no policy intervention, and a scenario with optimal congestion charges, in peak versus OP hours respectively. These costs can be broken down into various sources of costs, with the two most important being time costs for travelers and extra operating costs for the public transport producer.

[18] The previous version of BUPOV only crudely estimated parking fees, making no distinction between interzonal trips and trips in the inner zone only. These old estimates were EUR 6.0 per one-way trip in peak hours and EUR 3.0 per one-way trip in OP hours, that is, substantially higher than the new estimates.

[19] Car use is somewhat less common among low-income earners, but somewhat more common among the middle-low group. If the groups "low" and "middle low" are merged, these make up 73% of the total responses and 70% of the responses of car users.

[20] Asplund and Pyddoke (2020) found optimal public transport supply to be robust. In this study, simulations indicate that 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.

[21] In Uppsala, the reduction is 26% in peak and 23% in OP hours. Note that the difference from Table 5 is that "number of trips" in Table 5 refers to all trips in Uppsala, not only across the cordon.

Table 6
Marginal social cost of an extra vehicle passing through the city center in four cases.

	Scenario	
Time period	Baseline	Optimal CC
Peak	3.1	2.2
OP	1.0	0.7

For example, of the cost of EUR 3.1 for an extra vehicle in peak hours in the baseline scenario, EUR 1.8 is related to time and 0.8 to extra costs for the public transport producer.

Table 7 presents the welfare results corresponding to Table 5, excluding the operating costs of a congestion charging system. A central result is that implementing jointly optimized policies does little to increase the net welfare compared with implementing optimal congestion charges only. This implies that the optimization of parking fees and congestion charges are substitute policies, largely confirming the observation of Calthrop et al. (2000) that parking and road-use pricing 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 the number of car trips is similar across policies, and in all three scenarios the decreased delay due to decreased congestion in the inner zone is about the same. In peak hours, the delay (versus free-flow travel time) decreases from 89% in the baseline to 63–66%, while in OP hours, the delay decreases from 39% in the baseline to 29–36%.

The most important components of the net welfare calculations are: time savings of travelers and burdens of switching to a less preferred travel mode; increased revenues to the regional public transport agency; benefits due to increased revenues when considering the marginal cost of public funds; and wider economic benefits (costs) from decreasing (increasing) the costs of trips, while other effects such as environmental effects are small. Observe that the congestion benefits are about a tenth of the total congestion tax revenues, while the net value 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 somewhat less than a fourth of the total revenue. Comparing the numbers for the parking fee, the magnitude of the congestion benefits is similar, but the benefits from using the increased public revenue are less than the congestion charges.

Table 8 presents a rough cost–benefit analysis of the introduction of congestion charges. The introduction of congestion charges is compared with two policies: the baseline (i.e., doing nothing) and to optimizing parking fees. The results indicate that the 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 3–180 years, depending on whether the investment costs also follow city size and whether the optimization of parking fees is a viable option.

Table 7
Welfare results, excluding operating costs of the congestion charging (CC) technical system.

Welfare effect (EUR/weekday)	Parking fee	Congestion charges	Both
Consumer surplus	−80,992	−107,372	−95,386
Of which congestion benefits	*+ 8649*	*+ 10,439*	*+ 10,007*
Of which dead weight loss	*−7172*	*−13,316*	*−15,094*
WEB (0.30*CS_commute)	−10,077	−13,360	−11,868
Producer surplus, public transport	+5627	+7372	+2287
Congestion tax revenues	0	+104,142	+126,831
Producer surplus, public parking	+41,185	0	−14,287
Producer surplus, private parking	+41,185	0	−14,287
MCPF (0.30*PS_public)	+14,044	+33,454	+34,449
Congestion benefits for trucks	+374	+467	+446
Net of other external effects	−160	−314	−335
Of which CO_2 benefits	*+ 676*	*+ 1155*	*+ 1183*
Net social benefits	**+ 11,185**	**+ 24,389**	**+ 27,851**

Table 8
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	+24,389	+13,204
Welfare gain per year[a]	+6,097,286	+3,301,068
Net welfare gain per year, assuming Gothenburg operating costs = 11,700,000[b]	−5,602,714	−8,398,932
Net welfare gain per year, assuming Gothenburg operating costs divided by 3.7[c]	+2,963,110	+166,893
Payback time in years, assuming Gothenburg investment cost = 30,000,000 EUR[b]	+10	+180
Payback time in years, assuming Gothenburg investment cost divided by 3.7[c]	+3	+48

[a] Multiplying the daily gain by 250.
[b] Source: Göteborgs stad (2015).
[c] 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 the cities' inhabitants in 2018.

In Sweden there is a political goal to decrease domestic CO_2 emissions by 70% by 2030. Table 9 explores various policies for approaching this goal in Uppsala by decreasing the number of car trips in the city by 10%. The column "PT [public transport] supply" indicates that trying to achieve this by changing only public transport supply is both extremely costly and counterproductive, since it entails increasing public transport supply to a level so high that it becomes a serious environmental problem. The second column shows the results of the policy to provide public transport free of charge, which achieves a 5% reduction in car trips. In the third column, both frequencies and fares are adjusted to achieve a 10% reduction in 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 CO_2 reductions. Welfare-optimal congestion charges also give higher tax revenues than do welfare-optimal parking charges. The results suggest that if politicians truly want to reduce CO_2 emissions by reducing the number of car trips, it is necessary to increase the pricing of car trips.

Table 10 presents sensitivity analyses of different levels of: share of public ownership of parking, marginal cost of public funds, and valuation of CO_2 emissions.

The first column presents the effects 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 11,000 per workday to EUR 6000, while car trips are reduced by 5% instead of 7%. This analysis is motivated by the uncertainty concerning the market share of private parking. The second column presents the effects of a lower MCPF, 1 instead of 1.3, on optimal congestion charges. Lower MCPF reduces the burden and value of tax revenue. In this case, the optimal congestion charges are reduced from EUR 2.8 to EUR 1.9 in peak hours and from EUR 1.4 to EUR 0.8 in OP hours (i.e. much closer to the marginal costs in Table 6), and the welfare gain is substantially reduced from EUR 24,000 to only EUR 7000. This analysis is motivated by the uncertainty concerning the true marginal cost of public funds and the distributional effects of increasing revenues in these ways. The third column presents the effects of increasing the

[22] Own price elasticities for cars in the baseline model have been calibrated to match responses from the 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.

Table 9
Alternative policies to achieve a reduction in car trips by 10%.

Policy scenario		PT[a] supply	PT[a] price[b]	PT[a] price and supply	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%	178%	100%
	Inner, hour	100%	100%	100%	210%	100%
Congestion charges (EUR)	Inter, peak	0	0	0	0	2.9
	Inter, OP	0	0	0	0	1.5
Welfare effects (EUR)		**−2,297,299**	**+ 3980**	**−557,328**	**+ 9817**	**+ 24,336**
Congestion benefits (EUR)		*−68,328*	*+ 3681*	*−13,698*	*+ 10,791*	*+ 10,783*
CO_2 benefits (EUR)		*−7255*	*+ 580*	*−1499*	*+ 950*	*+ 1214*
Consumer surplus (EUR)		−47,118	+68,044	+99,789	−107,003	−111,754

[a] PT: public transport.
[b] Using only the PT price instrument is not enough to achieve a 10% reduction in car trips, since free PT achieves only 5%.

Table 10
Sensitivity analysis of key parameters.

Optimization variables		Sensitivity parameter			
		Share public parking[a]	MCPF[b]	CO_2[c]	Elasticity[d]
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	7.2	4.8	4.8	4.8
	Inner, hour	3.5	2.4	2.4	2.4
Congestion charges (EUR)	Inter, peak	0	1.9	3.1	3.5
	Inter, OP	0	0.8	1.6	1.4
Mode		**Changes in number of trips**			
Car		−5%	−6%	−11%	−10%
Public transport		+2%	+3%	+5%	+5%
Walking/cycling		+1%	+1%	+3%	+2%
Total		−2%	−2%	−3%	−3%
Welfare effects (EUR)		**+ 5715**	**+ 6777**	**+ 30,757**	**+ 25,728**
Congestion benefits (EUR)		+6761	+7168	+11,401	+10,532
Consumer surplus (EUR		−59,539	−68,375	−119,644	−118,964

[a] Decreasing the assumed share in baseline from 0.5 to 0.25.
[b] Decreasing the MCPF factor from 1.3 to 1.
[c] Increasing the CO_2 valuation from EUR 0.114 to 0.7 per kg of CO_2 relating to ASEK 6 and ASEK 7, respectively.
[d] Using own-price elasticities from Stockholm instead of Gothenburg.[22].

valuation of CO_2 emissions from EUR 0.114 to EUR 0.7. This increases the congestion charge in peak hours from EUR 2.8 to EUR 3.1 and in OP hours from EUR 1.4 to EUR 1.6. This analysis is motivated by the increase between version 6 and 7 in the Swedish national guidelines on the welfare economics of transport infrastructure investments (Swedish Transport Administration, 2016a and 2021). The last column indicates that the welfare gain is not very sensitive to the elasticity of demand.

6. Discussion and conclusion

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 in terms of 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, provided that the investment and operating costs are sufficiently low. A rough cost–benefit analysis shows that if congestion charge operating costs are proportional to city population size (relative to Gothenburg), then the introduction of congestion charges in Uppsala seems to be welfare improving. These crude estimates indicate that it would be worthwhile to conduct a detailed analysis of the introduction of congestion charges in Uppsala, and of the related operational costs. Furthermore, the optimal congestion charges are as high as EUR 2.8 in peak and EUR 1.4 in OP hours. The inference is that there are three important societal gains from pricing car traffic: increasing public tax revenues, reducing congestion, and increasing the revenues from public transportation, whose ridership is currently low. Although these effects are counteracted by the inconvenience of changing mode and the negative labor market effects of increased transportation costs, the positive effects are large enough to justify substantial car traffic pricing in Uppsala.

The study supports the notion that congestion charges and increased parking fees are largely substitutes for each other. If implementing congestion charges, there is little benefit from also implementing increased parking fees. An advantage of parking fees is that, unlike congestion charges, they do not require any further system costs. A disadvantage of parking fees is that if this policy is implemented, the share of public ownership of parking lots will likely decrease over time, meaning that this strategy will only be effective for a certain period, after which congestion charges will be needed. Although a parking tax is often mentioned in the theoretical literature as a sound policy tool and has been applied by some US cities, it is rarely applied in Europe

(Mingardo et al., 2015).

Optimal congestion charges decrease the number of car trips by about 10% in the short term, and probably by more in the longer term, while increasing the number of public transport trips by about 4% and walking and cycling trips by 2%, while the effects from optimal parking fees are somewhat lower. Ongoing trends that are likely to lead to increased demand for car use may increase the value of such policy instruments. Returning to the discussion of the relative merits of single policy instruments or policy packages in influencing car dependence, we note the following. Our simulation (Table 9) suggests that the total welfare costs of increasing the frequency of public transport are much larger than those of implementing car pricing.[23]

For both optimal congestion charges and optimal parking fees, the increased revenues are much larger than the 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 is therefore fiscal, in that they provide a means to tax citizens without distorting incentives as much as marginally increasing labor taxes would. This relates to a larger discussion of the "double dividend" from taxing external effects. For example, Jacobs and de Mooij (2015) indicated that in a completely optimized tax system (including distributional goals), the MCPF factor would equal unity. Correct consideration of the total general equilibrium effects of taxation is complicated. We accordingly limited our analysis to the partial equilibrium effects, using the standard marginal cost of public funds approach to value the increase in public revenue and using a WEB factor to account for the effect of the increased cost of commuting on the labor market. However, our finding of a fiscal net gain from introducing congestion charges is in line with the conclusions of Parry and Bento (2001), who concluded from a simple general equilibrium model that congestion charges theoretically imply a double dividend.

The redistribution of welfare from car users to the public sector resulting from payments of charges and fees is large, however, and the distributional effects will largely depend on how the additional revenues are used. In Stockholm (Eliasson, 2016) and Gothenburg (West and Börjesson, 2020), regressive distributional effects were found with the introduction of congestion charges. If public parking owners increase their prices, this will create an opportunity for private parking owners to follow suit and reap oligopolistic rents. This implies a redistribution from travelers to private parking owners that may be regressive if parking facility ownership is concentrated in the wealthiest decile.

The analysis presented here is subject to some important qualifications. 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 uses at low cost (e.g., bus or bike lanes). A second qualification is the uncertainty about the share of car trips associated with the 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 would likely reduce the effects of higher parking fees. A third qualification worth mentioning is that we do not analyze the health benefits of more exercise if there is more walking and cycling and if the city becomes more attractive with less car traffic. The availability of such cost–benefit values has been discussed by van Wee and Börjesson (2015), who argued that reliable values were unavailable and that values for health effects did not take full account of the fact that only some health effects are external. Attempts to find more recent estimates of values of average marginal effects on health gave little. Two recent papers modelling benefits from cycling cite earlier sources for this discussion (Liu et al., 2021; Standen et al., 2019). Given the lack of good data regarding these three qualifications, caution is called for. Nevertheless, modestly adjusting parking policy would seem to be robust policy advice. In Uppsala the official policy states that the city aims for a maximum of 85% occupancy of street parking. This policy appears to have been adopted from Shoup (cited by Inci, 2015, p. 58). A robust strategy would therefore be to consider increasing the parking fees in locations where occupancy is higher than 85%, and to consider converting parking spaces to other valuable uses, such as improved cycling infrastructure, in locations where occupancy is considerably below 85%. However, in locations where occupancy is low and no other use is feasible, it may be welfare improving to reduce the parking fees.

The following paths for further research are noted. Better estimates of the costs and ownership of parking would clearly improve the above calculations. More marginal benefits valuation studies on health effects from walking and cycling, including the degree of internalization is also warranted. Furthermore, by using long-term elasticities, certain long-term adaptations could be forecasted.

Finally, the generality of results may be commented. The present study gives a hint about the size of welfare optimal congestion charges (or parking fees) in cities with similar size, level of congestion and valuation of travel time. However, the optimal level of a specific congestion charge needs to be assessed separately for each case. The method described in the present study may prove useful when making such assessment also in other small cities. Other important results include that optimization of parking fees and congestion charges are close substitute policies, while increasing the public transport supply is a poor substitute policy for reducing congestion. The first of these two results is in line with the more theoretical results from Calthrop et al. (2000) and may be a general result. To our knowledge, this is the first study to demonstrate this phenomenon for a real city and it would be interesting to see if it would hold also in other cities. The second result however, that public transport supply increases is a poor substitute policy, crucially depends on the initial level of public transport supply and is hence not likely to hold in general.

CRediT authorship contribution statement

Disa Asplund: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Roger Pyddoke:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing.

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

Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tranpol.2021.09.008.

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* is walking time to reach bus stops, and *ch* is time to change 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 shifts 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 follows:

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

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

Calculating the consumer surplus with simultaneous cost changes for multiple goods (i.e., travel alternatives) is not straightforward. The correct way of doing this is to assume an arbitrary sequence of cost changes, and then shift the demand curve for each good after each change, and after each cost change apply the rule of one-half to own-price changes only. In BUPOV, this is implemented as follows 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 calculating the CS for the other travel alternatives. For example, the rule of one-half is next applied to OP car trips, using the updated "baseline" demand, then after that the baseline demands for the bus alternatives are updated, and so on.

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:

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

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

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

where $D_{\widetilde{OD,m,\ TP,\ i^*}}$ 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.

The total welfare effect of a given policy change is:

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

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 (i.e., public transport, parking, and congestion charge revenues), ΔPR_i is the total net benefit of changes in parking revenues from privately owned parking lots, ΔCT_i is congestion benefits for trucks, and ΔE_i is 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 ($\psi \in \varnothing$ defines the welfare optimum) and i^* denotes the user equilibrium.[26]

APPENDIX B. DATA

Table B1 summarizes the SAMPERS data used.

Table B1
SAMPERS data used.

OD pair	Walking time to/from 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 (persons per car)	1.2
	Share of commuting trips of car trips in Uppsala[27]	41.5%
Reported 2010 statistics for Uppsala	Bus fare	EUR 1.12
SKL (2014)	Mean point occupancy per bus in the baseline	11.1
ASEK 6 (Swedish Transport Administration, 2021; regional trips 2014)	Marginal cost of public funds (factor)	1.3
	VoT for car on empty street[28]	EUR 9.30/h
	Increased VoT for car, doubled travel time[29]	+1/3
	VoT for trucks[30]	EUR 31.2
	VoT for bus, empty vehicle	EUR 3.70
	Yearly capital cost per car (assuming average value of cars is half the price of a new one)	EUR 1242
Combination of Trafikanalys (2016) and Swedish Transport Administration (2016b)	Proportion trucks (of cars)	2.6%
Börjesson et al. (2017)	Per-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

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. Public transport travelers who come from outside the analyzed zones 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

[26] 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*.

[27] Taken as the mean of two estimation methods based on Table E1 in Appendix E. The first method is simply to assume that each trip to work generates a return trip on a one-to-one basis, i.e., the share of commuting trips is 46.6%. The other method is to exclude trips back to home and take the commuting trips as the share of trips to work in the new sample, i.e., 36.3%.

[28] Based on the shares of commuting trips, business trips, and other trips in Uppsala in 2015 (RVU, 2015).

[29] Estimated in this study to match ASEK recommendations, based on visual interpretation of a figure in the underlying study (i.e., Wardman and Ibáñez, 2012).

[30] Based on the crude assumption that the VoT of trucks is the same as for business trips.

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 situation changes. Although the elasticities probably differ somewhat from those of other travelers (especially for the car option), because these trips are relatively few, this assumption is unlikely 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. 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 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.

APPENDIX D. VOLUME DELAY FUNCTION CALIBRATION

Calibration of the volume delay function is done as follows. We used data for mean delays in Uppsala for 2015 from Tomtom (2017). However, Tomtom does not provide figures for the OP hours, only for the peak hours 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 (km^2)	Vehicle_equivalent_km/km^2/h, $Q^v_{z,\ TP}$	
		Peak	OP
Inner	12	1088	722
Outer	86	493	324

Table D.2 presents 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/km^2/h. Since the Tomtom data are not presented for different zones, this is not straightforward. We have the following equation system:

For each time period and zone.

$\delta_{z,\ TP} = \mathrm{VDF}(Q^v_{z,\ TP})$

For each time period:

$\delta_{TP} = \mathrm{Share\_inner} \cdot \delta_{inner,\ TP} + (1 - \mathrm{Share\_inner}) \cdot \delta_{outer,\ TP}$

This equation system was solved manually (by iteration) by assuming a quadratic form of the VDF, with the linear argument and intercept equal to zero.[31] The resulting VDF is:

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

[31] In an earlier version of Asplund and Pyddoke (2020), the linear argument was shown to contribute very little to total delay.

APPENDIX E. PARKING

Price data and calibration.

Table E1 presents calculations of the number of parking hours per trip.

Table E1

Calculation of number of 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, Appendix 1, Table 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	

In 2019, an extensive survey of the market prices of parking at various locations in the inner zone of Uppsala was performed in which all prices available online were compiled. There was also information about the number of parking spaces at each location, and this information was utilized to weight the average parking price in each zone. There were three types of fees: per hour, per day, and per month. For peak and OP trips, respectively, for each location the cheapest available price was chosen based on the following assumptions. It was assumed that only hourly prices were relevant for the OP trips, since these are much cheaper when parking for only 1.7 h. For peak trips, it was assumed that 20 identical trips per car per month were made, implying that the monthly fee, when available, was often the cheapest price. 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 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, analyzing these issues is rather demanding, 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:

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

The operating cost includes the quantity-dependent costs of the ticketing system and enforcement, for example, patrolling and supervision. The opportunity cost of space here refers to the potential rent or use value if the land were used for purposes other than parking. The operating cost is comparatively easy to estimate, while the location-specific rent is harder to estimate. The rent for office space could serve as an upper bound for the 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 the supply/pricing equilibrium for a specific product (a stationary version of eq. (7.1) in Hanley et al., 2007):

$$\frac{v}{p} = r - \gamma, \tag{E.2}$$

where v is the 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 is the yearly (percent) 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 spaces, 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 space outside the welfare optimum is then:

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

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

The current official real discount rate for infrastructure investments in Sweden is 3.5% per year. The same discount rate was estimated by Asplund (2018) to be 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 increased by 5.67% per year and consumer prices by 2.95% per year (Statistics Sweden, 2019b) between 1981 and 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 is that γ and r are not significantly different, so (E.3) can be simplified by approximating the last term to 0:

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

The opportunity cost of space has been estimated by compiling a small dataset of rents (exclusive of heating and hot water costs) for commercial buildings in the inner zone of Uppsala, from advertising on 12–13 March 2019 (Objektvision, 2019; see Table E2). The conversion cost has been estimated[32] to be EUR 282 per parking space per month based on 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 (m^2)	Monthly rent	No. of parking spaces*">*	Monthly rent per spaces	Monthly shadow rent**">**
S:t Johannesgatan 2	58	895	2.3	454	171
Eldkvarnsgatan 5	90	1350	3.6	441	158
Skyttelgatan 15	42	630	1.7	441	158
Vattholmavägen 10	131	1965	5.2	441	158
Åkaregatan 5	315	3300	12.6	308	25

* Assuming 25 m^2 per parking space.
** Subtracting cost of conversion from parking building to commercial use of EUR 282.

The mean value of the monthly shadow rent in Table E2 is EUR 134. Adding the operating cost of EUR 30 per month from Jernberg and Örnfeldt (2009) means that the total shadow cost of parking is about EUR 164 per month 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 EUR 238.[33] Considering that Q-park has considerable vacancies in their garages, a mean monthly revenue of about EUR 160 per parking space does not seem unreasonable. For simplicity, it has therefore been assumed that $v^* \approx 0$. It should be noted that the public sector manages only one parking garage in the inner zone of Uppsala, but a lot of on-street parking. The public sector owns further parking lots, though these are 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 high conversion cost between parking and other commercial use is that private supply is somewhat inflexible in the short term. $v^* \approx 0$ 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 if parking revenues decrease as a consequence of public intervention, it may be profitable to convert parking facilities to other use. However, the opposite does not hold in the short term. Parking prices must probably increase several fold to motivate conversion from other commercial use to parking facilities in the short term. An implication of this is that owners of parking lots possess some market power that may be utilized to set prices higher than the marginal cost of parking in the short term. Our short-term model of private parking owners is that supply is fixed, and that they set prices equal to those set by the public owner.

However, in the long term, higher prices may stop possible conversion of private parking facilities to other use, meaning that in the long term, 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 term this will imply large monetary transfers from car travelers not only to 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 in the wealthy end of the income distribution than is car use in Uppsala, this would have regressive consequences.

APPENDIX F. RESULTS

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

Table F.1
Policy scenarios (percent compared with 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%	80%	100%	31%	100%	22%
	I-I, OP	100%	49%	100%	27%	100%	12%
	I-O, Peak	100%	80%	100%	152%	100%	152%
	I-O, OP	100%	54%	100%	106%	100%	106%
	O-O, Peak	100%	80%	100%	17%	100%	17%
	O-O, OP	100%	54%	100%	6%	100%	6%
Parking fee	Inner, day	164%	159%	100%	100%	100%	92%
	Inner, hour	172%	152%	100%	100%	77%	56%
Congestion charges (EUR)	Inter, peak	0	0	28	31	28	32
	Inter, OP	0	0	14	15	16	18
Mode		**Changes in number of trips**					
Car		−7%	−8%	−10%	−11%	−9%	−9%
Public transport		3%	16%	4%	10%	4%	10%
Walking/cycling		2%	0%	2%	1%	2%	1%
Total transport demand		−2%	−1%	−3%	−3%	−3%	−2%

[32] The total building cost in Linköping, a similar city, was EUR 1532 per m^2 in 2009. Using a discount rate of 5.1% from Asplund (2018), 25 m^2 per parking space, and a 40-year calculation period, this translates to a shadow cost of EUR 282 per parking space per month.
[33] The mean of the cheapest monthly fee at Q-park eight locations in the inner zone of Uppsala (https://www.q-park.se/sv-se/?l=Uppsala C, Uppsala, Sverige).

Table F.2
Welfare results (EUR); here the results include public transport price optimization in columns indicated by 1 in row one.

	Parking fee		Congestion charges		Both	
PT optimization?	0	1	0	1	0	1
CS tot	−80,992	−45,052	−107,372	−108,399	−102,640	−95,386
CS time	*8649*	*8736*	*10,439*	*10,694*	*10,153*	*10,007*
DWL	*−7172*	*−8548*	*−13,316*	*−14,683*	*−13,446*	*−15,094*
WEB	−10,077	−5606	−13,360	−13,487	−12,771	−11,868
PS, PT	5627	−11,541	7372	4117	7198	2287
PS, CC	0	0	104,142	110,405	110,855	126,831
PS, PF1	41,185	34,387	0	0	−5912	−14,287
PS, PF2	41,185	34,387	0	0	−5912	−14,287
MCPF	14,044	6854	33,454	34,356	33,642	34,449
Trucks	374	379	467	483	452	446
EE tot	−160	−200	−314	−343	−310	−335
of CO_2	*676*	*781*	*1155*	*1246*	*1125*	*1183*
NSB	**11,185**	**13,607**	**24,389**	**27,131**	**24,603**	**27,851**

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 CO_2.
CO_2 = Benefits from carbon dioxide reductions.
NSB = Net social benefits, including MCPF and wider economic benefits.
PF1 = Publicly owned parking.
PF2 = Privately owned parking.

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