Towards zero emissions from Swedish urban transport

Report from the project
'To buy or not to buy'

Efthymia Kyriakopoulou,
Tingmingke Lu, Rob Hart

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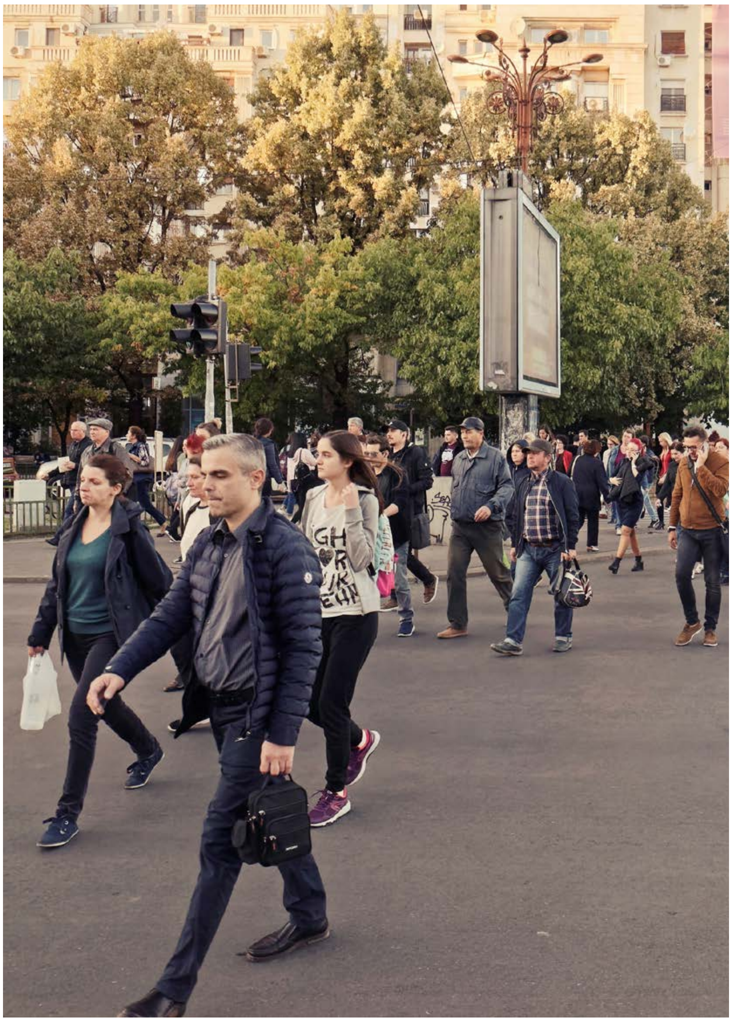

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SWEDISH ENVIRONMENTAL
PROTECTION AGENCY

Order
Phone: 08-505 933 40
E-mail: natur@cm.se
Address: Arkitektkopia AB, Box 110 93, 161 11 Bromma, Sweden
Internet: www.naturvardsverket.se/publikationer

The Swedish Environmental Protection Agency
Phone: 010-698 10 00
E-mail: registrator@naturvardsverket.se
Address: Naturvårdsverket, SE-106 48 Stockholm, Sweden
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Preface

This report titled "*Towards zero emissions from Swedish urban transport*" presents the results of the research project 'To buy or not to buy' which is one of six funded projects in the 2017 call: Sustainable and Efficient Transport in Society. The research results aim to increase knowledge of how the planning of the transport system can contribute to achieving climate and environmental goals.

The project has been funded with the Swedish Environmental Protection Agency's environmental research grant to support the Swedish Environmental Protection Agency's and the Swedish Agency for Marine and Water Management's knowledge needs.

The authors of this report are Efthymia Kyriakopoulou, Tingmingke Lu, and Rob Hart at the Swedish University of Agricultural Sciences.

The authors are responsible for the content of the report.

Stockholm, July 2021

Maria Ohlman
Head of the Sustainability Department

Förord

Denna rapport med titeln: ”*Towards zero emissions from Swedish urban transport*” presenterar resultaten av forskningsprojektet ‘To buy or not to buy’ som är ett av sex beviljade projekt inom utlysningen Hållbar och effektiv transport i samhället från 2017. Forskningsresultaten syftar till att öka kunskapen om hur planeringen av transportsystemet kan bidra till att uppnå klimat- och miljömålen.

Projektet har finansierats med medel från Naturvårdsverkets miljöforskningsanslag till stöd för Naturvårdsverkets och Havs- och vattenmyndighetens kunskapsbehov.

Denna rapport är författad av Efthymia Kyriakopoulou, Tingmingke Lu, och Rob Hart på Sveriges Landsbruksuniversitet.

Författarna ansvarar för rapportens innehåll.

Stockholm, juli 2021

Maria Ohlman
Chef för Hållbarhetsavdelningen

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Summary

In this report we analyse how urban transport policies can help Sweden move towards its environmental goals – including a 70 percent reduction in domestic transport emissions from 2010 to 2030 – at the same time as it meets the overall goal of ensuring a socio-economically efficient and sustainable transport system for citizens and businesses throughout the country. Our contribution is that we combine theory from urban economics and economic geography with welfare economic analysis and an econometric study of the outcome of a specific policy. We begin by examining trends in urbanization and transport in Sweden, with a particular focus on the environmental damages associated with transport choices. We go on to discuss the theory of urban structure, especially its relevance to transport policy and pollution. Next we discuss transport policy and the environment in the light of transport trends and the theory of urban structure, and present a detailed study of the effects of the Gothenburg congestion charge. Finally we build on the data and the theory to analyse potential routes towards zero emissions from Swedish urban transport, both in the medium run (up to 2030) and in the very long term.

Our analysis of urban development, transport and pollution shows that the road to zero transport emissions will be long, given the slow turnover of the car fleet and the fact that even in 2020 only around 10 percent of new cars were electric vehicles (EVs). In the absence of drastic measures to speed the retirement of fossil-powered vehicles, policies over the next 20 years will need to take account of a car fleet consisting of a mixture of fossil-powered and electric vehicles. Furthermore, while urban dwellers account for an increasingly large majority of emissions, policies must also account for the interests of rural people. This implies that policies are needed that explicitly target urban drivers, because the marginal damages of local emissions (such as NOx, particulates, and noise) are significantly higher in the urban context. This conclusion is further strengthened by the presence of traffic congestion in urban areas. Furthermore, urban workers have more options – as shown by the large and widening gap between car ownership per person in rural and urban areas, where rural people own more cars despite lower incomes – and thus are likely to react more strongly to policy.

In order to understand urban transport decisions, and what policies are required to move towards a socio-economically efficient and sustainable transport system, we must understand the urbanization process itself. The formation of large, centralized cities is driven by the benefits to firms of being close to one another, but braked by the cost to households of transport to the centre, as well as the polluting effects of buses and private cars. The upshot is that cheaper and cleaner forms of transport encourage the growth of large, monocentric cities, i.e. cities in which firms are concentrated in the centre and households in the surrounding area. This favours firm productivity (as firms benefit from positive spillovers when they are located close to one another) and hence should be encouraged by planning policy. Furthermore, policies are needed to encourage clean and efficient transportation, and to deal with transport congestion.

The historical direction of Swedish tax policy with respect to private transport can be summed up as follows: you are welcome to own a fossil-powered car, but please don't use it. Fuel taxes are high whereas the annual road tax is modest, and counterbalanced for urban drivers by subsidized parking. More recently, policy has moved in the direction indicated by our theoretical analysis: a range of policies have been introduced to encourage purchase of low-emission cars, small steps have been taken towards raising the cost of parking towards market rates, and congestion charges have been introduced in Stockholm and Gothenburg. In order to learn more about how urban residents respond to policy changes, we study the effect of the Gothenburg congestion charge. We study household car ownership and driving decisions over time, comparing households in Gothenburg with those in Stockholm and Malmö during the period within which the Gothenburg congestion charge was introduced, finding that the charge led to a fall in car ownership by 0.4 percent, and a fall in the mileage of the car-owning households by 1.6 percent. A back-of-an-envelope calculation indicates that these results translate into very low elasticities: if the annual cost of owning and running a car increases by 1 percent, the rate of car ownership declines by around 0.07 percent, while if the marginal cost of running a car increases by 1 percent, driving distance decreases by around 0.15 percent.

The key to achieving the 2030 climate target for the transport sector is at least as much about getting fossil cars off the road as it is about getting EVs onto the road. Given the much lower car ownership in cities than in rural areas, an obvious question is how we can go further in this direction. Of course it would help if urban car owners had to pay the true costs of parking their vehicles, and if fuel taxation were to a greater extent complemented by urban congestion charges (or other even more precisely targeted charges). However, the low sensitivity of urban Gothenburg's car owners to the congestion charge suggests that the key reason for lower car ownership in cities is not higher costs but lower perceived benefits. It seems that the added value to the household of owning a car, and especially a second car, compared to the alternative – using other forms of transport, perhaps combined with renting – is lower in cities. If so, the key to pushing down car ownership should be to further increase the speed and convenience of alternative modes of transport relative to private cars, which would imply that we need a package of measures including higher priority for public transport and cycling, and lower priority for private cars. Since public transport and cycling can deliver more people to city centres more cheaply and cleanly than cars, this would also encourage the further development of monocentric cities, leading to more efficient labour markets and more productive firms. More research is needed on the optimal make-up of such a policy package.

Sammanfattning

I denna rapport analyserar vi hur transportstyrmedel riktade mot tätortsområden kan hjälpa Sverige att nå sina miljömål, inklusive en minskning av inhemska transportutsläpp med 70 procent från 2010 till 2030, samtidigt som det övergripande målet att säkerställa en samhällsekonomiskt effektiv och hållbart transportsystem för medborgare och företag över hela landet nås. Vårt bidrag är att vi kombinerar teori från forskningsfältet 'urban economics' och ekonomisk geografi med välfärdsekonomisk analys och en ekonometrisk studie av resultatet av specifika styrmedel. Vi börjar med att undersöka trender inom urbanisering och transport i Sverige, med särskilt fokus på miljöskadorna i samband med transportval. Vi fortsätter med att diskutera teorin om stadsstruktur, särskilt dess relevans för transportpolitik och föroreningar. Därefter diskuterar vi transportpolitiken och miljön mot bakgrund av transporttrender och teorin om stadsstruktur och presenterar en detaljerad studie av effekterna av trängselavgiften i Göteborg. Slutligen bygger vi på data och teorin för att analysera potentiella vägar mot nollutsläpp från svensk stadstransport, både på medellång sikt (fram till 2030) och på mycket lång sikt.

Vår analys av stadsutveckling, transport och föroreningar visar att vägen till noll transportutsläpp kommer att bli lång, med tanke på bilflottans långsamma omsättning och det faktum att endast cirka 10 procent av nya bilar år 2020 var elfordon. I avsaknad av drastiska åtgärder för att påskynda skrotning av fossilfordon måste politiken under de närmaste 20 åren ta hänsyn till en bilpark som består av en blandning av fossildrivna och elektriska fordon. Medan stadsborna står för en allt större majoritet av utsläppen, måste politiken också ta hänsyn till landsbygdens intressen. Detta innebär att det behövs politik som uttryckligen riktar sig till stadsförare, eftersom de marginella skadorna på lokala utsläpp (som NOx, partiklar och buller) är betydligt högre i stadsmiljö. Denna slutsats förstärks ytterligare av förekomsten av trängsel i stadstrafiken. Dessutom har stadsbor fler alternativ – vilket framgår av det stora och ökande glappet mellan bilägande per person på landsbygden och i stadsområden, där landsbygdens människor äger fler bilar trots lägre inkomster – och därmed sannolikt kommer att reagera starkare på politiken.

För att förstå hushållens beslut angående transport, och därmed vilken politik som krävs för att gå mot ett socioekonomiskt effektivt och hållbart transportsystem, måste vi förstå själva urbaniseringsprocessen. Bildandet av stora, centraliserade städer drivs av fördelarna för företagen att vara nära varandra, men bromsas av kostnaden för hushållens transport till centrum, liksom de förorenande effekterna av bussar och privatbilar. Resultatet är att billigare och renare transportformer uppmuntrar tillväxten av stora, monocentriska städer, det vill säga städer där företag är koncentrerade till centret och hushåll i omgivningen. Detta gynnar företagets produktivitet (eftersom företag drar nytta av positiva spridningseffekter när de ligger nära varandra) och bör därför uppmuntras av politiken. Dessutom behövs politiska åtgärder för att uppmuntra rena och effektiva transporter och för att hantera trafikstockningar.

Den historiska inriktningen för svensk skattepolitik med avseende på privata transporter kan sammanfattas enligt följande: du är välkommen att äga en fossildriven bil, men använd den helst inte. Bränsleskatterna är höga medan den årliga

vägskatten är blygsam och motverkas av stadsförare genom subventionerad parkering. På senare tid har politiken gått i den riktning som vår teoretiska analys indikerar: en rad styrmedel har införts för att uppmuntra inköp av lågutsläppsbilar, små steg har tagits för att höja parkeringskostnaderna mot marknadspriser, och trängselavgifter har infördes i Stockholm och Göteborg. För att lära oss mer om hur stadsbor reagerar på politiska förändringar studerar vi effekten av trängselavgiften i Göteborg. Vi studerar hushållsbilsägande och körbeslut över tid och jämför hushållen i Göteborg med de i Stockholm och Malmö under den period som trängselavgiften infördes i Göteborg, och finner att avgiften ledde till ett minskat bilägande med 0,4 procent och en minskad körsträcka för de bilägande hushållen med 1,6 procent. En enkel beräkning indikerar att dessa resultat översätts till mycket låga elasticiteter: om den årliga kostnaden för att äga och driva en bil ökar med 1 procent minskar andelen bilägande med cirka 0,07 procent, medan om marginalkostnaden att köra bil ökar med 1 procent, körsträckan minskar med cirka 0,15 procent.

Nyckeln till att uppnå klimatmålet 2030 för transportsektorn handlar minst lika mycket om att få fossila bilar bort från vägen som om att få elbilar på vägen. Med tanke på det mycket lägre bilägande i städer än på landsbygden är en uppenbar fråga hur vi kan gå längre i den riktningen. Naturligtvis skulle det hjälpa om stadsbilsägare måste betala de verkliga kostnaderna för att parkera sina fordon och om bränslebeskattningen i större utsträckning kompletterades med trängselavgifter (eller andra ännu mer exakt riktade avgifter). Den låga känsligheten hos Göteborgs stadsägare för trängselavgifter tyder dock på att huvudorsaken till lägre bilägande i städer inte är högre kostnader utan lägre upplevda fördelar. Det verkar som att mervärdet för hushållet av att äga en bil, och särskilt en andra bil, jämfört med alternativet – att använda andra transportmedel, kanske i kombination med att hyra – är lägre i städerna. Om så är fallet bör nyckeln till att trycka ner bilägarskapet vara att ytterligare höja hastigheten och bekvämligheten för alternativa transportsätt i förhållande till privata bilar, vilket skulle innebära att vi behöver ett åtgärdspaket som innefattar högre prioritet för kollektivtrafik och cykling, och lägre prioritet för privata bilar. Eftersom kollektivtrafik och cykling kan leverera fler människor till stadskärnor billigare och renare än bilar, skulle detta också uppmuntra till vidare utveckling av monocentriska städer, vilket leder till effektivare arbetsmarknader och mer produktiva företag. Mer forskning behövs om den optimala utformningen av ett sådant policypaket.

1. Introduction

1.1 Urbanization, transport, and the environment

Most people in Sweden live in towns and cities, and the proportion is rising. Why? The key driving force is agglomeration effects, i.e. advantages to both households and firms which arise from the fact that we live close to one another. An important benefit for densely packed firms is that they benefit from knowledge spillovers from each other; furthermore, each individual firm benefits from the pool of labour (and potential customers) that the group of firms as a whole attracts. Each firm which chooses to locate in a city therefore generates benefits – known in economics as positive external effects – for the existing firms in the city. There are also benefits for densely packed households, especially the ready access to a wide range of jobs, amenities, schools, and culture which cities offer.

On the other hand, there are also downsides to moving to cities. The act of moving can involve the loss of social networks, and access to nature. Furthermore, the large number of firms and households can lead to large distances between home and work, hence a great need for transport. This transport in turn generates noise and air pollution, lowering the quality of life for city dwellers and leading to global damages through carbon emissions. These damages motivate policy, because the damages caused by each person's choices affect other people around them, both locally and globally. In Sweden a range of policies are already in place, including taxes on fuel use, the bonus–malus scheme to encourage the purchase of low-emission vehicles, and road tolls in Stockholm and Gothenburg. Given Sweden's ambitious goals regarding both local environmental quality and carbon emissions, tougher policy measures are undoubtedly necessary.

1.2 Swedish environmental goals and transport policy

The key goals to which Swedish transport policy must relate are the transport goals and the environmental and climate goals.[1] Central to the transport goals are the socio-economic efficiency, sustainability, and national coverage of the transport system. Socio-economic efficiency implies that we need to account for all the benefits and costs of transport policy, so while sustainability is essential, we need to find routes towards sustainability which maximize the net benefits of transport to households. And the emphasis on national coverage reminds us that when considering policy measures that might make sense for urban drivers, we must also take account of their effects in rural areas. Relevant environmental goals include 'clean air' and 'a good built environment', and the goals relating to carbon emissions. Regarding air

[1] The transport goals are set out in Prop. 2008/09:93, Goals for travel and transport in the future (https://lagen.nu/prop/2008/09:93).

quality, goals are set out in 'Luftvårdsprogrammet' and 'Luftkvalitetsförordningen'.[2] Turning to climate, the key goals set out most recently in the government's Climate policy action plan are a 70 percent reduction in domestic transport emissions from 2010 to 2030, and a more-or-less explicit goal of net zero from the domestic transport sector by 2045.[3] Therefore, according to the Climate policy action plan, policies for 2030 should also take into account longer-term perspectives such as planning of housing, buildings and infrastructure, and electrification of goods transport. How are these goals to be achieved?

How to achieve the environmental goals for transport is discussed both in the Climate policy action plan and in a series of reports related specifically to transport, of which we focus on the Strategic plan for conversion of the transport sector to non-fossil fuels, and the follow up of that plan.[4] All the reports agree that a three-pronged strategy is required: movement towards a transport-efficient society; energy-efficient and fossil-free vehicles; and biofuels. Our focus is on the former two, i.e. not biofuels. The most fundamental reason for this is that in our opinion the role of biofuels in a socio-economically efficient transition to zero emissions should be limited. This is for two separate reasons: firstly, the actual climate benefits of using Swedish biomass other than forest residues to produce vehicle fuel are at best modest and may even be negative,[5] and secondly extracting biofuels from forest residues is (and is likely to remain) a costly process and socio-economic benefits of using these residues for other purposes are likely to be greater.

In a 'transport-efficient society' connectivity increases while the total resources devoted to transportation of goods and people decline. This can be achieved by, for instance, better-planned communities, better public transport, and more coordination of transport, as well as remote working. Better planning of communities may involve changes to the location of houses, businesses, and public transport. The Climate policy action plan points out that an effective way of steering towards a transport-efficient society is through economic instruments, which contribute to the emission reductions being made where they cost the least. In this report we focus on the role of economic instruments for driving changes in urban transportation.

1.3 Economic efficiency

To understand why economic instruments – such as fuel taxes and congestion charges – can help us to achieve a transport-efficient society, we first need to understand the concept of economic efficiency. To explain efficiency we consider the specific

[2] See for instance https://www.naturvardsverket.se/Miljoarbete-i-samhallet/Miljoarbete-i-Sverige/Uppdelat-efter-omrade/Luft/Luftvardsprogram/ and https://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Luft-och-klimat/Miljokvalitetsnormer-for-utomhusluft/Gransvarden-malvarden-utvarderingstrosklar/

[3] The overall environmental goals – De svenska miljömålen – can be found at https://naturvardsverket.se/Documents/publikationer6400/978-91-620-8821-7.pdf?pid=23428). With regard to carbon emissions and climate policy the key document is Regeringens proposition 2019/20:65, An overall policy for the climate – climate policy action plan, https://www.regeringen.se/rattsliga-dokument/proposition/2019/12/prop.-20192065/. The net zero goal in 2045 is across all sectors (allowing for the possibility of negative emissions in some sectors). However, in the Climate policy action plan it is noted that the transport sector can reduce its carbon emissions relatively easily compared to some other sectors, for instance through electrification, both in the medium run and the long run, implying emissions at least close to zero in that sector if net zero is to be achieved efficiently.

[4] The original plan is Swedish Energy Authority (2017), and there is a follow-up (kontrollstation), Swedish Energy Authority (2020).

[5] See for instance Konjunkturinstitutet (2020), Biodrivmedel och kolförråden.

problem of reducing Swedish carbon emissions. An efficient reduction in carbon emissions should be achieved as cheaply as possible, implying that costs cannot be reduced by allowing one sector (say private transport) to increase its emissions while another (perhaps goods transport) makes a corresponding reduction. It follows that the allocation of effort to reduce emissions is efficient when the marginal costs of emissions reductions in each sector are equal. A simple way to achieve an efficient allocation in this case is to tax fuel equally in both sectors (private transport and goods transport), in such a way that the economic agent who burns some fuel and hence emits carbon dioxide pays the same in tax – per unit of carbon dioxide – whether they have burnt the fuel in a car or in a lorry.

The above discussion, focusing on achieving given reductions at least cost, begs the question of how much emissions should be reduced in an 'efficient' solution. Ideally, emissions should be reduced such that the marginal cost of further reductions is exactly equal to the marginal benefit (in terms of reduced damages) of such reductions. This marginal benefit, in the case of carbon emissions, is known as the Social Cost of Carbon (SCC), and its 'correct' level is hotly debated. On the one hand we have the mainstream and relatively conservative estimates of economists such as Nobel prize winner William Nordhaus, and on the other we have economists such as Nicholas Stern and Joseph Stiglitz (another Nobel winner) who argue – based on different views regarding intergenerational equity and the risk of disastrous outcomes – that a higher SCC is appropriate, consistent with much more drastic abatement measures. To put this debate into the policy context, the Paris targets are consistent with a high – 'Sternian' – SCC, as are Sweden's targets for 2030 and 2045.

The debate about optimal environmental policy is of course about far more than the correct level of the social cost of carbon. For instance, in the transport sector we have multiple additional pollutants as well as carbon, such as noise, NOx, particulates, etc. These pollutants are very different from carbon because their effects are mainly felt locally and in the short run, rather than globally and in the long run. Consequently the damage they cause varies depending on where and when they are emitted, with higher damages in urban areas and at certain times of day, when many people are affected. Furthermore, emissions of such pollutants are not linked in a simple way to a measurable (and taxable) input factor such as fuel use. All of these factors make the policy problems posed by such pollutants more complex than the problem posed by carbon emissions. On top of this, transport systems are also linked to other effects which are not well captured by market transactions: one such effect is congestion, where my decision to drive helps contribute to congestion which affects others negatively; another is the benefit that firms (and hence also society) gain from locating close to one another in city centres, i.e. the agglomeration effects mentioned above. We discuss all of these issues in the remainder of the report.

2. Trends in Swedish urbanization and transport

2.1 Urbanization trends in Sweden

Sweden is characterised by a high degree of urbanization, with 88 percent of the population living in urban areas in 2020. Although the degree of urbanization is already high compared with the rest of Europe and Northern Europe, where 75 percent and 82 percent of the population lives in urban areas, respectively, the number of urban residents continues to increase. By 2050, the urbanization rate in Sweden is expected to be 93 percent, as opposed to the European average of 83 percent (UN, 2018). Figure 1 shows the proportion of the population living in urban and rural areas in Sweden (left panel), as well as the percentage of the urban population in Sweden, Northern Europe and Europe (right panel).

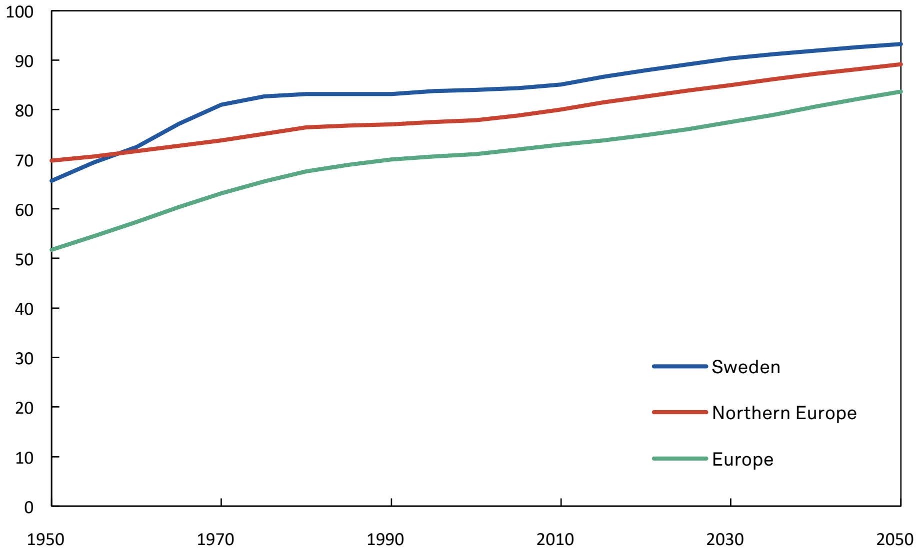

Figure 1. Urban population in Sweden compared to Northern Europe and the whole of Europe, expressed as a percentage of total population, 1950 to 2050. (Data from UN, 2018.)

The process of urbanization does not always follow the same pattern. Increasing urbanization is sometimes followed by a decentralization of the population from congested urban centres to the surrounding regions.[6] In Sweden, along with the large cities and medium-sized towns that will experience a 10 percent population

[6] See Veneri, 2018.

growth between 2019 and 2030, commuting municipalities near those areas are also expected to experience significant increases in their population. In particular, population in the commuting zones near large cities is predicted to grow slightly faster than in the core during the next decade. In total, 63 percent of the population is projected to live in large cities, commuting municipalities near large cities, and medium-sized towns by 2030. The increase in the population of the small towns is smaller than the national average, while rural municipalities is the only region where the population is expected to decline, by 5.2 percent between 2019 and 2030 (see Table 1).

Table 1. Population in 2019 and 2030 and increase (percent) in municipality groups (Statistics Sweden, 2020).

	Population 2019	Population 2030	Percent growth
Large cities	1897500	2101200	10.7
+ commuting environs	1929600	2140900	11
Medium-sized towns	2454600	2718300	10.7
+ commuting environs	856200	897000	4.8
Small towns	1311200	1360200	3.7
+ commuting environs	602200	612000	1.6
Rural areas	493200	467700	−5.2
Sweden	10327600	11094900	7.4

Why is Sweden experiencing such a high urbanization rate, which exceeds the one observed in the rest of Europe or in the Northern neighbouring countries? According to SCB (2020), international migration and a higher rate of immigration than emigration are two of the reasons that contribute to the largest part of the projected urban population increase. In Stockholm County, though, population growth is mainly caused by the higher number of births compared to deaths, while in Uppsala County, domestic migration is expected to be the major contributor.

Along with immigration trends, the fundamental driver of urbanization is technological progress, which reduces urban transport costs in relation to agglomeration benefits, and reduces employment in intrinsically rural sectors such as farming. For firms that are not tied to rural areas agglomeration effects tend to favour urban locations. As worker productivity increases, so do the benefits of agglomeration. If urban transport costs can be held down, incentives for firms to locate in cities increase. Meanwhile, increases in labour productivity (which is intimately connected to the continuous adoption of new technologies) result in fewer worker-hours per year needed to manage production on the fixed quantity of agricultural and forest land. Initially this trend was driven by mechanisation, as shown in Figure 2 where we see a steep decline in the number of farmers coinciding with the arrival of tractors and harvesters. However, the downward trend is now driven by other forms of new technology.

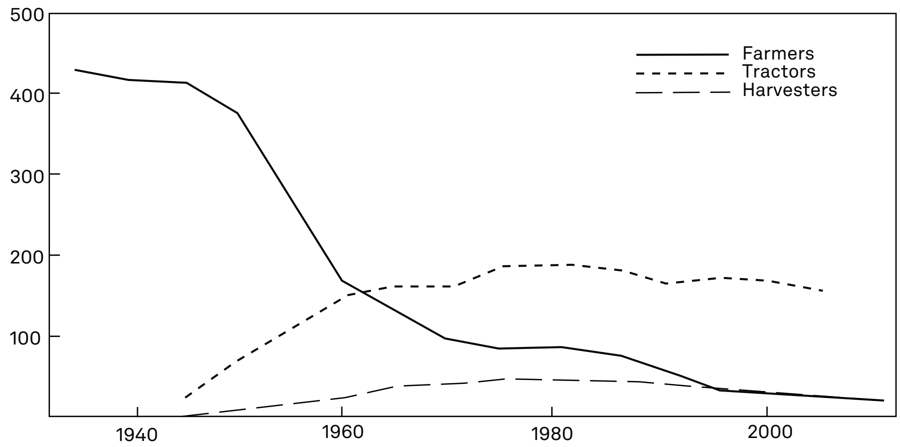

Figure 2. Farmers, tractors and harvesters (thousands) in Sweden (Data: Hedlund, 2017).

2.2 Transportation trends in urban areas

The overall picture regarding private transport (especially by car) in Sweden is complex. We begin by looking at the static picture, and then discuss trends over time. The static picture is that city dwellers are less likely to own cars, but those that do own cars drive them more, and hence also emit more pollution. And the larger and denser the urban area, the bigger are the effects (lower car ownership, higher mileage). To give a sense of the size of these effects, note that car ownership per person in northern Sweden is around 40 percent higher than in Stockholm, whereas annual mileage per person is around 30 percent higher in the north compared to Stockholm, reflecting the fact that those Stockholmers who choose to own a car proceed to drive high mileages; annual mileage per car is around 12 percent higher in Stockholm than in the north.

Trends in car ownership and mileage are broadly similar across the different regions. Annual mileage per person shows no clear long-term trend, although all regions show a decline since 2017. However, households are spreading their miles over more cars: the number of cars per person is increasing, while mileage per car is going down. Across the whole of Sweden, over the period 2009–2019 car ownership per person rose by 5 percent, while average mileage per car declined by 10 percent. However, when we focus specifically on cities we see diverging trends: in the four largest cities – Stockholm, Gothenburg, Malmö, and Uppsala – accounting for 20 percent of the total population, car ownership fell by 5 percent over the same period.

The current levels of transport emissions per person broadly reflect mileage per person as described above, hence emissions per car-owner in Stockholm are significantly higher than the national average, but emissions per person are lower. However, trends in emissions are more complex. Carbon emissions from private transport are trending slowly downwards, with a decline of around 20 percent over the period 2010–2018. Above all this reflects the increasing efficiency of vehicles, partly driven by improved technology, and partly by the switch to diesel. A further contributory factor is the slight decline in average mileage per person over the period. On the other hand, the increasing population of Sweden, and the increasing average weight and power of vehicles, have countervailing effects. Turning to pollutants other than carbon, the picture is even more complex. For instance, for

NOx we see a significant increase in emissions over the same period, driven above all by the switch from petrol to diesel vehicles. Finally, note that the number of electric vehicles on the road up to 2019 is too small to significantly affect emissions in our data. However, we see an extremely rapid rise in EV registrations in 2019 and 2020, especially in urban areas. For instance, in Stockholm the proportion of newly registered cars that are EVs rises from less than one percent to almost nine percent between 2006 and 2020.

We group county-level data by region and present the trends described above in the following figures.[7] In Figure 3(a) we show that car holdings per person are growing slower in city clusters along the east and west coast relative to the rest of the country. In fact, when plotting such trends of the ten largest Swedish cities in Figure 4(a), the average car holding has been declining in the four largest cities that account for more than 20 percent national population, while other cities in the figure have observed a modest increase in the average car holding during the past decade.

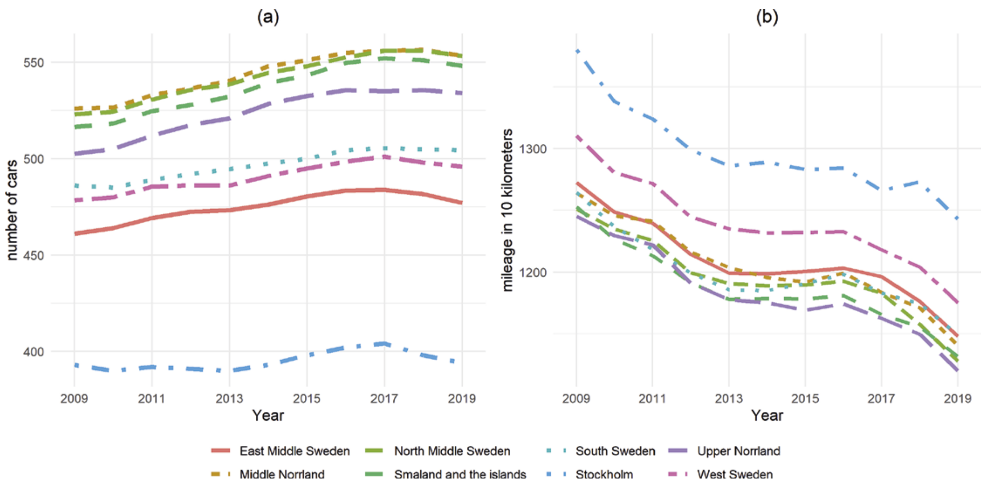

Figure 3. Car holding and mileage in the 8 regions of Sweden: (a) car ownership; (b) annual mileage per car. Source: Regional Utveckling och Samverkan.

[7] According to the National Areas of Sweden, we group counties into eight regions: Stockholm (Stockholm län), East Middle Sweden (Uppsala län, Södermanlands län, Östergötlands län, Örebro län, Västmanlands län), Småland and the islands (Jönköpings län, Kronobergs län, Kalmar län, Gotlands län), South Sweden (Blekinge län, Skåne län), West Sweden (Hallands län, Västra Götalands län), North Middle Sweden (Värmlands län, Dalarnas län, Gävleborgs län), Middle Norrland (Västernorrlands län, Jämtlands län), and Upper Norrland (Västerbottens län, Norrbottens län).

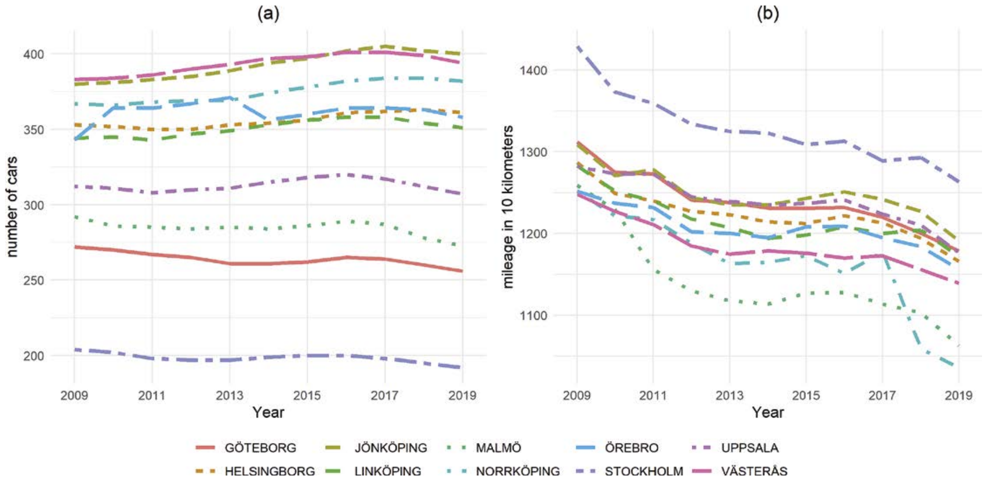

Figure 4. Car holding and mileage of the ten largest Swedish cities: (a) car ownership; (b) annual mileage per car. Source: Statistikmyndigheten SCB.

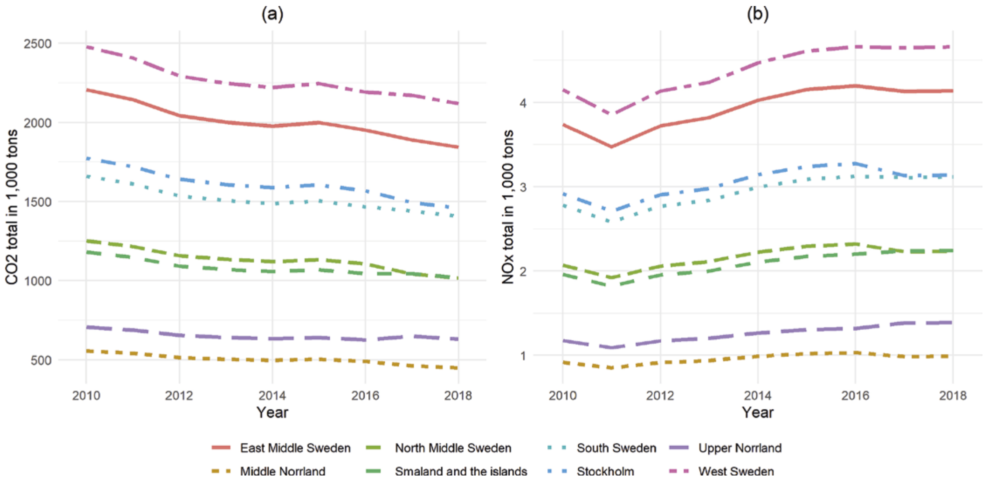

Figure 5. Emissions from private passenger car use by region: (a) carbon dioxide; (b) NOx. Source: Regional Utveckling och Samverkan.

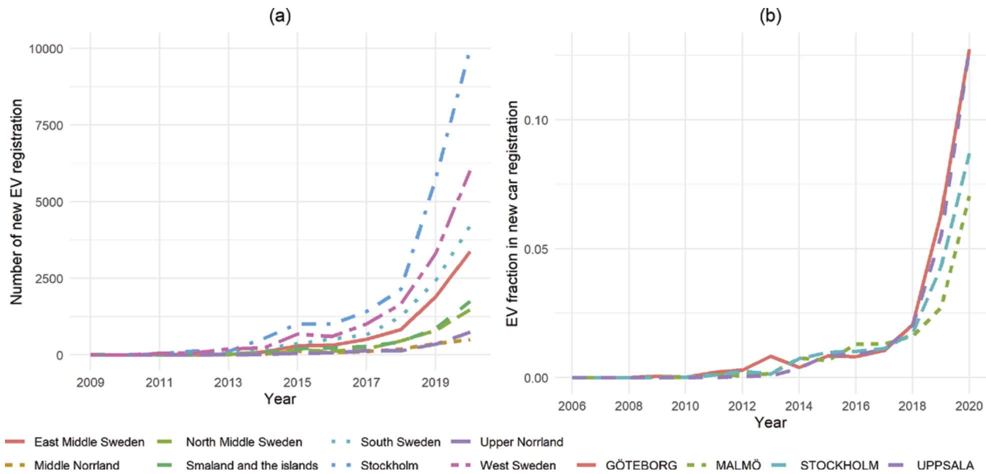

Figure 6. New EV registrations: (a) number of registrations per region; (b) proportion of newly registered cars that are EVs. Source: Statistikmyndigheten SCB.

Although sharing the same declining trend, Figures 3(b) and 4(b) indicate that regions with differentiated urban structures are showing different levels in annual mileage per car.[8] In Figure 5 we show that the carbon dioxide emissions have been declining between 2009 and 2019, while a gradual increase in the nitrogen oxides emissions is observed over the same period. This difference in emission patterns could be suggesting that the reduction in the CO2 emission intensity of passenger cars is realized partly through an induced increase of diesel car shares (Michielsen et al. 2015). Regarding EV adoptions, in Figure 6, we show that the period between 2018 and 2020 has seen a rapid increase in new EV registrations, but new EV market shares are still neglectable across the country.

The health effects from pollution in Swedish cities are significant, but lower than in most other European countries. A recent study in the Lancet[9] estimates that avoidable deaths from particulate matter and NO2 account for between 4 and 8 percent of all mortality in Sweden's four largest cities, with Malmö the highest and Uppsala the lowest. This corresponds to over 1 000 deaths per year.

The transition to green cars is a long process, as shown by Figure 7, where we see that well over 50 percent of the Swedish private passenger car fleet consists of relatively old petrol cars, and that these 10-year-olds account for almost 40 percent of the mileage. Furthermore, despite the high sales of diesels since the mid-noughties, diesels are still a small proportion of the vehicle fleet, and account for less than half of the mileage.

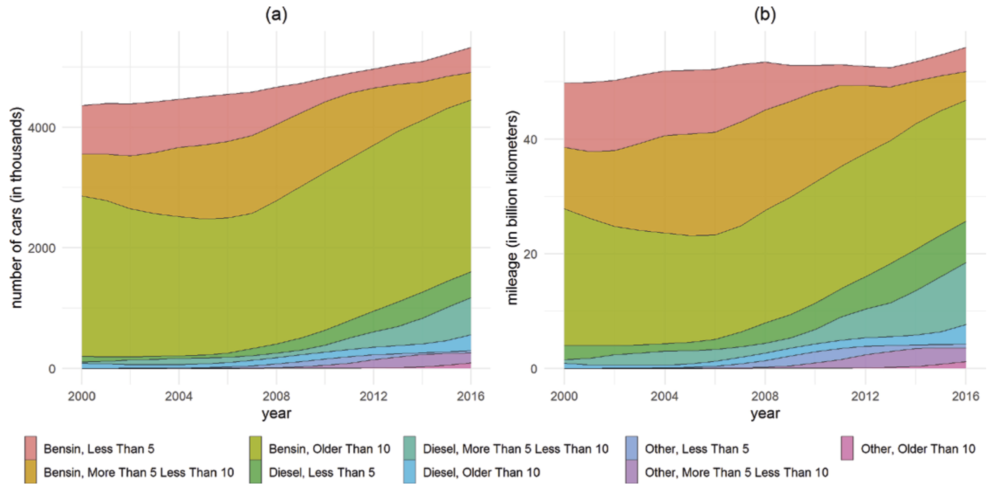

Figure 7. Car count and total mileage by fuel type and age. Source: MONA.

[8] Such a declining trend could be explained by either changes in demographics and economic characteristics of households or changes in driving habits (Leard et al. 2019).

[9] Khomenko et al. (2021). Note that we quote the means and uncertainty is large.

3. Urban structure and transport policy

In order to understand urban transport decisions, and what policies are required to move towards a socio-economically efficient and sustainable transport system, we must understand the urbanization process itself and its links to transport policy. Therefore, we now discuss how the internal structure of cities is determined, and how traffic pollution affects that process.

3.1 Urban structure 1: Knowledge spillovers and transport costs

Since the emergence of civilization, human activities and economic agents have been unevenly distributed across space (Braudel, 1985). While land is offered at a low price in many places of the world, the majority of the population lives in metropolitan areas where large business clusters have been formed and provide jobs to people who locate there. Urban economics investigates the location decisions of economic agents, usually households and firms.

In urban economics we distinguish between agglomeration (or centripetal) forces, which promote the concentration of economic agents in spatial clusters, and dispersion (or centrifugal) forces, which encourage their spatial dispersion. Agglomeration forces include knowledge spillovers among firms, large and active markets for labour, goods, and services, social interactions between households, and natural advantages of particular locations, such as harbours. Dispersion forces include high land rents, immobile factors, and some negative externalities such as pollution, congestion or high crime rates in the central areas. Previously the fall in transportation and commuting costs was believed to foster a more balanced distribution of economic activity across space, but it is now understood that lower transportation costs make the economic mechanisms yielding agglomeration of activities more important.[10] Hence falling transport costs have helped to drive urbanization.

How do economic agents decide on where to locate in the interior of a city? And how do these decisions affect the observed urban patterns? Mixed or specialized areas in the interior of a city are the outcome of a trade-off between agglomeration and dispersion forces. The exchange of information between firms and the knowledge spillovers obtained through their close communication are believed to be the main forces favouring clustering of firms. However, such clustering increases the average commuting distance for workers and drives up land rents close to the cluster, which implies that firms have to pay higher wages to compensate their workers for these costs. The balance between these opposing forces – and the effect of regulations – determines the residential and the business clusters in the interior of a city. High

[10] See for instance Lafourcade and Thisse, 2011.

commuting costs promote the formation of mixed areas where firms and households co-locate, whereas low commuting costs favour production/business activities concentrated at the (often unique) centre of the city. Another way to think about the process of land allocation is through the highest bids that firms and households would be prepared to make to rent land in each location. In a monocentric city, firms outbid residents in the centre, and vice versa in the suburbs. However, in an integrated or partially integrated city there are zones where the bids made by firms and residents are equal, and these zones are then shared between the two uses.

Three city types, denoted monocentric, integrated, and partially integrated, are illustrated in Figure 8. The figure illustrates both how firms and residents (households) may be distributed across the space of the city, and how this relates to the relative willingness to pay (WTP) of firms and residents respectively: the type with the highest WTP wins the bidding war and occupies the land.

Any change in the agglomeration or dispersion forces can affect the city size and lead to urban growth. Urban growth is thus the result of any change that increases the strength of agglomeration forces or reduces the magnitude of dispersion forces. Cities grow or decline as they move to the new equilibrium sizes. When different variables keep growing, such as population, cities grow up to a point, and beyond that threshold we observe the formation of new cities.[11] Urban growth also has an impact on the internal structure of cities, where multiple business centres might be formed.[12] Finally, urban development patterns might lead to urban sprawl. In those cases, the urban area contains a large amount of land where density is low.[13]

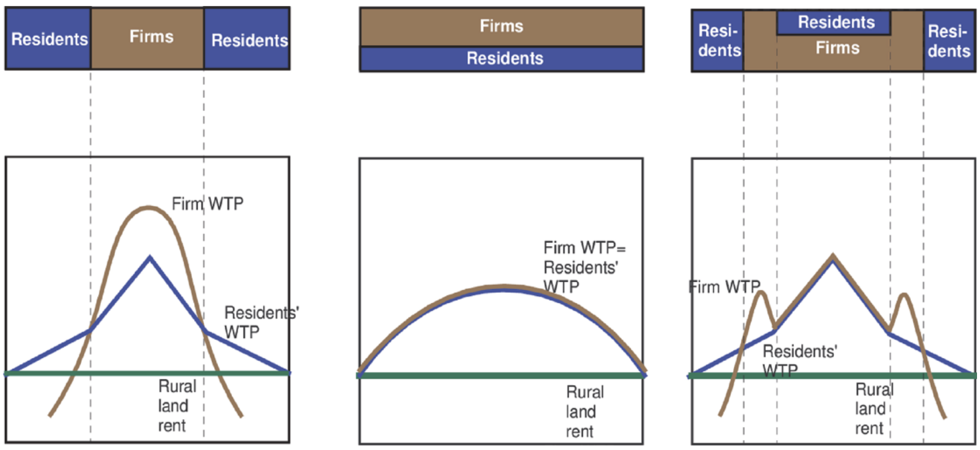

Figure 8. Three city types: (a) monocentric, (b) integrated, and (c) partially integrated. In the monocentric city we have a zone in the centre exclusively occupied by firms, and zones in the periphery occupied by households. In the integrated city both firms and households are dispersed over the entire city. And in the partially integrated city we have zones of each of the three types. The lower panels illustrate the maximum willingness to pay of firms and residents to rent land in different parts of the city. Where one type has higher WTP than the other then that type occupies the land exclusively. Figure based on Kyriakopoulou and Picard (2021).

[11] See Ioannides, 1994; Rossi-Hansber and Wright, 2007; Ioannides and Rossi-Hansberg, 2008.
[12] Fujita and Ogawa, 1982; Lucas and Rossi-Hansberg, 2002.
[13] OECD, 2018.

Urban planning is crucial for dealing with the increasing urbanization rate and mitigating people's vulnerabilities. The speed and scale of urbanization, along with the general increase in the amount of built-up area per person, impose many challenges on sustainable development. Unplanned urban sprawl creates additional concerns about the resilience and the sustainability of urban communities (UN, 2020). It puts pressure on natural resources and land, and might be detrimental for the welfare of residents. The 11th UN Sustainable Development Goal emphasizes the importance of creating sustainable cities and communities and discusses the ways that will ensure well-planned, inclusive, safe and resilient human settlements. Urban planners, environmental scientists and policy makers should all work together towards that direction.

We should also keep in mind that once a city has been built, it may be locked in for generations. Office buildings are not easily converted into housing, and transport infrastructure cannot often keep up with mobility growth. However, there are some quick fixes that can facilitate the promotion of more sustainable urban transport or even change the structure of cities. These include the conversion of car lanes into bike or bus lanes and the creation of low emission zones in the interior of cities. These changes will improve air quality, which, in turn, will have an impact on the attractiveness of different spatial points in the interior of cities.

3.2 Urban structure 2: Pollution

Into this story we now add pollution. The majority of the existing literature focuses on the impact of point-source pollution – coming mainly from the industrial and residential sectors – on urban structure. Our focus however is on the mobile-source pollution from the transport sector. The spatial framework allows us to consider the total amount of commuting in the interior of the city and not only the number of commuters. Even if the number of commuters remains constant, changing the location of commuters is likely to increase or decrease the aggregate commuting distance, which will have an impact on aggregate pollution.

Existing literature that studies how pollution from road transportation affects the internal structure of cities and the location decisions of economic agents considers cities with one (often unique) spaceless business centre. In other words, they consider some predetermined location for firms (CBD) and they study where workers would like to locate in relation to these firms. Their decisions determine the aggregate commuting distance in the city, which in turn affects aggregate pollution levels. This is illustrated in Figure 9. Related work studies the interaction between business agglomeration externalities and urban traffic pollution, defines the optimal city size, as well as the optimal densities in the interior of the city, and proposes policy instruments that will internalize the negative pollution externalities.[14]

[14] See, for instance, Verhoef and Nijkamp, 2004; Schindler et al. 2017; Borck and Brueckner, 2018; Denant-Boemont et al. 2018; Kyriakopoulou, 2021.

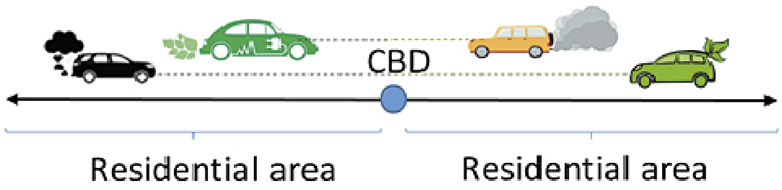

Figure 9. A monocentric city where workers' location decisions affect aggregate commuting distance and aggregate pollution levels.

Our contribution is to extend these models by assuming that land is used both for residential and for business purposes, as shown in Figure 8, above. Small cities usually have an integrated city structure, medium-sized cities start separating the two land uses ending up in a partially integrated urban form, while large cities become monocentric, as firms have strong incentives to locate close to each other forming a CBD.

Studying different urban forms that mix or specialize the different land uses allows us to give answers to questions such as: is a monocentric city configuration optimal from a welfare and ecological point of view? What is the difference between the optimal and the equilibrium urban structures? Which are the policies that will promote more sustainable urban structures? Our analysis shows that the consideration, not only of the aggregate commuting distance, but also of the density across the urban transport network is fundamental for the design of optimal and second-best transport policies, that will be in line with the polluter pays principle.

3.3 Our model

In our theoretical model, we consider the location decisions of firms and residents – workers in the interior of a city. Firms and workers interact through competitive labour and land markets. Workers consume land and a quantity of composite good, while they are harmed by their exposure to traffic-induced pollution. We start by assuming that pollution is purely local; it only affects the place where it is generated. This allows us to study the effect of pollutants such as NOx, PM10 and PM2.5 on the urban structure. Note that residents are harmed by local pollution at their place of residence.[15] This pollution (P) is generated by commuters crossing that location (x) and depends on the number of commuters (N) and on the type of vehicle they use. Thus, local pollution at the spatial point x is given by $P(x) = \varepsilon N(x)$, where ε measures the per-vehicle pollution, that is, the local pollution emitted by each vehicle at a specific location (e.g. ton of pollutants per vehicle).

Local pollution levels in different spatial locations can be affected by a number of changes, such as changes in the number of commuters who use private vehicles or switches to cleaner, electric vehicles. The parameter ε in our model captures technology and policy features. It falls with improvements in fuel efficiency, imposition of catalytic converters, ban of diesel engines, etc. It also captures the urban develop-

[15] Here pollution is assumed to be purely local. Even though this is mostly the case of air pollutants, such as NOx, PM10 and PM2.5, there might also be some small diffusion of this type of pollution depending on the temperature and the wind.

ment of bike lanes, metros and peri-urban transit parking, to the extent that those reduce the share of car vehicles independently of the workers' residences.

Firms hire workers who commute from home to workplace with private vehicles. They produce a composite good that is shipped and sold in the national market. They also decide where to locate in the interior of the city and benefit when they locate in pure business clusters, where the density of firms is higher.

Workers maximize their utility taking into account their budget constraint. The maximization problem defines the residential bid rent, which is the maximum amount of money that they can offer in order to locate in different spatial points in the interior of the city. Firms are free to enter and produce in the city. Free entry pushes their profits to zero and defines the business land rent, that is, the maximum rent that a firm can offer at each spatial point. In equilibrium, land will be occupied by the agents who offer the highest bid-rent. We show that in smaller cities where the number of firms is small, production externalities are not strong. In those cases, we observe cities with mixed areas where firms and residents co-locate in space. In larger cities though, there are stronger incentives for firms to create pure business centres and benefit from strong production externalities, which results in the formation of specialized areas in the interior of the city.

The role of local pollution

Local traffic-induced pollution is shown to affect the urban structure by impeding the formation of more specialised urban configurations. Let us consider the example of the monocentric city (more specialised) as opposed to the partially integrated city (less specialised). If we assume that both configurations have the same size and the same population, then the monocentric city implies higher aggregate commuting distances. Thus, local traffic-induced pollution that works as a dispersion force in our model prevents the formation of pure specialized areas, and promotes the formation of some mixed areas in the interior of a city.

By contrast, the use of cleaner vehicles promotes the formation of more specialised urban configurations, such as monocentric cities or partially integrated cities with larger residential and business areas. This is shown in Figure 10, which illustrates the case of a city with a given population size. When the pollution factor increases (on the vertical axis in the figure) we observe the formation of mixed areas at the centre of the city. In other words, when cars become more polluting, firms and residents tend to integrate in the central area to reduce car travel. The pollution factor can change due to technological progress, or policy changes: it falls with improvements in fuel efficiency, imposition of catalytic converters, bans on diesel engines, introduction of electric cars etc. Thus our model shows that these policies and technological improvements encourage the formation of monocentric cities.

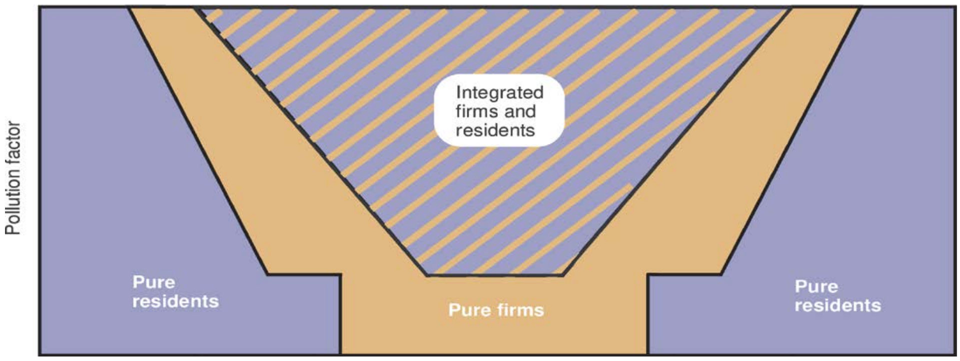

Figure 10. Equilibrium urban structure in the absence of regulations, as a function of the pollution factor of private transport. When the transport is pollution free (pollution factor zero) we have a monocentric city, but beyond a certain threshold we shift to a partially integrated city with an integrated central zone, as in Figure 8(c). The more polluting transport becomes, the larger the integrated zone becomes.

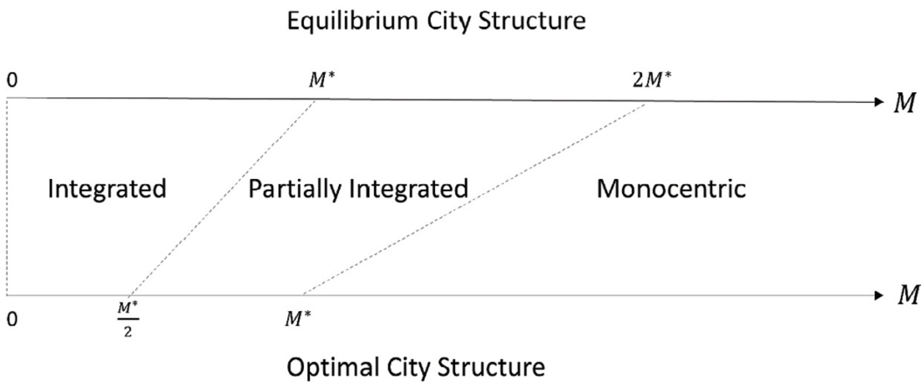

Figure 11. Equilibrium and optimal city structure for different population sizes (M). The equilibrium city structure is the outcome of the unregulated market, whereas the optimal city structure is the outcome under optimal regulation.

When it comes to the size of the cities, we show that as the city population size grows, the urban structure moves from integrated to partially integrated and then to monocentric configuration. Bigger cities have a higher number of firms and therefore stronger production externalities. As a result, firms make higher profits and offer higher bid-rents in the central area, which shifts residents to the suburbs. This result is illustrated in the upper part of Figure 11, where M is the population of the city.

In the presence of production and pollution externalities, the equilibrium urban configurations are not optimal. In Figure 11, it can be seen that all equilibrium monocentric cities remain monocentric at the social optimum, all equilibrium partially integrated cities become monocentric while equilibrium integrated cities with high population sizes become partially integrated. In other words, mixing business and residential activities is less efficient and thus, the urban planner has an incentive to promote the creation of more specialized urban configurations. So, for example, the monocentric city is an optimal city structure even for smaller population sizes (i.e. for $M > M^*$ compared to $M > 2M^*$ that is the threshold for the formation of a monocentric city in equilibrium). The optimal urban structure can be decentralized with the use of policy instruments that are discussed below.

Our analysis shows that the wider use of electric vehicles will improve the air quality in the interior of the cities, which means that the spatial locations around the business centre will be less polluted and will become more attractive. This will facilitate the creation of larger specialized areas and might turn partially integrated cities into monocentric. This however implies longer commuting distances which might offset some of the advantages of switching to cleaner vehicles. Our analysis highlights the need to jointly consider the urban planning and the policies that promote the switch to electric vehicles.

Note that changes in the structure of cities might take some time and require the collaboration between different actors, such as urban planners, environmental scientists and policy makers. However, the pandemic has created the need to consider more rapid changes in urban structure. Even changes that were considered to be possible only in the long run, such as the change in the land use, are currently at the centre of the discussion of urban planners. Several cities around the world (for example, City of London and Brussels) are planning to create new homes from offices and other buildings that are left empty because of the pandemic. In other words, when there are new needs with respect to office and housing space in the interior of cities, we can observe changes in their structure, which, however, should follow some type of formal, national urban plan.

Global pollution

In the previous section, we discussed the case of local traffic pollution that affects only the place where it is produced. We now discuss how global pollution – i.e. pollution that diffuses fully in space – can modify our results. This is illustrated in Figure 12, for the case of a partially integrated city. In the central area, there is no local pollution as people and firms locate next to each other. People living in the residential area (*b*1, *b*2) commute to the business area (*b*0, *b*1) generating some amount of local pollution. The highest amount of local air pollution is observed at the spatial location *b*1, which is the border between the business and the residential districts and is crossed by all the residents when going to work. The level of local pollution at each spatial point in the interior of the city is given by the triangles denoted by LP.

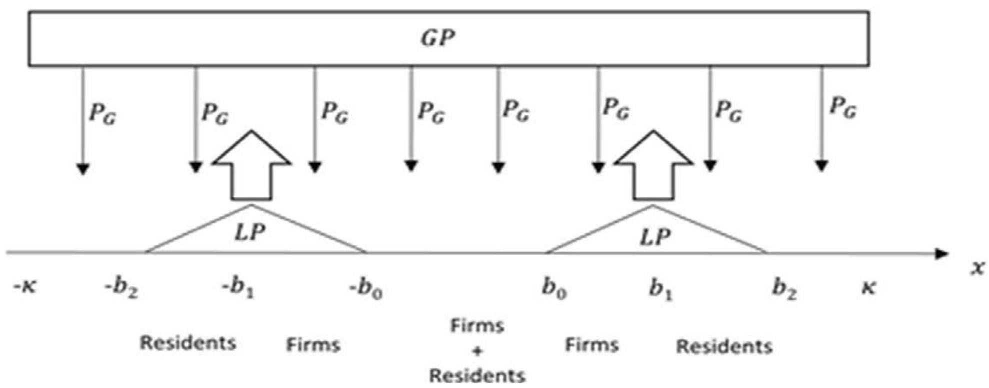

Figure 12. Local vs. Global pollution.

Under pollution diffusion, each resident is exposed to the same amount of pollution, independently of where they decide to locate. Global pollution is denoted by GP in the figure and it is shown to exceed the boundaries of the city under study. The comparison between global and local pollution is intuitive because it is shown to affect the urban structure in a different way and additionally, it allows us to compare our results with the related literature that accounts only for the global pollution coming from road transportation.[16]

Our results indicate that the diffusion of pollution shrinks the mixed areas and enlarges the specialised areas in partially integrated cities, while it facilitates the formation of monocentric cities. In fact, our analysis reveals that the structure of the city boundaries under global pollution are those established with zero local pollution effects. The reason is that individuals are affected in the same way by global pollution so that land rents within the city are not altered by pollution.

3.4 Optimal and second-best policies for road transportation

As illustrated in Figure 11, the optimal urban structure differs from the equilibrium one. To achieve the optimum in the model we need two site-specific instruments; a site-specific tax imposed on workers that will internalize the negative effect of their commute on all the residents along their commuting route, and a site-specific subsidy given to firms that will internalize the positive effect on other firms. The optimal environmental policy here indicates that long distance commuters and drivers of polluting vehicles should be charged by means of higher taxation. The urban analysis provides additional insights on which are those policies that will provide the right incentives to firms and residents with respect to where to locate in the interior of a city. Subsidising firms when choosing to locate at the right place not only boosts aggregate productivity in the area, but also affects the aggregate commuting distance of workers. It is thus important to jointly consider these urban externalities.

We now focus on the optimal environmental policy. Figure 13 illustrates the optimal tax in the case of a monocentric city. Workers live in the residential area and commute daily to the business centre using their private vehicles. The optimal tax (solid, blue line) increases as we move away from the city centre. In other words, long-distance commuters who negatively affect a higher number of people pay a higher taxation. To make it clear, the optimal tax depends on (i) how polluting the vehicle is, (ii) the distance between the place of residence and the working location and (iii) the residential density along the urban transport network, i.e. on the number of people who are negatively affected by traffic-induced pollution. The continuous red line in Fig 13 shows the increase in the optimal taxation in the case of more polluting vehicles or in the case of higher residential density.

Two of the most common transport policies in Sweden are fuel taxes and road tolls. Fuel taxes imply a higher cost for the drivers of more polluting, less fuel-efficient cars, and for the long-distance commuters. So, fuel taxes satisfy conditions

[16] See e.g. Regnier and Legras, 2018; Denant-Boemont et al. 2018.

(i) and (ii) above. But they do not satisfy condition (iii), so people who drive the same car in more and less densely populated areas (say Stockholm and Umeå) pay the same tax. Therefore, the fuel tax has negative distributional consequences for people living in rural areas, whose driving behaviour affects negatively a much lower number of people. In addition, imposing the same taxation on rural and urban residents may be thought to be unfair because the former often lack to option to switch to public transportation when the tax increases and driving becomes more expensive.

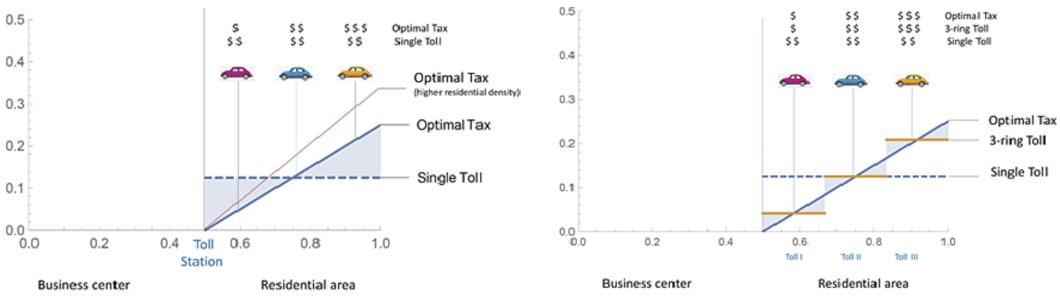

Figure 13. Road toll policies in the monocentric city: (a) comparison of an optimal policy in which the tax increases with distance from the centre, with a flat toll for entering the central area; (b) unchanged except for the addition of a three-ring system.

The second transport policy discussed here is the road tolls in Stockholm and Gothenburg. The primary purpose of the road tolls is to reduce congestion and improve the environmental conditions in the two biggest cities in Sweden, where the population density is high (condition iii). Drivers are taxed when entering the city centre during peak hours, so drivers are penalized for using their cars when the marginal damage of driving is highest. However, this policy does not account for the conditions (i) and (ii) described above. More precisely, there is no differentiation in the price paid by drivers with vehicles that emit a lower or a higher amount of pollutants. The same is true for short- and long-distance commuters; they all pay the same price. The road toll, in case of a single toll station when entering the city centre, is illustrated in Fig 13(a). The inefficiency of the taxation, as compared to the optimal tax, is shown by the light blue area between the two curves.

Is it possible to reduce the inefficiency of the road toll policy? Figure 13(b) shows the case where there are three toll rings around the city centre. This could illustrate the road toll system in Oslo. More precisely, in Oslo, there are three rings around the city centre, where congestion charges and environmental differentiation rates are applied. So, long distance commuters pay a higher tax (condition ii). Drivers of polluting vehicles pay a higher price compared to the ones who drive electric or hybrid vehicles (condition i). And finally, condition (iii) might be taken into account in the different prices charged across the different toll stations. Note that the inefficiency of the three-ring toll system is lower than the corresponding one in the single toll system (smaller light blue areas in Figure 13(b) compared to 13(a)).

Another policy that has been introduced in many cities is the creation of low emission zones where access to polluting vehicles is restricted or deterred. The effectiveness of this policy has attracted the attention of the transport economists. Studies in Germany show that pollution levels in the 44 cities were reduced after the introduction of low emission zones.[17] The same is true for London, for which a related, recent study showed that low emission zones led to a reduction of 5.5 percent in PM10 concentrations.[18] In Sweden there are low emission zones in eight cities. In all cases, except for Stockholm, low emission zones affect only lorries and buses. In Stockholm, low emission zones are implemented also for cars. Low emission zones are an important instrument for improving air quality and can help to significantly reduce the concentrations of nitrogen dioxide and particulate matter in urban areas, where the density of the population is high and air pollution exceeds the WHO standards. It can work as an additional instrument to the price-based ones, such as the fuel tax and the road tolls, especially in the cases where air pollution levels are still high after the introduction of price instruments.

[17] See, e.g., Wolff, 2014; Gehrsitz, 2017.
[18] See Zhai and Wolff (2021).

4. Environmental damages from transport and the role of policy

4.1 Policy instruments: Fuel taxes, green car subsidies, and tolls

The historical direction of Swedish tax policy with respect to private transport can be summed up as follows: you are welcome to own a fossil-powered car, but please don't use it. This is reflected in the sum of energy taxes and carbon taxes on fossil fuel, which cost drivers around 40 billion SEK in 2017.[19] In addition we have over 3.5 billion SEK for congestion charges and tolls. Meanwhile road tax (a fixed cost of owning a car) cost drivers 10 billion SEK in the same year. Given a total of around 4 million vehicles, taxes on driving amount to approximately 10 000 SEK annually per vehicle on the road, and the road tax to approximately 2 500 SEK annually per vehicle.[20] Furthermore, car ownership is subsidized in various ways, for instance through the generous tax treatment of company cars, and (in the urban context) provision of cheap on-street parking in residential areas, and planning regulations determined by local authorities that require builders to include some minimum number of parking spaces associated with apartment buildings. As we explain below, these planning regulations can lead to a subsidy to an urban car owner parking on-street or in subsidized housing-association parking of the order of 15 000 SEK annually, thus dwarfing road taxes and approximately equalling the entire tax payments made by the same owner.

Since 2006 Swedish policies have also been encouraging "green car" purchases. At the national level, there was a tax incentive of SEK 10 000 for each "green car" purchase made by a private person between April 2006 and July 2009. Following that, all new "green cars" registered after 1st July 2009 were exempted from paying annual road taxes for five years. Starting in January 2012, such a tax incentive was replaced by a new premium that subsidizes SEK 40 000 for purchasing an electric car or a "super green car" with carbon dioxide emission below 50 g/km. In the meantime, electric cars with an energy consumption of 37 kWh per 100 km or less, and hybrid vehicles with CO2 emissions of 120 g/km or less were exempted from the annual road tax for the first five years from the date of their first registrations. This set of incentives remained in place until June 2018, after which the Swedish "Bonus/Malus" scheme came into effect. This scheme applies a bonus of a maximum of SEK 60 000 for cars with low carbon dioxide emissions of up to 60 g/km. Also, within this scheme, increased vehicle

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[19] See for instance Table 1 in Nilsson et al. (2020), VTI, Framtidens beskattning av vägtransporter. For the data see VTI (2018).

[20] Note that drivers also pay sales taxes on both fuel and cars. However, such taxes are part of the tax 'baseline' along with income taxes, capital gains taxes, etc. Hence it makes more sense to treat relief from such taxes in a specific sector as a subsidy to that sector, rather than the baseline taxation as a cost. Consider for instance how RUT and ROT are effectively subsidies to home improvement sectors broadly defined.

taxes over three years are levied for petrol- and diesel-powered cars with the model year 2018 or later.

Owners of “green cars” also enjoy benefits from local policies that support environmentally friendly car adoptions. For example, between May 2005 and January 2009, green car owners living in the inner city of Stockholm were exempted to pay for residence parking fees. And “green cars” registered between 2007 and 2009 were exempted from the Stockholm congestion charge until 2012 regardless of fuel efficiency levels.

Once a household has purchased a vehicle (or multiple vehicles) the most obvious policies affecting incentives to drive are fuel taxes and (in Stockholm and Gothenburg) congestion charges, both of which discourage driving. On the other hand we also have tax deductions for commuting by car,[21] and most fundamentally the provision of the road network. From a theoretical perspective, we would ideally choose to tax fuel based on damages that flow directly and measurably from fuel use, which means the damages from carbon emissions. Other damages – from congestion and local pollutants such as NOx and particulates – vary depending on location, timing, vehicle, etc. They are therefore not directly (linearly) linked to fuel use, hence should be dealt with in other ways. As we mentioned above, the appropriate pricing of damages from carbon emissions is hotly debated. Based on a conservative – Nordhausian – estimate of the Social Cost of Carbon, fuel taxes in Sweden are higher than the damages caused by the corresponding carbon emissions. However, if we instead were to take Sweden’s own climate targets as setting an implicit carbon price – calculated by first finding the cheapest path consistent with the targets, and then calculating the marginal cost of the measures taken during the 2020s on that path – then the result would be a much higher carbon price, probably approximately in line with the fuel tax.

Non-carbon damages – local pollutants and congestion – are typically higher in urban areas and at peak travel times. Internationally published journal articles, such as Parry (2005) and Santos (2017), typically argue that such damages are large and important, and go a long way to equalizing tax payments and marginal damages, even though fuel taxes are highly imperfect instruments for internalizing these damage costs, because damages are not directly linked to the actual fuel use. On the other hand, note that some Swedish studies, including Nilsson et al. (2020) argue that the latter costs are negligible or already dealt with in the Swedish context (see their Table 2). Again, if we take the perspective of Sweden’s own targets for air quality – many of which are currently not being met – then clearly we need stronger measures, consistent with a relatively high damage cost. Alternative methods of incentivizing optimal driving behaviour are therefore called for, complementing fuel taxation. If such damages are indeed much larger in urban areas then congestion charges may be appropriate from a theoretical perspective.

In contrast to fuel taxes, urban parking charges in Sweden are undoubtedly too low from the perspective of welfare economics: car owners do not pay the full costs of the space used to park the car, and households therefore have excessive

[21] Tax breaks for commuting are linked to the idea that the tax system should raise revenue while having the minimum possible negative effect on labour supply. See Hart and Stråle (2021) for a sceptical discussion on taxation and labour supply, and https://www.regeringen.se/4adacc/contentassets/c5c41347278a4b839157c303514badaa/skattelattnad-for-arbetsresor-sou-201936.pdf for more on the system of tax breaks for commuting, and proposed reforms.

incentives to own cars. This is especially worrying from a policy perspective because we know that households in urban areas have a relatively high degree of flexibility about whether to own a car or not, given the wide availability of practical alternatives to transport by private car.[22] Surveys of commercially available garage parking in Stockholm and Uppsala show that prices are typically above 3 000 SEK per month, whereas housing associations charge their residents around 1 500 SEK per month for the equivalent service, amounting to an implicit subsidy to car owners of around 15 000 SEK annually. The direct cause is obvious: minimum parking requirements. That is, local authorities impose requirements on builders to include some minimum number of parking spaces in apartment buildings, and once the associations have an excessive number of spaces their rational strategy is to rent them out cheaply.[23] On the other hand, until recently on-street parking has typically been provided for free in many suburban residential areas, and again commercial rates for equivalent parking show the presence of a large subsidy.[24] However, major Swedish cities have seen increases in residential parking charges. For example, the residential parking charge in Stockholm's inner city went up by about 20 percent in 2016. And residents in suburban areas of the Stockholm region are now required to pay for residential parking, which was free of charge before 2016.[25]

4.2 Effects of the policy instruments

Mileage

Many empirical studies show that, given the choice to own a car, the effect of driving costs on mileage is modest. According to Dimitropoulos et al. (2016) the elasticity of car usage with respect to the marginal driving cost varies between −0.15 and −0.8, so a 1 percent increase in costs per mile leads to a reduction of less than 1 percent in driving distance. And more recently, Langer et al. (2017) estimate the same elasticity to just −0.12 for drivers in the US.

Fuel costs are only a part of marginal mileage costs, hence the elasticity of demand for mileage with respect to fuel costs should be lower than the elasticity with respect to all costs. The empirical literature has shown that the elasticity of demand for driving with respect to fuel prices in European countries lies between −0.3 and −0.45 (De Borger et al. 2016; Frondel and Vance, 2013; Gillingham and Munk-Nielsen, 2019), whereas corresponding elasticities in the US have been estimated to between −0.15 and −0.3 (Gillingham et al. 2015; Gillingham, 2014; Knittel

[22] One of the aims of the project behind this report was to perform a detailed investigation of parking subsidies and their effect on car ownership and driving decisions. However, due to difficulties obtaining appropriate data – in particular data which would allow us to delineate 'natural experiments' and hence make causal inferences – we concentrated our empirical efforts on the effects of congestion charging.

[23] Why do local authorities impose minimum parking requirements? A reason commonly suggested in the literature is that it is because of a failure to price other forms of parking, such as on-street parking: when on- street parking is underpriced,residents will tend to cruise for on-street parking spaces, which causes external costs (see for instance Van Ommeren and Wentink, 2012). As Van Ommeren and Wentink point out, the obvious remedy to this problem is to correct the existing distortion (free on-street parking) rather than creating another one (cross-subsidized parking for apartments).

[24] Note then when housing associations provide cheap parking, the true cost is paid collectively by all the households in the apartment block or housing association. The fact that this may be to a large extent the same households is irrelevant to the effect on incentives to own a car.

[25] Another possible reason for generally low parking charges is acceptance, or rather a lack of acceptance by households of the need to pay the costs of car parking.

and Sandler, 2013). Such a difference in car usage responses could be explained by highly accessible public transport in European cities (Gillingham and Munk-Nielsen, 2019). Focusing on Swedish data, Eliasson et al. (2018) demonstrate that the price elasticity of car use in Sweden ranges from −0.13 to −0.59, where high-income households tend to have a more inelastic demand for driving relative to low-income groups. The authors also show that rural areas carry a larger burden of fuel taxes than urban areas, and suburbs carry a larger burden than central cities.

A handful of studies have examined the influence of congestion charges on private passenger car driving patterns and its impact on public health. Investigating an unexpected suspension of Milan's congestion charge, Gibson and Carnovale (2015) provide results suggesting that drivers respond to the charge by shifting trips to the unpriced period and driving around the boundary of the priced area. Green et al. (2020) show that the London congestion charge leads to a large decline in the total amount of driving and improved speeds within the charged cordon where the latter is likely contributing to lowered pollution per mile of charged vehicles. In the Swedish context, Simeonova et al. (2019) show that the congestion charge in Stockholm reduced local air pollution by up to 15 percent, with resultant decreases in the rate of acute asthma attacks among young children.

Car ownership

Policy affects both what vehicles are purchased, and the decision about whether to purchase a vehicle at all. The former decision is easier to study as the risk for confounding factors is smaller, and the effects of policies are thus clearer. Huse and Lucinda (2014) estimate the effectiveness of the Swedish green car subsidies between 2007 and 2009 to show that such a policy increases the market shares of "green cars", but that the cost in reducing carbon dioxide emissions through this approach is five times the price of an emission permit. Furthermore, Huse (2018) shows drivers of flexible fuel vehicles strongly prefer fossil over alternative fuels when the prices of the two are similar. Therefore, high fuel taxes are required to switch drivers from petrol to ethanol, but the allocative inefficiency introduced by the taxes makes them prohibitive. Overall, the findings in Huse (2018) suggest that non-price attributes play an important role in household car choice and usage decisions.

Regarding accelerating EV adoptions in Sweden, Egnér and Trosvik (2018) examine local policy instruments that determine EV adoptions. They show that public charging infrastructure has a significant and positive impact on the EV adoption rate. Additionally, although the impact of parking benefits on growing the EV share is positive but not robust, the authors suggest that providing free parking could be a viable approach to lifting the EV adoption in municipalities where parking is expensive and limited. Finally, Egnér and Trosvik (2018) point out that a higher public procurement of EVs has the potential to effectively increase EV adoptions because municipalities that use EVs in their own work are likely to create a positive externality of knowledge spillovers in spreading valuable information to non-adopters. Additionally, Isaksen and Johansen (2020) demonstrate that it's also possible to implement a congestion charge scheme that differentiates driving costs by vehicle type for inducing the adoption of battery-electric vehicles. Furthermore, Winston and Yan (2021) show that an efficient congestion charge could reduce vehicle sizes and their concomitant externalities given that there is a valid causal relationship between highway congestion and vehicle size (e.g., the highway "arms race").

Studies show that the estimated value of the elasticity of demand for private passenger cars with respect to the fixed cost of car ownership varies between −0.03 and −0.8 (Dargay, 2002; De Jong et al. 2009; Van Ommeren et al. 2014). In the meantime, a small but growing body of empirical literature has explored the relationship between residential parking charges and the demand for private passenger cars. Employing observed market rates for residential parking in Japan, Seya et al. (2016) show that the residential parking price elasticity of car ownership is −0.48. Applying the implicit price of parking identified from Dutch data, Ostermeijer et al. (2019) obtain the price elasticity of car ownership estimate equalling −0.7. Furthermore, the authors show that the disparity in parking costs between the city centre and the outskirt explains around one-third of the difference in average car ownership rates between these areas.

Andersson et al. (2016) is the only study, to the best of our knowledge, that has examined the effect of parking regulations in Sweden. The paper estimates the effect of the minimum parking standards on housing stock in Sweden. The authors argue that the building requirement increases the production cost of housing construction thereby reducing profitability of construction companies.

4.3 Alternatives to existing policies

The large differences between the external damages of driving in rural and urban areas point clearly to the need for changes in the regulation of private transport. Another reason to reform the system is the future need to make up for the dramatic loss of tax revenue which will occur due to the shift from fossil fuels towards EVs. These points have been well made in recent reports such as Hennlock et al. (2020) from IVL, and Nilsson et al. (2020) from VTI. In both reports, the case is made for mileage taxes differentiated depending on when and where each car is driven, and potentially also on the specific characteristics of the vehicle. Such a system would necessitate continuous data collection on each car's location, and such a radical change would require a lot of preparatory work, as Hennlock et al. point out. Hence a system of this type will not be introduced before 2030 at the earliest. Furthermore, as Nilsson et al. (2020) point out, the priority for the next 10 to 20 years is to get fossil-powered vehicles off the road, and high kilometre-based taxes on EVs would not facilitate this process.[26]

So a high-tech system involving tracking and charging of individual cars may be an option for the distant future, but will not get us to the 2030 goal of 70 percent reductions in carbon emissions. In the meantime, our analysis suggests that urban planning decisions (including public transport) should encourage the formation of monocentric urban areas with efficient and clean transport solutions. To encourage the trend away from private transport in cities, it seems that (i) efforts should be made to close the gap between commercial parking rates and charges for parking provided by local authorities and housing associations, and (ii) congestion charging schemes should be extended.

[26] Note that differentiated vehicle mileage taxes have also been discussed in the international literature; see for instance Langer et al. (2017).

An example of an extended congestion charge scheme is that in Bergen, which is analysed by Isaksen and Johansen (2020). The scheme in Bergen differentiates driving costs by vehicle type, as well as by zone and time, and Isaksen and Johansen show that it helps lower driving, improve ambient air quality, and induce adoption of EVs, especially by richer households. On the other hand, it has no effect on the total number of cars. In the next section we focus on finding evidence from Gothenburg regarding how households respond to congestion charging, both with regard to mileage and car ownership.

5. Lowered car ownership and reduced driving: The case of the Gothenburg congestion charge

We have argued that the negative effects on others of one person's driving vary greatly depending on the context: they are greater in urban areas where more people are affected by the resulting pollution, and they are greater at 'peak times' when each extra car exacerbates congestion. Because traffic delays are non-linear, adding just a few more cars at the wrong time can slow traffic dramatically, while taking just a few cars off the road at the right time can substantially improve both traffic speed and throughput (Taylor, 2017). Therefore, a one-percent reduction in aggregate driving could lower aggregate pollution by more than one percent because the underlying congestion may worsen ambient air pollution if the traffic comes to a standstill.

Due to the above characteristics, road tolls (also known as road pricing, or congestion charges) are a popular policy option, and they have been introduced in many European cities over the last 20 years, including of course Stockholm and Gothenburg. When used together with fuel taxes they have the potential to yield much greater socio-economic efficiency: road toll policies, when well designed, penalize drivers for using their cars when the marginal damage of driving is high, whereas fuel taxes take care of the damages from carbon emissions. Hence a road-pricing approach has the potential to allocate limited roadway capacity to the highest-valued users to reduce traffic congestion and local pollution.

To further explore how such policies facilitate a transition towards zero emissions from Swedish urban transport, in this part of the report, we examine the overall impact of the Gothenburg congestion charge. We focus on investigating channels through which the Gothenburg households adjust their travel behaviour in response to the introduction of a congestion charge. We show that the average annual mileage decreases by about 120 kilometres per car-owning household during the first three years after implementing the charge, representing a 1.6 percent reduction in total car usage. In the meantime, the implementation of the congestion charge is estimated to decrease the probability that the household chooses to own at least one car by about half a percentage point. Our study complements previous studies that compare outcomes before and after the policy change for evaluating the impact of congestion charges in the Swedish context.

5.1 The Gothenburg congestion charge

The Gothenburg congestion charge was introduced as part of a large infrastructure investment package, in which financing regional transport infrastructure improvement using the Gothenburg congestion charge revenues serves as the prerequisite for an equally large state grant. Therefore, the overarching objective of implementing the Gothenburg congestion charge scheme is to raise sufficient revenues for financing regional development (Börjesson and Kristoffersson, 2015; Hysing et al. 2015).

The traffic congestion in Gothenburg mainly happens on arterial roads leading to the highway hub on the north. The congestion charge zone consists of 36 control points located along a single cordon surrounding the centre part of Gothenburg, with additional control points built at key locations outside the cordon to prevent people circumventing the tax zone by using local streets.

The Gothenburg congestion charge scheme requires all Swedish-registered vehicles entering the cordon between 6:00 am and 6:29 pm on workdays to pay a fee with the amount of charge depending on the time of day. The charge is levied in both directions. Vehicles that pass multiple control points within 60 minutes only need to pay the highest charge once. And the charge is capped at a daily maximum. Drivers do not pay the congestion charge between 6:30 pm and 5:59 am on workdays, during weekends, and in July. Private drivers using company cars as a fringe benefit are exempt from paying the congestion charge or pay it at a substantial discount.

The West Swedish Agreement that includes the Gothenburg congestion charge initiation was adopted by the government on 1st April 2010. The congestion charge charge system came into effect on 1st January 2013. Traffic volume data have shown that there is a larger reduction in traffic volume in the morning peak relative to the evening peak, with the traffic volume remaining largely unchanged outside the charged hours.

5.2 Research design and data

In what follows, we apply difference-in-differences (DiD) methods to investigate household-level behavioural changes in car-owning and driving decisions after introducing a congestion charge in Gothenburg. We exploit Swedish private passenger car registration data paired with mileage information obtained through vehicle inspection records. In addition, we supplement vehicle-level microdata with rich household demographic information extracted from the Swedish population register to account for the effects of changes in the demographic composition.

Estimating the effects of a citywide policy intervention

For estimating policy effects, a social experiment would ensure that the treated group experiencing a policy intervention and the control group are equal in all other aspects except the policy intervention status through randomization. By applying a quasi-experiment research design, we attempt to make use of some form of randomization across groups in the assignment to policy changes.

Our analysis focuses on major urban areas in Sweden. In our research design, we define a policy intervention as the implementation of the Gothenburg congestion charge starting in 2013, hence our 'treated group' is households living in Gothenburg. To estimate changes in vehicle ownership and usage decisions among residents in response to this policy change, we need cities other than Gothenburg to serve as a control group that has experienced no road policy changes during the sample period; this control group consists of the residents of Stockholm and Malmo, which is appropriate since road pricing policies in both Stockholm and Malmo were unchanged during the period of our study, from 2009 to 2015. Therefore, we apply DiD estimators to citywide cross-section data between 2009 and 2015 to examine the causal effect of the Gothenburg congestion charge on households' car ownership and usage decisions.

Our study reckons on the fact that a new congestion charge system is introduced in Gothenburg while the road pricing policy remains unchanged in Stockholm and Malmo during the same period. We use two sets of differences to estimate the impact of the Gothenburg congestion charge. The first set is done by comparing outcomes within Gothenburg before and after the policy intervention happens. In this comparison, persistent confounding factors that may bias the estimate are held constant. The second difference compares outcomes within the control group, before and after the policy intervention happens in Gothenburg. The second comparison reflects how outcomes would have changed in the absence of the Gothenburg congestion charge. Combining information recorded before and after implementing the Gothenburg congestion charge, we explore a citywide policy change to learn changes in households' car ownership and usage decisions.

We recognize that households' behavioural response is not solely determined by the congestion charge. Some residents do not rely on private passenger cars even without a congestion charge, while others will stick to driving despite such a charge. Therefore, we are estimating the average impact of introducing a congestion charge, which is a mixture of adjustments made by Gothenburg residents responding to the policy change and a zero effect on those who do not respond. To estimate this average treatment effect on treated, repeated cross-sectional data would be enough for the average group fixed effects to cancel out in the before-after differences, as long as treatment and control groups are separated prior to the policy change (Blundell and Dias, 2009). Therefore, after conditioning on a vector of household-level demographic information, the DiD estimators are able to remove city fixed effects through sequential differences in our research design.

Data source and variables

We use Swedish vehicle registration and inspection records to collect information on car ownership and car usage. In Sweden, a change of ownership is required to be registered once an individual has bought or sold a car. The first technical inspection needs to be conducted three years after the vehicle was first put into use. The second inspection takes place after another two years and then annually. In addition, we gather information on household demographics and dwelling type from the Swedish Longitudinal Integration Database for Health Insurance and Labour Market Studies. Based on these two main data sources, we carefully assemble microdata that includes repeated cross-section observations at the household level.

Table 2 reports summary statistics on the private car ownership and annual mileage per car-owning household in Gothenburg and the other two cities that form the control group, during the pre- and post-policy intervention periods, which are 2009–2012 and 2013–2015 respectively. These numbers suggest two points. First, the fraction of car-owning households is higher in Gothenburg and car owners in Gothenburg drive more on average relative to their counterparts in Stockholm and Malmo. Second, trends in the fraction of car-owning households and their driving are similar between the treated group and the control group, although the drop in car-owning rate and driving is relatively larger in Gothenburg. The statistics seem to indicate that the congestion charge reduces the car-owning probability and driving in Gothenburg, but the reduction could be caused partly or entirely by changes in urban structure and the demographic composition of the sample.

Table 2. Summary Statistics.

	Gothenburg	Control Cities
Panel A: Car-owning households (percentage)		
2009–2012	0.393	0.351
2013–2015	0.382	0.346
Difference	−0.011	−0.005
Panel B: Annual mileage per car-owning households (1000 kilometres)		
2009–2012	11.836	11.089
2013–2015	11.463	10.843
Difference	−0.373	−0.246

Notes: Car-owning dummy equals one if the household owns at least one private passenger car, zero otherwise. Only car-owning households are included in the annual mileage sample.

5.3 Estimation and results

We use information collected at the household level from cities in both treated and control groups in time periods before a congestion charge was introduced in Gothenburg and after the charge went into effect to examine the impact of the Gothenburg congestion charge on car ownership and driving. Given that the policy intervention is defined as the implementation of a congestion charge in Gothenburg starting from 2013, neither group was exposed to the intervention prior to 2013, while only the treated city (i.e. Gothenburg) was exposed to the policy change in the post-intervention period.

In order to estimate the average treatment effect of the policy intervention, we employ city fixed effects to capture possible differences among cities.[27] We also apply year fixed effects to account for aggregate factors that would cause changes in outcomes over time even in the absence of a policy intervention. For pinning down the compositional change in our sample, we include a vector of household and neighbourhood demographics in the regression model. Elements considered here are the number of family members and the number of workers in a household, the annual disposable income of a household, the type of housing unit ownership (i.e. owner, BRF, public utility owned, and other), and the total number of house-

[27] We are not applying household fixed effects because our current data does not track households over time.

holds and the average household annual disposable income at the postal code level. Including such a set of control variables also provides the possibility to improve the precision of our estimates because the error variance in the residual terms will be smaller after including these demographic controls if they are not systematically correlated with the policy intervention indicator.

The DiD approach requires the same initial outcome gap across treated and control groups spans into the post-intervention period. Our baseline model rules out confounding from any time-invariant factor. Employing demographic controls helps account for possible form of time-varying confounding that may affect the results. In addition to relying on time fixed effects to absorb common shocks affecting all cities in each year, we also apply city-specific trends to account for heterogeneous time effects. Such a practice is a good robustness check for the underlying common time effects assumption of the DiD approach.

The aggregate effect of the Gothenburg congestion charge

Table 3 presents the aggregate effect estimates. Our sample consists of observations from about 1600 postal code areas across three cities. We cluster the standard errors at the postal code level to account for dependence within postal code areas and across years. The main results of our analysis are robust when applying either the Huber-White standard errors or standard errors estimated using the bootstrap procedure proposed by Cameron et al. (2008).

Panel A of Table 3 presents the estimated impact of the Gothenburg congestion charge on car ownership. Here we regress a car-owning dummy on the congestion charge policy indicator, a set of demographic controls, a set of fixed effects, and city-specific trends. A car-owning dummy equals one if the household owns at least one private passenger car, zero otherwise. In columns (1) through (4), we investigate the influence of the Gothenburg congestion charge on the decision about whether or not to become a car-owning household, in which we do not distinguish one-car households from multi-car households. In column (5), we examine the policy effect on the probability that a household chooses to own just one car, while in column (6) we report estimated impact of the Gothenburg congestion charge on households' decisions about holding multiple cars.

Two points emerge from Panel A of Table 3. First, coefficient estimates reported in the first four columns suggest that the Gothenburg congestion charge has a negative impact on car ownership. In particular, our preferred specification in column (4) indicates such a citywide policy intervention reduces the probability that a household chooses to own at least one car by 0.4 percentage point during a three-year period after implementing the charge. Second, results in columns (5) and (6) reveal that introducing a congestion charge scheme in Gothenburg reduces the proportion of one-car households but not the fraction of multi-car households. It seems that fewer non-car households decide to get their first cars because of the policy intervention. In addition, our results indicate that living in an area with a higher population density is linked to a lower car-owning probability. If we consider more populated areas to have better public transport availability, this result makes sense because households tend to rely less on private passenger cars if the public transport network is easily accessible.

Table 3. Aggregate Effects.

	<1>	<2>	<3>	<4>	<5>	<6>
Panel A: Changes in car-owning probability						
Gbg x Post	−0.006	−0.004	−0.003	−0.004	−0.004	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Panel B: Changes in annual mileage per car-owning household (1 000 kilometres)						
Gbg x Post	−0.126	−0.102	−0.109	−0.112	−0.125	−0.028
	(0.020)	(0.019)	(0.027)	(0.026)	(0.026)	(0.079)
Demographic controls	No	Yes	No	Yes	Yes	Yes
City and year dummies	Yes	Yes	Yes	Yes	Yes	Yes
City x time trends	No	No	Yes	Yes	Yes	Yes

Notes: All columns report standard errors clustered at the Postal code level in parentheses. The dummy variable Gbg equals one if household i lives in Gothenburg, and zero otherwise. Similarly, the dummy variable Post equals one if year t equals calendar year 2013 or later, and zero otherwise. In Panel A, columns (1) through (4) report results from regressing car-owning dummies on explanatory variables. A car-owning dummy equals one if the household owns at least one private passenger car, zero otherwise. The dependent variable for the regression in column (5) is the one-car household dummy that equals one if the household owns one private passenger car, zero otherwise. The dependent variable used in column (6) is the multi-car household dummy, which equals one if the household owns more than one car, zero otherwise. The number of observations is 6 537 734 for regressions. In Panel B, the dependent variable is annual mileage in thousand kilometres for all results reported in this table. Columns (1) through (4) apply regressions to all car-owning households, with a sample size equalling 2 358 796. Column (5) reports results from examining 2 041 511 one-car households. In column (6), 317 285 multi-car households are analysed.

In addition to the linear probability model reported in Panel A of Table 3, we also analyse the impact of the congestion charge on the number of cars owned by households using a count outcome model. Specifically, we apply the specification employed in column (4) of Table 3 to a Poisson regression model and replace the dependent variable with the number of cars owned by a household. The Poisson regression coefficient for the policy intervention indicator is −0.011 with a robust standard error equalling 0.003. The result implies that the expected number of cars owned by a household after implementing the Gothenburg congestion charge decreases by about one percent, holding all other variables constant.[28]

In Panel B of Table 3, we apply the same set of regression models as used in Panel A to the car-owning household sample, with the dependent variable of interest here being the total annual mileage over all the cars a household owns measured in thousand kilometres. When comparing across columns (1) through (4), the regression analysis indicates that introducing a congestion charge reduces driving. When focusing on the entire car-owning household sample, the policy intervention indicator estimate in column (4) suggests that the Gothenburg congestion charge leads to a 112 kilometres reduction in annual mileage per car-owning household. When separating one-car households and multi-car households, columns (5) and (6) suggest that the reduction in annual mileage of one-car households is about 125 kilometres, while the charge has no impact on the car usage decision of multi-car households.

Results in Table 3 speak directly on the overall impact of the Gothenburg congestion charge on private passenger car ownership and driving. Households respond to the policy intervention on both extensive and intensive margins. After implementing the congestion charge, non-car households are less likely to acquire

[28] After introducing the congestion charge, the mean number of cars owned by a household changes by a factor $exp(-0.011) = 0.9891$, or decreases by about one percent ($exp(-0.011) - 1 = -0.011$).

a car and car-owning households choose to drive less. In the meantime, it seems that one-car households are more responsive to the congestion charge than multi-car households in altering their car usage decisions.

The dynamic effect of the Gothenburg congestion charge

After examining the aggregate effect of the Gothenburg congestion charge, we now turn to estimating the extent to which the charge affects car owning and driving decisions over time and across different types of households. Examining the annual effect of the policy intervention also allows us to further verify the underlying common time effects assumption of the DiD estimators. Such an assumption of common time effects across groups makes sure that the randomization hypothesis that rules out selection on untreated outcomes holds.

In the dynamic analysis we replace the single policy intervention indicator in the previous regression analysis with a full set of policy intervention leads and lags. If we use the last year prior to introducing the Gothenburg congestion charge as the reference year, then the coefficient estimates for these leads and lags measure the difference in an outcome variable between households in Gothenburg and households in control cities, relative to the reference year. In our DiD framework, we would expect there to be no change in households' car-owning and driving decisions before the Gothenburg congestion charge kicks in, so the corresponding estimates should not be statistically different from zero. In the meantime, if the Gothenburg congestion charge indeed reduces car-owning probability and driving, as shown in the previous subsection, we would expect estimates for the year of adoption and years after that to be smaller than zero.

We present the dynamic effect of the Gothenburg congestion charge on private passenger car ownership in Figures 14 and 15. In each figure, the vertical line marks the reference year coefficient estimate, which is normalized to zero. Each dot in the figure represents the coefficient estimate that captures the average difference in the households' responses between Gothenburg and the control cities relative to the difference in the reference year, with the shaded areas spanning 95 percent confidence intervals.

In Figure 14 we demonstrate the dynamic effects of the Gothenburg congestion charge on car ownership: in 14(a) we show the effect on the probability of owning one car, and in 14(b) we show the probability of choosing to own more than one car. In both figures, the coefficient estimates for the years prior to the reference year are all close to zero, which indicates that the difference in car-owning probability between Gothenburg and the control cities are similar during the pre-policy intervention years. The pattern of the estimates for the post-policy intervention years shows that households in Gothenburg become less likely to own a single private passenger car after the congestion charge kicks in, and the drop in car owning probability remains over a three-year period after implementing the congestion charge. On the other hand, there is no sign of any effect on household decisions about holding multiple cars.[29]

[29] Note that when we plot the combined data (not shown) the result is very similar to Figure 14(a). The main reason for this is that over 80 percent of car-owning households in the sample own just one car.

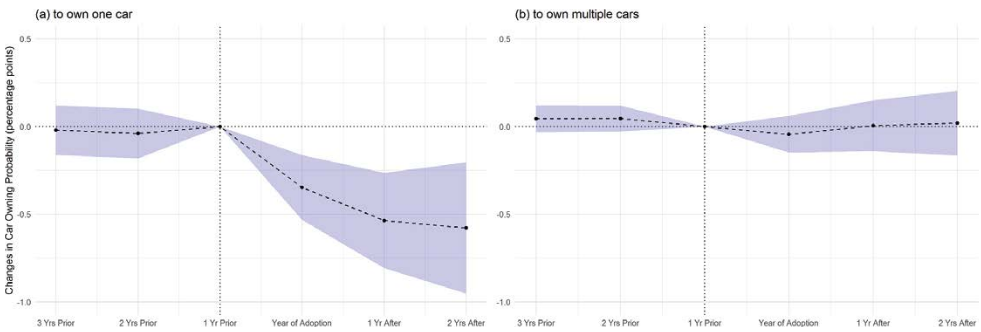

Figure 14. Effect of the Gothenburg congestion charge on private passenger car owning probability over time: (a) probability of owning just one car; (b) probability of owning more than one car. The figure plots coefficient estimates representing the difference between households in Gothenburg and households in control cities, from three years prior to the policy intervention to two years after. Shaded areas span 95 percent confidence intervals.

Next we examine the dynamic effects of the Gothenburg congestion charge on households' car usage decisions by estimating a same regression specification with the dependent variable being the annual mileage of car-owning households. In Figure 15(a) we show the effect on car usage of one-car households, and in 15(b) we show the effect on multi-car households. Starting with the one-car households, we see that the difference in driving between car owners in Gothenburg and the control cities is close to zero prior to introducing the congestion charge, while there is a clear sign indicating reduced driving of car-owning households in Gothenburg during the first three years after implementing the charge. For multi-car households, although the point estimates in Figure 15(b) show reduced driving of multi-car households, the wide confidence intervals indicate such estimates are not precise enough to characterize their actual behavioural responses. As in the case of car ownership, the overall results (not shown) are similar to the results for the one-car households.

The distributional impact of the Gothenburg congestion charge

We have shown that the Gothenburg congestion charge lowers car ownership and reduces driving. But is this policy redistributive? To examine how policy intervention affects the transport choices of low- and high-income households differently, we regress the car owning probability and the amount of driving on the policy intervention indicator, household income, the interaction between these two, and other demographic controls. Therefore, we are able to examine how car owning probability and the amount of driving vary as a function of the annual household disposable income when there is no congestion charge, and how this relationship changes when the Gothenburg congestion charge kicks in. Moreover, in such a regression framework, we are able to tell how the gap in car owning probability and driving between rich and less affluent families changes after introducing a congestion charge.

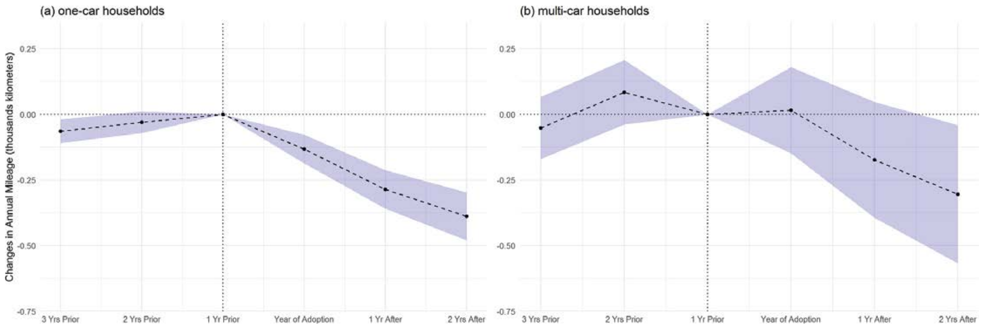

Figure 15. Effect of the Gothenburg congestion charge on private passenger car usage over time: (a) car use by one-car households; (b) car use by multi-car households. The figure plots coefficient estimates representing the difference between car owners in Gothenburg and car owners in control cities, from three years prior to the policy intervention to two years after. Shaded areas span 95 percent confidence intervals.

Our estimates suggest that introducing the Gothenburg congestion charge reduces the car-owning probability, which is consistent with results reported in Table 3. In addition, our estimates indicate that shifting the household annual income from zero to one million SEK leads to a 43 percentage point jump in the probability that the household chooses to own at least one car when there is no congestion charge. Furthermore, we show that this gap in car-owning probability between poor and rich families does not seem to expand when the congestion charge kicks in. Similarly, we see implementing the Gothenburg congestion charge reduces driving and a higher income leads to a higher level of car usage. Again, we find no evidence suggesting that the congestion charge aggravates this difference in car usage between wealthy and less affluent car-owning households.

Price elasticities of demand for car ownership and driving

Using our estimates from the congestion charge study, a back-of-an-envelope calculation of price elasticities reflects fairly inelastic demand for private passenger cars and car usage: if the annual cost of owning and running a car increases by 1 percent, the rate of car ownership declines by around 0.07 percent, while if the marginal cost of running a car increases by 1 percent, driving distance decreases by around 0.15 percent.[30] Our calculations of elasticities are comparable to the elasticity estimates obtained from the recent empirical literature examining the effectiveness of various transport policies. Based on such comparisons, a properly designed congestion charge scheme could be as effective as fuel taxes, mileage taxes, or residential parking charges in reducing car ownership and car usage.

[30] The charge brought in revenue of around 800 million SEK per year during the years of our study. There were around 150 thousand registered cars in Gbg. Hence around 5300 SEK per registered car owner in the city. If half is paid by drivers from outside the city we have 2650 SEK. Annual cost of owning and running car is approximately 50000 SEK, whereas running costs are approximately 25000 SEK. So a 5.3 percent increase in total costs led to a 0.4 percent decrease in ownership, whereas a 10.6 percent increase in running costs led to a 1.6 percent decrease in mileage.

6. Conclusions – Potential routes towards zero urban emissions

The switch towards electric vehicles is well underway, and accelerating. Clear signals from the government about future policy are crucial to this transition, as well as systems such as bonus–malus. However, the key to achieving the 2030 climate target for the transport sector is at least as much about getting fossil cars off the road as it is about getting EVs onto the road. Furthermore, transport policy is about much more than zero carbon. In an electric and transport-intensive future, differentiated mileage taxes based on tracking of individual vehicles might be able to solve many of our problems, but such systems will not be ready before 2030. Under these circumstances, what transport policies are required for the next ten years?

Of course it would help if urban car owners had to pay the true costs of parking their vehicles, and if fuel taxes (for carbon emissions) were complemented urban congestion charges (or other even more precisely targeted charges). Following Norway's example, such charges could be extended to more cities, and the degree of sophistication could be increased (with for instance zonal charging). Such systems could not only improve traffic flows and hence reduce pollution, but also incentivize switches to EVs, and incentivize the scrapping of older polluting vehicles. The latter possibility is particularly interesting in the light of our study. In Figure 7 we saw that around 50 percent of total mileage is by fossil-powered cars that are over 10 years old. Meanwhile, our study of the congestion charge in Gothenburg shows that single-car households diminished significantly in number in response to the charge, while multi-car households were unaffected. A reasonable conjecture is that the charge 'tipped the balance' for thousands of households with relatively old and polluting cars, i.e. households with low annual costs for car ownership (including depreciation). These are precisely the vehicles that should be taken off the road in a socially optimal transition towards zero emissions. Making urban dwellers pay the true costs of parking their vehicles would be expected to have a similar effect. More research is needed on how policy instruments – from fuel taxes to congestion and parking charges – incentivize the scrapping of older vehicles.

Congestion charges may be great, but are they the solution to all our problems? The dramatically lower car ownership in Stockholm shown in Figures 3 and 4 predates the congestion charge there. And our finding that the sensitivity of urban Gothenburg's car owners to the congestion charge is low shows that the main reason for lower car ownership in cities is probably not higher costs, but rather lower perceived benefits. It seems that the added value of owning a car, especially a second car, compared to the alternative – using other forms of transport, perhaps combined with renting – is lower in cities. If this is true, the key to pushing down car ownership should be to further increase the speed and convenience of alternative modes of transport relative to private cars. This suggests that we need packages of measures including further shifts towards higher priority for public transport and cycling, and lower priority for private cars, as well as encouraging alternative models such as car-sharing. Since public transport and cycling can deliver more people to city centres more cheaply and cleanly than cars, this would also encourage the further development of monocentric cities, leading to more efficient labour markets and more productive firms. There is however little evidence on the exact make-up of the optimal package of measures. This suggests another area for further research, which is to use the detailed data available on household choices with regard to car ownership and driving to investigate causal effects of infrastructural and other investments on travel patterns. For instance, to what extent do major road investments cause households to purchase cars and shift their entire transport strategy towards private vehicles?

Finally, no discussion of future urban transport policy can be complete without mention of Covid-19 and teleworking, which is expected to persist after the end of the pandemic and change the structure of the cities in multiple ways. Less office work offers a lot of flexibility and changes the willingness of workers to offer high rents in order to locate close to the business centre. According to estate agents, people are reassessing their housing needs, which has already increased the demand for larger houses or apartments in many big cities. Remote workers want more space and seem willing to locate at the outskirts of big cities. At the same time, firms will need less space, while the commuting distance between firms and workers will increase. Implications for transport policy are as yet unclear, but an obvious danger is that a shift of urban and suburban residents to 'the countryside' will actually lead to sprawling patchwork of settlements in previously rural areas, with poor connectivity to public transport networks. Hence commuters may make fewer journeys, but these journeys may be longer and more likely to be in private vehicles.

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Towards zero emissions from Swedish urban transport

Report from the project 'To buy or not to buy'

In this report we analyse how urban transport policies can help Sweden achieve its environmental goals. We combine theory from urban economics and economic geography with welfare economic analysis and an econometric study of the outcome of the Gothenburg congestion charge.

We cannot rely on electric vehicles alone to achieve the 2030 climate target for the transport sector: we must get fossil cars off the road. Car ownership is relatively low in cities, even though urban drivers do not pay the full costs of congestion, local pollution, and parking; plugging these gaps would help further reduce ownership and driving. However, the low sensitivity of urban Gothenburg's car owners to the congestion charge suggests that the key reason for lower car ownership in cities is not higher costs but lower perceived benefits, hence the key to pushing down car ownership should be to further increase the speed and convenience of alternative modes of transport. We therefore need a package of measures including higher priority for public transport and cycling, and lower priority for private cars. Such measures would also encourage the further development of centralized cities, leading to more efficient labour markets and more productive firms.

NATUR VÅRDS VERKET

SWEDISH ENVIRONMENTAL PROTECTION AGENCY

Naturvårdsverket, SE-106 48 Stockholm. E-mail: registrator@naturvardsverket.se, www.swedishepa.se
Visiting address Stockholm: Virkesvägen 2. Visiting address Östersund: Forskarens väg 5, hus Ub.
Orders ordertel: +46 8-505 933 40, e-mail: natur@cm.se, www.swedishepa.se/publications