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# Optimal kilometre tax for electric passenger cars

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## Abstract

We simulate the external costs from road transport in a 2040 scenario where all gasoline vehicles are replaced by EV's, and we do this for the densest regions of Sweden with a similar degree of urbanization to many other European countries, including cities, suburbs, towns and rural areas. We analyse the optimal kilometre tax based on three motives for taxing use and ownership of EVs: internalizing external cost, cost recovery of the public spending on the road sector, and fiscal taxation for raising revenue over and above what is justified by the two previous principles. We conclude that the optimal Pigouvian tax will be too low to justify the cost of a nationwide GPS-based kilometre tax for many years ahead, for which enforcement would drive the cost. Taxes collected based on roadside equipment systems in the big cities and surrounding highways would be a substantially cheaper way of internalizing most of the congestion cost. A shift from fuel taxes to national congestion taxes would, however, imply a large transfer of resources from the biggest city or cities to the rest of the country, where most of the kilometres are driven

*Keywords*
kilometre tax, milage tax, congestion charges, equity, infrastructure investments, electric cars, fiscal taxes, benefit principle

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R41, R42, R12

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# 1 INTRODUCTION

In most OECD countries, car use and ownership are also among the goods that are taxed the most (OECD, 2019, 2020a). However, increased fuel efficiency and electric passenger cars are progressing fast in the world[1], implying that governments' fuel tax revenue as well as the external costs of road transport will fall. This has led to increasing interest in kilometre taxes in some US states and OECD countries (Coyle et al., 2011; Duncan et al., 2020). In this paper, we add to the literature by simulating the Pigouvian kilometre tax on the link level for the most urbanized part of Sweden (Mälardalen, four million inhabitants), including cities, suburbs, towns and rural areas in a 2040 scenario where all cars are fully electric. We apply the national transport model, which proved to forecast the response to the congestion charges in the two major cities, Stockholm and Gothenburg, with high accuracy (Eliasson et al., 2013; West et al., 2016). Existing studies estimating the congestion cost of electric cars (Kaddoura et al., 2020) are scarce and have focused on big cites.

The results should be fairly transferable to many other countries, since Mälardalen has a similar "degree of urbanization" to that of the Netherlands and the UK and Sweden has a similar "degree of urbanization" to that of the EU, according to Eurostat's (Eurostat, 2021a; SKL, 2017) classification. Sweden also has the same average modal share of road transport and urbanization level as the EU (Eurostat, 2021a, 2021b), and a similar GDP/capita to the US. The population density is 99 inh/km$^2$, similar to that of Spain, Portugal and the US. Our marginal congestion cost is consistent with Delucchi and McCubbin (2011), which is based on US data.

We discuss the effects of the kilometre tax in the light of three common motives for taxing car use and ownership: internalizing external cost, cost recovery of the public spending on the road sector, and fiscal taxation for raising revenue over and above what is justified by the two previous principles. We analyze the spatial distribution and stress the importance of taking into account administrative cost, and in some cases equity and fairness considerations.

All three principles above are presently applied in different parts of the world, and they are not mutually exclusive. The EU adopts the marginal cost principle as well as the financing principle for road transport. In some countries, for instance the US, the revenue from fuel taxes is earmarked specifically to finance the road transport sector (the user or beneficiary pays principle[2]). In Singapore, road user charges were introduced in 1975, primarily as a means to address severe

[1] In Norway 52.2% of cars registered in Norway in 2020 were BEV (Fevang et al., 2021). The Swedish Transport Administration (2020) forecasts that 60 % of new cars will be electric in 2030 and 90% in 2040. EU requirements for the average emissions of newly registered vehicles in 2025 and 2030 are difficult to achieve without a high proportion of electrification.

[2] The old fairness norm that the tax on a person should reflect the benefits of the spending.

congestion following a fast economic and population growth within a geographically small and densely populated country (Theseira, 2020).

Without doubt, there will be a strong case for collecting revenue to internalize the external cost of car use, in particular in big cities, and to collect revenue from the users to cover the public costs for the road transport sector even in an era of electric vehicles (EV). We also find that revenue from the optimal Pigouvian tax would cover the Government's public costs for road transport (as it should in theory if spending is optimal and there are constant returns to scale in capacity extension[3]) (Mohring and Harwitz, 1962). However, we also find that such national taxes would, however, imply a large transfer of resources from the big cities to the rest of the country because the distribution of optimal congestion charge is heavily skewed to the right. In the region of Mälardalen, the optimal congestion tax for electric passenger cars will be higher than the average optimal congestion tax for only 27 percent of the VKT (vehicle kilometres travelled), and this is primarily within the Stockholm County. For half of the VKT in the Mälardalen region, the optimal congestion tax is below 0.025 €/km (roughly 40% of current fuel tax per kilometre for a gasoline car). For the entire country, the tax will be much lower. Since the overwhelming majority of the research papers published on pricing of road transport in the last decades deal with cities, it is easy to gain the impression that most VKT should be heavily priced, but this does not actually seem to be the case.

Moreover, as we describe in Section 3, a key challenge is how to design a technical solution for a kilometre tax that does not result in high enforcement costs (Weatherford, 2011). The administrative cost of fuel taxes is low (roughly 1 % in the US (Kirk and Levinson, 2016)), as it is levied early in the supply chain, from a relatively small number of oil companies. Levying a kilometre tax, differentiated by vehicle type, place and time, requires a comprehensive system for measuring and identifying individual vehicle movements and then claiming the tax from each vehicle owner separately. There is currently no available evidence on the cost of a real GPS-based kilometre tax system, and it is difficult to assess since it is the enforcement that drives cost (Hamilton, 2012). However, we conclude that the optimal Pigouvian tax will be too low to justify the cost of a nationwide GPS-based kilometre tax for many years ahead.

We also find that, in Sweden, the tax revenue from car usage other that the fuel tax (purchase and ownership, parking and congestion charges) exceeded the public spending on road infrastructure (investments and maintenance) costs in 2018. Hence, it cannot be taken for granted that a kilometre tax is needed to comply with the beneficiary pays principle even if the fuel tax is zero. Even if this is not clearly communicated by governments, taxes imposed on car use and ownership usually also have a fiscal purpose (e.g. Leicester (2005) and Fullerton (2008)). Parry and Small (2005) and Lin and Prince (2009) also argued that the gasoline tax is an efficient fiscal tax, because the price elasticity is low (the Ramsey (1927) result). However, as we discuss in Section 2, the fuel price

[3] i.e. x% more spending gives x% more capacity. Capacity must also be a continuous variable for the theorem to hold.

elasticity is not that low, and the Ramsey model disregarded equity and other possible tax instruments. The classic work by Atkinson and Stiglitz (1976) included equity concerns and income taxation, and based on this, Mankiw et al. (2009) concluded that commodities typically should be taxed equally across goods. One intuition behind this result is that goods with low price elasticities are often consumed proportionately more by low-income households.

Moreover, register data on car use from Statistics Sweden display a substantial within-income-group variation in driving distance, due to variation taste and other factors relating to geography and family status (driving distance per adult is higher in rural households and in households with children). This large variation might be a concern for fiscal taxes on car use over and above the tax justified by externalities and the beneficiary pays principle. A common criterion for the horizontal equity of such fiscal tax is that similar households should pay a similar tax (Mankiw et al., 2009). Fiscal taxes (above the Pigouvian tax) on commuting might also introduce deadweight losses on the labour market if its base partly overlaps with an income tax (Parry and Bento, 2001; Van Dender and Tikoudis, 2021).

# 2 THE CASE FOR FISCAL CAR TAX

This section analyses the efficency and equity of a purely fiscal kilometre tax, over and above the tax justified by externalities and the beneficiary pays principle. Now, equity concerns are not limited to such fiscal taxes but also exist for Pigouvian taxes on fuel and congestion (Eliasson, 2016; Eliasson et al., 2018; Levinson, 2010; Small, 1992; Sterner, 2012). But a key difference is that the latter implies that individuals pay the full marginal production cost, as they do for commodities without external effects in a free market. Moreover, at least in Europe, the equity concern for corrective Pigouvian taxes often seems to have a limited impact on car tax policies: it is uncommon to award low-income individuals a discount on taxes imposed on car use and ownership. A contributing reason for this could be that many governments in Europe are in fact both willing and able to undertake substantial redistributions of wealth via the purely fiscal tax and transfer system and the welfare state. Moreover, some would also argue that the beneficiary pays principle, and the polluters play principle are fair in road transport, i.e. that it is fair that car users should cover the public spending on the car transport sector and that those polluting and consuming scarce road space should pay for this.

Ramsey's (1927) work has often been used to advocate a fiscal fuel tax. Assuming no income tax and identical individuals, he showed that the optimal commodity tax is inversely proportional to its price elasticity, because this minimizes deadweight losses from behavioural changes. This was, however, challenged by a second wave of tax literature starting with Mirrlees (1971) and continuing with Atkinson and Stiglitz (A&S) (1976), incorporating distributional aspects as well as income taxation into the models. Since then, an enormous number of papers on optimal taxes have been published. The literature was reviewed in Mankiw et al. (2009), concluding based on A&S that commodities typically should be taxed equally across goods (except for Pigouvian taxes), given the presence of an optimal income tax. Mankiw noted that although the result by A&S does not always hold, it still provides a powerful benchmark.

For a thorough review and understanding of the models and results, we further refer to the review by Mankiw et al. or a textbook in public finance. But the intuition behind the result of Mirrlees (1971) and A&S (1976) is the underlying assumption that the government seeks to tax (exogenously given) ability but avoid taxing (endogenously given) effort. The fundamental problem, they suggest, is that ability and effort cannot be separately observed, implying that the government needs a screening tool, or proxy, for ability. One such tool is labour income; another is the consumption of different commodities (Mankiw et al. review more such possible screening tools). A&S also point out that the efficiency-driven Ramsey result might be regressive because goods with low price elasticities are often necessity goods and thus consumed proportionally more by low-income individuals. For this reason, Ramsey's efficiency term is counteracted by an equity term on the optimal commodity tax. A&S write (pp. 63) that "*With an additively separable utility function and constant marginal utility of leisure, demands depend on the ratio of commodity price to wage. This means that a commodity with a low elasticity of demand appears from an efficiency standpoint to be a good candidate for taxation, but that since the consumption of such a commodity rises only slowly with w [wage], this points to low tax rates for equity reasons. Which of these factors will predominate depends on the form of the social welfare function and on the shape of the distribution of abilities.*"

Ramsey's efficency argument for fiscal taxes on fuel can be questioned, based on the price elasticity. Sterner (2012) summarized the international literature on fuel demand price and income elasticities and stated that although there was a large variation in estimates, there was a consensus that the long-term price elasticity was around -0.8 and the long-term income elasticity around 1.[4] This is higher than, for instance, the price and income elasticity for food, at -0.6 and 0.3 in high-income countries (Clements and Si, 2016; Green et al., 2013) This implies that fuel tax erodes over time, which also seems to be the case.

Following A&S, the relatively normal price elasticity for fuel is an indication that high fuel taxes might attain an acceptable degree of vertical equity. This indication is also supported by Casler and Rafiqui (1993) (for the US). For Sweden, the final column of Table 1 shows that VKT is proportional to the mean income per decile over a large range of the income span, and in addition to this, high-income households have been paying more fuel tax per kilometre, since they have tended to drive bigger and thirstier cars (disregarding the fact that the fuel tax is not paid by more affluent EV owners (Davis and Sallee, 2020; Guo and Kontou, 2021)).

A kilometre tax might be more efficient than a fuel tax, but also have more negative effects on equity, because the (absolute) price elasticity on VKT is lower than on fuel demand (Brons et al., 2014). This is because consumers cannot avoid

[4] Fuel taxation is much lower in the short run than in the long run. On average over studies, it was -0.22 to -0.31 in the short term, and -0.80 to 1.01 in the long term (Lin and Prince, 2009).

tax by driving less thirsty cars. Specifically, low-income households cannot reduce their tax by switching to smaller and less thirsty cars.[5] Conditional on car choice, Bento et al. find a fuel price elasticity on VKT at -0.34 for the US. Small and Van Dender (2007c) report the long-run price elasticity on VKT of -0.21 for the US; this could be lower than that of Bento et al. because drivers can adapt by changing car. Bastian et al. (2016), find higher VKT fuel price elasticities for France, Australia, the UK (-0.31, -0.36 to -0.37) and lower elasticities for Germany, the US and Sweden (-0.14, -0.18, -023). Dahl and Sterner (1991), find fuel price and income elasticities of around -0.3 and Sterner and Dahl (1992) find a similar figure for Sweden. Hence, because the price of electricity on VKT is in general lower than for fossil fuel, a kilometre tax risks being less progressive than the fuel tax has been in the past, since low-income households cannot adapt to smaller cars.

In addition, the natural horizontal equity criterion, whereby individuals with similar income pay the same tax, could be a concern for a purely fiscal kilometre tax, due to the substantial within-income group variation in VKT. Table 1 shows that there are many high-income households not owning a car, and there are low-income households driving frequently. Moreover, household composition and the geographical dimensions play an important role for VKT. Table 1 shows that the average VKT per adult is almost 50% higher for households with children. This means that a fiscal taxation on car use would imply higher taxes on families. Also, those living outside suburbs and medium-sized cities drive on average more, while big city dwellers drive substantially less. But even within these groups there is a substantial individual variation.

Another concern for fiscal taxes on car use, in countries with high marginal income tax rates, is related to the efficiency of the labour market. Commute trips is a complement to labour supply, and hence a tax on driving could result in an increase in the effective tax rate on labour, which can have a negative effect on labour supply and thereby on welfare. This might even be a problem for the optimal Pigouvian tax when income taxes are high, resulting in higher effective labour taxes when alternatives for driving are scarce and when working arrangements are rigid, because the share of commute trips is highest in peak hours when the external effects from driving are also highest. The negative effect on labour supply is weakened if the time of day or transport mode of commuting trips can be adjusted (Parry and Bento, 2001). It may also be weaker if working from home full days is possible (which may increase after the COVID-19 pandemic) or if more productive workers have high values of time (Anderstig et al., 2012).

[5]Older cars are less fuel-efficient, but not only low-income households are largely obliged to turn to the used car market. In Sweden only 30% of new passenger cars are bought by private individuals (the rest are sold to legal entities) but private individuals own almost 80% of all passenger cars. And for cars of the same age, smaller cars consume less gasoline.

*Table 1: Yearly income and VKT per adult in households by income decile and household type (with or without children < 19 years), 2016. Roughly 30 percent of the households do not have a car in the household, and the 10 decile is zero in all rows.*

| | Average net income €/y | Mean VKT km/year, thousands | VKT, Sd km/year, thousand | VKT 90 percentile km/year, thousands | Number of households million | Ratio: mean VKT/ income km/€ |
|---|---|---|---|---|---|---|
| 1 | 5 560 | 1.9 | 26.9 | 6.4 | 0.5 | 0.34 |
| 2 | 13 506 | 2.1 | 6.0 | 8.2 | 0.5 | 0.16 |
| 3 | 16 398 | 3.3 | 6.5 | 11.6 | 0.5 | 0.20 |
| 4 | 20 016 | 4.9 | 8.1 | 15.4 | 0.5 | 0.24 |
| 5 | 22 926 | 6.4 | 8.8 | 17.6 | 0.5 | 0.28 |
| 6 | 25 561 | 7.2 | 9.1 | 18.8 | 0.5 | 0.28 |
| 7 | 27 697 | 7.3 | 8.6 | 18.1 | 0.5 | 0.26 |
| 8 | 27 956 | 7.8 | 7.4 | 16.9 | 0.5 | 0.28 |
| 9 | 31 585 | 8.4 | 7.1 | 17.3 | 0.5 | 0.27 |
| 10 | 63 945 | 7.3 | 6.8 | 16.0 | 0.5 | 0.11 |
| Total | 25 514 | 5.7 | 11.4 | 15.8 | 5.3 | 0.22 |
| No children | 24 068 | 5.1 | 12.0 | 15.2 | 4.15 | 0.21 |
| Children | 30 743 | 7.5 | 8.6 | 16.9 | 1.15 | 0.24 |
| Total | 25 514 | 5.7 | 11.4 | 15.8 | 5.3 | 0.22 |
| Big city > 200,000 inh | 28 689 | 3.2 | 19.1 | 11 | 1.0 | 0.11 |
| Suburb - big city | 30 253 | 5.6 | 7.7 | 15.1 | 0.8 | 0.18 |
| Medium-sized city > 50,000 inh | 24 184 | 5.7 | 7.8 | 15.6 | 1.6 | 0.24 |
| Rest of Sweden | 22 864 | 7.1 | 9.3 | 17.9 | 1.9 | 0.31 |
| Total | 25 514 | 5.7 | 11.4 | 15.8 | 5.3 | 0.22 |

Even if this paper primarily deals with passenger cars, we note in passing that Diamond and Mirrlees (1971a, 1971b) advise against fiscal taxation of freight transport (over and above the optimal Pigouvian tax) since this is an input in the production, and not, like most passenger car use, a consumer product.

Almost all tax literature has underscored the importance of taking the administrative cost of the tax into account, which is a third argument against a fiscal kilometre tax.

# 3 ADMINISTRATIVE COST OF A KILOMETRE TAX

The administrative cost a fuel tax is roughly 1% in the US and in Sweden (Kirk and Levinson, 2016; Transport Analysis, 2018). The cost of a kilometre tax will always be higher because the movement of a large number of vehicles must be monitored in some way. The more precisely the tax is required to match the external cost, the higher the costs will be because more dimensions of the use must be more accurately monitored.

User charge systems exist worldwide, but their design varies and there are roughly three different technical approaches. The first, a time-based vignette, is common for heavy traffic, and is often a charge linked to a registration number and registered in a database. For passenger traffic, a yearly vehicle tax is similar to a vignette. This is cheap but since they are flat taxes, they cannot be differentiated by distance travelled, time, space, or temporary vehicle configuration, such as the presence of trailers. (Still, since the total travel distance of a heavy truck varies less than for a passenger car this might be less of a problem if congestion is disregarded).

The second approach is based on roadside equipment, often using ANPR (automatic number plate registration) cameras in combination with DSRC (Dedicated Short-Range Communications) transponders in the vehicles, where DSRC often acts as the primary source of vehicle identity and ANPR is used for enforcement. The congestion tax systems in London, Stockholm and Gothenburg were among the first to rely entirely on ANPR, so that no equipment is required in the vehicle. Since the congestion charge was introduced in London in 2003, the precision and capacity of ANPR have increased, and costs have decreased, and there is no indication that this development is levelling out. Moreover, a monitored road network could generate additional benefits if used by other authorities such as the customs and the police. The cost of the Swedish congestion charging systems based on ANPR is now down to an administrative cost of 15% per year, but was 31% in the first year (Börjesson and Kristoffersson, 2018; Trafikanalys, 2018). The system cost of the London charging system in 2016 was 35% of the revenue (Transport for London, 2016), which is still a large improvement from the initial 76% for the first year (Transport for London, 2004).

The system cost of Norwegian toll rings (based on DSRC transponders and ANPR for enforcement) was 8.4% of the revenue in 2019, and this has steadily decreased as the revenue has more than tripled since 2002 (Statens vegvesen, 2020). The revenue of the Norwegian road tolls in 2019 was just below €1.2 billion, roughly five times more than the combined revenue of Stockholm and Gothenburg congestion charges in 2019 (€0.25 billion) and similar to the revenue of the London system in 2018, £0.23 million. Hence, the lower and declining cost of the Norwegian toll system indicates economies of scale effects. The administration cost of parking fees in Stockholm is in the same range, 18% (Trafikanalys, 2018), and it is again enforcement that drives the costs.

The third approach is based on autonomous onboard devices in the vehicles, constantly recording the vehicles' movement and configuration by satellite positioning (GPS). In some areas, typically where buildings are high, such a system needs to be supplemented with roadside equipment. To achieve this, however, authorities must be able to trust the system. If the authority needs to verify the onboard devices by a parallel enforcement system of roadside equipment the costs rapidly grow, in particular if the road network is large. Because the enforcement system can be expensive, the administrative cost of such a system is difficult to assess. There are no large-scale satellite-based kilometre charges for light traffic yet, although Singapore plans to introduce a similar technology, and has found that a substantial amount of supplementary roadside equipment is required (Theseira, 2020). This will drive cost, in particular if the system covers a large geographical area.

In the ANPR-based systems the enforcement is built-in, and they do not need the same precision, because if a vehicle passes unidentified, it is not taxable. But this could not be the case for a GPS-based system, because it would be too easy to systematically manipulate the onboard unit for satellite positioning to report fewer kilometres than are actually driven. Those who try must therefore be discovered and fined to maintain the legitimacy of the system. The tax authority may reduce the cost of enforcement by independent observations by only allowing trusted on-board units, protected from tampering (even though there will always be some risk). The development of such units would, however, come at a large, fixed cost, and so for small countries the cost would be high per unit. This would be a smaller problem if the fixed costs could be shared by many through global coordination, or at least within large markets at the EU or the US level.

Moreover, if the authorities required on-board units based on a strict technical specification, which in the worst case is developed locally, the cost would probably be higher than if it were based on functionality requirements. In the latter case, the customers can choose equipment from whichever supplier they want, as long as they meet the requirements set by the government. Competition would be introduced among manufacturers of the equipment in a market where they have incentives to look for innovation, economies of scale and coordination with other functions.

Until such a system exists, a good alternative could be to extend (or implement) an ANPR-based system in the parts of the road network with high congestion, rather than to introduce GPS-based systems, in Sweden and elsewhere. As we will see in the applied modelling study, such a strategy would probably internalize most of the congestion cost.

The issue of integrity has been raised. Still, it has become a matter of course that we leave traces of most of what we do in our digital lives. This is a political rather than an economic issue that is not limited to the taxation of car use.

# 4 CASE STUDY: MÄLARDALEN, SWEDEN

## 4.1 The Study Area

In this section, we will simulate the optimal kilometre tax for EVs internalizing congestion and other external costs for Sweden, excluding for the moment administration costs. We will show how the tax varies substantially between links, areas and regions. We will also compare the total revenue from such a tax (excluding administration costs) and compare it with the public costs for the road transport sector, to study the cost coverage of a Pigouvian tax for EVs.

We will focus on the entire Mälardalen area, where roughly 40% of the Swedish population (four million) live, and which includes the two cities with most congestion in Sweden (Stockholm and Uppsala), as well as medium-sized towns and rural areas. The main reason for choosing Mälardalen as the study area is that there exists a carefully estimated and calibrated state-of-practice transport model for the area. It is unique in that it has been validated against two real-world large-scale implementations of congestion charges (in Stockholm and Gothenburg). The model has also been validated against later increases in the congestion charge. The model is static, which means that it will underestimate the cost of congestion on the most heavily congested bottlenecks to and from central Stockholm (Eliasson et al., 2013). Still, the model was able to predict the impact on travel times in the rest of the network with high accuracy, and also the impact on the traffic volumes in all parts of the network. Moreover, the model was able to predict changes in both travel times and volumes in response to the congestion charges in Gothenburg with good accuracy (West et al., 2016). Hence, it should be able to predict effects on travel times with good accuracy outside the worst bottlenecks of Stockholm.

A relevant issue is the representativity of the simulated congestion cost, and its spatial distribution. For this reason, Table 2 aims at describing the degree of urbanization of Sweden and the study area Mälardalen, relative to other European countries. The table indicates that our results for the study area Mälardalen, and for Sweden as a whole, should be fairly transferable to many other countries, since Mälardalen has a similar “degree of urbanization” to that of the Netherlands and the UK and Sweden has a similar “degree of urbanization” to that of the EU, according to Eurostat’s (2021a) classification. Sweden also has the same average modal share of road transport and urbanization level as the EU (Eurostat, 2021a, 2021b) and a similar GDP/capita to the US.

*Table 2: Degree of Urbanization for the EU and for a selection of European countries and our study area Mälardalen 2020. Source Eurostat (2021a) and SKL (2017).*

| | Cities | Towns and suburbs | Rural areas |
|---|---:|---:|---:|
| Austria | 32% | 30% | 39% |
| Belgium | 28% | 58% | 14% |
| France | 45% | 20% | 35% |
| Germany | 39% | 40% | 20% |
| Italy | 34% | 47% | 18% |
| Netherlands | 58% | 33% | 10% |
| Spain | 55% | 34% | 13% |
| Switzerland | 30% | 52% | 19% |
| United Kingdom | 58% | 29% | 12% |
| European Union-27 | 40% | 34% | 26% |
| Sweden | 37% | 36% | 27% |
| Mälardalen | 60% | 31% | 9% |

This paper focuses on passenger cars. However, since heavy traffic causes substantially greater external costs in terms of wear and tear on the road, accidents and congestion, an optimal Pigouvian kilometre tax on heavy (electric or not) vehicles will generate a significant revenue. However, the large proportion of trucks driving outside the country they are registered in, will probably increase the enforcement cost of a kilometre tax for heavy vehicles. There are, on the other hand, factors indicating a lower administration cost for a kilometre tax for heavy vehicles: the number of unique heavy trucks is relatively small compared with the number of light vehicles (roughly 1.5% of the vehicles registered in Sweden are heavy), the external cost per kilometre of heavy trucks is higher, and the yearly distance per vehicle is high. Kilometre taxes for heavy traffic are also already imposed in many countries. To assess the optimal revenue from road transport, we include heavy trucks in the calculation of the revenue from the optimal Pigouvian kilometre tax.

## 4.2 Marginal external cost of EV other than congestion

The main external costs for passenger cars are emissions, noise, accidents, wear and tear on the infrastructure, and congestion. For heavy vehicles, the marginal cost of wear and tear is a much larger external marginal cost.

We approximate the external cost of emissions from electric vehicles to zero within EU, since the external cost of the electricity production is internalized by the EU-ETS system. Emissions from the electric car while driving are limited to particles from tyre abrasion and the brakes (Garg et al., 2000). However, since this is the biggest source of particle pollution (Amato, 2018), and because electric cars are heavier than other cars, it is unlikely that they will emit fewer particles than gasoline cars (OECD, 2020b). Using valuations from Nilsson and Johansson (2014) and emission factors for gasoline cars from HBEFA 4.1 (2019), the Swedish government agency Transport Analysis (2021) arrives at the figures in the first row of Table 3.

The marginal cost of noise reduces with the baseline noise level (Haling and Cohen, 2007) and increases with population density, implying that it is higher in urban areas and at night. Moreover, below speeds of 40 km/h the noise from the engine dominates and for electric vehicles this is very low. Hence, in urban areas, where speeds are low, and in particular at night, the marginal external noise cost of electric vehicles will be lower. At higher speeds, noise stemming from tyre aerodynamics dominates and the marginal external cost of noise will be similar for EVs and for standard cars. Hence, the marginal cost of noise will be more similar between night and day and for urban and rural areas for EVs than for cars with combustion engines. According to appendix A, the marginal cost of noise in daytime and urban areas is roughly 0.1 ¢/km in Europe (and average across night and day and 0.2 ¢/km for Sweden). We assume that the cost of noise from EVs at night will drop to the day level so that the total average will be 0.1 ¢/km. For some rural areas this will probably be an overestimation, but we keep it for simplicity. For heavy traffic we assume that the noise cost will remain at the same level as for present-day trucks, since speeds are normally high.

The marginal external cost of accidents referred to in the previous US and European literature is reviewed in Appendix A and lies in the range of 0-2 ¢/vkm. The key issue determining the external cost of traffic accidents is the extent to which the accident rate ($\lambda$) increases with increasing traffic flows (Q). Dickerson (2000) assumes that the number of accidents is in the form $N = \lambda Q^{\alpha}$, implying that the average cost is $\lambda Q^{\alpha-1}$ and the marginal cost is $\alpha\lambda Q^{\alpha-1}$, such that the external cost is $\lambda Q^{\alpha-1}(\alpha - 1)$. If accidents involve two vehicles and the probability of accidents depends only on the number of passing vehicles, the number of accidents N will increase as the square of the flow Q such that $\alpha$ =2. However, if drivers adapt behaviour in response to the higher risks induced by larger traffic volumes, $\alpha$ is lower. If $\alpha$ equals one, such that the number of accidents is proportional to the traffic flow, the external accident cost has traditionally been taken to be zero in the literature (even if this is not entirely correct because in this case other drivers are making costly behavioural adjustments as a marginal driver is added, but how costly they are is difficult to measure). Vickrey (1968) estimates $\alpha$ for Californian freeways at 1.5. Newbery (1988) argues that 1.25 is more appropriate. Vitaliano and Held (1991) estimate $\alpha$ at 0.98 for New York State. Also, a newer Swedish study by Isacsson and Liss (2016) indicates that the marginal external cost of accidents in 2004–2012 was roughly zero. In this study, we therefore assume that the external cost of accidents is zero. Increased automation of EVs is also likely to decrease the risk of accidents.

In addition, we will assume wear and tear cost for passenger cars and trucks based on Nilsson et al. (2020) in Table 3. The figures refer to vehicles with combustion engines and we assume that these are the same for electric vehicles.

Table 3 summarizes the external marginal costs assumed for electric passenger cars and heavy trucks in this paper. The numbers are based on 2018 price levels. In the analysis, we assume that the valuation of noise and emissions increases by 1.5 per year up until 2040 due to increasing incomes. Congestion is not included in the table and is the topic of the next section.

*Table 3: Assessed marginal external cost of road transport for electric vehicles in Sweden, euro cents (¢)/km.*

| | Light vehicles ¢ /km | truck without trailer ¢/km | truck with trailer ¢/km |
|---|---|---|---|
| Emissions from brakes and tyres *Souce: Transport analysis (2021)* | 0.2 (0.6/0.01 urban/rural). | 1.6 (4.8/0.05 urban/rural). | 1.2 (5.8/0.05 urban/rural). |
| Noise (for trucks the *source: Nilsson et al. (2020))* | 0.1 | 0. 7 | 1.8 |
| Accidents *Souce: Isacsson and Liss (2016)* | 0 | 2.6 | 2.6 |
| Carbon emission | 0 | 0 | 0 |
| Wear and tear on the road infrastructure *Source: Nilsson et al. (2020)* | 0.4 | 4.1 | 16.9 |
| Sum | 0.7 ¢/km | | |
| Congestion | To be simulated | To be simulated | To be simulated |

## 4.3 External congestion cost

Tables 10 and 11 in Appendix A summarize the congestion cost for a number of countries. They show that the average congestion costs are in general higher for the UK than the US, which is probably due to lower average population densities in the latter. Still, the tables show that there is huge variation across time and space. The estimates for Germany show a substantial variation between different types of road. A large variation even within a city is demonstrated by Kaddoura (2020), calculating the optimal congestion charge in Berlin with dynamic simulation, and finding that for 95 percent of all trips, it ranges within 0.05-0.3 €/km. But for some trips, the external congestion cost can reach 7 €/km. Because of the large variation, we will simulate the external congestion cost of Sweden for the year 2040 using the Swedish National Transportation model (described in Appendix B), in a scenario where all cars are electric.

Assume for simplicity in this subsection that delay is the only marginal external cost of the traffic. Let the generalized travel cost be $c = W \cdot t(D) + \tau$, where *t(D)* is the travel time, depending on the traffic volume *D,* and $W$ is the value of travel time. The parameter $\tau$ is the kilometre tax. Let *p(D)* be the inverse demand function. Assuming that there is only one origin-destination pair, the total welfare is

$$\Omega \ = \int_0^D p(x)dx - cD + \tau D \ = \int_0^D p(x)dx - [Wt(D) + \tau]D + \tau D =$$
$$= \int_0^D p(x)dx - Wt(D)D.$$

Deriving $\Omega$ with respect to $D$, equating to zero, and using that *p(D)* = *c* in equilibrium, yields the optimal tax $\tau = Wt'(D)D$. Now, in a network with many origin-destination pairs, the welfare changes must be summed over all origin-destination pairs (Neuburger, 1971) as in Kaddoura et al. (2020). If, as we do in this paper, we optimize welfare and calculate the optimal tax at link level, an error is induced if the tax introduces a route choice effect. We disregard this error because it should be relatively small in the Stockholm network, where we have the most congestion, because route choice effects are limited in a city build on islands.

The road network in the region Mälardalen is coded in the form of 52 006 links ($k$) with an average length of just over 700 metres. To approximate $t'(D)$ we design a baseline 2040 scenario and an EV scenario for 2040. The scenarios are developed by the Swedish Transport Administration, but the driving costs are changed in line with Table 4. The assumed electricity price is higher than the current Swedish price but lower than the German price (EUROSTAT, 2020), since we assume that the electricity price will increase due to increased demand and due to the EU-ETS target gradually being reduced to reach zero in 2050.

*Table 4: Driving costs in baseline and EV scenario. Price level 2018.*

| | Baseline | EV |
|---|---|---|
| Fuel consumption | 0.06 l/km | 0.18 KhW/km |
| Fuel price | 1.5 €/l | 0.27 €/kWh |
| Fuel cost | 0.09 €/km | 0.05€/km |
| Capital cost, depreciation | 0.09 €/km | 0.09 €/km |
| Tax 2021 € | 0.97 €/l gasoline | 0.04414 €/kWh |
| Tax 2021 €/km | 0.06 €/km gasoline | 0.008 €/kWh |
| Weighted average[6] $\overline{W}$ | 24 €/h | 24 €/h |

[6] The average W is 48, 14 and 18 €/km for business, private regional and private long-distance trips, respectively, constituting 27%, 15%, and 58% share of trips on the aggregate level.

The travel times for a given link *k* and a time-of-day *h (am peak, mid-day, pm peak, night)* is for the baseline (0) and the EV-only scenario (1) $t_{h,k}^{0}$ and $t_{h,k}^{1}$, respectively. The optimal tax for link $k$ (with length $l_k$) and time period $h$ is approximated as

$$\tau_{h,l} = \frac{\bar{W} t'_{h,k}(D) D_{h,k}}{l_k} \approx \frac{\frac{\bar{W} D_t \Delta t_{h,k}}{\Delta D_{h,k}}}{l_k},$$

where $\Delta t_{h,k} = \left(t_{h,k}^{1} - t_{h,k}^{0}\right)$ and $D_{h,k}$ is the number of vehicles on the link. $\bar{W}$ is the weighted average value of time.[5] Since the derivative $t'_{h,k}$ increases with traffic volume *D,* the accuracy of the approximation will mostly depend on the real outcome of the traffic volume in 2040, which will also be impacted by factors such as population and GDP growth, as well as urbanization car ownership.

The Mälardalen region, shown in the left part of Figure 1, is divided into five counties. The figure shows the difference in travel time between the two scenarios in the peak. The county of Stockholm, suffering from the highest congestion levels in the country, is depicted with a purple line on the left map and zoomed in on the right map. The figure shows significant effects on the travel time in central Stockholm and on urban motorways to and from Stockholm. On the overall level, we find a total increase of 8% for passenger cars due to the lower cost of the EVs. This can be compared with the 30% higher traffic level in the baseline 2040 scenario compared to 2017, due to economic growth and population growth, which has impacted the travel times in the baseline scenario.

The 8% increase in VKT of passenger cars implies a fuel price elasticity of -0.17. This is lower than the price elasticity on VKT of -0.3 reported in section 2. One reason for the lower estimate could be a stronger response to price increases than to price drops (Bastian et al., 2016; 1997). Interpreting the reduction in kilometre cost as a gain in fuel efficiency would imply the rebound effect of 0.17, i.e. that 0.17 of the fuel cost savings implied by the increase in fuel efficiency would be cancelled out due to longer driving distances. Since a transport model is estimated on cross-section data in equilibrium, we can interpret this as a long-run rebound effect. The figure is in line with De Borger et al. (2016) and Small and Van Dender (2007), finding a rebound effect in the range 0.07 - 0.2, where the long-run effect tends to be higher (De Borger et al., 2021).

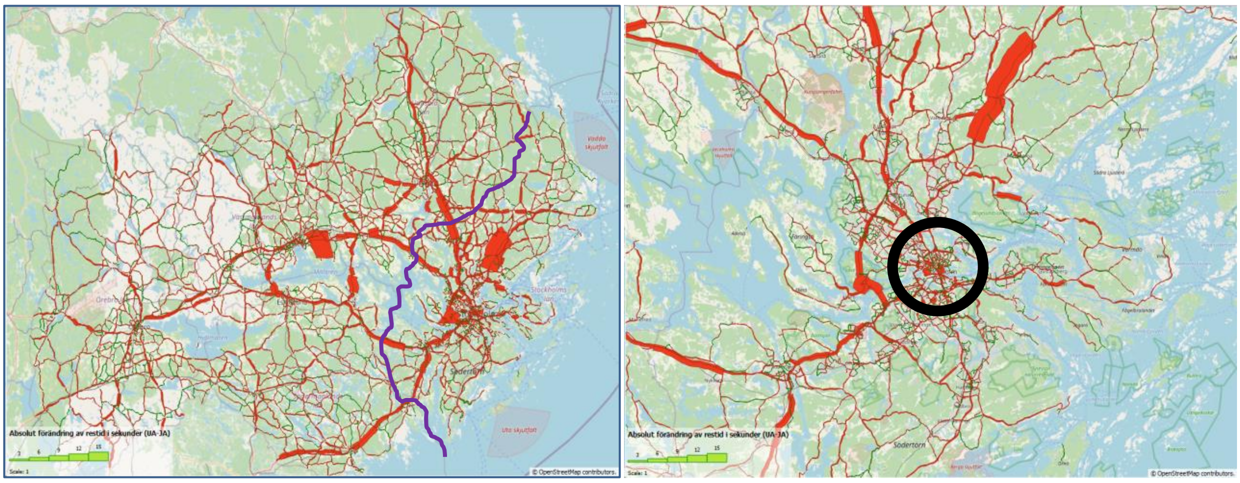
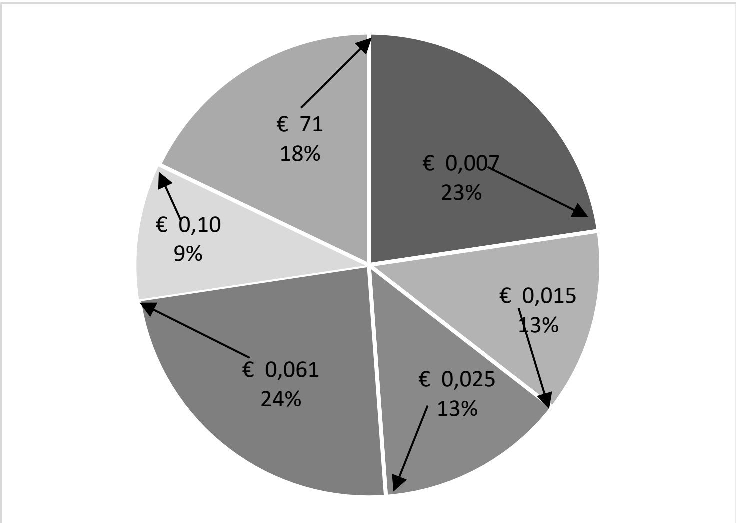


*Figure 1: Changes in travel time in minutes between the scenarios. Left: Mälardalen region, Stockholm County depicted in purple. Right: Stockholm County, current congestion charging cordon depicted in black.*

*Table 5: Percentiles for the optimal kilometre tax in euro per km [€/km] calculated for four time periods. Weighted average kilometre tax is shown on the bottom line.*

| Percentile | AM peak: 7AM-9PM | PM peak: 3PM-6 PM | Mid-day 9AM-15PM | Night PM 6 - AM 7 |
|---|---|---|---|---|
| 50 | 0.0 | 0.01 | 0.0 | 0.00 |
| 75 | 0.09 | 0.12 | 0.07 | 0.02 |
| 90 | 0.34 | 0.40 | 0.27 | 0.08 |
| 99 | 2.36 | 2.55 | 1.62 | 0.40 |
| 99.9 | 9.96 | 10.74 | 3.82 | 0.79 |
| Average tax in the network (weighted by the length of the links) | 0.013 | 0.016 | 0.001 | 0.003 |
| Average tax (weighted by the VKT of the links) | 0.089 | 0.109 | 0.063 | 0.018 |




| Distribution of $\tau_{h,l}$ for all links and time periods | |
|---|---|
| 0.007 €/km | 75 percentile |
| 0.015 €/km | mean |
| 0.025 €/km | 90 percentile |
| 0.10 €/km | 98 percentile |
| 71 €/km | 99.99 percentile |

*Figure 2: The shares of total kilometres paying the maximal kilometre tax depicted. All thresholds correspond to percentiles or means of the distribution of $\tau_{h,l}$ for all links and time periods except for 0.061 €/km, which is the mean of the optimal kilometre tax for all VKT driven. Note that the mean for all VKT is much higher than the mean for all time periods and links, because links and time periods with more VKT have higher kilometre tax.*

The distribution of the optimal kilometre tax by time period is shown in Table 5. In the final row, the average optimal tax weighted by the VKT is shown: 0.10 €/km for the afternoon peak and 0.02 €/km for the night hours (for the region as a whole). The average is lower if weighted by link length, because the VKT is higher on links with high tax. The average tax weighted by VKT over all time periods is 0.06 €/km. The optimal tax is moderate for most links and periods. However, there are some specific links with very high optimal taxes. Table 12 in the Appendix shows that the average optimal kilometre tax is roughly five times higher in the Stockholm County than elsewhere in the peak hours.

Our estimates of the average costs are lower than Mayeres and Proost's (2000) figures for Belgium, Newbery's (1990) figures for the UK and Kaddoura at al.'s (2020) calculation for Berlin (Appendix A). This is partly because the region we model is less dense (including rural areas), and possibly also because Stockholm already has congestion charges. Our numbers are, however, consistent with Delucchi and McCubbin (2011), estimating the marginal congestion cost for the US at 0.006-0.05 with the same density as the Mälardalen region.

What is most important here, however, is the huge variation in optimal congestion cost over time and space, and that a large part of the distance driven takes place at times and places with very low congestion. Figure 2 shows how the VKT in the Mälardalen is distributed on links and time periods with different taxes. 27% of the VKT is driven on links with higher charge than the average tax 0.061 €/km. Hence 73% of the VKT takes place on links with lower charge. Almost half of the VKT are on links with a lower tax than 0.025 €/km. This implies that an optimal kilometre tax replacing a national fuel tax would mean a large transfer from denser areas to the less dense.

## 4.4 Revenue from a Pigouvian Tax on EVs

We continue with an assessment of the revenue that an optimal kilometre tax would generate, disregarding administration and investment costs of the system, shown in Table 6. Columns 1 and 2 show the revenue from the optimal tax internalizing congestion in 2040 for the six counties in Mälardalen, for light vehicles and heavy trucks, respectively. To compute the latter, we use a rough assumption that the marginal congestion cost of trucks without trailers is 1.5 times and twice that of passenger cars.[7] The total revenue for the other counties of Sweden is assessed by assuming that the revenue by county is proportional to population density times the total VKT. Column 6 shows the yearly congestion tax paid per inhabitant by county. The citizens of Stockholm pay roughly twice the national average.

Next, the table shows the revenue from an optimal congestion tax internalizing other external cost than congestion (see Table 3), for light vehicles and trucks. The final columns show the total revenue from an optimal Pigouvian tax internalizing congestion and other external cost, and the total tax per person. The total revenue would be roughly €5 B/year but only just above 50% would be

[7] According to the Swedish Transport Administration (2013), the passenger car equivalent is between 1.3 and 3.4, depending on whether the truck has a trailer and the slope of the road.

collected from passenger cars, and just below 30% of the total tax (and 50% of the congestion tax) would be collected in Stockholm. Because we have simulated the optimal congestion tax applying a static model, we have probably underestimated the optimal congestion tax in the bottlenecks in central Stockholm but not in the rest of the country, so the tax burden might be relatively higher in the Stockholm region.

*Table 6: Revenue of an optimal Pigouvian tax assuming that all vehicles were electric and assuming no administration cost.*

| | Congest -ion tax rev., M€/y | | Vehicle km million per year, EV-scenario 2040 | | | Congestion tax revenue per person €/year | Tax revenue external cost excl. congestion M€/year | | | Tax revenue total M€/year | Total tax revenue per person €/year |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Light vehicles | Higher tax trucks | 2040 | 2017 | Population 2020 | | Passenger cars | Truck without trailer | Truck with trailer | | |
| Stockholm | 1018 | 174 | 13 571 | 9 940 | 2.39 | 498 | 99 | 96 | 92 | 1 479 | 618 |
| Uppsala | 89 | 17 | 3 857 | 2 825 | 0.39 | 275 | 28 | 22 | 45 | 201 | 518 |
| Södermanl. | 58 | 17 | 2 965 | 2 172 | 0.30 | 251 | 20 | 22 | 52 | 170 | 568 |
| Gotland | 3 | 0 | 418 | 306 | 0.06 | 52 | 3 | 2 | 1 | 10 | 159 |
| Örebro | 58 | 21 | 2 766 | 2 026 | 0.31 | 259 | 19 | 22 | 64 | 183 | 600 |
| Västermanl. | 62 | 18 | 2 441 | 1 788 | 0.3 | 290 | 17 | 18 | 45 | 160 | 576 |
| **Mälardalen** | **1274** | **276** | **26 019** | **19 057** | **3.7** | **416** | **186** | **183** | **298** | **2 217** | **595** |
| **Other** | **289** | **63** | **45 374** | **33 234** | **450** | **100** | **324** | **319** | **519** | **1 514** | **429** |
| *Sweden* | *1949* | *422* | *101 442* | *74 300* | *10.4* | *228* | *724* | *712* | *1 161* | *4 969* | *479* |

For comparison, Table 7 gives some indication of how a kilometre tax proportional to VKT (similar to a fuel tax) would be distributed. It shows that in Sweden only 11% of the VKT is driven by the population of the big cities. Another 15% is driven by the population in the suburbs, including commuting to the city, but since only 25% of VKT constitutes commuting, little of this is driven in the city. The peak city and suburban trips to the centre thus constitute roughly 10% of the total VTK, which is the traffic which would be subject to a significant congestion tax (this share is also what most literature in transport economics has focused on). Another 30% of the VKT takes place in small urban areas with mostly low congestion cost with some exceptions in specific areas or links. Finally, almost half of the VKT takes place in the rest of Sweden, where the congestion cost is close to zero. In this group, the travel distance per person is also higher.

*Table 7: Travel distance per adult in households by type of municipality, 2016.*

| | VKT, mean km/year, thousand | # households million | Share of total VKT in Sweden |
|---|---|---|---|
| Big City > 200 000 inh | 3.2 | 1.0 | 11% |
| Suburb outside big city | 5.6 | 0.8 | 15% |
| Small urban areas > 50 000 inhabitants | 5.7 | 1.6 | 30% |
| Rest of Sweden | 7.1 | 1.9 | 44% |
| Total | 5.7 | 5.3 | 100% |

Given the high administration cost of a GPS-based nationwide kilometre tax as discussed in section 3, a good option would be an extension of the ANPR-based congestion charging system to the most congested motorways and bottlenecks in Stockholm, and a few more urban areas by 2040. This would probably internalize most of the congestion in the country. To internalize other external costs of passenger car, and possibly remaining congestion cost, a yearly vehicle tax could be a possible instrument with relatively low administration costs. For EU-ETS member countries (internalizing the social cost of carbon from electricity production) that already have a tax on electricity, like Sweden and Germany, the electricity tax possibly already internalizes the external cost of car use not related to congestion. In Sweden, the tax per kilometre of EVs is presently 0.008 €/km (the excise duty on electricity is 0.045 €/kWh in 2021 and the energy consumption of electric cars is around 0.18 KhW/km), which is very close to the external cost of passenger cars excluding congestion according to Table 3. However, Sweden has a higher tax on electricity than most other OECD counties.

## 4.5 Cost coverage of a Pigouvian Tax on EVs

In Sweden the fuel/energy tax per vehicle kilometre for an electric car is presently 13 percent of the tax of a gasoline car.[8] This share is high compared to most European countries, for which the ratio is mostly below 10%, depending on the excise duties on electricity and the fuel tax (OECD, 2019). For many of the OECD countries outside Europe, the ratio is close to zero. This raises the issue of how to internalize external effects that are not captured by a congestion tax in the cities and maintaining the cost coverage of public spending on road infrastructure (if these natural principles apply). Vehicle ownership and purchase taxes  are levied in most OECD countries (OECD, 2020a) and can contribute to the public funding of road infrastructure, even if the electricity tax is low. Vehicle taxes are increasingly being used to impact the consumer choices of greener vehicles, which might reduce the tax revenue (van Dender, 2019), but when the vehicle fleet is all electric, exemptions, subsidies and tax reliefs could be removed.

Taking Sweden as an example, the maintenance and investment costs for road infrastructure amounted to 2.5 B€/year in 2018. The tax and fees collected from road users were in the same year 9.3 B€ (yearly vehicle tax and VAT on car purchases 2.4 B€/year, congestion tax 0.3 B€/year, fuel tax (plus VAT for private traffic) 5.5 €/year, and parking fees etc.) (Transport Analysis, 2018).  Hence, even with zero fuel tax, other taxes on car users (4 B€/year) would still exceed the public infrastructure cost of 2.5 B€/year.

Note also that the optimal Pigouvian tax 2040 of 5 B€/year (collected by extending the present congestion tax system, excise duty on electricity and possibly yearly vehicle tax), would alone cover the spending on road infrastructure if this spending did not more than double (in real terms) between 2018 and 2040.

# 5 CONCUSION

For various reasons, it is commonly assumed that the present fuel tax in many countries will be replaced by a kilometre tax in an era of electric vehicles. This

[8] Assuming fuel consumption of 0.65 l/km for gasoline cars and 0.18 KhW/km for electric cars. The excise duty on electricity is in 2021 0.045 €/kWh and the gasoline tax is 0.947 €/l.

paper has added to the literature by simulating the external costs from road transport in a scenario where all gasoline vehicles are replaced by EV's, and we do this for the densest region of Sweden, including cities, suburbs, towns and rural areas. We have concluded that there will be a strong case for internalizing the external cost of light and heavy traffic even in an era of electric cars, and that the lower driving cost of EVs will increase congestion. However, we have also pointed out several hurdles for the implementation of a kilometre tax, and also analysed it from an efficency, equity and fairness standpoint.

In Sweden, the optimal Pigouvian tax would generate a total revenue of roughly 5 B€/year (excluding administration costs) on the national level – which is of the same magnitude as the current fuel tax revenue. This optimal Pigouvian tax alone would cover the public spending on road infrastructure if this spending did not more than double between 2018 and 2040 and if administration costs are disregarded. This is consistent with the cost-recovery theorem, assuming that the public spending on road infrastructure is optimal, that there are constant returns to scale in capacity extension, and that capacity is a continuous variable, yielding that optimal marginal cost pricing generates a revenue that covers the optimal infrastructure spending (Mohring and Harwitz, 1962).

However, only just above 50% of the revenue of the optimal Pigouvian tax would be collected from passenger cars, and just below 30% of the total tax (and 50% of the congestion tax) would be collected in Stockholm alone. So, replacing the fuel tax with an optimal Pigouvian tax would imply a large transfer of resources from the city population and from the truck traffic. This means that the political-economic reality may be a major hurdle for replacing the fuel tax with a national kilometre Pigouvian tax, given the low public (Grisolía et al., 2015; Hess and Börjesson, 2016; Schuitema et al., 2008) and political (Börjesson and Kristoffersson, 2015) support for congestion charges, in particular since electric cars are at present exempt from many taxes (Davis and Sallee, 2020; Fridstrøm, 2019).

The political problem might be partly solved by giving the regions the power over the revenue and the design of the kilometre tax as suggested by De Borger and Proost (2015); regional power over the design and revenues was also the key issue for the implementation of the Swedish congestion charges (Börjesson et al., 2012). Still, such reform would be less efficient because the regions would be tempted to exercise a tax-exporting behaviour (Fung and Proost, 2017). Another problem is that the revenue of an optimal tax will probably not cover the government's cost for maintenance and investment in the road sector in many regions. This is because the revenue of the optimal congestion tax is spatially concentred to the big cities, as demonstrated in this paper. This in turn is an effect of the congestion cost being highly non-linear and the vast majority of the VKT (and of the length of the road transport network to be maintained) taking place outside the biggest cites.

A national kilometre tax would also imply high fixed and operational cost and low external cost outside the largest cities, at least before an EU or US standard for such a system exists. It is the enforcement that would drive costs. However, an extension of the ANPR-based congestion charging system, for which the enforcement is inbuilt in the system, to the highways around the big metropolitan areas would be a relatively cheap way of internalizing external costs. But even roadside equipment systems (ANPR and DSRC transponders) such as the London and Swedish congestion charging systems, as well as the Norwegian toll system, are relatively costly compared to a fuel tax.

To internalize the remaining external cost of passenger car use, and also maintain cost coverage of the road transport system, a purchase tax and a yearly vehicle tax could be possible instruments with relatively low administration costs. For EU-ETS member countries (internalizing the social cost of carbon of electricity production) that already have a tax on electricity, like Sweden and Germany, the electricity tax possibly already internalizes the external cost of car use not related to congestion.

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# 7 APPENDIX

## 7.1 Appendix A: Marginal external accident and congestion costs

*Table 8 Marginal external accident cost, euro-cents ¢ per vehicle kilometre*

| | | |
|---|---|---|
| Jochem (2016) | 0.105, 0.06 and 0.01 ¢/vkm | urban, suburban, and rural, day |
| | 4.6, 0.3 and 0.05 ¢/vkm | urban, suburban, and rural, Night |
| Nilsson and Haraldsson (2018) and Nilsson and Johansson (2014). | 0.2, 9 and 0.3 ¢/vkm | Average, urban, suburban, and rural, average day and night |

*Table 9 Marginal external accident cost*

| | | |
|---|---|---|
| Delucchi and McCubbin (2011); USA price level 2006; (conversion rate $ 1 = €0.8) | 0.021-0.072 €/pkm | Lemp and Kockelman (2008): 4.1 to 14.4 US cents/passenger-mile of travel (pmt) (6.6/pmt weighted avg) |
| | 0.01 €/pkm | 1.9 US cents /pmt Parry et al. (2007) |
| | 0.01-0.02 €/pkm | 1.14 to 4.9 US cents /pmt Delucchi (2004b) |
| | 0.01-0.02 €/pkm | 1.9 to 4.0 US cents/pmt Miller (1997) |
| Mayeres and Proost (2000); Belgium price level 2000 | 0.02 €/vkm | |
| Jochem (2016) from CE Delft et al. (2011); Germany, price level 2010 | Road type Marginal accident costs<br>Motorways 0.00416 €/vkm<br>Rural roads 0.0217 €/vkm<br>Urban roads 0.0551 €/vkm<br>All roads 0.0158 €/vkm | |
| Lindberg (2005) Sweden 1997–1999. Price level 2005. | 0.02 €/vkm | |
| Isacsson and Liss (2016); Sweden 2004–2012; Price level 2005. | ≈0 €/vkm | |

*Table 10 Marginal external congestion cost*

| | | |
|---|---|---|
| Parry and Small (2005); US price level 2000); Based on literature review “studies suggest”. | 0.013 and 0.025 $/km | 2.5 to 5 US cents/mile |
| Delucchi and McCubbin (2011); US price level 2006; recommended value based on literature | 0.0055-0.047 €/vkm | 0.88 -7.5 $cent/mile |
| Delucchi and McCubbin (2011); USA price level 2006; (conversion rate $ 1 = €0.8) | 0.024 €/pkm | Lemp and Kockelman (2008): 4.75 US cents /pmt |
| | 0.02 €/pkm | 3.8 US cents /pmt Parry et al. (2007) |
| | 0.01-0.037 €/pkm | 1.93 to 7.46/pmt US cents Delucchi (2004) |
| | 0.004 €/pkm | 0.88 US cents/pmt Levinson et al. (1998) |
| Mayeres and Proost (2000) Belgium 2000 | 0.18 €/km peak<br>0.03 €/vkm off-peak | |
| Newbery (1990) in Parry and Small (2005); UK, 2000 | 0.05-0.06 €/km | 10-12 US cents/mile |
| Kaddoura (2020) Berlin 2020 | 95 percent of all trips: 0.05-0.3 EUR/km. For some trips the external congestion cost can reach 7 EUR/km. | |

*Table* 11 *Marginal external congestion cost Germany in CE Delft et al. (2011) (Table 38); 2008 prices € per vkm.*

| | min | Central | max |
|---|---|---|---|
| Urban motorways | 0.33 | 0.56 | 1 |
| Urban collectors | 0.22 | 0.56 | 1.3 |
| Local streets centre | 1.67 | 2.22 | 3.33 |
| Local streets cordon | 0.56 | 0.83 | 1.11 |
| Small Urban areas motorways | 0.11 | 0.28 | 0.44 |
| Small Urban areas collectors | 0.06 | 0.33 | 0.56 |
| Small Urban areas Local streets cordon | 0.11 | 0.33 | 0.56 |
| Rural Motorways | 0 | 0.11 | 0.22 |
| Rural Trunk roads | 0 | 0.06 | 0.17 |

*Table 12: Percentiles and means for the optimal kilometre tax per link tax in euro cent per km [¢/km] calculated for four time periods and the six counties.*

| | Län | # links | 5 | 25 | 50 | 75 | 90 | 95 | Medel | Max |
|---|---|---|---|---|---|---|---|---|---|---|
| AM peak: 7AM-9PM | Stockholm | 19984 | 0.0 | 0.0 | 0.0 | 1.5 | 6.1 | 14.4 | 3.7 | 7080 |
| | Uppsala | 7272 | 0.0 | 0.0 | 0.1 | 1.0 | 3.0 | 5.2 | 1.0 | 75.4 |
| | Södermanland | 7120 | 0.0 | 0.0 | 0.1 | 0.7 | 2.2 | 3.7 | 0.8 | 78.1 |
| | Gotland | 2214 | 0.0 | 0.0 | 0.0 | 0.2 | 0.8 | 1.5 | 0.3 | 10.8 |
| | Örebro | 8840 | 0.0 | 0.0 | 0.0 | 0.5 | 2.1 | 4.9 | 0.8 | 59.6 |
| | Västmanland | 6576 | 0.0 | 0.0 | 0.0 | 0.7 | 2.7 | 4.9 | 0.8 | 33.6 |
| PM peak: 3PM-6 PM | Stockholm | 19984 | 0.0 | 0.0 | 0.0 | 1.9 | 7.2 | 15.4 | 5.6 | 17590 |
| | Uppsala | 7272 | 0.0 | 0.0 | 0.2 | 1.3 | 3.7 | 6.6 | 1.4 | 123.6 |
| | Södermanland | 7120 | 0.0 | 0.0 | 0.1 | 0.9 | 2.6 | 4.0 | 1.0 | 136.5 |
| | Gotland | 2214 | 0.0 | 0.0 | 0.1 | 0.5 | 1.5 | 2.5 | 0.5 | 11.8 |
| | Örebro | 8840 | 0.0 | 0.0 | 0.0 | 0.6 | 2.5 | 5.3 | 0.9 | 33.5 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Västmanland | 6576 | 0.0 | 0.0 | 0.1 | 0.8 | 3.0 | 5.0 | 0.9 | 26.7 |
| Midday 9AM-15PM | Stockholm | 19984 | 0.0 | 0.0 | 0.0 | 1.0 | 3.7 | 8.7 | 2.0 | 2700 |
| | Uppsala | 7272 | 0.0 | 0.0 | 0.0 | 0.8 | 2.7 | 4.9 | 0.9 | 30.1 |
| | Södermanland | 7120 | 0.0 | 0.0 | 0.0 | 0.6 | 2.1 | 3.6 | 0.7 | 50.2 |
| | Gotland | 2214 | 0.0 | 0.0 | 0.0 | 0.3 | 0.8 | 1.5 | 0.3 | 9.6 |
| | Örebro | 8840 | 0.0 | 0.0 | 0.0 | 0.4 | 1.9 | 5.0 | 0.7 | 22.4 |
| | Västmanland | 6576 | 0.0 | 0.0 | 0.0 | 0.6 | 2.6 | 4.8 | 0.8 | 22.7 |
| Night PM 6 - AM 7 | Stockholm | 19984 | 0.0 | 0.0 | 0.0 | 0.3 | 1.1 | 2.0 | 0.4 | 26.5 |
| | Uppsala | 7272 | 0.0 | 0.0 | 0.0 | 0.3 | 0.8 | 1.5 | 0.3 | 6.4 |
| | Södermanland | 7120 | 0.0 | 0.0 | 0.0 | 0.2 | 0.7 | 1.1 | 0.2 | 8.0 |
| | Gotland | 2214 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.1 | 3.3 |
| | Örebro | 8840 | 0.0 | 0.0 | 0.0 | 0.1 | 0.6 | 1.4 | 0.2 | 6.6 |
| | Västmanland | 6576 | 0.0 | 0.0 | 0.0 | 0.2 | 0.9 | 1.6 | 0.3 | 8.4 |

## 7.2 Appendix B: The transport model

The model used for forecasting the effects during the scheme design process was the national transport model *Sampers.* Sampers consists of a nested logit demand model linked to the network assignment model EMME/2. The demand model was estimated on data from the Swedish national travel survey Riks-RVU 1994-2001.

The demand model is tour-based, comprising choices of trip frequency, destination and mode, with separate sub-models for seven trip purposes (commute, service, shopping, leisure, visit, giving someone a ride and employer's business), comprising five modes (car as driver, car as passenger, public transport, walk and bicycle). Demand matrices are split into four time-of-day matrices (morning, midday, afternoon and night) using constant time-of-day shares (i.e. departure time choices are not modelled). Demand matrices are then assigned to road and transit networks using the network assignment model. Road assignment is carried out using multi-class assignment with five value-of-time classes. Professional traffic (freight, distribution, garbage collection etc.) is represented by a fixed matrix, meaning only route choices change in the analyses. A few other fixed matrices are also added before the assignment step, e.g. long-distance traffic to and from the Stockholm ports. The travel times and costs from the assignment model are then fed back into the travel demand models in an iterative feedback loop until convergence is reached.

The work trip demand model is doubly constrained, meaning that the total number of work trip ends per zone is constrained to be equal to the number of workplaces in the zone. The model predicted that work trip destinations would adapt as a response to the charges, despite the fact that adaptation by switching workplace is unlikely to happen in the short run. The best solution would have been to constrain the work trip O-D matrix to be constant in the forecast of the charges, but this turned out to be unfeasibly complicated due to the structure of the nested logit model (with destination choice below mode choice). Instead, model results had to be reinterpreted and adjusted to account for this.

The Sampers model can be said to constitute “best practice” for large-scale transport models. Its structure – logit demand models linked to a network assignment model – is similar to most operational, large-scale multi-modal transport models. It has been carefully estimated and calibrated using state-of-the-art methods, and validated against in-sample data. However, it does not model changes in departure times, nor does it include novel features such as activity-based travel demand or simulation-based network assignment. Since the model does not model departure times, the effect of kilometre charges differing by time of day are not captured. However, the time-of-day varying congestion charges had no effect on the time-of-day distribution of the aggregate demand in Stockholm (Eliasson et al., 2009) or Gothenburg (Börjesson and Kristoffersson, 2014a). Moreover, when modelling the departure time in a departure time model linked to a dynamic network assignment model, the scheduling parameters estimated by stated preference (Börjesson, 2008) had to be substantially reduced to match the observed effects of the Stockholm charges (Börjesson and Kristoffersson, 2014b), implying that the benefit of introducing departure time choices in the model should not be over-stated.

Travel times in static assignment models do not reflect effects of severe congestion, such as spillback queues, dynamic congestion and blocking of intersections and ramps. For this reason Sampers underestimates effects on travel times, and thus the marginal cost in the form of congestion, in networks with high congestion that arise due to queues forming on links upstream of the bottlenecks and thus reducing the speed of traffic in transverse directions (Eliasson et al., 2013) . The optimal kilometre tax that we calculate for central Stockholm is therefore probably an underestimation. But in Gothenburg, which has considerably lower congestion than Stockholm, and very limited spillback queues, Sampers forecasts the effects on the travel time of the introduction of congestion taxes well (West et al., 2016). According to TomTom (2020), there is only one city that has a higher congestion than Gothenburg and that is Uppsala (the three cities with the highest congestion index are according to the TomTom Stockholm index 24%, Uppsala 19% and Gothenburg 14%).

The latter indicates, besides the traffic towards central Stockholm and Uppsala on the major traffic routes, that Sampers should be able to forecast the effects on travel times and thus optimize kilometre taxes relatively well. The optimal charges should, however, be interpreted with more caution for Stockholm due to higher congestion levels. Nevertheless, the congestion levels in Stockholm are still moderate in an international context, partly because congestion charges already apply. The congestion level in Stockholms corresponds to those of Manchester, Antwerp and Munich (congestion index around 24% (TomTom, 2020)), but is considerably lower than the congestion in Berlin, Brussels and Paris (congestion index around 30%).

We only model Mälardalen here, i.e., Stockholm, Uppsala, Södermanland, Gotland, Västmanland and Örebro counties, and assess the effect in the rest of Sweden based on this result.