Should Electric Cars Pay?

Exempting Electric Cars from the Gothenburg Congestion Charges

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Abstract:

Pollution and congestion from automobile traffic are two major issues facing urban areas today. Noxious gases lead to health problems and early deaths, congestion leads to an increase in traffic accidents as well as increased travel times for people living in these areas. To combat these effects, several cities have instituted congestion charges, charging cars to drive within certain areas of these cities. A number of these congestion charges have included exemptions for more environmentally friendly cars, hoping to stimulate increased adoption of these types of cars.

In 2013, Gothenburg implemented a congestion charging scheme that did not include any exemptions for environmentally friendly cars. In this thesis, we examine the potential effects that an exemption from the congestion charges for electric cars could have in the city of Gothenburg. We do this by performing a cost-benefit analysis, using information obtained from previous studies to calculate the values of different externalities. We also model the growth of the electric car market in Gothenburg, from 2019 to 2030, to see how such growth affects the impact of an exemption for electric cars. This time horizon matches the Swedish government's ambition for a car fleet that is independent of fossil fuels by 2030.

Our conclusion is that instituting an exemption from the congestion charges for electric cars would not be socially beneficial. The net present value of our cost-benefit analysis remains negative under all examined growth scenarios.

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1 Introduction

1.1 General introduction and motivation

As concerns about the environment have grown in the last few decades, the harmful effects of automobiles on the environment has become a major issue around the world. In general, fossil-fueled cars contribute to global climate change, and in urban areas in particular, other harmful effects such as nitrous oxide emissions, noise, and traffic accidents are some of the notable negative effects of automobile traffic. To combat problems related to the congestion caused by increased use of automobiles in urban areas, several cities have implemented congestion charges, charging cars entering or leaving a certain area of the city centre. In 1975 such charges were implemented in Singapore, in 2003 in London, in Stockholm 2007, in Milan 2008, and in Gothenburg in 2013.

Another method of combating the harmful effects of fossil-fueled automobiles is promoting more energy efficient and climate friendly vehicles. Alternative fuels such as ethanol and biogas have recently been supplanted by hybrid-electric vehicles and pure electric vehicles as the leading environmentally friendly vehicles. Electric cars in particular, being the only category of vehicle with no emissions, have become a rapidly growing and highly talked about category of vehicle. That being said, electric cars and hybrids still represent a small minority of the total car fleet (Trafikanalys, 2020a). Trying to mitigate this problem, and stimulate higher adoption of these categories of more environmentally friendly cars, different types of incentives have been implemented by governments around the world.

One such incentive, implemented by both London, Milan and Stockholm, is congestion charges with differentiated price structures, based on the amount of pollution the vehicles emit. A fundamental part of these price structures is exemptions from the charges for certain categories of cars. Although the limited amount of studies on the effect of this incentive has shown a positive effect (City of Stockholm, Environment and Health Administration, 2009; Whitehead et al., 2014), Stockholm quickly abandoned its exemption, Milan changed its pricing scheme to include more categories of vehicles in the congestion charge, and London is gradually phasing out its exemptions, planning to totally end them by 2025. Gothenburg has never had any such exemptions from its congestion charges.

Many studies exist on the efficacy of congestion charges, but the research is more limited as to the effects of differentiated pricing schemes and exemptions from congestion charges as an environmental incentive. An interesting topic of research is thus whether the possible positive effects of exempting certain categories of cars might outweigh possible negative effects.

1.2 Research question

The aim of this thesis is to examine the effects of an exemption from the congestion charges for electric cars in the city of Gothenburg. We compare the negatives against the positives of such an exemption by doing a cost-benefit analysis, simulating the effects such an exemption might have in the time span 2019-2030.

1.3 The disposition of the thesis

In section 2 of this thesis we have a review of a few important topics regarding congestion charges, traffic, and clean cars. Section 3 is a review of relevant theory regarding environmental taxes and negative externalities, as well as the theory behind cost-benefit analysis. In section 4 we go through the major sources of data used in this thesis. Section 5 describes the methodology used for the thesis, and in section 6 we present and briefly discuss the results. In section 7 we summarise and discuss the conclusion of the study, as well as some limitations of the thesis and suggestions for further research.

2 Background

2.1 Congestion charges around the world

Congestion charges as a way of combating the harmful effects of automobile traffic in urban areas have been around since 1975, when Singapore implemented the Singapore Area Licensing Scheme. It took until 2003 until the first major European city launched a similar congestion charge, when London launched the London Congestion Charge. In 2007 Stockholm launched its congestion charge, in 2008 Milan launched its Ecopass scheme, and in 2013 Gothenburg launched its congestion charge.

The idea of a congestion charge is to mitigate negative externalities within a city, such as congestion and pollution, by charging people a price for driving within a certain area in the city. This is typically done by setting up a cordon around the congestion charge area and charging cars for passing through this cordon.

The structure of the pricing schemes, as well as the level of the fees, vary between the different cities. London and Milan only charge cars for entry into the zone, whereas Stockholm and Gothenburg charge every trip through the cordon, with a daily cap on the charge. In Milan and London, drivers only pay a flat fee for entering the congestion charge area, while the charges in Gothenburg and Stockholm are higher during what is considered peak hours. During evenings and weekends no charges are applied, either in London Milan, Stockholm and Gothenburg.

Most congestion charges in Europe currently have, or have in the past had, some kind of exemption from the charges for vehicles considered more environmentally friendly. When the Milan Ecopass scheme launched in 2008, a differentiated pricing structure was implemented, following the euro emissions standard (Rotaris et al., 2010). This approach was abandoned in 2012, in favor of a simpler pricing scheme, where all cars entering the area had to pay a €5 charge during charged times. Electric and hybrid cars are still exempt from the congestion charges in Milan. In London, electric vehicles and certain hybrid-electric vehicles are exempt from the congestion charges. From 2021, only battery electric vehicles will be exempt, and in 2025 all clean vehicle exemptions will be abolished (Transport for London, 2020). Stockholm had an exemption from the congestion charges for alternatively fueled cars when the congestion charge was launched in 2007, but in 2009 they started phasing out the exemption, abolishing it in 2012 (Whitehead et al., 2014, p. 27). Concerns over increased congestion by a greater number of exempt cars, as well as lost revenue were the two main reasons for this decision (Finansdepartementet, 2008).

Multiple studies have shown congestion charges to be effective at reducing congestion. Gibson and Carnovale (2015) used a natural experiment, the temporary suspension of the Area C congestion charge in 2012, to estimate the effects of the congestion charge. They found that the congestion charge reduced trips into the charge zone by 14.5%, and reduced pollution by between 6% and 17%. Rotaris et al. (2010) showed that the earlier Ecopass scheme led to significant pollution abatement and a reduction in entries to the charged zone of 14.2%.

Leape (2006) writes that the London congestion charge reduced traffic delays within the charged area by 30%, reduced traffic circulating within the area of 15%, and reduced the amount of vehicles entering the area during charged times by 18%. Transport for London (2008) showed that the reduction of traffic entering the charged area in 2008 was 17% and the reduction in traffic within the area was 10%, but that congestion had bounced back to the levels before the charges were implemented. One possible explanation they give for this bounce-back is reduced road capacity for cars due to a reallocation of road capacity towards pedestrian, bicycle, and bus traffic. It could also reflect a long-standing trend of increased congestion. This shows that studying phenomena such as road pricing is often complicated by the fact that pricing schemes often are not implemented in isolation, and traffic systems are complex and dynamic.

The Stockholm congestion charge has been the subject of many studies. The charges were first implemented as a trial in 2006, and was seen as a success. An evaluation found that traffic across the charging cordon decreased more than expected, travel times fell, and both harmful emissions and negative health impacts fell (Congestion Charge Secretariat, City of Stockholm, 2006). As the trial was a success, the charges were implemented on a permanent basis. More studies continued to be performed, showing the continued success of the charges. A cost-benefit analysis done in 2009 showed that the congestion charges were socially beneficial, and that operative costs and investments would be recouped within four years, if the charges were kept long enough (Eliasson, 2009). Börjesson et al. (2012) found a persistent "charge effect", which is to say a reduction in non-exempt vehicles, controlled for external factors, of about 30%. It was also found that congestion dropped significantly when charges were introduced, and stayed at the lower level.

As far as exemptions go, there are not as many studies out there. Two studies have tried to gauge the effects of the exemption from the congestion charges in Stockholm on sales of so-called energy efficient vehicles (EEVs), a category including electric cars, hybrids, and alternatively fueled cars. Whitehead et al. (2014) examine the effect of the exemption for EEVs on purchases of EEVs by people belonging to different demographics in relation to the charge cordon. The study determined an effect of about 10.73% on EEV car sales due to the exemption to the congestion charge, and an effect of 10.49% on electric car sales due to the exemption (Whitehead et al., 2014, p. 37). The city of Stockholm Environment and Health Administration (2009) summarises Stockholm's effort to promote the purchase of alternatively fueled vehicles from 1994 to 2008, and includes a simulation that estimates the effect of the exemption from the congestion charge on sales of EEVs of 23%. This second analysis differs from Whitehead et al. (2014) in that it includes company cars, but also that the methodology used is less complex. It also does not include breakout statistics of different categories of EEVs.

2.2 The Gothenburg congestion charges

The Gothenburg congestion changes were implemented in 2013. The official reason was to control congestion, but it has been argued that raising revenue was the true reason. Political support was centered around co-financing of a large infrastructure project called the West Swedish Agreement, where the national government would give a large grant, matching the contribution to the project from the congestion charge (Börjesson and Kristoffersson, 2015). A consultative referendum in 2014 resulted in a 57 percent rejection of the charges, but the local government decided to go ahead with the charges anyway. However the support from the charges can be hard to separate from the support for the infrastructure package, since they are so intertwined.

The charge cordon consists of 36 stations, encircling an area of central Gothenburg, as well as two ribbons along the river, as illustrated in Figure 1.

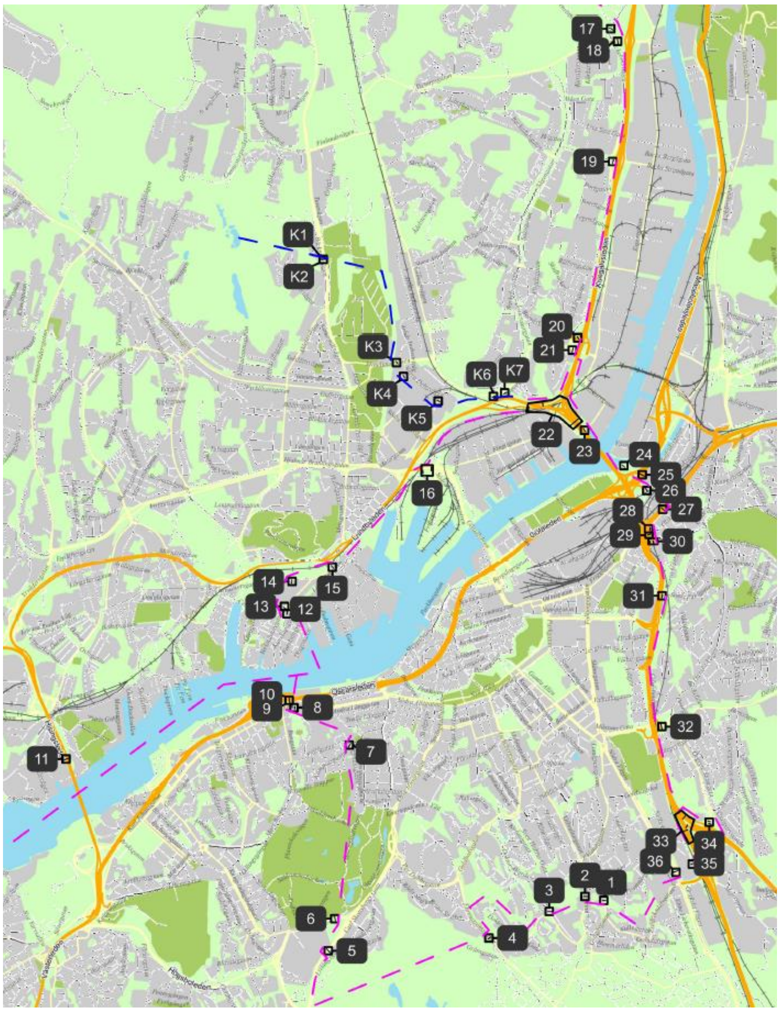

Figure 1. Map of the congestion charge cordon in Gothenburg (Transportstyrelsen, 2017)

Cars passing through the stations between 6:00 and 18:29 during weekdays are charged according to a differentiated price list, depending on which hours of the day are considered peak hours. There is a multi-passage rebate, where a driver passing through several stations within 60 minutes is charged only once (the most expensive passage is charged). There is a daily cap on the amount a driver can be charged. The amounts are listed in Table 1. There are no charges during the month of July.

Time of day	**Charge**
06:00-06:29	9 SEK
06:30-06:59	16 SEK
07:00-07:59	22 SEK
08:00-08:59	16 SEK
08:30-14:59	9 SEK
15:00-15:29	16 SEK
15:30-16:59	22 SEK
17:00-17:59	16 SEK
18:00-18:29	9 SEK
Daily cap:	60 SEK

Table 1. Prices of the Gothenburg congestion charge. Data taken from the Swedish Transport Agency (Transportstyrelsen, 2020a)

Some categories of vehicles are exempt from the congestion charge. These include emergency vehicles, buses with a weight of at least 14 metric tonnes, diplomatic vehicles, motorcycles as well as military vehicles (Transportstyrelsen, 2012). Importantly, there is no exemption for any vehicles based on emissions or environmental impact.

Börjesson and Kristofferson (2015) reviews the congestion charges in Gothenburg, from the design stage to the implementation stage, as well as the effects. They found a decrease in traffic across the cordon during charged hours that stabilised at 12%, and estimated the decrease inside the city centre to be around 9%. In a cost-benefit analysis, West and Börjesson (2020) shows that the congestion is socially beneficial, with a social surplus of €20 million yearly, but notes that because of distributional effects, the net consumer surplus is negative for almost all income classes. They also argue that a very important factor is what the revenue is spent on. The revenue from the congestion charges are spent on an ambitious infrastructure project called the West Swedish Agreement, which they argue will mainly benefit people living outside of the city.

2.3 Traffic in Gothenburg

2.3.1 The West Swedish Agreement

The city of Gothenburg and the entire western region in Sweden is rapidly growing both economically and population wise (Trafikverket, 2015). With an estimated population of 570.000 inhabitants and with many opportunities for work and education it is easy to see that the city requires well functioning infrastructure. Currently the city is undergoing a substantial amount of reconstruction and development.

As previously mentioned, congestion charges were implemented in the city mainly as a way to combat congestion as well as attaining revenue for the West Swedish Agreement. The entire project is estimated to cost 34 billion SEK, in which 14 billion SEK is estimated to come from the congestion charges and the rest is financed from local and regional authorities (Trafikverket, 2016). The West Swedish Agreement includes several different reconstructions and infrastructure projects. The west link project and the congestion charges are both part of the Western Swedish Agreement. The west link project is supposed to create three new underground stations for railway traffic which aims to alleviate the cities public transport system in many ways. The construction started in 2018 and is estimated to finish 2026.

Reconstruction of the bridge Hisingsbron and the construction of the new tunnel called Marieholmstunneln are also projects that attempt to improve the passability in the city (Västsvenska Paketet, 2020). The Swedish Transport Administration considers it an important prerequisite for both regional growth and a sustainable development (Trafikverket, 2015).

2.3.2 Modes of transportation

Börjesson and Kristoffersson (2018) points out that congestion in Gothenburg was not an extensive issue and that congestion was concentrated around a few highway junctions. Around these junctions congestion usually occurred during morning peaks and was significantly reduced as a result of the charges. The modal split in the city is divided into 4 categories which include cars, public transport, bicycles, and walking. In 2019 the distribution was 43%, 30%, 7% and 21% respectively (Trafikkontoret, Göteborgs stad, 2020). In Stockholm, however, the share of public transportation is substantially higher (Börjesson and Kristoffersson, 2018). Even though Gothenburg is a smaller city than Stockholm both the congestion charges roughly generate the same amount of revenue. This is as a result of a higher car dependence in Gothenburg, leading to a larger amount of people that regularly pay toll charges (Börjesson and Kristoffersson, 2018).

Regarding public transportation, the city of Gothenburg has initiated a goal that by the year 2035, at least 55% of all motorised trips should involve public transport (Trafikkontoret, 2019). The strategy of increasing public transport in the city was first implemented in 2011 and is, as of 2020, developing better than planned. To reach the goal the city has evaluated that a minimum of a 2.5% annual increase in public transport is necessary to achieve said target by 2035 (Trafikkontoret, Göteborgs stad, 2020). According to the Traffic Administration Office the current average annual increase is at 3.6% from 2011 to 2019. As stated by the administration the steady increase is due to an increasing demand for trips, as well as an expanding awareness of sustainable modes of transportation. However, the same source tells us that in 2019 the city is still looking at roughly the same amount of private car trips as it did back in 2011 (43% vs. 48%). Furthermore, the Traffic Administration Office informs the public that when the congestion charges were first implemented in the city there was a decrease in car trips by 4.6% between 2012-2013.

2.4 The politics of congestion charges

Because of the increasing awareness of the impact of human activity on the environment, measures such as congestion charges are being considered as a remedy for some of this damage. However, in Europe, only a handful cities have implemented congestion charges. Popular support for such measures is at times low, and measures like congestion charges are politically controversial. One example of this was a plan in France to institute congestion charges in several major cities. The plan was scrapped because of the yellow vest protests (The Local, 2018). Public support in cities that have implemented congestion charges have been varied. Charges tend to be less popular before they are implemented, but gain in popularity after the implementation. This trend has been observed in both Gothenburg and Stockholm (Börjesson and Kristoffersson, 2018). However, the charges are much more popular in Stockholm than in Gothenburg. This could be a consequence of larger usage of cars in Gothenburg than in Stockholm. Other factors, such as the fact that the charges are mainly seen as a means to finance a large infrastructure project in Gothenburg, whereas they have been marketed as an environmental policy in Stockholm, could have an effect.

In 2009 the Swedish government issued a bill declaring that Sweden should have a vehicle fleet that is entirely independent of fossil fuels by the year 2030 (Miljödepartementet, 2009). The bill also discussed smaller targets for earlier years, as a way to assign checkpoints, or intermediate goals. One of these goals was to decrease greenhouse gases by 40% until 2020. By 2018, greenhouse gases had decreased by 27%, with a 1.8% decrease compared to the year before (Naturvårdsverket, 2019). Even though no numbers for 2020 exist yet, it is clear that further incentives to reduce emissions are needed.

Proposals to differentiate the congestion charges in Sweden, as an incentive to decrease emissions in the transport sector, is a topic that has come onto the agenda lately.

In 2018, several members from the Center Party submitted a private members motion to Swedish Parliament, arguing for the implementation of differentiated congestion charges (Ådahl et al., 2018). The motion addressed Sweden's goal of reaching a fossil free vehicle fleet by 2030, arguing that incentives and fees such as the congestion charges has proven to be very efficient at changing behaviour by helping the general public to become more socially aware of the environment. They further argue that a discounted charging rate for environmentally friendly cars could increase the demand for environmentally friendly cars and will help Sweden reach its 2030 goal. The motion also points out the potential negative effects on congestion that such rebate schemes could have, and that a balanced approach is needed.

In a debate article published in 2020, several prominent members of the Green Party in Gothenburg addressed the topic of differentiated congestion charges, suggesting that vehicles should pay a congestion fee according to the damage they cause (Plejjel et al., 2020). This could mean that, for example, electric cars that cause less damage could be charged a smaller fee as opposed to fossil-fueled cars which are generally more harmful. An additional thing to note is that the authors also frame raised congestion fees as a way to acquire funding for public transport.

From a political point of view, further research into different types of differentiated congestion charging schemes is thus important, something that this thesis hopes to contribute to.

2.5 Harmful effects of automobile traffic

Increased congestion in urban areas creates a number of negative externalities. When addressing these externalities, the main issues that are discussed include, degrading air quality due to pollution, increased traffic accidents, raised noise levels, and travel time uncertainty. Even though emissions caused by traffic has decreased over the years, some areas still experience high levels of pollution, which could be dangerous to human health (Trafikverket 2019). Emissions due to traffic are said to induce around 2,800 premature deaths annually in Sweden.

2.5.1 Emissions

2.5.1.1 CO_2

Carbon dioxide (CO_2**)** is considered one of the most common greenhouse gases and is known to be one of the main causes of global warming (Kolstad, 2011). Carbon dioxide can develop not only from the combustion of fossil fuels, coals, woods etc., but also in smaller doses caused by respiration from living mammals.

Since the industrial revolution there has been a clear increase of CO_2 in the atmosphere. In 2009 the estimated amount of annual CO_2 emissions had reached 30 billion tonnes worldwide. The combustion of fossil fuels plays a big part in the large amount of emitted CO_2 today. In 2017 the Traffic Administration estimated that 30% of all carbon dioxide emissions in Sweden were caused by the road transport sector (Trafikverket, 2017).

Higher global temperature levels are causing different effects on the planet such as rising sea levels and unpredictable weather patterns, which affect agricultural productivity (Kolstad, 2011 p.29-30). Despite the consensus in the scientific community regarding higher global temperatures, there is still some political disagreement concerning the urgency in dealing with this issue. Amongst economists, there are different views on this topic. Some economists argue that the damages from increasing global temperatures needs to be mitigated using vigorous measures, while others have proposed a more moderate approach. Nonetheless, the amount of damage from climate change to the economy is still rather uncertain (Kolstad, 2011 p.32-33).

2.5.1.2 Particulate matter

Particulate matter (PM) emissions are usually divided into two categories, PM10 and PM2.5. The numbers represent the diameter of the particulate matter in micrometers respectively, i.e. 10μm and 2.5μm. As a consequence of the microscopic size of these particles, the human respiratory system cannot stop them from entering the lungs, which can lead to different harmful diseases such as cancer (Timmers and Achten, 2016).

The main cause of this problematic and harmful pollutant is increased traffic in urban areas. According to Timmers and Achten (2016) there is a prevalent misconception amongst governments worldwide that particulate matter will decrease with more electric vehicles on the roads. There seems to be a correlation between non-exhaust PM-emissions and the weight of a vehicle. Electric vehicles are said to be 24% heavier on average than similar corresponding fossil-fueled vehicles (Timmers and Achten, 2016).

The report concluded that electric vehicles essentially produce as much particulate matter as a conventional vehicles. This is largely due to the fact that the main cause of particulate matter emissions still come from non-exhaust sources. For the purpose of this thesis we will be using the assumption that an electric vehicle produces as much particulate matter as a fossil-fueled vehicle.

2.5.1.3 NO_x

Nitrous oxides (NO_x) involves two different but quite similar gases, namely NO and NO_2. Similar to carbon dioxide, nitrous oxides form when combustion occurs in various scenarios. However, burning fuels such as from a motor vehicle is seen as one of the primary sources of nitrous oxides (US EPA, 1998). Furthermore, NO_x is a major part of several environmental issues such as, the formation of acid rain, ground-level ozone (smog), water quality deterioration, visibility impairment and particles. The problems arising from NO_x does not only affect the environment negatively but also global health. For example, problems such as smog and visibility impairment can lead to adverse health issues as well as societal complications. Particles from this pollutant can block the transmission of light, which impairs visibility in urban areas. Smog, which is often recognized by its reddish-brown colourisation of the air, creates a bundle of problems including, several respiratory problems and agricultural difficulties. Along with carbon dioxides, NO_x also raises the global temperature and boosts global warming.

2.5.1.4 Other pollutants

The most common harmful pollutants from the transport sector apart from those already mentioned in this study include carbon monoxide (CO) and Volatile Organic Compounds (VOC) (Trafikverket 2019). Carbon monoxide can prevent oxygen from distributing evenly throughout an individual's body, leading to unconsciousness and in worst case death. However, as a result of more frequent usage of emission control devices in modern vehicles, such as catalytic converters, these emissions have decreased dramatically (Trafikverket 2019).

VOCs can also cause different harmful effects on humans such as various types of cancer. Moreover, similar to CO, this pollutant is also decreasing with time and technological advancements. Since 1990 there has been an estimated decrease of 90% (Trafikverket 2019).

2.5.2 Accidents

Traffic accidents is a very problematic issue caused by automobile traffic. In a study on the connection between congestion and traffic accidents, Retallack and Ostendorf (2019) mention how there is a clear positive linear trend between total accidents and the amount of traffic on the road. However, it is also common to find a U-shaped curve between accidents and congestion, where we see higher levels of accidents due to increased speed when there is low traffic and vice versa.

Every year traffic accidents impose high costs on countries all around the globe. The Swedish cost for traffic accidents with respect to personal injuries amounted to 7 billion SEK in 2014, with almost 5.8 billion SEK of the cost concerning loss of production. Other costs due to traffic accidents may involve different types of hospital fees and home care, as well as transport costs (Olofsson et al., 2016). Retallack and Ostendorf (2019) further discuss the cost of accidents by demonstrating how in the United States close to half the deaths of 19-year olds can be linked to traffic accidents.

The amount of accidents in Gothenburg vary considerably each year, making it difficult to do an accurate analysis on the progress the city is trying to achieve. Another complication with accidents is the difficulty of measuring the amount of damage generated by a single accident. For example in 2019 a single accident occurred in Gothenburg which lead to a collision that caused 7 fatalities (Trafikkontoret, Göteborgs stad, 2020). The same year there was a total of 10 fatalities in Gothenburg.

In the long run Gothenburg is actually seeing a lower amount of fatal accidents. Since 2013 there has been an increase in injuries, however this is partly due to a reporting improvement from the healthcare sector (Trafikkontoret, Göteborgs stad, 2020). In recent years the motorized scooter has become a popular method of transportation in the city, this further complicates the analysis regarding accidents since many recent accidents involve this method in combination with other means of transportation (Trafikkontoret, Göteborgs stad, 2020).

2.5.3 Traffic noise

Traffic noise is a common problem in urban areas all over the world. The Gothenburg Administration of Environment estimate that in 2016 around 137,100 people were being exposed to traffic noise that reached a higher level than 55 dBA and 65,100 people were being exposed to noise levels higher than 60 dBA. These levels had increased since 2013 where the numbers were 110,000 and 55,000 respectively. However the traffic noise data from Gothenburg is not only measured from the noise that takes place on the roads from private cars and other vehicles. We also see noise in the city from trams and trains (Miljöförvaltningen Göteborgs Stad, 2019). According to the World Health Organisation, traffic noise above 53 dBA may cause adverse health risks. The potential health risks according to the WHO are, sleep disturbance, increased stress levels, cardiovascular and physiological effects, mental health effects amongst several others (World Health Organization, Regional Office for Europe, 2018). The societal costs in Gothenburg caused by traffic noise are estimated at 1.5 billion SEK per year (Miljöförvaltningen Göteborgs Stad, 2019)

2.6 Electric cars and the automobile market

In 1997 Toyota released the first generation of the Prius, the first popular hybrid-electric car in the modern era. A hybrid-electric car is a car that uses an electric motor as a complement to an internal combustion engine. Generally the electric motor and the combustion engine are used in clever ways to reduce emissions from the fossil fuels used. At low speed, the car uses only electricity, and at higher speeds, the internal combustion engine is used in conjunction with the electric motor, at the same time as it is charging the battery to be used by the electric motor (Toyota, 2020).

Another category of hybrid-electric car is the plug-in hybrid-electric car. The plug-in hybrid is a hybrid-electric car that is able to charge from an external electric power source. Generally, plug-in hybrids have the ability to drive on pure electricity for a limited range, while mostly driving like normal electric hybrids. When we refer to hybrids in this thesis, we are referring to pure hybrids, with no ability to charge from an external power source.

Ín the last few decades, hybrids have grown as a category, with 41 different models of hybrids sold in Sweden during 2019. In 2006 2,851 electric hybrids were sold in Sweden, in 2019 that number had grown to 33,123 (Trafikanalys, 2020a).

A battery electric car is driven by battery power alone, so it produces no gas emissions by itself. The electricity used in an electric car can however be a source of different pollutants, at the production source. With the potential of large scale renewable electricity generation using sources such as solar and wind, the electric car is the only type of car that can be considered truly potentially emissions free.

Two issues that are particular to electric cars, is the electric charging infrastructure, as well as the battery range. For an electric car to be a viable alternative to a fossil-fueled car, drivers will have to be able to charge the battery when needed, and the battery needs to last long enough for them to get to their destination without running out of power.

The two most popular models of electric car in Sweden (Power Circle, 2020a) is the Renault Zoe, with a range of between 240 km and 385 km on a fully charged battery (Renault, 2020) , and the Tesla model 3, with a range of up to 530 km per charge (Tesla, 2020). A quick calculation using the average yearly trip length in Sweden of 11,710 km (Trafikanalys, 2020b) shows that the daily trip length of a Swedish car is about 32 km. The average electric car can thus drive for several days on a charge. With the ability to charge at home overnight, electric car owners can thus be independent of external charging infrastructure. Since 48.8% of Swedes lived in apartments in 2019 (Statistiska Centralbyrån, 2020), a large number of Swedish households lack the ability of setting up a home charging solutions themselves. This could be one major roadblock for the adoption of the electric car. That being said, there are over 9,000 electric car charges throughout Sweden (Power Circle, 2020b). Trosvik and Egnér (2017) shows that an increased number of charging points increases the adoption rates of electric vehicles.

In 2008 Tesla released their first electric car. The same year, only one electric car was sold in the entire country of Sweden, while in 2019, 15,795 electric cars were sold

(Trafikanalys, 2020a). In 2019, 30 different models of electric car were sold in Sweden (Bil Sweden, 2020). Electric and hybrid-electric cars have become main categories of environmentally friendly cars sold in Sweden, taking over from ethanol and gas.

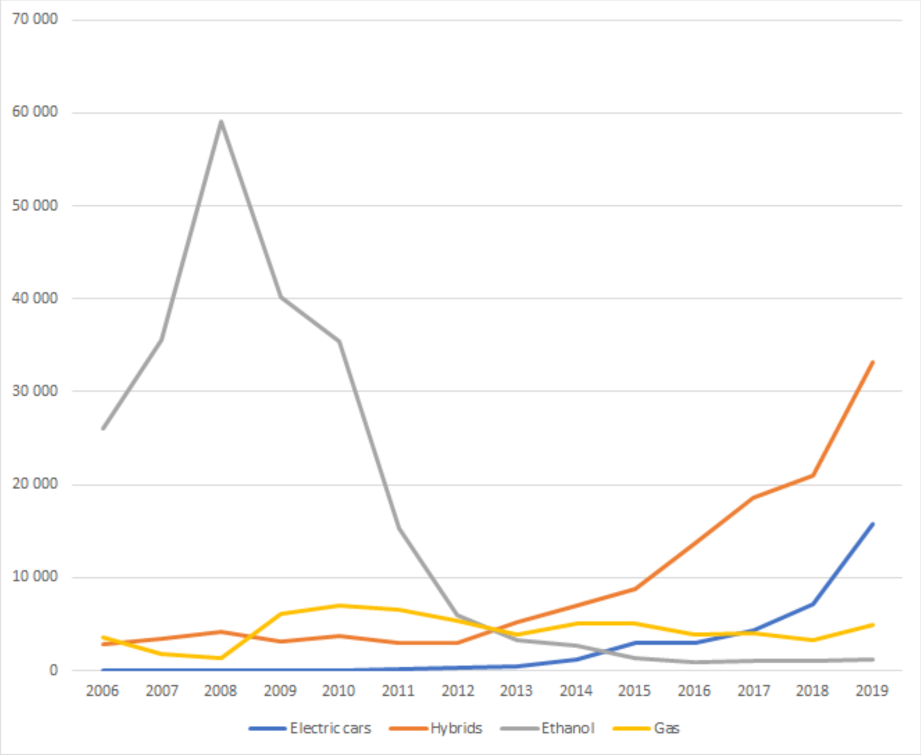

Figure 2. The evolution of car sales of different categories of environmentally friendly cars in Sweden. Yearly amount of newly registered cars from 2006 until 2019 (Trafikanalys, 2020a).

From a situation where a few manufacturers dominated the market for electric cars and hybrids we have a situation where most major automobile manufacturers have one or several hybrid-electric cars in their lineup. The development of the different categories of environmentally friendly cars since 2006 is described in Figure 2.

Despite this growth, only 0.6% of all cars in Sweden were electric in 2019 (Trafikanalys, 2020a). In Gothenburg the number was slightly higher, at 1.1%. Electric cars are thus still a very small part of the car fleet. The new registrations of electric and hybrid-electric cars, as well as the total registrations between 2011-2019 is illustrated in Figure 3.

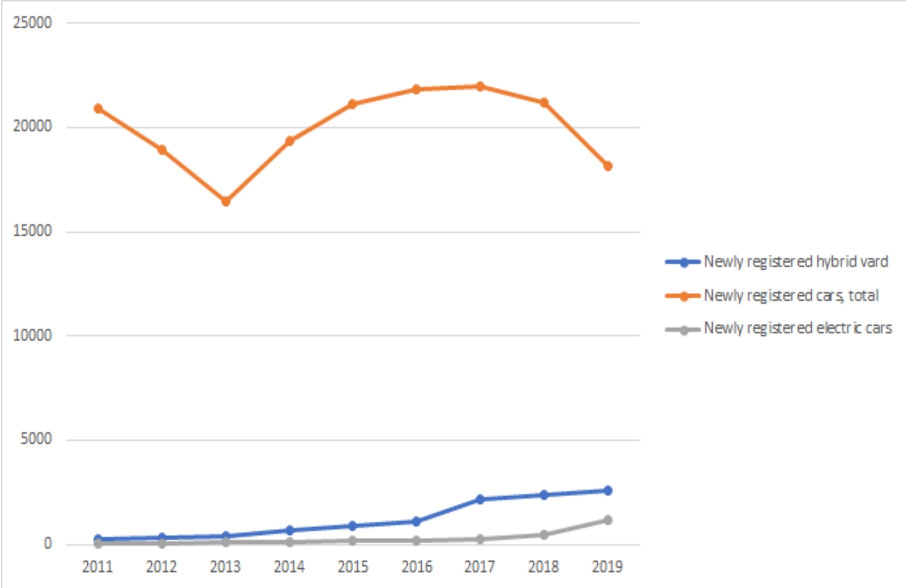

Figure 3. Graphs of the new registrations of electric and hybrid-electric cars in Gothenburg, as well as the total number of newly registered cars, from 2011 to 2019 (Trafikanalys, 2020). The number newly registered electric cars and the number of newly registered hybrids, are growing, while the total number of newly registered cars fluctuate up and down, without any clear long term trend.

Given that the electric car is the only truly fossil free alternative for drivers, and the still small market share of electric cars, an important topic of research is what factors determine the growth of the electric car market, and which incentives can be effective in stimulating sales of electric cars. One potential such incentive is an exemption from congestion charges.

3 Theory

3.1 Congestion as an externality

To understand externalities and how it is related to congestion charging we first have to consider the different types of goods and bads that are available. A good (or bad) can be rivalrous or non-rivalrous, excludable or non-excludable. When a good is both excludable and rivalrous it is considered a private good, while it is considered a public good otherwise.

3.1.1 Rivalry and excludability

If an act of consumption of a good removes the availability of that particular good, it is then seen as a rivalrous good and vice versa (Kolstad 2011, p. 93). For example, a rivalrous private good might be an apple, if you were to purchase and consume said apple, no one else can use that same apple. Most tangible goods can be seen as rivalrous. A non-rivalrous public good could perhaps be a public road, where everyone is permitted to use it. One simple way of looking at it is that if the marginal cost of the good is zero i.e. there is no extra cost with more people using the good, then the good is non-rivalrous.

Kolstad (2011 p.90) further explains how excludability is a key concept in economics because it helps us to attach prices to goods, which in turn let us know who is allowed to consume the good. An apple may be an example of an excludable good, once purchased no one else is allowed to consume it. Air pollution on the other hand is seen as a non-excludable public bad. If you were to walk outside in a city with high pollution levels you would consume the same amount of bad air as any other person nearby.

3.1.2 Open access

The open access problem is described as a problem that arises due to a resource being open for everyone. One simple example is how open roads which are not regulated by fees or tolls easily become congested (Kolstad, 2011 p.84). This in turn slows down speed, increases air pollution and traffic accidents.

A public highway may be non-rivalrous at first, but with a higher level of road-users the road quickly becomes congested. When a public road becomes increasingly congested the value of the trip diminishes as the waiting time increases together with the cost of the trip (Kolstad, 2011 p.86). This problem is also commonly known as the "Tragedy of the Commons", when nobody owns the open resource and can control who uses it, there is a great chance for the public to overuse the open resource.

3.1.3 Externalities

An externality according to Kolstad (2011 p.87) occurs when the actions of an individual firm affects a third actor without their approval. There could be both negative and positive externalities. Negative externalities from the transport sector may include, noise irritations, traffic accidents, congestion, air pollution and other environmental effects. With open access to public roads these externalities are not being accounted for by those causing the effects.

These externalities can be divided into two categories with the first one being called "intra-sectoral externalities" which involve externalities like congestion and accidents that drivers impose on one-another. The second category is called "inter-sectoral externalities" which are costs that fall on society as a whole e.g. harmful environmental effects (Verhoef, 2000). An exemption of electric cars from the congestion charges would for example reduce a great deal of the inter-sectoral externalities such as decreasing emissions. However, an exemption of electric cars may increase the intra-sectoral externalities since they contribute to congestion in the same manner as fossil-fueled cars.

3.2 Pigouvian taxes

One way to combat negative externalities such as pollution is to put a fee on the amount of pollution a polluter emits. A polluter is going to pollute to the point where the marginal savings from pollution matches the fee. If a polluter saves more from polluting one unit than they have to spend on the fee, emitting another unit is going to give them a net benefit and they are going to continue to pollute. This is going to continue until the marginal saving equals the fee.

A fee is called Pigouvian, named after the economist Arthur Pigou; the first economist that proposed such fees in the 1920's; when the fee is set such that the marginal savings from pollution equals the marginal damage done to society by pollution (Kolstad, 2011, p. 236). This is the fee leading to an optimal amount of pollution from society's point of view.

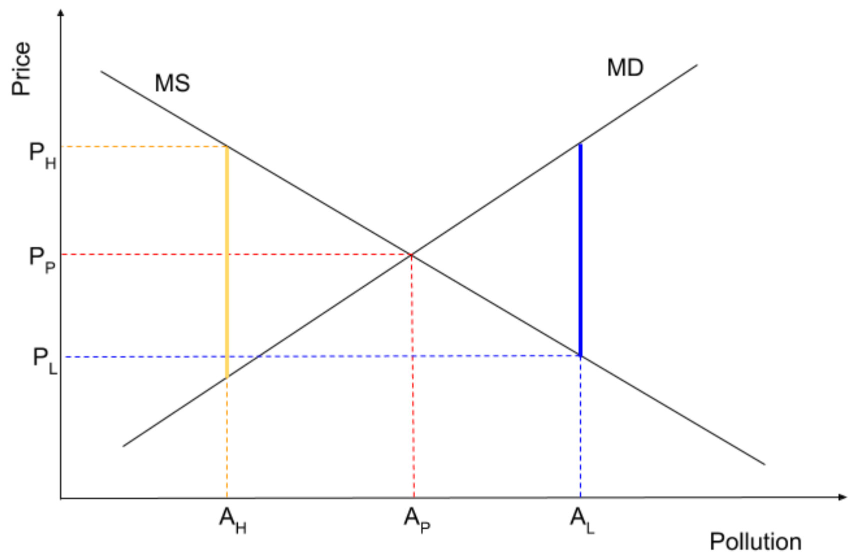

Figure 4. Plot of marginal savings (MS) as well as marginal damage (MD) caused by pollution. P_P is Pigouvian fee, and A_P the amount of pollution emitted at this price. P_L is a price that is too low, causing a too high amount of pollution (A_L). The solid blue line shows that the marginal damage is much higher than the price paid. P_H is a price that is too high, leading to pollution being "too low". The solid yellow line shows that the polluter is paying much more than the damage it is causing.

If the price is set so that marginal savings are lower than the marginal damage, the polluter is not going to pay for all the damage it does by polluting, and the amount of pollution is going to be too high. If the marginal savings is higher than the marginal damage, the amount of pollution is going to be too low. The polluter is going to pay more in fees than society gains from abating pollution. All of this is illustrated in Figure 4. Generalising this logic to all types of negative externalities, for example congestion fees, the optimal fee should be equal to the marginal damage caused by the externality.

One could also pay a subsidy to try to encourage polluters to pollute less. An exemption from a congestion fee could be seen as a subsidy. Subsidies work more and less the same at taxes. Exemptions from congestion charges are not that simple though, from a Pigouvian perspective. An exemption from congestion charges would be seen as subsidising drivers that buy electric cars, thereby emitting fewer pollutants, but at the same time subsidising electric car drivers to drive more often, increasing the negative externalities linked to congestion. An exemption therefore has two, diametrically opposite effects when it comes to negative externalities linked to automobile traffic.

Croci (2016) argues that congestion charges tend to not be set at an optimal Pigouvian level, because of political reasons, as well as the fact that the charges are not differentiated according to damage caused. In Stockholm and Gothenburg, charges are differentiated depending on time of day, but not depending on damage caused in regards to externalities such as pollution. In London and Milan, charges are somewhat differentiated depending on emissions, but not depending on time of day. The theory of Pigouvian charges suggest that charges should be differentiated according to the damage caused. Ideally, all the damage caused by each driver individually should be internalised as an individual charge, something that of course is practically impossible.

3.3 Cost-benefit analysis

When evaluating the implications of policy decisions and major projects, it is important to contrast the positive effects of the policy with the negative effects, to see if the policy is worthwhile or not. Do the societal benefits of the policy outweigh the negative effects? One way to try to gauge this is by using a cost-benefit analysis.

A cost benefit analysis aims to put monetary values on all societal benefits and costs, comparing these to each other, and come up with a net benefit, stated in monetary terms. Putting pollution abatement against the monetary costs of abatement, it is easy to think that the optimal solution is to reduce all pollution, no matter the cost. What should be remembered in that the money and resources used for abatement of pollution could be used for other socially beneficial projects. It is important to remember that policy decisions do not exist in a vacuum, and that policy makers are always working with limited resources. By putting monetary values on externalities, even very negative externalities such as fatal accidents, a cost-benefit analysis aims to be a tool to help policy makers compare and contrast the usage of resources, to find the most socially optimal use.

Often when a cost benefit analysis is made, the most important factors have no obvious monetary value. Externalities may have no market value at all, or may be wrongly valued, because of issues such as the tragedy of the commons. The cost-benefit analysis is thus dependent on non-market valuation of these factors. There are two main valuation categories, revealed preferences and stated preferences. We mention these two methods so that the reader can get an overview of methods used to value environmental goods. In the thesis, we use the monetary values recommended by the Swedish Transport Agency, without concerning ourselves as to the exact methods used to determine these values (Trafikverket, 2018).

3.3.1.1 Revealed preferences

Revealed preferences is a category of methods whereby the researchers try to infer the price of an environmental good or bad from prices of actual markets connected to the environmental good. For example, one might look at the housing market and observe that houses are less expensive in areas with cleaner air and more expensive in areas with more polluted air, and from this observation deduce a price for clean air (Kolstad, 2011, p. 137). Revealed preferences is the best way of pricing environmental goods, in that they reflect actual consumer behaviour. However, the situation is often such that there is no way of measuring the price of an environmental good using revealed preferences.

3.3.1.2 Stated preferences

Stated preferences is a category of methods that depend on consumers stating how much they value a particular environmental good. The most common approach, called contingent valuation, constructs hypothetical markets, and values environmental goods based on surveys where consumers get asked what they would have been willing to pay for a certain amount of an environmental good. Stated preferences methods suffer from a number of problems, the most important one being hypothetical bias (Hausman, 2012). When consumers get asked how much they would pay for an environmental good, but do not actually have to pay, they have a tendency to misstate the amount they are willing to pay, often overstating it. Stated preference methods are therefore problematic when it comes to valuation of environmental goods, and the trustworthiness of these valuations can be put into question.

3.3.1.3 Discounting

Discounting in the context of cost-benefit analysis is based on the economic concept of present value (Mishkin and Eakins, 2018, p. 78-79). If I have €1 in my hand today, and put it into a bank account with 5% interest rate, in a year I am going to have 1*1.05=€1.05. In other words, €1.05 in a year is worth €1 today, with a market rate of 5%. If the process is reversed, €1 in a year can be said to be worth 1/1.05=€0.95 today. It is said that the present value of €1 in a year is €0.95. With FV being the future value, PV the present value, r the interest rate and n the number of years, the present written according to Eq. (1).

$$PV = \frac{FV}{(1+r)^n} \tag{1}$$

This same concept is applied in the case of a cost benefit analysis, except that the discount rate is not the market interest rate, but what is called the social discount rate. With a market rate of 5%, it is clear from the above example that if we have to spend €1,000,000 next year too, for example, remove a certain pollutant, the present value of that expenditure is €950,000. What is not clear, though, is how you value for example 1 ton of CO_2 released into the atmosphere in one year compared to the same amount released today, or an injury from a traffic accident in five years compared to an injury today. The discount rate is used to calculate the inter-generational change in value of different externalities is called the social discount rate, and is determined by how people value the future compared to the present in more general terms. The so called net present value (NPV) of a cost-benefit analysis, ie. the discounted difference between costs and benefits over time is given by Eq. (2).

$$NPV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} (B_t - C_t) \tag{2}$$

Here, r signifies the social discount rate, B_t the total benefits at time t, C_t the total costs at time t, and T the last time period in the time interval examined. The net present value is typically the value used to examine the validity of a proposal or project in a cost-benefit analysis.

Another interesting metric could also be the benefit-cost ratio. The ratio between benefits and costs can show how profitable a project is, independent of how big the benefits and costs are in absolute numbers.

The social discount rate is a debated topic within the field of environmental economics, since it can be seen as quite arbitrary, yet it has an enormous effect on calculations over time, due to its exponential nature. Some people argue that there should be no discounting when it comes to policy decision, since a government that is expected to last for a long time should prioritise all citizens the same, no matter what generation they belong to (Kolstad, 2011, p. 114-117). Others argue that the discount rate should be higher, since people are expected to be richer in the future, and so €1 will be worth even less in comparison to the future wealth of society.

Whatever discount rate one chooses, it is important that it stays consistent between projects that are to be compared, since disparities in discount rate can lead to large biases toward the projects using the lower rates. We use the discount rate recommended by the Swedish Transport Agency (Trafikverket, 2018). In our case, the interest rate is not as crucial, since out costs and benefits occur within the same time periods, which means they will be discounted at the same rate as each other.

3.4 The S-curve and the adoption of new technology

Technology adoption is often viewed from the perspective of what is called the Technology Life Cycle. One view of the Technology Life Cycle is the S-curve, where technology adoption over time exhibits slow growth in the early stages of technological development, faster growth as technological hurdles are overcome, steady growth the product becomes more commonplace, and a leveling off as the market matures. Taylor and Taylor (2012) summarizes different perspectives in the Technological Life Cycle, and describes the typical stages of the S-curve as Embryonic, Growth, Maturity and Ageing. The City of Stockholm (City of Stockholm, Environment and Health Administration, 2009) describes the adoption of so called energy efficient vehicles in terms of the s-curve, arguing that the exemption from congestion charges that was in effect in Stockholm at that time managed to shift the curve towards earlier adoption. The S-curve is shown in Figure 5.

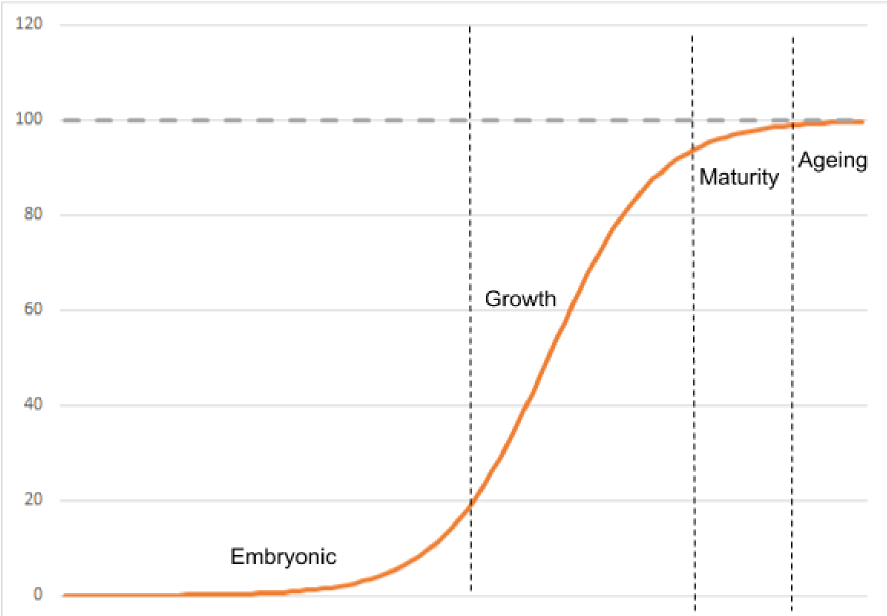

Figure 5. An illustration of how an s-curve might look when it comes to a new technology such as electric cars, with slow growth accelerating into fast growth in the embryonic stage, growth becoming more steady in the growth stage, levelling off in the maturity stage, and flattening in the ageing stage.

4 Data collection

4.1 Traffic data

The traffic data in this thesis is taken from the website of the Swedish Transport Agency (Transportstyrelsen, 2020b), where data regarding passages through the congestion charge cordon is published monthly. This data includes the number of total passages through the cordon, but also the monthly revenues from the charges, as well as the number of monthly tax decisions.

4.2 Car fleet data

Data regarding the composition and size of the car fleet in Gothenburg is taken from Trafikanalys, which is a government agency tasked with evaluating current and proposed transport policies in Sweden (Trafikanalys, 2020a). On their webpage, detailed statistics about a variety of traffic related data is accessible, including road traffic, public transport and travel habits.

4.3 Emissions data

All the statistics regarding emissions from the different pollutants are gathered from the National Emission Database (RUS, 2020). The data is available for each region and municipality in Sweden. The database is administered by the governmental organisation RUS (Regional Utveckling och Samverkan i miljömålssystemet). They work as coordinators facilitating cooperation between national authorities and the different regions in Sweden. The emission data is collected and distributed by several different organisations working together including, the Swedish Environmental Emission Database, the Swedish Central Bureau of Statistics, the Swedish Institute of Environment. The annual data collection is financed by the Swedish Environmental Protection Agency. Sweden uses this source when reporting yearly emission levels to the United Nations Framework Convention on Climate Change.

4.4 Elasticities

Our externalities are calculated mainly using elasticities between the externalities and the change in traffic flow, taken from a cost-benefit analysis done by Danna et al. (2012), where they examined the possibility of implementing a congestion charge in downtown Seattle. These elasticities were calculated based on data taken from Stockholm, London and Milan.

When calculating the effects on the composition of the car fleet, the results used are from a study of the Stockholm congestion charge done by Whitehead et al. (2014). This is not an elasticity, but the result of a simulation determining the effect on private car sales of the exemption for so called energy efficient vehicles. We round this effect down to an even 10% when doing our calculations. In the sensitivity analysis, a number taken from the City of Stockholm Environment and Health Administration (2009) is used to compare with our baseline scenario.

The change in traffic volume is calculated using an elasticity between charge price and traffic volume for Stockholm, determined by Börjesson and Kristoffersson (2018) .

Factor	Elasticity (or percentage increase where no elasticity could be found)	Source
Traffic change due to toll	-0.52	Börjesson and Kristoffersson (2018)
EV sales change due to toll	10.49%	Whitehead et al. (2014)
PM emissions	0.5882	Danna et al. (2012)
NO_x	0.3571	Danna et al. (2012)
CO_2	0.5042	Danna et al. (2012)
Travel time	0.1471	Danna et al. (2012)
Traffic accidents	0.15	Danna et al. (2012)

Table 2. Elasticities used to calculate amounts

4.5 ASEK

ASEK, which stands for "Analysmetod och samhällsekonomiska kalkylvärden" (freely translated: Analysis Method and Economic Values), is a document published by the Swedish Transport Authority, outlining the recommended methods and values to be used when calculating cost-benefit analyses within the transport sector in Sweden (Trafikverket, 2018). All of the monetary valuations of externalities, as well as the recommended annual discount rate, are taken from ASEK.

Factor	**Value**
Fatal accidents (SEK/accident)	46,597,000
Severe accidents (SEK/accident)	16,641,200
Minor accidents (SEK/accident)	4,238,200
CO_2 (SEK/KG)	1.14
NO_x (SEK/KG)	20
Particulate Matter (PM) (SEK/KG)	5,884
Travel Time (SEK/HOUR)	116

Table 3. The different externalities calculated in the thesis, and their monetary values taken from ASEK (Trafikverket, 2018).

5 Method

5.1 Cost-benefit analysis

A cost-benefit analysis (CBA) was performed, examining the costs and benefits of exempting electric cars from the congestion charges in Gothenburg. Our cost-benefit analysis was partly modeled on a previous CBA done by Durakovic and Eiderström Swahn (2014), as well as a CBA done by Danna et al. (2012).

Pure electric cars were chosen because they are the only category of cars that has the potential to be truly emissions free. Calculations regarding negative externalities are also easier to perform, and less ambiguous, when zero emissions cars are compared to fossil-fueled cars.

A simplified model assuming total substitution of electric cars to non-electric cars was used, where the total number of newly registered cars, is assumed static. This is fairly consistent with current data, where there is a growing trend in the number of newly registered electric vehicles, but no such trend can be observed in the total newly registered electric cars (Trafikanalys, 2020a). This means that an increase in the number of newly registered electric cars leads to an equal decrease in the number of non-electric cars. The total size of the car fleet is also considered constant, which also is fairly consistent with data (Trafikanalys, 2020a). This means that every newly registered car replaces an old car, and the total number of cars remains constant.

The composition of vehicles in traffic is assumed to be the same as the composition of the car fleet. The proportion of electric car trips through the charge cordon is thus assumed to be the same as the proportion of electric cars in the vehicle fleet.

Electric cars are assumed to lead to zero emissions of greenhouse gases, NO_x and other pollutant gases. Regarding all other externalities they are assumed to be similar to an average car.

2019 is used as the base year for our calculations. We use vehicle and traffic data from 2019 to simulate the effects if an exemption for electric cars would have been implemented, calculating the costs and benefits based on this simulation.

One thing to note is that revenue loss from decreased payment of fuel taxes, as well as direct revenue loss from non-payment of the congestion charge by exempt vehicles has no effect on the balance of costs and benefits from a societal point of view. The cost to the government is cancelled out by an equally large benefit to the consumers. Another such factor one could take into account would be lost revenue from decreased use of public transport. This revenue loss is also assumed to be cancelled out in the same way. We will, however, take into account the revenue loss, as well as the associated benefit to consumers, caused by exempt vehicles not having to pay the charge. Revenue has been an important factor for decision makers when it comes to the congestion charges in Sweden, and revenue loss was an important factor in ending the exemption in Stockholm (Börjesson and Kristoffersson, 2015) .

The change in costs and benefits are calculated as follows: first, the increase in newly registered electric vehicles, which is the same as the decrease in non-electric vehicles, is calculated, and the vehicle fleet is recompositioned based on this change. The composition of traffic is assumed to be the same as the composition of the car fleet. Based on this new simulated vehicle fleet, the increase in traffic, based on lower driving cost for electric vehicles, is calculated. After these two steps, different benefits associated with the change in the composition of the vehicle fleet and costs associated with increased traffic are calculated.

Lastly, the net present value of these costs and benefits are discounted over time, using 2030 as an end year, taking into account the growth and saturation of the electric car market in a simplified model.

5.2 Change in vehicle fleet

Our model assumes that car sales stay constant, and a pure substitution occurs between EVs and non-EVs when sales of electric cars increase. This is somewhat consistent with current statistics.

In 2019, there were 18,123 newly registered cars, of which 1,147 were electric, representing 6.33% of the total number of newly registered cars. The total number of registered electric cars was 2,068, out of a total of 189,565 cars. This number includes all newly registered electric cars in 2019. The total percentage of electric in the car fleet was 1.1%. The amounts that are most relevant to our calculations are listed in Table 4, and the relevant percentages are listed in Table 5.

Assuming the exemption leads to a 10% increase of newly registered electric cars (ΔEV), the increase in newly registered electric cars would be 114.7. The number of electric cars sold would be 1,261.7. The percentage of electric cars (%EV) in the car fleet (CF) after our exemption is given by Eq. (3).

$$\%EV = \frac{EV_{previous} + \Delta EV}{CF} = \frac{2068 + 114.7}{189565} = 0.0115 = 1.15\% \tag{3}$$

Factor	Before exemption	Efter exemption	Change
number of newly registered electric cars	1,147	1,261.7	114.7
number of newly registered cars, total	18,123	18,123	0
number of electric cars in the car fleet	2,068	2,182.7	114.7
number of cars in the car fleet, total	189,565	189,565	0

Table 4. The number newly registered cars and of the total cars in the car fleet, before and after simulation of a congestion charge exemption

Factor	Before exemption	After exemption	Change, percentage points	Change, percent
newly registered electric cars	6.33%	6.96%	0.63%	10%
newly registered non-electric cars	93.67%	93.04%	-0.63%	-0.67%
electric cars in the car fleet	1.1%	1.15%	0.05%	5.55%
non-electric cars in the car fleet	98.9%	98.85%	-0.05%	-0.06%

Table 5. Relevant percentages relating to the composition of the car fleet

5.3 Change in traffic volume

Traffic volume is measured as the total number of passages through the charge cordon, taken from the Swedish Transport Agency (Transportstyrelsen, 2020b). For 2019 there was a total of 140,051,000 trips through the cordon. We assume that the percentage of trips that are electric is the same as the percentage of cars that are electric. 1.15% of the trips through the cordon are thus done with electric cars, after accounting for a recomposition of the vehicle fleet, but before accounting for any increase in traffic due to lower trip costs. This amounts to a total number of trips of 1,612,583.

Since only electric cars are exempt from charges in our model, we assume that only trips with electric cars are the only ones affected by the exemption. This means that we are not considering any possible decrease in traffic from non-electric car drivers due to increased congestion.

We use the recompositioned traffic of electric cars to calculate the change in traffic according to Eq. (4). and Eq. (5). The two steps of the traffic change calculations are illustrated in Figure 6.

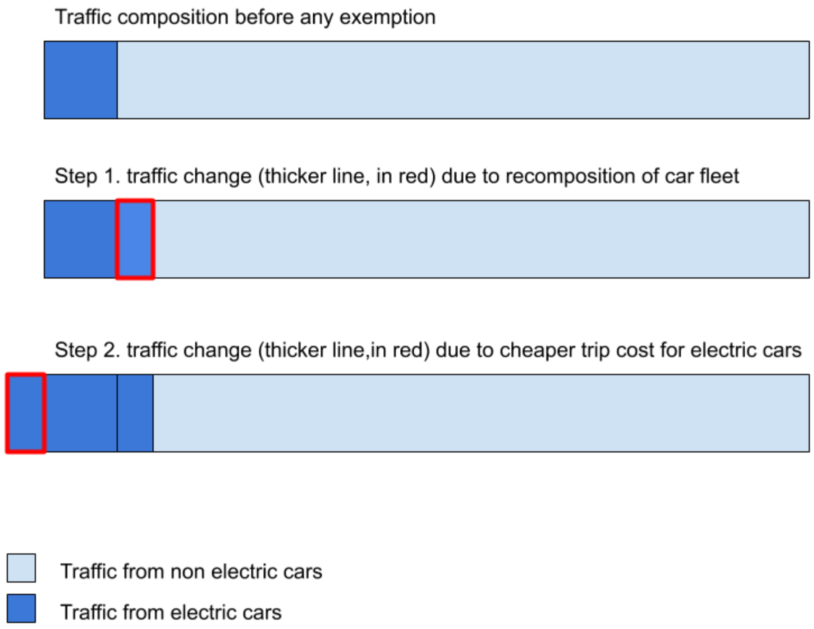

Figure 6. Illustration of the two steps of traffic change according to our model. The rectangles represent the size of the traffic. In step 1, total traffic does not change, only the amount of electric car traffic in relation to the non-electric car traffic. In step 2, the number of trips from electric cars increase, due to lower trip costs. This leads to a change in total traffic.

Using the elasticity (ε) between the congestion charge (c) and the electric vehicle traffic (T_{EV}) , we can calculate the change in the number of trips because of lower trip costs for electric car drivers. C_T signifies the trip cost.

$$\Delta T_{EV} = \varepsilon\left(\frac{c}{C_T}\right)T_{EV} \tag{4}$$

The charge we use to calculate the decrease of trip costs is the average monthly charge paid, calculated from statistics taken from Transportstyrelsen (Transportstyrelsen, 2020). The trip cost used is the cost per kilometer used by the Swedish tax authority, multiplied by the average number of kilometers a driver in Västra Götaland drives in a month (Trafikanalys, 2020). The price elasticity for the congestion charge is taken from Börjesson and Kristoffersson (2018), which for 2015 was calculated to -0.52. This gives us:

$$\Delta T = -0.52 \times \left(\frac{-157.93}{1.85 * 1015.83}\right) \times 1612583 = 70468$$

To calculate the externalities using the elasticities from previous studies, we need the percentage change in total traffic. To do this we divide the increase in the number of trips for electric cars with the total number of trips through the charge cordon.

$$\%\Delta T = \frac{\Delta T_{EV}}{T} = \frac{70468}{140051000} = 0.0005 = 0.05\% \tag{5}$$

5.4 Costs

5.4.1 Increased travel time

Increased traffic leads to increased travel times. In the case of our simulation, a small increase in traffic is observed, due to increased traffic from electric cars. Using an elasticity between traffic change and travel time change, obtained from Danna et al. (2012), we can first calculate the percentage change in travel time based on the percentage change in traffic volume. Here, t signifies travel time and T signifies traffic.

$$\%\Delta t = \varepsilon(\%\Delta T) = 0.1471 \times 0.0005 = 0.00007355 \tag{6}$$

We then multiply that percentage with the average travel time per trip (t_{trip}), obtained from a travel survey from the Gothenburg traffic office, and in turn multiply this with the total number of trips (T), to get the total amount of extra travel time due to the traffic increase.

$$t_{tot} = \%\Delta t \times t_{trip} \times T \tag{7}$$

$$\Rightarrow 0.0007355 \times \frac{25}{60} \times 140051000 = 4319.1$$

Lastly, we take the value per hour of travel time(c_{hour}) from ASEK, and determine the economic cost (EC) of the extra travel time due to the increase in traffic.

$$EC_{tt} = t_{tot} \times c_{hour} = 4319.1 \times 116 = 501015.85\, SEK \tag{8}$$

5.4.2 Increased travel uncertainty

Uncertainty about travel time is another cost for society. The effects travel uncertainty can be estimated as a third of the effects of increased travel time (Danna et al., 2012). This gives us Eq. (9).

$$EC_u = \frac{EC_{tt}}{3} = \frac{501015.85}{3} = 167005.28\, SEK \tag{9}$$

5.4.3 Increased accidents

Numerous studies show that when toll charges are implemented as a way to combat congestion there is generally a noticeable decrease in traffic volume. This could be a probable reason to assume fewer traffic accidents. A decreasing amount of vehicles should naturally lead to fewer injuries linked to traffic accidents. However, when differentiated charging rates like exempting electric cars are introduced, instead of a decreasing amount of vehicles an increase of electric cars will occur in traffic, which naturally leads to an increasing amount of accidents.

Using an elasticity taken from Danna et al. (2012), the percentage change in accidents is given by Eq. (10). We see a slight and comparatively insignificant increase is seen in traffic accidents.

$$\%\Delta A_{tot} = \varepsilon_a\,(\%\Delta T) \tag{10}$$

$$\Rightarrow\ 0.15 \times 0.05032 = 0.007548$$

The expression on the left-hand side represents the percentage change in total traffic accidents (A_{tot}) which is obtained by multiplying the elasticity of traffic accidents, which is gathered from Danna et al (2012), with the increase in traffic (T) due to exempting electric vehicles.

The economic costs of increased traffic accidents are calculated according to Eq. (11).

$$EC_A = \%\Delta\, A_{tot} \times A_f \times V_f + \%\Delta\, A_{tot} \times A_s \times V_s + \%\Delta A_{tot} \times A_m \times V_m \tag{11}$$

$$\Rightarrow 0.00007548 \times (10 \times 46597000 \times 50 \times 16641200 \times 422 \times 4238000) = 232966.45368$$

The formula contains three different types of accidents from the year 2019. There were 10 fatal accidents (A_f), 50 severe accidents (A_s) and 422 minor accidents (A_m). The different types of injuries caused by the accidents are valued using ASEK (V_f,V_s andV_m).

5.4.4 Increased emissions of PM-particles

Electric cars are assumed to emit as much particulate matter as fossil-fueled cars, therefore an increase in PM-emissions will occur due to an increase of electric vehicles in the city centre (Timmers and Achten, 2016).

Due to the uncertainty of how much of every specific type of pollutant each individual car emits, the values for PM10 and PM2.5 have been grouped together. The elasticity for the pollutant is retrieved from Danna et al (2012). The increase in PM-emissions due to an increase in traffic volume is given by Eq (12).

$$\%\Delta E_{PM} = \varepsilon_{PM}(\%\Delta T) \tag{12}$$

$$\Rightarrow 0.5882 \times\ 0.050316\ \approx\ 0.0296$$

The percentage increase in PM-emissions depends on the increase in traffic volume (T) multiplied by the elasticity for particulate matter (ε_{PM}). The elasticity for the pollutants is retrieved from Danna et al (2012). The increase in PM-emissions due to an increase in traffic volume is given by Eq. (13).

$$EC_{PM}\ =\ E_{PM}^{Previous}\ \times c_{PM} \times \%\Delta E_{PM} \tag{13}$$

$$\Rightarrow 14636 \times 5884 \times 0.000296 = 25\ 495{,}32656$$

The formula shows how the previous emission level of particulate matter ($E_{PM}^{Previous}$) is multiplied with the cost of PM times the percentage increase in particulate matter results in an economical cost in the analysis. The previous level of the particulate matter (14,636 kg/year) is gathered from The National Emission Database (RUS, 2020). The cost of the emissions are estimated at 25,500 SEK.

5.4.5 Lost revenue from congestion charge

According to our model, with a 10% increase in sales of electric vehicles because of the congestion charge exemption, the number of electric vehicles (EV) in the car fleet would have been 2,182.7.

The average charge paid per car and month in 2019 is calculated by taking the total monthly revenue from the charge and dividing it with the monthly number of charge decisions (each driver is charged monthly). This number (C_{month}), averaged over the whole year, comes out to 157.9 SEK. Eq. (14) gives the yearly economic cost (EC) due to lost revenue loss of.

$$EC = EV \times C_{month} \times 12 = 2182.7 \times 157.9 \times 12 = 4136529\ SEK \tag{14}$$

5.5 Benefits

5.5.1 Lower CO_2 emissions

Since electric vehicles emit no harmful gases as opposed fossil-fueled vehicles, a decrease in the CO_2 levels will occur due to a reduction in fossil-fueled vehicles. The elasticity for greenhouse gases such as this one is again obtained from Danna et al (2012). To calculate the reduction in CO_2 , we use Eq. (15).

$$\%\Delta E_{CO_2} = \varepsilon_{CO_2}(\%\Delta T_{nev}) \tag{15}$$

$$\Rightarrow\ 0.5042 \times (-0.0611743) = -0.03084408206 \approx -0.030844$$

The percentage decrease of CO_2 is determined by the elasticity times the decreasing amount of non-electric vehicles (T_{nev}).

CO_2 is measured in tonnes/year and is specific for privately owned cars in the Gothenburg region. The values for 2019 are estimated at 340,178,300 kilograms. The costs (c_{CO_2}) are measured using ASEK and are measured in kr/kg. The economic benefits due to reduced CO_2-emissions is given by Eq. (16).

$$EB_{CO_2} = E_{CO_2}^{Previous} \times c_{CO_2} \times \%\Delta E_{CO_2} \tag{16}$$

$$\Rightarrow\ 340178300 \times 1.14 \times 0.00030844 = 119614.038$$

The formula shows how the economic benefits (EB) are determined by the previous output of carbon dioxide emissions ($E_{CO_2}^{Previous}$) multiplied with the cost of CO_2 multiplied with the magnitude of the percentage change of emissions ($\%\Delta E_{CO_2}$) caused by a decreasing amount of non-EVs.

5.5.2 Lower NO_x emissions

Due to the decrease of non-electric cars in the vehicle fleet we observe a reduction in NO_x emissions. The percentage decrease of NO_x-emissions is calculated using Eq. (17), using an elasticity taken from Danna et al. (2012).

$$\%\Delta E_{NO_x} = \varepsilon_{NO_x}(\%\Delta T_{nev}) \tag{17}$$

$$\Rightarrow\ 0.3571 \times (-0.0611743) = -0.02184534253 \approx -0.021845$$

The percentage decrease of NO_x is determined by the elasticity (ε_{NO_x}) multiplied by the decreasing amount of traffic from non-electric vehicles (T_{nev}). The magnitude of the percentage decrease in then multiplied with the cost per kg of NO_x-emissions taken from ASEK, and the previous emission level of NO_x, according to Eq. (18).

NO_x is measured in kg/year (converted from tonnes/year) and is specific for privately owned cars in the Gothenburg region. The values for 2019 are estimated to be 723,354 kg. The costs (20 kr/kg) are once again valued using recommendations from ASEK.

$$EB_{NO_x} = E_{NO_x}^{Previous} \times c_{NO_x} \times \%\Delta E_{NO_x} \tag{18}$$

$$\Rightarrow\ 723354 \times 20 \times\ 0.00021845 = 3\ 160.33$$

From the formula, which is very similar to the previous one regarding CO_2, the benefits are determined by the previous level of NO_x , times the cost, times the reduction in absolute percentage values which was obtained from the previous formula.

5.5.3 Lower driver costs

Like mentioned before, lower driver costs are identical to lost revenue from the congestion charge. We simply have a transfer of funds, from the local government to private citizens. The benefit from consumer is given by Eq. (19).

$$EB = EV \times C_{month} \times 12 = 2182.7 \times 157.9 \times 12 = 4136529\ SEK \tag{19}$$

5.6 Other factors

5.6.1 Traffic noise

One would expect lower noise levels with a vehicle fleet that has a decreasing amount of fossil-fueled vehicles, since electric vehicles are proven to emit less noise (Venheijden and Jabben, 2010).

However, even if you halve the traffic flow you only get a decrease of about 3 decibel (Congestion Charge Secretariat, City of Stockholm, 2006). Furthermore, lower traffic noise would only be significantly noticeable by a vehicle fleet that almost exclusively consists of hybrid and electric vehicles (Venheijden and Jabben, 2010).

Since the exemption of electric cars does not affect traffic flow to a large enough extent, trying to calculate the benefits of decreased noise levels would be impractical.

5.6.2 Public transport

How an exemption of electric vehicles might affect the public transport system is uncertain. The public transport system in the city of Gothenburg is somewhat unique in the way that ticket sales are handled. An individual is not refused a ride without a ticket, it is optional to tap the card or pay by the app using your phone. This freedom of choice creates a free-rider problem which makes statistics regarding public transport unreliable (Börjesson and Kristoffersson, 2015).

Mainly due to the unreliability of the statistics in Gothenburg, any changes in the public sector due to an exemption of electric vehicles would not only be limited but also insignificant. Furthermore, any revenue lost due to fewer public transport trips is cancelled out by increased consumer surplus.

5.6.3 Other pollutants

The cost-benefit analysis does not include any potential changes in VOCs, CO, and SO_2. Since no elasticities were found for VOCs and SO_2 a calculation using our main method was not possible. ASEK does however include VOCs and SO_2 among the most common emission factors caused by traffic, but they do not include monetary values for CO, which creates difficulties when trying to calculate the cost. Furthermore, the Swedish Environmental Protection Agency states that both CO and SO_2 has decreased substantially during the last decades. The majority of the SO_2 in Sweden comes from sources outside of Sweden, and most of SO_2 emitted in Sweden is from industrial sources (Naturvårdsverket, 2020).

We estimate that any potential changes in the CBA caused by these pollutants would not have had lead to any significant change in the conclusion.

5.7 Growth and discounting over time

When doing a cost benefit analysis over time, one has to account for the change in different factors going into the model used. In our case, the factor experiencing the largest growth is the market share of newly registered electric vehicles. Using data from Trafikanalys

(2020a), we estimate the average year over year growth of newly registered electric cars in Gothenburg between 2011 and 2019 to be 68%.

Growth varied considerably during this period, and has accelerated dramatically during recent years. In 2018 the number of newly registered electric vehicles in Gothenburg was 437, in 2019 this same number was 1,161. This is an increase of 166%.

Making predictions of continued growth in such an early stage in the development of a new technology is difficult. In 2017, Trafikanalys predicted a year over year growth of 30% in Sweden, while in their short term prognosis made in 2019 they predicted a yearly growth of 50% during 2020, 40% during 2021, and 20% during 2022. We use a year over year growth rate of 30% as our base scenario, simulating other growth rates in our sensitivity analysis. This growth rate is called the ”natural growth” in this thesis.

Our model will assume a natural growth (g_{nat}) of 30% annually, until market saturation. For every year, we increase the number of newly registered electric vehicles ($NREV_t^{nat}$), at time t, by this factor. The natural growth of newly registered electric vehicles is given by Eq. (20).

$$NREV_t^{nat} = NREV_0(1 + g_{nat})^t \tag{20}$$

A factor representing the additional growth of the amount of newly registered electric cars (g_{ex}) is then added, according to Eq. (21). The number of newly registered electric cars is then added to the total number of electric cars from the year before (TEV_{t-1}), resulting in the total number of electric cars in the car fleet with a congestion charge exemption (TEV_t). This is given by Eq. (22).

$$NREV_t = NREV_t^{nat} + g_{ex} NREV_t^{nat} \tag{21}$$

$$TEV_t = TEV_{t-1} + NREV_t \tag{22}$$

Traffic is assumed to be proportional to the car fleet. Total traffic is assumed constant, it is assumed that there is no natural growth in traffic. The actual growth in traffic through the charge cordon in Gothenburg, that can be observed through data, seems to be quite small in reality (Transportstyrelsen, 2020b).

Without any further assumptions, market saturation will occur when the exponential growth of newly registered electric cars meets the line representing the constant amount of newly registered cars. At this point all newly registered cars will be electric.

The effect of an exemption on the amount of newly registered electric cars disappears at this point, but the effect of the exemption on increased trips taken by already existing electric cars is maintained. Different “saturation levels” will be explored in the sensitivity analysis.

In reality, new technology conforms to an S-curve, which means that our model is oversimplified. The net present value of the cost benefit analysis is still expected to be the same sign as if a proper S-curve would have been used, since the curves are expected to shift in the same direction due to an exemption, and all externalities are proportional to this shift. The difference between our exponential model and the S-curve is illustrated in Figure 7.

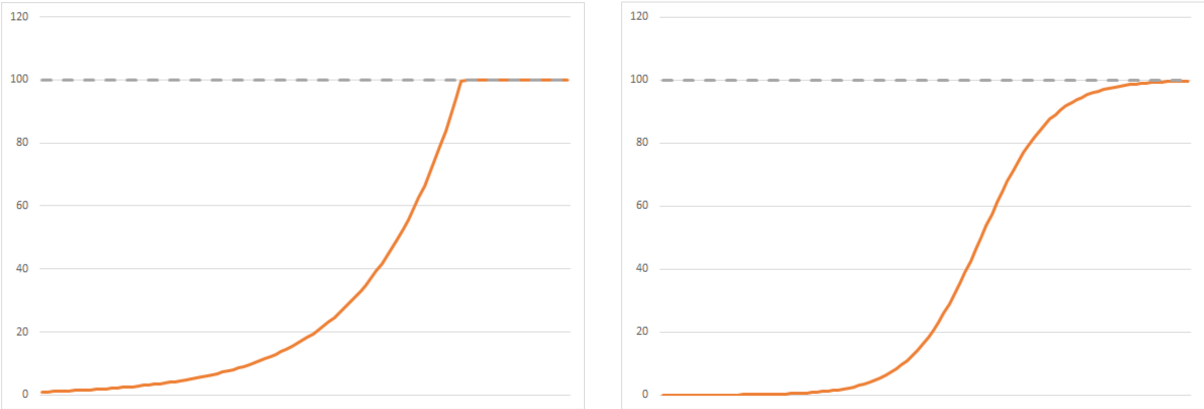

Figure 7. An illustration of our growth model for newly registered electric cars (to the left) versus the more realistic s-curve (to the right).

The discount factor used in the cost benefit analysis 3.5%, as recommended by ASEK (Trafikverket, 2018).

The time span chosen for the CBA was 12 years, from (and including) 2019 to 2030, which aligns with the Swedish government's ambition to have a fossil free car fleet by the year 2030.

5.8 Sensitivity analysis

The sensitivity analysis of this thesis focuses on three factors, the natural growth of the electric car market, the effect of the exemption on the purchase on new electric cars, and the saturation point of the market. Three scenarios per factor is investigated, one low effect scenario, one medium effect scenario and one high effect scenario.

In the sensitivity analysis regarding natural growth, our baseline scenario is considered to be the medium scenario. We also simulate a high growth rate of 68%, which corresponds to the average year over year growth rate since 2011, as well as a lower growth rate of 5%.

Natural growth of newly registered electric cars	
Low growth	5%
High Growth	30%
Very High Growth	68%

Table 6. Different scenarios when it comes to the natural growth of the electric vehicle market.

The baseline scenario for the increased sales is considered to be the medium scenario in the sensitivity analysis. The City of Stockholm Environment and Health Administration simulates an effect of 23% for Stockholm City, which will be the high scenario (City of Stockholm, Environment and Health Administration, 2009). This effect is quite uncertain, since there is not a lot of data on it.

Effect of an exemption on the sales of electric cars	
Low effect	5%
Medium effect	10%
High effect	23%

Table 7. Different effects of the exemption on new registrations of electric cars.

When it comes to market saturation, the baseline scenario is considered the high scenario, since this scenario assumes that the market is saturated when 100% of newly registered cars are electric. It seems reasonable to assume that 100% market saturation will not happen. Certain drivers have certain preferences, access to charging infrastructure might make electric cars an unrealistic alternative for certain drivers, and the supply of electric car models might not meet every driver's demand.

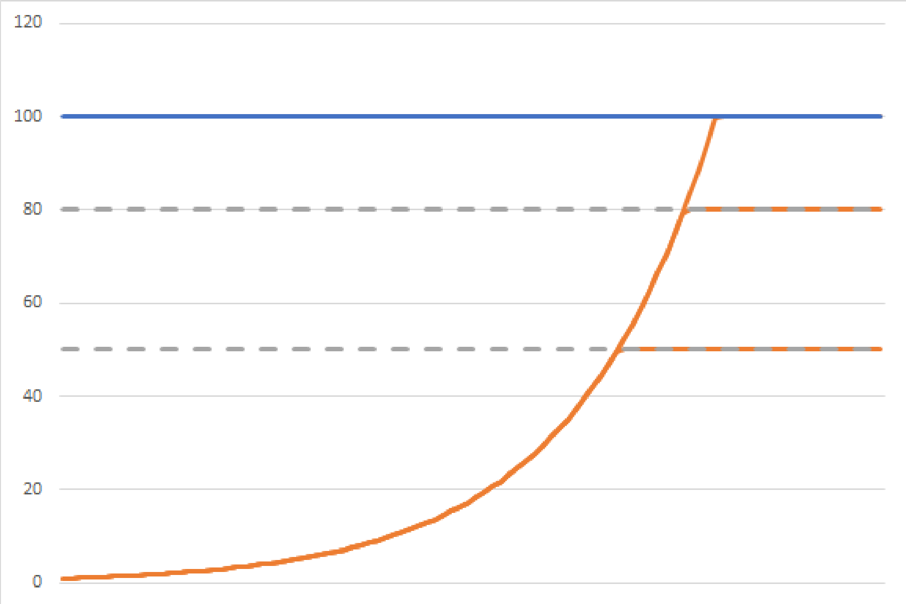

Figure 8. An illustration of different levels of market saturation in newly registered electric vehicles. The number of newly registered electric cars grows exponentially until the growth stops at a certain level. The solid blue line represents the total amount of newly registered cars, and the dashed lines shows when the newly registered electric cars stop growing at lower percentages than 100% of the total number of newly registered cars.

Since the electric car market is rapidly growing, our low scenario is set quite high at 50%, and the medium scenario is set quite close to the baseline scenario, trying to simulate a more realistic scenario where we have a high amount of market saturation, but still a certain amount of non-EVs being sold. Andersson and Kulin (2018) predicted that the share of newly registered electric cars would be between 50% and 80% in the years beyond 2025, which matches are low and medium scenarios. The different saturation levels are given in Table 8, and illustrated in Figure 8.

Market saturation	
Low saturation	50%
Medium saturation	80%
High saturation	100%

Table 8. Different scenarios when it comes to market saturation.

6 Results

6.1 Cost-benefit analysis

Modelling the data from 2019 according to our model yields Table 9, listing the monetary values of the different externalities as well as the end result. The model suggests a net negative benefit of -803,687.95.

benefits (SEK)		costs (SEK)	
CO_2-emissions	119,614.04	Travel time	501,015.85
NO_x-emissions	3,160.33	Travel time uncertainty	167,005,28
Lower driver costs	4,136,529	PM emissions	25,495.32
		Accidents	232,954.16
		Lost revenue	4,136,529
total benefits	4,259,303.83	**total costs**	5,062,991.78
total net benefits		-803,687.95	

Table 9. Results from CBA för 2019

One interesting take away from this result is the relative magnitude of lost revenue and consumer surplus (lower driver costs) relative to the other factors.

Modelling the traffic changes year for year, discounting and summing the costs and benefits yields Table 10. The total net present value (NPV) of exempting electric cars from the congestion charge is -108,551,900.4 SEK. Included as well is the benefit-cost ratio, which is a relevant number when compared to other scenarios in the sensitivity analysis.

benefits (SEK), discounted	**costs (SEK), discounted**
522,279,914	630,831,814.4
total NPV	-108,551,900.4
total benefit-cost ratio	0.8279

Table 10. Results of CBA from 2019-2030.

Here, one can note that the NPV resulting from the analysis over time is very large as compared to the value obtained from the year 2019 (about 135 times larger). This is likely due to certain assumptions in the growth model, most notably the assumption of exponential growth until the market is saturated.

6.2 Sensitivity analysis

Table 11 lists the results of our sensitivity analysis relating to the natural growth of the electric car market. We can see that the NPV becomes more negative as the natural growth factor for electric cars increases, yet the benefit-cost ratio stays roughly the same. As the natural growth increase, the number of electric cars, will of course increase, and the magnitudes of costs and benefits will increase.

However, the small variation in the benefit-cost ratio suggests that the net social costs of exempting electric cars from the congestion charge remains roughly the same, independent of the natural growth. We can see that although future growth can be hard to predict, our results are robust with respect to different growth scenarios. For all levels of natural growth tested, there is a negative social benefit.

Natural growth of newly registered electric cars			
Level of effect	**Percentage**	**Net Present Value**	**Benefit-cost ratio**
Low	5%	-41,357,524.04	0.8241
Medium	30%	-108,551,900.4	0.8279
High	68%	-225,613,638.1	0.8201

Table 11. Results of the sensitivity analysis regarding natural growth of the amount of newly registered electric cars.

Table 12 lists the effect of exemptions on electric car sales. When it comes to the effect an exemption has on electric car sales, we see the same effect, although not as dramatic. More than doubling the effect compared to our baseline scenario leads to an increase of magnitude of our NPV of less than 4%. In all scenarios the NPV remains negative, and the benefit-cost ratio remains almost the same.

Effect of an exemption on the sales of electric cars			
Level of effect	**Percentage**	**Net Present Value**	**Benefit-cost ratio**
Low	5%	-107,199,965.6	0.8226
Medium	10%	-108,551,900.4	0.8279
High	23%	-112,586,971.8	0.8380

Table 12. Results of the sensitivity analysis regarding the effect of the exemption on the amount of newly registered electric cars.

Table 13 lists the effect of different levels of market saturation. When it comes to market saturation, we seem the same trend. An increasingly negative NPV as the saturation percentage is increased, but a more or less static benefit-cost ratio. This makes sense, since he higher the saturation percentage, the longer the exponential growth will go on, and the more electric cars will be on the road.

Market saturation			
Level of effect	**Percentage**	**Net Present Value**	**Benefit-cost ratio**
Low	50%	-99,741,923.2	0.8218
Medium	80%	-107,674,824.4	0.8251
High	100%	-108,551,900.4	0.8279

Table 13. Results of the sensitivity analysis regarding saturation of the electric car market.

The sensitivity analysis shows that for all factors tested, an increase in the factor is correlated with an increase in the magnitude of the net present value of the cost benefit analysis. However, the benefit-cost ratio stays roughly the same in all scenarios. The sensitivity analysis confirms that under all scenarios, there is a negative net present value, and as such, an exemption from the congestion charge is not profitable from a societal point of view.

7 Conclusion and discussion

In this thesis we have examined the costs and benefits of exempting electric cars from the congestion charges in Gothenburg. We did this by performing a cost-benefit analysis, putting the costs related to increasing congestion against the benefits of having fewer fossil-fueled cars on the road. First we did a cost-benefit analysis for the year 2019, then we did an analysis for the time span 2019-2030. Additionally, a sensitivity analysis was performed, controlling for several different growth factors.

The results of our analysis indicate that an exemption from the congestion charge for electric vehicles is not socially beneficial. However, the effects are relatively small. The lost revenue and consumer surplus are much larger than the other factors. Policy-wise, this could affect the conclusions of the CBA, depending on what factor is considered particularly important. From the point of view of the authorities, lost revenue is a crucial factor, since revenue from the congestion charge is used for the West Swedish Agreement infrastructure project. Revenue from the charges has even been considered by some as the main reason for the charges being implemented in the first place (Börjesson and Kristoffersson, 2015).

When calculating the CBA over time, the results were negative as well. The magnitude of the NPV may seem very large in comparison with the results for 2019 alone. This is largely due to our model assuming that the current growth rate would continue unchanged until the market is saturated. This assumption is of course not entirely realistic. As we mentioned before, the real growth would probably conform to an S-curve that is hard to predict. We have tried to take this into consideration in the sensitivity analysis.

It is clear that in all scenarios of the sensitivity analysis, the conclusion remains the same. The NPV is negative in all scenarios. Our model seems to be robust when it comes to our assumptions about growth. There are several factors that we have not calculated. However, the effects of these factors are probably weak, and in some cases the direction of the effects is unclear.

The negative NPV is largely due to the congestion effects, such as travel time, having a bigger impact than pollution effects. How different factors are valued monetarily has a large effect on the tradeoff between pollution effects and congestion effects, especially considering the potential problems associated with methods such as contingent valuation. Like mentioned before, we have used the values recommended by ASEK, without analysing them more in depth. The conclusion that congestion effects are stronger than pollution effects seems to confirm the results by Rotaris et al. (2010).

Removing exemptions for clean cars, like London has done, seems to be a good idea. If a local government wants to stimulate the demand for electric cars, there are other possible effective incentives that do not increase congestion, such as improving the local charging infrastructure (Trosvik and Egnér, 2017).

It is important to note that our results do not invalidate other types of differentiated charge structures. Pigouvian theory suggests that drivers should be charged according to the damages they impose. Since all cars contribute to congestion, exempting any category from the charges does not make sense from this perspective. However, other types of differentiated schemes, where drivers pay according to the damage they cause with respect to externalities such as pollution, could make more sense.

The effect of differentiated price structures for congestion charges is an important topic for further study, since the idea of differentiated congestion charges seems to be an emerging idea within environmental politics, and existing studies on such charges are very limited. This would include studies on how differentiated price structures affect the markets for cleaner vehicles, but also possibly how elasticities with regards to traffic volume are affected.

Another important topic of further research is the distribution effects of congestion charges. Who are the winners, and who are the losers? Distribution or equity factors could possibly have an effect on the support for congestion charges, and studies on these factors can contribute to the design of congestion charges that are both effective and supported politically.

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