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UPTEC STS 19021
Examensarbete 30 hp
Juni 2019

Modelling CO2 emissions from passenger cars for Swedish municipalities

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Abstract

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The ratification of the Paris agreement has motivated nations to investigate how substantial greenhouse gas emission reductions can be accomplished for limiting global warming under two degrees Celsius. In Sweden, the magnitude of CO2 emissions from domestic transportation is approximately one third of all other emission sectors combined. It is therefore crucial for Sweden to stimulate substantial reductions in this sector. Local actors' possibilities to contribute to climate change mitigation are central to succeed albeit constrained in the transportation sector due to data and resource limitations. With the intention to benefit local climate change mitigation work, a model capable of estimating the tailpipe CO2 emissions from passenger cars was created. The modelling exploited traffic work data from mandatory vehicle checks conducted in Sweden for calculating CO2 emissions per car and year for the period of 1999-2017, to thereafter be aggregated for a municipality, i.e. a bottom-up approach. The model and model results have been validated with official data and emission factors from HBEFA, whereas model configurations have also been controlled with sensitivity analyses. The model was applied for a case-study, Järfälla, a municipality who recently had a carbon budget developed. Model results illustrated an increasing trend in CO2 emissions for the period of 1999-2017 and were also presented over fuel technology, mass and car age. Moreover, the model was applied to produce CO2 estimates per postal codes in the municipality for 2017 and to quantify the effect of explorative scenarios, i.e. policy goals, on CO2 emissions.

Handledare: Jesse Benjamin Schrage
Ämnesgranskare: Mikael Hook
Examinator: Elísabet Andrésdottir
ISSN: 1650-8319, UPTEC STS 19021
Tryckt av: Uppsala University

Foreword

Employees at Transport Analysis, the Government Agency of Traffic, the Swedish Environmental Research Institute and the Swedish Meteorological and Hydrological Institute have been very helpful, and all of them on multiple occasions. A special thank you to Anette Myhr at Transport Analysis, to Håkan Johansson at the Government Agency of Traffic, to Muhammad-Reza Yahya at the Swedish Environmental Research Institute and to Stefan Andersson at the Swedish Meteorological and Hydrological Institute. Furthermore, Anette Myhr and Muhammad-Reza Yahya have also provided the master thesis with essential data for the master thesis.

Sammanfattning

Transportsektorn är fundamentalt för ett land utifrån många anledningar. Transport av varor och människor utgör en viktig del och bilen har blivit en del av samhället på många sätt. Det har alltid funnits ett fokus på att öka säkerheten och därmed minska olyckorna, vilket många gånger överensstämt med att förbättra flödet av trafiken. Betydelsen av trafikflödet kan förstås utifrån betydelsen av transporter för ett lands ekonomi eftersom, till exempel, förseningar ökar kostnader för företag. Det finns dock många andra anledningar till bilens integrering i det moderna samhället, till exempel friheten och bekvämligheten den skänker till befolkningen. Under de senaste tjugo åren har dock klimatfrågan seglat upp jämte andra prioriteringar och då handlar det istället om att sänka växthusgasutsläppen där koldioxid utgör den absoluta merparten av utsläppen.

Riokonferensen 1992 kan ses som startskottet för globala ansträngningar att sänka växthusgasutsläppen. Kyoto Protokollet 1997 var ytterligare ett steg i denna riktning där länder, inklusive Sverige, förband sig att sänka sina växthusgasutsläpp. Sverige lyckades även sänka sina territoriella utsläpp, men de globala utsläppen har däremot fortsatt uppåt. Nu under senare år har Sverige även undertecknat Parisavtalet från 2015 och en stor skillnad mellan Kyoto Protokollet och Parisavtalet är inkluderingen av nästintill alla länder i världen. Sverige, liksom en överväldigande majoritet av världens länder, har därmed som ambition att bidra till att begränsa den globala uppvärmningen till under två grader Celsius inom detta sekel.

Sveriges klimatambitioner är dock inte lätta att förena med transportsektorns utsläpp, vilket för övrigt är en minsta gemensam nämnare i världen: Transportsektorn står för en betydande andel av världens globala växthusgasutsläpp. I Sverige är inrikestransport den största utsläppssektorn och motsvarar ungefär en tredjedel av Sveriges territoriala utsläpp idag. Att finna en förklaring på den markanta utsläppsnivån är inte svårt. Den totala sträckan som körs på svenska vägar har i princip, med undantag för enskilda år, alltid ökat och gör så än idag. Teknologiska förbättringar har inte vägt upp ökningen av den totala körsträckan avseende CO_2 utsläpp och utsläppen har således ökat relativt andra utsläppssektorer.

Klimatfokuset är ett relativt nytt fenomen i sammanhanget och trafikdata är inte insamlad för detta syfte. Först kring millenniumskiftet uppskattades den totala körsträckan i Sverige och då även tillbaka till 1950. Uppskattningen, i brist på annat, använde ett lapptäcke av olika datakällor samt informationskällor. På sistone har datakällorna förbättrats avsevärt och uppskattningar av den totala körsträckan är god. Det är inte nödvändigtvis fallet när det kommer till uppskattningar av växthusgasutsläppen från transportsektorn. Uppskattningar av CO_2 utsläpp är visserligen inte komplicerad om noggrann statistik över den mängd bränsle som förbränts finns tillgänglig. Statistiken är dock endast tillgänglig för den nationella skalan. För uppskattningar avseende mindre geografiska skalor, som kommuner och/eller specifika användarenheter, som till exempel personbilar, är dessa i regel osäkra.

Den här rapporten beskriver utvecklande av en modell som kan uppskatta koldioxidutsläppen från personbilar, vilka varit i trafik, och som ägs av antingen invånare

eller juridiska personer, för en specifik kommun med hjälp av data från bilbesiktningen. Anledningen till att en ny modell utvecklades kopplade till att befintliga uppskattningar av CO_2 utsläpp presenterade för kommuner i Sverige inte nödvändigtvis kopplade till den verkliga utvecklingen av samma utsläpp. Modellen syftade till att bidra med tillräckligt noggrann lokal information för att underlätta kommuners lokala klimatarbete. Möjligheten att kunna använda modellresultaten i det klimatförebyggande arbetet har ställt stora krav på modelleringen. Modellresultaten behövde vara tillräckligt korrekta och dessutom med relativt hög detaljeringsnivå för att vara meningsfulla att applicera i det lokala klimatarbetet. Därutöver behövde modellresultaten koppla samman den nationella och lokala skalan för att säkerställa att kommunen bidrar till Sveriges utsläppsminskningar i enlighet med den internationella rapporteringen. Ett problem i utvecklandet av modellen var den begränsade möjligheten att validera modellstrukturen liksom modellresultat eftersom tillgängliga valideringsdata är osäkra och speciellt så på kommunal nivå. Modellstrukturen blev därför validerad i olika steg med hjälp av metoder som kopplar till hur Sveriges nationella koldioxidutsläpp beräknas.

Modellen har testats på en fallstudie, Järfälla kommun, och då har ton CO_2 utsläpp per bränsleteknologi, per åldersklasser, per viktklasser samt per postnummer, beräknats. Modellen har även modellerat explorativa scenarion med syfte att undersöka hur CO_2 utsläppen påverkas av specificerade mål under givna betingelser. De explorativa scenarierna kan jämföras med policys som syftar till att minska utsläppen från personbilar. De olika modellresultaten visade således på utvecklingen av CO_2 utsläpp utifrån olika perspektiv. Till exempel visade sig utsläppen ha ökat mellan 1999–2017, men då en stor del av ökningen sammanfallit med en befolkningsökning i Järfälla, kan resultaten framställas som en minskning när de redovisas per kommuninvånare. Vidare upptäcktes att en betydligt större andel av utsläppen idag beror av trafikarbetet från tunga dieselbilar jämfört med tidigt 2000-tal. Slutligen visade de explorativa scenarierna fördelen med att minska det totala trafikarbetet för att på så sätt uppnå kraftiga CO_2 minskningar. När endast bensin- och dieselbilarnas trafikarbete minskade så upptäcktes att ytterligare antaganden krävdes för att åstadkomma en kraftig sänkning av utsläpp.

Abbreviations and terms

Traffic Work	Traffic work is equivalent to the distance driven for one or multiple cars in the report and it is the context that determines the specific meaning.
Fuel Economy	The fuel economy of a car is the fuel consumed per specified distance as given by car manufacturers, for example, 7 liters per 100 km.
Fuel Technology	Fuel technology is a term that informs the reader of the specific fuel combusted in a car and therefore also connects to the technology in the engine of a car. For example, a passenger car can be specified according to a fuel technology like gasoline.
Ethanol and E85	Ethanol and E85 are used interchangeably in the report and represent the fuel technology for cars driving on ethanol. Observe that ethanol cars also can drive on gasoline and diesel fuel.
Gas- and vehicle gas car	Gas- and vehicle gas cars are used interchangeably in the report to specify cars with the vehicle gas as the primary fuel technology. Observe that ethanol cars also can drive on gasoline and diesel fuel.
Biomass and biofuels	Biomass are the biological matter in biofuels. Biofuel is a fuel which can be blended with fossil fuels, but some biofuels can also replace fossil fuels completely.
Car age	Car age, as used in the study, relates to how old a car was in relation to a calendar year. The car age can albeit be interpreted as the time spent since the car was bought, though not in this study.
GHG	Greenhouse gas emission is an emission contributing to the global warming. CO_2 is the most common anthropogenic greenhouse gas.
SEPA	The Swedish Environmental Protection Agency.
Trafikverket	The Government Agency of Traffic in Sweden.
Vägverket	The former Government Agency with specific responsibility of roads and road traffic, now part of Trafikverket.
IVL	The Swedish Environmental Research Institute.

TRAFA	Transport Analysis, an organization commissioned by the Swedish Government.
SMHI	The Swedish Meteorological and Hydrological Institute.
AoE	The Government Agency of Energy in Sweden.
SCB	The Government Agency of statistics in Sweden.
NEDB	National Emission Database.
EEA	European Environmental Agency.

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1. Introduction

The Kyoto protocol in 1997 and the Paris agreement in 2015 can be viewed as global efforts to reduce greenhouse gas emissions (GHG:s), which are needed for limiting global warming and to minimize the risks thereof. Sea level rise, ocean acidification and an increased intensity of extreme weather events constitute some of the risks (IPCC, 2014a), each with severe consequences for both humans and ecosystems. To reduce GHG:s is albeit not easy as interpreted from statistics in IEA (2018): CO_2 emissions have increased for nearly all years between 2000-2017. Considering the risks associated with global warming, the increasing emissions can be viewed as paradoxical, but they also illustrate how integrated economic development is with GHG:s. For example, AFLOU ('agriculture, forestry, and other land use change'), industry, energy production and transportation are critical to a functioning society today, but the economic sectors are simultaneously responsible for well over 70 percent of the global anthropogenic emissions in 2010 (IPCC, 2014b). The sectors are dependent on fossil fuels and a reduction of GHG:s may thus risk constraining economic development, which may be the reason of why GHG reductions are not accomplished. The decoupling of economic development from GHG emissions is therefore important and improvements, though too slow, are apparent from the beginning of the 2000s (IEA, 2018).

The transportation sector characterizes the above dilemma. The sector was responsible for 14 percent of the global anthropogenic GHG:s in 2010 (IPCC, 2014b). Transportation is also important for countries' economic development, for industries when importing or exporting products as well as for the convenience of citizens when travelling, commuting and/or shopping. In relation to the Paris agreement, countries have also highlighted the importance to reduce the sector's emissions (IEA, 2017). Electric vehicles, biofuels and more efficient cars can benefit countries to reduce the climatic impact from transportation (SOU, 2013; IEA, 2017), but it is likely not enough to accomplish the required reductions in time. Recommendations in IEA (2017) point to the need of raising the costs for transportation modes with relatively high GHG emissions. Non-motorized transport and public transportation are additional options to further exploit for reducing CO_2 emissions (Velazquez et al., 2015). The CO_2 emissions have, though, increased with 2.5 percent annually between 2010-2015. For countries part of the Organization for Economic Co-operation and Development (OECD), emissions (including upstream emissions) need to be reduced by at least 20 percent compared to existing emission levels before 2025 (IEA, 2017).

In the European Union (EU), the challenge of reducing the GHG emissions from transportation is recognized from the global context. Emissions are needed to be reduced by 66 percent before 2050 compared to 1990, but the existing emission trends give no reason for optimism. Instead, international aviation and shipping has increased by more than 100 and 30 percent respectively, whereas the emissions from road transport has increased by 22 percent (EEA, 2018).

The EU Member State Sweden was a signatory to the Kyoto Protocol and also managed to reduce the territorial GHG emissions by 26 percent in 2017 compared to 1990 (SEPA, 2018b). Sweden has also ratified the Paris agreement. The transportation sector's GHG emissions represent 33 percent of Sweden's territorial emissions, but the emissions have been reduced by 16 percent compared to 1990 when including domestic aviation and shipping (SEPA, 2018b). For road transport, a reduction of less than 13 percent in 2017 compared to 1990 is apparent, though if the distance all vehicles drive on Swedish roads (i.e. the traffic work) would have been static since 1990, the reduction would nearly triple to 34 percent. Consequently, the traffic work in Sweden has increased considerably, from 64.4 billion to 83.7 billion kilometers, and the impact on emissions has been substantial (Trafikverket, 2018a). The number juggling with estimates from the transportation sector highlights the importance of the models applied for estimating the GHG emissions, including the accuracy of them.

The need of accurate estimates is dependent on the requirements of the context they are to exploited in (Ljung and Glad, 2004). Modelling of CO_2 emissions from transportation can for example inform of the magnitude of emissions as well as how they develop over time. It would then be problematic if estimates vary substantially from year to year because of the methodology in use, or even worse, are too far from real-world emissions. Moreover, local CO_2 reductions should be estimated correctly and mirrored in the national estimates since GHG reductions has not been easy to accomplish, as implied in the first paragraph. If faulty or contradictory information is exploited in decision making, it is easy to see why decisions do not accomplish the goal at hand. For modelling to be beneficial in local climate change mitigation work, model results should be accurate enough for indicating the trend in- and magnitude- of emissions. Model results also need to be consistent over time to allow for mitigation measures' impact on emissions to be analyzed. Confusion over the development and/or the efficiency of measures may otherwise risk delays in climate change progress and priorities in the overall climatic work may also be ill-advised. Most importantly, GHG emissions may not be reduced as needed.

Modelling of CO_2 emissions can be categorized into top-down and bottom-up approaches. Top-down approaches start in a big geographical scale, for example, a country where national statistics can be utilized (Alam et al., 2018). The application of national statistics of fuel deliveries for estimating CO_2 emissions is an example of a top-down approach. Top-down approaches can also be downscaled though with the risk of losing detail level due to a low resolution in macro statistics (Hofer et al., 2018). Bottom-up approaches, however, utilize data relevant for a smaller scale, for example, a single vehicle, but aggregating data of multiple single vehicles' can make results applicable for a larger scale (Hofer et al., 2018). Bottom-up and top-down approaches can also be used in combination for analyzing model results, i.e. comparing two models investigating the same question (SEPA, 2017a).

The specific scale of model results is another way to categorize modelling approaches. Macroscale modelling aims to produce results relevant for a large geographical scale and have been applied to forecast the transport energy consumption for a country (Limanond et al., 2011). Moreover, macroscale modelling have also been applied to forecast the future development of CO_2 emissions in a country (Antanasijević et al., 2014) and to estimate CO_2

emissions due to urban traffic for a relatively large city (Hofer et al., 2018). Microscale modelling estimates results relevant for a smaller geographical scale, for example, the estimation of CO_2 emissions for specific roads (Alam et al., 2018). Other examples include to identify urban areas with relatively high emission concentrations (Nyhan et al., 2016) and to analyze emissions in relation to environmental legislations (Peitzmeier et al., 2017). Both macro-and micro modelling can thus inform of important aspects in relation to CO_2 emissions from the transportation sector.

The master thesis applied a case-study for the municipality of Järfälla, Stockholm, Sweden, for which a carbon budget was developed to in the fall of 2017 (Anderson et al., 2017). The carbon budget was created by CEMUS (‘Centrum för miljö-och utvecklingsstudier) which is a cooperation between Uppsala University and the Swedish University of Agriculture Science. Compared to monetary budgets that regulate activities and projects in monetary values to avoid an economic deficit, carbon budgets can regulate projects according to the corresponding emitted mass CO_2 to avoid a ‘climatic deficit’. As such, carbon budgets can be beneficial for decoupling economic growth from GHG emissions as well as to gain a systematic control over CO_2 emissions.

In the developed carbon budget to Järfälla, CO_2 estimates from the transportation sector relevant from 2005 and onwards were presented and these became the focus of the master thesis initially. The purpose of the thesis was to model CO_2 emissions from passenger cars more accurately than previously for the municipality and to improve the applicability of model results to be exploited for reducing them. The purpose was rather specific, and this constrained the possibility to find a feasible modelling approach from academic literature. Local government authorities (LGA:s), though, often lack the pre-requisites to reduce emissions substantially from the transportation sector emissions (Grote et al., 2016). Consequently, the struggles of LGA:s for cutting emissions may render the national reductions insufficient. As such, there is a demand to improve modelling approaches to support LGA:s with low-carbon ambitions. Novel approaches may in fact even be required when requirements are specific (Hofer et al., 2018).

1.1 Objective and research questions

For model results to be applicable for the municipality, the following criteria were defined: Model results can be disaggregated over car characteristics impacting the magnitude of CO_2 emissions; model structure facilitates an annual update of model results; results are accurate enough to control the progress of climate change mitigation measures in relation to the development of CO_2 emissions from passenger cars. The thesis will answer the following research question:

- How can CO_2 emissions from passenger cars for the municipality of Järfälla be modelled over time under the requirement of model results being distinctly connected to the national accounting of the same emissions?

A personal purpose of the master thesis has been to learn more about climate change and how the global and local mitigation work function, and to possibly contribute to Swedish municipalities with low-carbon ambitions for the transportation sector.

1.2 Limitations of the study

Only tailpipe CO_2 emissions were modelled in the study and life cycle analysis has not been applied. The results of the thesis thus ignore the impacts of, for example, the production and transportation of fuels and passenger cars, so model results do not capture how CO_2 emissions have developed in other parts of the production chain. Likewise as with other environmental impacts (e.g. eutrophication, loss of biodiversity, acidification, etc.).

1.3 Overview of thesis

The Background includes information of climate change in relation to the greenhouse effect as well as information of global efforts to reduce GHG emissions. Furthermore, the carbon budget developed to Järfälla was central in the start-up of the thesis for analyzing how the global and local contexts were connected. Information of carbon budgets, described on the basis of the carbon budget developed to Järfälla, was included in the Background, likewise as a brief introduction of the municipality of Järfälla and the emissions from passenger cars.

To understand how the global and local contexts were connected mathematically, the CO_2 estimates used in the carbon budget needed to be scrutinized. An investigation into how CO_2 emissions from passenger cars were estimated in Sweden as well as for Swedish municipalities was conducted. The findings are presented in Sweden's accounting of CO_2 emissions from passenger cars presented after the Background.

The Methodology includes information acquired from literature reviews relevant for how CO_2 emissions from passenger cars are recommended to be estimated as well as information of car characteristics with relevance for the magnitude of CO_2 emissions. Moreover, emissions from cars as derived from tests conducted in Europe were highlighted to diverge from real-world driving by more and more in the 2000s. Information of the discrepancy between test-values and real-world driving are also presented in the Methodology.

Building on the information in the preceding sections, the model construction was presented after the Methodology under the intuitive headline Model construction. The section begins by an analysis of the CO_2 estimates from transportation used in the carbon budget developed to Järfälla. Thereafter, a description of the model, of the developed model results, a rationale for the model, the data, sensitivity analyses and the validation are presented. The section ends by presenting the utilized assumptions in the modelling.

The Result section first presents the result of the sensitivity analyses since the results were used to inform the validation, whereas the validation, in turn, was exploited to elicit relevant model configurations when calculating the model results for Järfälla. The model results of Järfälla are therefore presented after the validation results. The disposition can as such be compared as a step-by-step description of the model with the hope to improve the understanding of both the modelling and the model results to the reader. Thereafter, the result of when CO_2 emissions over postal codes in Järfälla were modelled as well as the result of explorative scenarios with, are presented.

The Discussion will focus on the model results from a broader perspective, including advantages, policy implications, the validation results and improvements. The report ends with the Conclusion where the main findings of the master thesis are stated.

Considerable efforts have been spent on specifying the assumptions and the data to allow the study to possibly be repeated. Additionally, an adequate transparency benefits the modelling conducted in the thesis as it becomes easier for other researchers to analyze the model structure, including the data and assumptions, and the model results. Hence, the transparency enables the modelling methodology to potentially be improved. Especially since a novel approach was applied in the study. Multiple appendixes were included in the report where calculations, assumptions, and supporting data were included instead of overloading the reader with information in the main report. Appendixes are referenced throughout the report where relevant.

The main results of the report in section 6.3 and therefrom can be read independently of the other sections in the report, likewise as with section 2 and 3.

2. Background

The section begins by presenting information of how the scientific knowledge of climate change has developed. Global efforts for reducing GHG emissions are thereafter presented, followed by information of carbon budgets and a short description of the case-study, the municipality of Järfälla. The section ends with an introduction to emissions from passenger cars.

2.1 Climate change and the greenhouse effect

Climate change and global warming can be understood according to the greenhouse effect. The greenhouse effect was first mentioned in an academic paper in 1827 by Fourier and important contributions thereafter include Tyndall in 1861, Langley in 1884 and Arrhenius in 1895 and 1903, but many other researchers have also contributed (Jones and Henderson-Sellers, 1990). Around the year 1900, the gas CO_2 was associated with an increasing global mean temperature. The researcher Callendar identified anthropogenic sources in the 1950s, i.e. the combustion of fossil fuels, for the increased levels of CO_2- and the long lasting effect of CO_2- in the atmosphere (Jones and Henderson-Sellers, 1990). There are, though, other gases than CO_2 contributing to the greenhouse effect. The gases of water vapor, CO_2, CH_4 and N_2O have been identified as the gases most contributing to climate change (Aleklett et al., 2016) and this have important consequences for global warming. For example, Ramanathan's work in the 80s identified how water vapor increases due to warming, a so called climatic feedback mechanism (Jones and Henderson-Sellers, 1990). Other examples of feedback mechanisms for global warming are related to a shrinking ice sheet and ocean-atmosphere interactions (Jones and Henderson-Sellers, 1990). As such, the improvement of scientific knowledge of the greenhouse effect is apparent in Jones and Henderson-Sellers (1990) as well as thereafter, which have strengthened the evidence of an anthropogenic climate change. For example, isotope analyses of carbon from the atmosphere have specified anthropogenic sources as the reason for the increased CO_2 in the atmosphere (Ghosh and Brand, 2003). Analyses of ice cores from Antarctica show the current atmospheric levels of CO_2, CH_4 and N_2O, have never been higher during the last 800 000 years (Brook and Buizert, 2018). Notwithstanding the improved knowledge, model results by many different climate modelers differ, sometimes substantially (Jones and Henderson-Sellers, 1990). Uncertainties have also persisted in later years. Uncertainties are mostly related to how climatic feedback mechanisms and the climatic carbon sensitivity, i.e. the response time of the earth in relation to changing carbon levels in the atmosphere, are modelled in climate models. It is not possible to determine the climatic carbon sensitivity with relevance for the 21st century today. Hence, projections in the shorter time frame up until 2100 are susceptible for large uncertainties (Mauritzen et al., 2017). Additionally, as interpreted from the founder of the term "Peak Oil", the International Panel for Climate Change (IPCC) latest report, the Fifth Assessment Report, includes scenarios up until 2100 not very plausible. The problem relates to scenarios assuming unrealistic consumptions of energy from fossil reserves, see more information in Aleklett et al. (2016). However, it is certain that the concentration of CO_2 has increased from under 300 parts per million (ppm) in the late 18^{th} century to over 400 ppm in 2016 (Le Quéré et al., 2018; Aleklett et al., 2016). Thus, the human race can be said to have altered the composition of the atmosphere, simultaneously as the greenhouse effect is dependent on the atmosphere. The exact timing of the realization of (negative) consequences due to the changing composition of the atmosphere cannot, though, be stated due to the lacking knowledge of feedback mechanisms as well as the carbon sensitivity. Nevertheless, for the carbon concentration in the atmosphere to be reduced, a global peak in GHG emissions is needed to thereafter be followed by removals of emission (Rogelj et al., 2016). Consequently, GHG reductions are necessary and increasingly so.

2.2 Global efforts for reducing GHG emissions

The Rio conference in 1992 illustrated politicians had started to consider anthropogenic climate change seriously in the 90s and following the Rio convention, the United Nations Framework Convention for Climate Change (UNFCCC) was created in 1994 (Aleklett et al., 2016). The signing of the Kyoto Protocol in 1997 was another step in the direction to mitigate anthropogenic climate change. The result of the Kyoto protocol may not be framed as encouraging, but the 37 signatory countries did reduce their emissions by approximately 16 percent compared to 1990 levels, but the global emissions continued to increase (Schiermeier, 2012). A problem with the protocol was that not all countries were obliged to reduce their emissions. As such, "developing" countries including China, did not want, could or needed to be part of the protocol, simultaneously as polluting industries in signatory countries- as well as in other richer nations- were being outsourced to non-signatory countries (Schiermeier, 2012). Take the signatory country Sweden as an example. Sweden's territorial emissions were 52.7 million tonnes in 2017, representing a reduction by 26 percent compared to 1990, which can be considered an adequate contribution to avoid anthropogenic climate change. Emissions are albeit up to around 100 million tonnes (e.g. a 40 percent increase) when abroad emissions are included due to Sweden's consumption of products produced in other countries (SEPA, 2018b). But the lessons from the Kyoto protocol may prove valuable for future climate change mitigation (Schiermeier, 2012).

In Paris 2015, 196 nations part of the UNFCCC aimed to limit global warming by 2 degrees Celsius compared to pre-industrial levels, i.e. the so called Paris Agreement (UNFCCC, 2018a). The Paris agreement have thereafter been ratified by 181 out of 196 nations (UNFCCC, 2018b), thereby illustrating a global commitment to reduce GHG emissions. Intended Nationally Determined Contributions (INDC:s) have now been submitted to the UNFCCC by the ratifying nations where their GHG reductions after 2020 are specified. The INDC:s submitted imply global warming will overshoot 2 degrees Celsius by 2100, thereby illustrating a demand for countries to ramp up their ambitions (Rogelj et al., 2016). Moreover, the challenge to limit global warming implies a need for systematic reductions.

2.3 Carbon budgets

The gap to limit global warming by 2 degrees Celsius, as quantified from nations' INDC:s, can be reduced if cities and municipalities within nations start playing a bigger role in climate change mitigation. By aiming to reduce their GHG emissions before 2030, cities and municipalities can help nations overachieve their own submitted INDC (Rogelj et al., 2016). With this in mind, CEMUS developed a carbon budget to the municipality of Järfälla, Stockholm, Sweden in the fall of 2017, see Anderson et al. (2017). A carbon budget is here not advocated to replace a monetary budget, but to complement it and enable systematic reductions of CO_2 emissions both locally and globally. The information in the following two sections originate by large from the developed budget to Järfälla.

2.3.1 Global allocation of greenhouse gas emissions

The performed allocation of GHG emissions described below has been used by international organizations since 2011 (Anderson et al., 2017).

IPCC estimates the global cumulative emissions from 2011 and onwards to be between 850 and 1000 $GtCO_2$, in order to limit global warming under 2 degrees Celsius. Emissions should thereafter be zero or negative (IPCC, 2014a). A minimum of 260 $GtCO_2$ have been emitted globally since 2011 and the cumulative emissions from July 2017 to be emitted are consequently already down to 590-740 $GtCO_2$. Deforestation and cement production are though not included. After rather optimistic assumptions, 100 $GtCO_2$ are allocated to cement production and deforestation is excluded on the basis that it can be compensated in the future, the allowable range is down to 490-640 $GtCO_2$ (Anderson et al., 2017). However, deforestation is estimated as ongoing (FAO, 2016). Anyhow, the allowable range is to be allocated between OECD countries and non-OECD countries. Important factors influencing the allocation procedure are:

1) Countries' historical emissions.
2) OECD countries have a better capacity to combat climate change.
3) Non-OECD countries have the right to continue developing.

As such, non-OECD countries are allocated a larger share of GHG emissions than the OECD countries. Moreover, the specific timing of when the peak in emissions occurs for the non-OECD group is central to the allowable range of the OECD countries. For example, 20 or 140 $GtCO_2$ are allocated to the OECD group depending on whether the peak for the non-OECD group occurs in 2025 or 2020, respectively (Anderson et al., 2017).

The next step is to allocate the allowable range within the respective two groups. The historical emissions since 2010 and the population size of a country have been used to guide the allocation. Using Sweden as an example, the country has emitted 0.361 percent of the historical emissions in the OECD group and represent 0.767 percent of the population, yielding an allocation of 300-600 $MtCO_2$. The given range is due to the assumption of the emission peak of the non-OECD group occurs between 2022-2023. Due to the importance of the emissions peak, it is more suitable to aim for higher reductions if the purpose is to mitigate climate change. For example, if Sweden aims for minimum annual reductions, other countries must aim for higher annual reductions (Anderson et al., 2017).

Finally, Sweden's allocation of emissions is disaggregated to all Swedish municipalities, but there is no official guidance available in Sweden for this. Population size, historical emissions and ability to pay for emissions, are recommended principles to guide the allocation of emissions between municipalities. Emissions due to consumption are however not included in the budget developed to Järfälla (Anderson et al., 2017).

2.3.2 Municipal carbon budget: Järfälla

A carbon budget was developed to the municipality of Järfälla in the fall of 2017 and it was the first municipal carbon budget created in Sweden. The municipality is located in the capital city of Sweden, Stockholm, with an area of 2465 hectares making up 6 percent of Stockholm's areal (SCB, 2017a). The municipality's population have increased from just over 60 000 in 1999 to well over 76 000 in 2017 (SCB, 2019). The population is further expected to increase to a bit under 116 000 in 2030 on the basis of the municipality's building plans (Statisticon, 2017). A map of the municipality's location in Stockholm is presented below, see figure 1. In figure 1, the motorway E18 can be seen passing through the municipality which will be highlighted later on in section 3.2.

Figure 1. A map of the municipality of Järfälla in Stockholm. The municipality is towards the left upper corner in the figure demarked with a red line and also indicated by a black line stating "Järfälla". The yellow lines in the map represent big roads and the yellow line through Järfälla is E18. The map is modified from Google maps (Google, 2019).

The following sectors' territorial CO_2 emissions were included in the carbon budget developed to Järfälla: Energy production, working machines, transportation and product use, and the CO_2 estimates originate from the National Emission Database (NEDB). When comparing the magnitude of these sectors' CO_2 emissions, the dominance of the transportation sector for Järfälla becomes clear. With a given estimate of just over 50 000 ton in 2014, the transportation sector's CO_2 emissions were approximately 250 percent more than the other included sectors combined. Passenger cars constitute the absolute biggest share of these CO_2 emissions (Anderson et al., 2017). Actually, the dominance of transportation is mirrored in Sweden's CO_2 emissions since domestic transportation represents approximately one third of Sweden's territorial emissions (SEPA, 2018b).

The carbon budget prescribed annual reductions between 7.5-16 percent (Anderson et al., 2017) and the question naturally becomes: How can the emissions be reduced to be in line with those prescribed? Or rather, what support would be beneficial for the municipality to accomplish these reductions?

It was mentioned when communicating with an employee at Järfälla municipality that estimations of different mitigation measures and their effect on emissions would be suitable to include in a carbon budget (M. Huber 2018, Personal communication, 2018). Many political decisions are albeit decided on the county- or national level, thereby reducing the possibilities for a municipality to ramp up their climate change mitigation work. Municipalities are for example not responsible for transportation strategies relevant for the whole of Stockholm (SLL, 2018). Furthermore, a quantification of mitigation measures' effect on emissions pre-requisites accurate estimations of emissions already exists since the impact otherwise cannot be evaluated quantitatively. Anyhow, population development is another important aspect in municipalities' climate change work since absolute emissions tend to increase with an increasing population. It was also communicated by the above employee that the municipality prefers to view the development of emissions in the unit [mass CO_2 per citizen] (M. Huber 2018, Personal communication, 2018).

In Sweden, municipalities represent the closest governance level for citizens and can as such be a crucial actor to enable local reductions (Robèrt et al., 2017; Grote et al., 2016). Local knowledge can moreover enable decisions to better be suited to the local environment and specificities (COMPLEX, 2016). Thereby potentially improving the efficiency in policies decided on the municipal level as well as increasing the acceptance of them, including policies designed to aid citizens to reduce their emissions.

2.4 Introduction to emissions from passenger cars

Gasoline, diesel and natural gas, i.e. petroleum products, are composed by carbon and hydrogen in different mixtures. If an ideal combustion of these fuels took place, the hydrogen would chemically transform to water, whereas the carbon would be emitted as CO_2. Combustion is albeit never ideal and other pollutants are created as well (EEA, 2016b). CH_4 and N_2O are, apart from CO_2, two other GHG:s being emitted, but there are also other pollutants posing health hazards. For example, oxides of nitrate (NOx), Non-methane Volatile Organic compounds and particulate matter (PM) (IPCC, 2006a). All in all, CO_2 and H_2O are still the dominant emissions from the combustion of fuels (EEA, 2016a). For example, 99 percent of the emitted carbon is emitted as CO_2 as derived from Euro5 and 6 cars[1] (Fontaras et al., 2017). Most of the non-CO_2 emitted carbon also transform into CO_2 over time in the atmosphere (IPCC, 2006a; Perby, 1989). Considering the negative climatic effect of vehicle emissions, it should be stressed that pollutants also are problematic for the local environment and to human health (EEA, 2016b). It is important to avoid a trade-off between improvements for the climate and for human health since both are needed.

EU strategy to reduce emissions

The improvement of the fuel economy for cars is important for the EU strategy of reducing GHG emissions (EEA, 2016b) as fuel consumption and CO_2 emissions are proportionally related (Fontaras et al., 2017). EU regulations and policies have been implemented to stimulate car manufacturers to reduce average CO_2 emissions per kilometer for new cars (Fontaras et al., 2017; Fontaras and Dilara, 2012). One regulation set standards for the year 2015 and 2021, i.e. 130 g CO_2 / km and 95 g CO_2 / km respectively (EEA, 2016b). Other EU policies have increased the share of diesel cars as well as motivated consumers to buy smaller cars (Fontaras and Samaras, 2010). The car manufacturers accomplished the standards of 2015 well in advance as indicated by the standardized testing conducted in Europe, the new European driving cycle (NEDC) (EEA, 2016b).

GHG emission trends from the transportation sector in Sweden

The emissions from the transportation sector are not in line with those stated in environmental goals. For example, Sweden's vehicle fleet should be carbon neutral in 2030, and this is interpreted by the Government Agency of Traffic, Trafikverket, as a reduction of

[1] Euro is an environmental legislation with the purpose to regulate emissions and implement emission control technologies (EEA, 2016a).

80 percent between 2010 and 2030. The situation is similar in other countries and the transportation sector, considering its large share of emissions, must reduce its emissions drastically if society are to fulfil the stated environmental goals (Trafikverket, 2012). The goal was after 2012 redefined or reinterpreted to 70 percent which translates into a need to reduce the passenger car transport by 10-20 percent until 2030, given the technology development in fuel economy continues (Trafikverket, 2017). In cities, personal transportation by car should be transferred to walking, bicycling and public transportation (Trafikverket, 2017). For 2017, GHG emissions from the transportation sector were reduced by two percent, but on average eight percent in annual reductions are required to accomplish the goal of a 70 percent reduction of GHG emissions (Trafikverket, 2018a).

3. Sweden's accounting of CO_2 emissions from passenger cars

Carbon budgets are connected to the Paris agreement (Anderson et al., 2017) and Sweden is obliged to report its greenhouse gas emissions to the UNFCCC, i.e. Sweden's greenhouse gas inventory. The greenhouse gas inventory includes multiple sub-sectors categorized into five overarching sectors: Energy, Industrial processes and product use, Agriculture, Land-use and land-use change and forestry, Waste and other (SEPA, 2017b). The following of this section will describe how CO_2 emissions from vehicles, including passenger cars, are estimated in Sweden.

3.1 The emission model, Handbook Emission Factors for Road Transport

Road traffic, where CO_2 emissions from passenger cars are included, is categorized in the greenhouse gas inventory under domestic transportation together with aviation, railways and navigation. Domestic transportation, in turn, is categorized under fuel combustion which is categorized under the overarching sector of energy (SEPA, 2017b). The fuel consumption of gasoline and diesel for vehicles is estimated by an emission model, the Handbook Emission Factors for Road Transport (HBEFA) (SEPA, 2017b). HBEFA is used by multiple European nations, including Sweden, France, Germany, Norway, Austria and Switzerland (Grote et al., 2016). The estimated fuel consumption by HBEFA is balanced according to national fuel statistics for Sweden since the IPCC guidelines states that only fuel purchased within the country border should be included in the greenhouse gas inventory (SEPA, 2017b). The Swedish Environmental Institute (IVL) updates HBEFA each year with the statistics needed for the calculations (IVL, 2017). In the next paragraphs, HBEFA and important models providing input to the emission model will be presented more closely.

HBEFA estimates greenhouse gas emissions, including CO_2, as well as the consumption of gasoline and diesel for the following vehicle categories: Passenger cars, light commercial vehicles, heavy goods vehicles, buses, coaches and mopeds and motorcycles. Biofuels constitute of biomass and are classified as having no CO_2 emissions for road traffic and are excluded from the calculations (SEPA, 2017a).

Emission factors are needed for estimating the emissions. Emission factors can be compared with a mathematical factor enabling the magnitude of CO_2 emissions to be calculated. See more information of emission factors in section 4.1. The emission factors used in HEBFA come from the Passenger car and Heavy-duty Emission Model (PHEM), developed by Graz University of Technology (VTI, 2017). They are adapted to the Swedish vehicle fleet, as confirmed in an email conversation with M-R Yahya employed at IVL (M-R Yahya 2018, Personal communication 27th of November). These emission factors have been derived for many different car models and under different engine modes, including transmission losses and friction (VTI, 2017).

The accuracy of emission models in general depends on whether the applied emission factors are representative for the conducted traffic work (Franco et al., 2013). For this purpose, HBEFA uses traffic work data specified according to traffic situations when estimating the CO_2 emissions (Smit et al., 2010; SEPA, 2017a). The traffic situations are categorized into traffic flow (e.g. free flow, heavy traffic, congestion and stop and go) and road type (e.g. highway, rural, urban, etc.) (SEPA, 2017a). The emission factors are then fitted to the specified traffic work over traffic situations (Fontaras et al., 2017). The inclusion of traffic situations should result in more accurate calculations since they can have a large impact on emissions per kilometer travelled (Fontaras et al., 2017; Tsanakas et al., 2017; Grote et al., 2016). Furthermore, data from mandatory vehicle checks conducted for all vehicles in Sweden are also utilized in HBEFA with the purpose to derive segments' average traffic work, where also the car age and euro classes are specified, as confirmed by IVL (M-R Yahya 2018, Personal communication 27th of November). The segments are specified in vehicle category, the fuel technology and engine size. The annual traffic work *per vehicle category* used in HBEFA, however, is estimated with another model named the National road mileage model (SEPA, 2017a). Categories' average traffic work is there calculated by dividing the estimated total traffic work in Sweden with the number of vehicles within each category (Edwards et al., 2000; Björketun et al., 2007). As such, traffic work, traffic situations and emission factors can be combined to estimate the emissions, including CO_2 emissions, and the fuel consumption. The calculations by HBEFA, though, yield a lower estimate than what the national statistics show. For diesel, the divergence between the two methods has grown considerably since 2001 and reached around 13 percent ($\approx$500 000 m^3) in 2015. No substantial divergence can however be observed for gasoline from 2000 and onwards in SEPA (2017a). The difference between the approaches is redistributed over the relevant subsectors of domestic transportation (SEPA, 2017b). A schematic figure was created to ease the interpretation of how the national accounting of CO_2 emissions from vehicles are conducted, see figure 2.

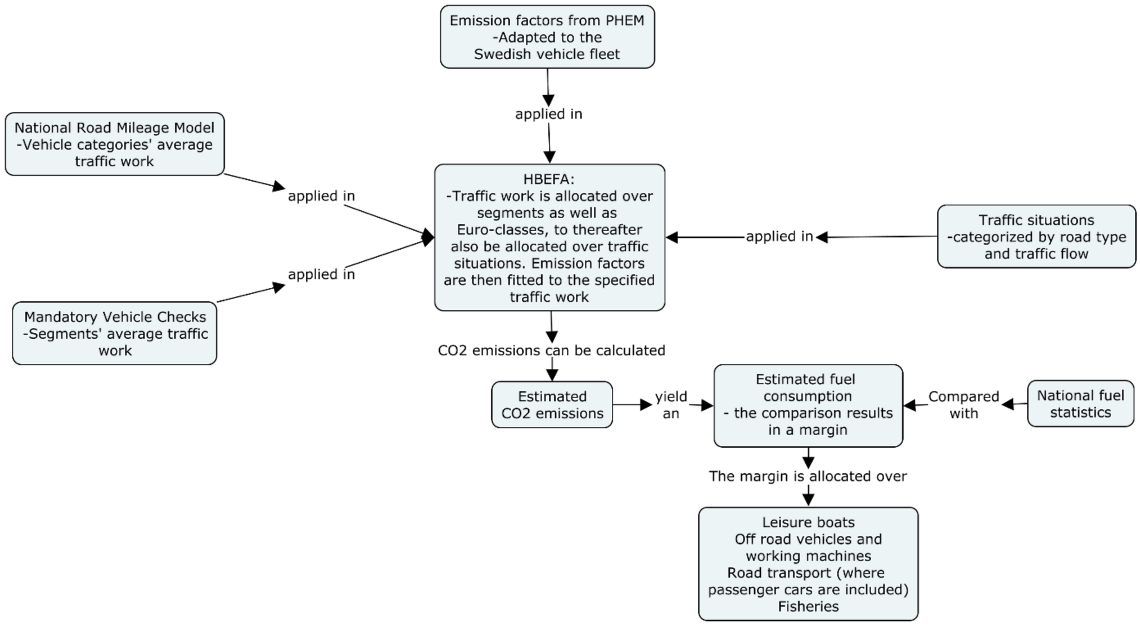

Figure 2. The figure illustrates schematically how CO2 emissions from vehicles, including passenger cars, are estimated in Sweden. The boxes represent important steps, i.e. data, the emission model HBEFA and calculations, with additional information where needed. The text in between boxes indicate what the 'box' with the outgoing arrow facilitates in the estimation in relation to the following box. See text in figure for further explanations. The figure was created with CmapTools (https://cmap.ihmc.us/cmaptools/).

Annual data from the mandatory vehicle checks were however not available for HBEFA before 2014, so up until then, HBEFA used data from 2004 (VTI, 2013). The estimates have not been modified after the annual data from the mandatory vehicle checks became available in 2014, as confirmed in an email conversation (M-R Yahya 2018, Personal communication 27th of November).

It is here important to realize that HBEFA and its results are dependent on data from other models. Furthermore, emission models also apply data with origin from car manufacturers (VTI, 2017) not representative for real-world driving (VTI, 2017; EEA, 2016b; Fontaras et al., 2017; Fergusson, 2013). More information about car manufacturers with relevance for the modelling conducted in the thesis is presented in section 4.2. The National road mileage model and the allocation of traffic work over traffic situations will be described next, starting with the former.

3.1.1 The National road mileage model

The national road mileage model (NRMM) was created to estimate the Swedish traffic work for the years 1950-1997 (Edwards et al., 2000; VTI, 2013) and the model has thereafter been significantly modified on two separate occasions (Björketun et al., 2007; TRAFA, 2013). A scaling factor is central in the first version of NRMM by Edwards et al. (2000). The scaling factor is founded on the assumption of a static traffic work of the state-road network in relation to the municipal- and private-road network which together make up the Swedish road network. The share of traffic work for the state-road network was estimated as two thirds, whereas the smallest share, four percent, was allocated to private roads, which left the rest to be allocated to the municipal roads. After estimating the traffic work on the state-road network according to point estimates, traffic flow measurements, national statistics and surveys, the total traffic work could be calculated by multiplication with the mentioned scaling factor (Edwards et al., 2000).

The first modification by Björketun et al. (2007) was motivated when new data from the mandatory vehicle checks became available as well as requirements to adapt the model to international standards. Data originating from three consecutive mandatory vehicle checks, i.e. 2001, 2002 and 2003, were used to estimate averages representing the vehicle categories' traffic work share (Björketun et al., 2007; VTI, 2013). The averages were used in combination with the relative change of the vehicle fleet composition to modify the estimates of traffic work for the years 1950-2005 (Björketun et al., 2007). Additionally, the assumption of a static traffic work between the road networks was modified. Measurements performed continuously on 83 locations on the state-road network were used to derive an annual change factor that in practice allowed the scaling factor to change between years (Björketun et al., 2007). The scaling and change factor are hence most important for the accuracy of the NRMM. The scaling factor has been reduced over time, from 1.51 in 1990 to 1.48 in 2005, and this is equivalent to an increase in the traffic work share of the state-road network over time (Björketun et al., 2007).

It is no simple task to estimate the change factor and the sources of errors are the following: Errors in the background data acquired from the national road database (NVDB); the population under investigation (e.g. the 83 measurement points) may diverge from the population of interest (e.g. the Swedish road network); sample error; a systematic error in the measuring equipment; and biased data due to the measurement equipment. It is only the sample error which is specified, but there is no indication of the other errors being insignificant, as stated in Trafikverket (2013).

After the last modification by TRAFA (2013), NRMM now estimates the traffic work as an average of two different methods. The first method is a modified[2] version of the NRMM by Björketun et al. (2007), whereas the second method applies annual data from the mandatory vehicle checks. Judging from the total traffic work estimated in Sweden 1999-2011, the two different methods have closed the divergence between estimates over time. The discrepancy when comparing the vehicle category of passenger cars is albeit bigger and around 5 percent for the period (TRAFA, 2013).

3.1.2 Traffic work allocated over traffic situations

HBEFA has been credited to facilitate an adequate incorporation of the effects of traffic situations on emissions from transport (Fontaras et al., 2017), and it is important since

[2] The number of days in traffic for the vehicle categories has been recalculated, the effect of traffic work from foreign lorries is mitigated and data from the mandatory vehicle checks can now be used for all years (e.g. 2000 and onwards), not only 2001-2003.

increases of up to 40 percent in emissions have been reported (Fontaras et al., 2017; Tsanakas et al., 2017).

Between 2005-2006, the specification of traffic work over traffic situations for HBEFA was conducted for the years 1990, 1994, 1998, 2000 and 2004, and the year of 2009 was added between 2010-2011 (WSP, 2015). For 2012, the allocation procedure of traffic work over traffic situations is described in WSP (2015). Data relevant up until 2012, including estimates of total traffic work, traffic flow measurements from the state-road network and simulated results of the traffic work over the municipal-road network, were then applied (WSP, 2015). The methodology can simply be described as the total traffic work first being disaggregated over the different road networks, then over urban and rural environments, and finally over the traffic flows identified from traffic flow measurements. However, no reliable data relevant for the municipal-road network were available for the simulation of traffic work in 2012. Instead, data from 2009 were applied. Furthermore, the allocation exploits estimated mean speeds. Mean speeds are considered inadequate for the purpose of specifying the fuel consumption and the corresponding emissions due to traffic situations, but data limitations dictated the choice (WSP, 2015).

The problem of using mean speeds has been demonstrated with experiments from Stockholm under morning rush hour. The use of mean speeds was there found to minimize the occurrence of traffic work being allocated to the traffic flow of stop and go, irrelevant of whether stop and go occurs substantially (Tsanakas et al., 2017). Thereby possible explaining the low share, i.e. only 0.05 percent, for stop and go as reported for 2013[3] in Sweden's greenhouse gas inventory (SEPA, 2017a). It is, though, the stop and go condition that corresponds to much higher emissions per kilometer travelled (Tsanakas et al., 2017). As a comparison, TomTom[4] (namedropped in Grote et al. (2016)) shows travel time increases due to congestion by well over 20 percent on average in Stockholm between 2008-2016: Close to 50 percent increases in morning rush hour and over 60 percent in evening rush hour. Congestion issues are not equal to the specific flow of stop-and-go, but congestion issues are likely much worse in Stockholm than what can be interpreted from SEPA (2017a).

When the traffic work is allocated over traffic situations in WSP (2015), other uncertainties include: Traffic flow measurements are only available from the state-road network; the applied share of traffic work for the private-road network is over 15 years old (see Edwards et al. (2000) in the NRMM paragraph above); and how the total traffic work estimate is interpreted by WSP (2015).

3.2 CO_2 estimates calculated for Swedish municipalities

As mentioned in section 2.3.2, the CO_2 estimates given in the carbon budget developed to Järfälla, see Anderson et al. (2017), originate from the NEDB where every Swedish

[3] In SEPA (2017a), the year 2013, not 2012 is mentioned, but considering how traffic situations are updated in HBEFA as well as the references used in SEPA (2017a), the correct year is more likely 2012, as described in WSP (2015).

[4] https://www.tomtom.com/en_gb/trafficindex/city/stockholm [2019-03-18].

municipality's territorial emissions can be acquired. The CO_2 emission estimates are available for the vehicle categories of passenger cars, light commercial vehicles, heavy goods vehicles, buses and mopeds and motorcycles. The estimates can be used to illustrate the development of emissions over time, as was also conducted in the carbon budget. In the case of Järfälla, the estimates for passenger cars illustrate a reduction from 50 000 ton in 1990 to around 35 000 ton in 2014. The identified reduction was mostly related to a substantial reduction between 2009 and 2010, though a slight decreasing trend can be observed after 2010 as well. A static development is however apparent for heavy goods vehicles and light commercial vehicles with values around 10 000 ton and 5000 ton for the whole period respectively. Buses have emissions over 2000 ton for the whole period, whereas mopeds and motorcycles have values between 200 to 400 ton. The dominance of passenger cars, as the largest emitter of CO_2 emissions in Järfälla, is apparent in the data. See figure 3.

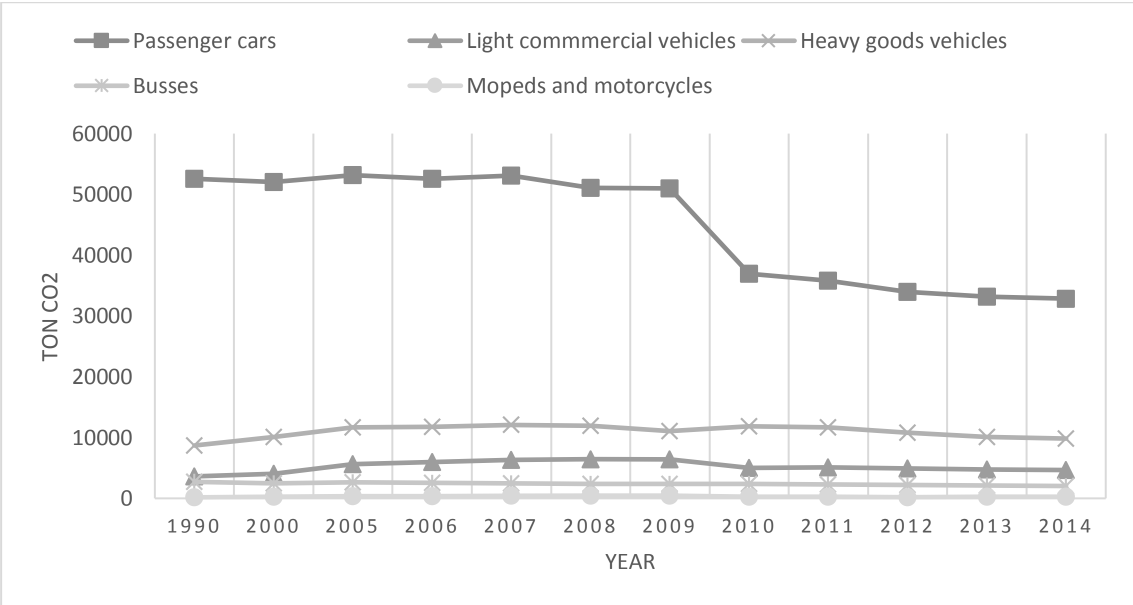

Figure 3. See description of the included curves over the chart and observe the nonlinear x-axis. The figure illustrates the included categories, except passenger cars, had a rather static development, whereas passenger cars' emissions were reduced substantially between 2009–2010. Passenger cars were moreover shown to the biggest source of CO2 emissions. The data used in the figure originate from NEDB (2015).

The sudden drop in the emissions for passenger cars was analyzed as possibly due to the financial crisis in 2008-2009, whereas the decreasing trend was analyzed as a positive sign of the technology development for cars in Järfälla. However, after scrutinizing the methodology in use to estimate the emissions, both analyzes were identified to be incorrect, see more information below.

The estimates acquired from the NEDB have been calculated according to a geographical distribution of emissions by the Swedish Meteorological Hydrological Institute (SMHI). The methodology by SMHI has the purpose to estimate Sweden's territorial emissions and it can be used for estimating the magnitude of CO_2 emissions from vehicles' traffic work within the border of municipalities. The traffic work data supporting the methodology have been acquired through traffic flow measurements and from the NVDB. The measurements are conducted on different road networks over Sweden, but the quality of these are higher for the state-road network, and the municipal traffic work is also simulated with a model called SAMPERS (SMED, 2017). Trafikverket delivers the traffic work data allocated over all roads in Sweden, including road type, speed limit, etc., as told by SMHI (S Andersson 2018, private communication, 17th of December). Emission factors from HBEFA are then fitted to the traffic work data for each road to enable emissions to be estimated, as also told (S Andersson 2018, private communication, 17th of December). The result is then scaled with the Swedish national emissions to produce the so called "allocation keys", equivalent to an emission raster with a resolution of 1*1 km^2 over Sweden. The allocation keys are derived with an emission distribution model called SIMAIR (SMED, 2017). The allocation keys can be used to illustrate the geographical national share of a specific emission like CO_2 for municipalities as well as specific vehicle category's traffic work in Sweden. Anyhow, due to missing traffic work data from Trafikverket, allocation keys have only been possible to calculate for two years. One for 2007, applied for the years 1990-2009 and one for 2015 used for the period of 2010-2015 (SMED, 2017). For other years than 2007 and 2015, it is the development of the national emissions per vehicle category which determines the development of CO_2 emissions presented for municipalities.

It has further been told by SMHI that even though bigger roads were included, traffic flow data were missing for many municipal roads for the two years when the allocation keys were calculated (S. Andersson 2018, private communication, 4 Dec). The missing values increased the uncertainty in values for all years and Trafikverket was consulted to acquire information of any uncertainty in the estimates: Private companies were then told to be responsible for the simulation of traffic work over the municipal-road network (H Johansson 2018, Private communication, 18th of December); and Trafikverket was further told to not be specifically involved in the simulation as it is between the private companies and SMHI (A Bornström, Private communication, 2019). Hence, it was not possible to acquire the needed information of the uncertainties.

The methodology of the geographical distribution described above nevertheless enabled the CO_2 emissions from passenger cars within Järfälla to be calculated and plotted as a share of the national CO_2 emissions of passenger cars. The calculation was based on two datasets from the NEDB relevant up until 2014 and 2016. The national total of CO_2 emission from passenger cars was acquired from SCB. The use of two datasets was motivated since the values of 2006-2009 were missing in the most recent dataset, whereas the dataset of 2014 was used in the carbon budget developed to Järfälla (Anderson et al., 2017). The calculation illustrated equal and static values of approximately 0.42 percent for both datasets up until 2005. Thereafter, the dataset of 2014 continued to be static up until 2009 when the share was reduced to 0.31 percent and thereafter static till the end. The dataset of 2016 illustrated a drop already in 2005, with a new static value of 0.38 percent from 2010-2016. See figure 4 below.

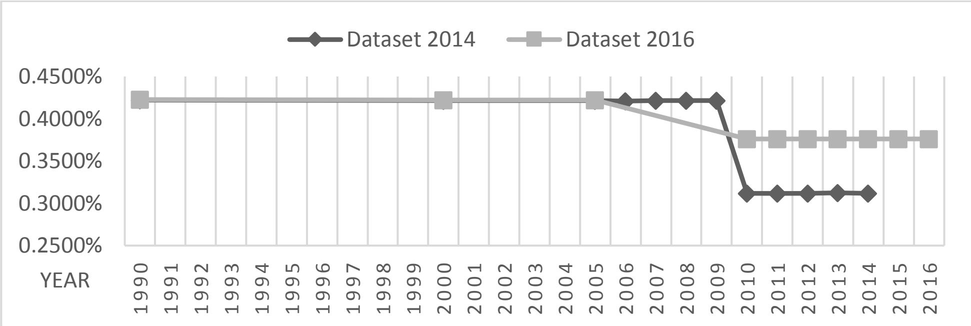

Figure 4. See above the diagram for a description of the included curves. The figure illustrates both datasets had an equal static value up until 2005 when the share of the dataset of 2016 was dropped. The dataset of 2014 dropped in 2009. The datasets originated from NEDB (2015;2017) and the CO2 estimates of the national total from SCB (2017).

Figure 4 illustrated sudden drops in the share of CO_2 emissions, and this was analyzed to be related to the allocation keys of 2007, relevant for the years 1990-2009, and 2015 relevant for the years 2010 and onwards. The dataset of 2014 fitted perfectly with this analysis, while the dataset of 2016 only confirmed to the information after 2009. The different timing of the drop for the two datasets visible in figure 4 was analyzed as illusionary and due to the missing values of 2006, 2007, 2008 and 2009 in the dataset of 2016. Accordingly, the substantial reduction in CO_2 emissions visible in figure 3 between 2009-2010 can now be explained: It was because of the difference between the two allocation keys of 2007 and 2015. Moreover, the decreasing trend also visible in figure 3 was due to a decreasing trend in the national CO_2 emissions.

The magnitude of CO_2 emissions was also identified to vary substantially between years due to the methodology. A difference of around 10 000 ton, i.e., 14-17 percent, was apparent between the datasets of 2014 and 2016 and thus illustrated a substantial difference between datasets with only 2 years in between. See figure 5.

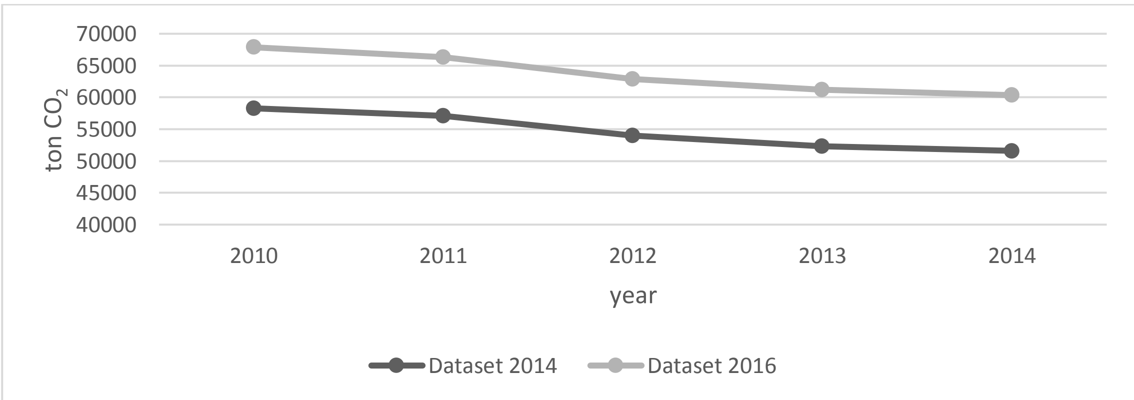

Figure 5. See under the chart for a description of the included curves. The figure illustrates a substantial difference in the magnitude of CO2 estimates between dataset 2014 and 2016. Data originate from NEDB (2015;2017).

As highlighted earlier, the motorway E18 passes through the municipality of Järfälla, see figure 1 in section 2.3.2, and this has much relevance for the territorial CO_2 estimates presented for Järfälla. The length of E18 in Järfälla is around 11 km[5] and the average[6] theoretical daily traffic flow is approximately 52 000 vehicles per day (Trafikverket, 2018b). A simplified calculation on the basis of this information was conducted to estimate the corresponding CO_2 emissions from E18. The result was 35 000 tonnes CO_2 per year over 2012-2017 and it should be viewed as an underestimation since only an emission factor for passenger cars was then applied, while heavier traffic also is conducted on E18. 35 000 ton still represent over half of Järfälla's total CO_2 emissions from transportation in 2014 or 2016. For the calculations used for the analysis in section 3.2, see Appendix A.

4. Methodology

This section presents information of the literature review conducted for acquiring information of how CO_2 emissions from cars can be estimated and to identify important car characteristics with relevance for the magnitude of CO_2 emissions. The section also includes information of the divergence between test-values conducted for cars in Europe and real-world driving, referring to emission estimates.

4.1 How can CO_2 emissions from passenger cars be estimated?

IPCC (2006a) prescribes three different alternatives for calculating emissions from transport, Tiers 1, 2 and 3. Tier 1 represents a simplified approach where only the carbon content in the fuel is considered as the combustion is assumed ideal (e.g. 100 percent oxidation of carbon). That is, the carbon going into the combustion chamber must also come out as CO_2 (IPCC, 2006a). Tier 1 results in relatively accurate CO_2 estimates which is not the case for other GHG:s or pollutants since they are more dependent on the specific combustion process. The difference between Tier 1 and 2 is related to whether country specific emission factors can be applied. Country specific emission factors take into consideration the specific carbon content of fuels for the country of interest. As such, the accuracy of estimations for the country should improve when country specific factors (IPCC, 2006a). Additionally, when Tier 2 is applied, the assumption of 100 percent oxidation can be modified (IPCC, 2006b). The emission factor of CO_2 will then be reduced since carbon is acknowledged to be emitted as other pollutants as well. The equation of Tier 1 and 2 is presented below in equation 1.

$$E_{CO2} = \sum_i F_i * EF_i \qquad (1)$$

[5] Courtesy to www.hitta.se and their tool to measure distances on an interactive map.
[6] The data from the different traffic flow points were aggregated and thereafter divided by the number of measuring points, relevant for time period of 2012-2017.

In equation 1, E_{CO2} is the CO_2 emissions in unit [mass CO_2], F_i represents the quantity of fuel *i* combusted in unit [volume] and EF_i is the corresponding emission factor for fuel *i* in unit [mass CO_2/volume]

The quantity of the fuel consumed is preferably derived through national statistics of the fuels sold within the country border, but using traffic work data is a feasible alternative (IPCC, 2006b). IPCC (2006b) estimates the uncertainty of country specific CO_2 emission factors as less than two percent. Tier 3, as stated in IPCC (2006a), provides only better accuracy for non-CO_2 emissions, as the following quote motivates:

“There is no Tier 3 as it is not possible to produce significantly better results for CO_2 than by using the existing Tier 2” (IPCC, 2006b, p 3.12).

To improve the estimates, countries should instead focus on improving the data of the carbon content in fuels as well as on the quality of national statistics of fuels sold in the country (IPCC, 2006b). However, emission factors should, if needed, be informed by fuel type, vehicle category, emission control technology and parameters which influence the fuel economy. Additionally, the use of alternate fuels (e.g. fuels other than gasoline and diesel) can create uncertainties in estimates and should be analyzed (IPCC, 2006b). For example, the fuel economy can change due to the energy content (e.g. carbon content) being different in the alternate fuel compared to the conventional fuel (Fontaras et al., 2017).

The CO_2 emissions due to the combustion of biomass should be excluded since they are categorized as carbon neutral and the share of biofuels in conventional fuels should be specified for commercially relevant fuels. Moreover, the origin of the biomass in biofuels should be specified since not all biomass can be considered carbon neutral and this should modify the calculation of CO_2 emissions. The modification can be accomplished by multiplying the fossil emission factor with the fossil fraction in the fuel (IPCC, 2006b).

As mentioned above, no Tier 3 equation is available, but it is still applied in emission models like COPERT and HBEFA. Tier 3 separates emissions into whether the engine is hot or cold, whether the traffic work is conducted in urban, rural or motorway settings as well as also incorporate the effect of speeds by specifying mean speeds (EEA, 2016a). Finally, modifications of the Tier equations are conducted officially as apparent in EEA (2016a) albeit still stated to adhere to the IPCC guidelines.

4.2 Divergence between real-world and test driving

The NEDC was not adequate for the purpose of deriving emission estimates for passenger cars representative for real-world driving (Fontaras and Dilara, 2012; Kågeson, 1998; Pavlovic et al., 2018). Car manufacturers were allowed a high flexibility when the cars’ fuel consumption and emissions were measured with the NEDC and this was exploited to yield lower estimates of CO_2 emissions. For example by using lower a resistance for tires, a lower mass of vehicles and also an optimal driving cycle (Pavlovic et al., 2018), but many other loopholes were also exploited (Fergusson, 2013). To summarize, cars were optimized for the

NEDC and not for real-world driving with the purpose to achieve lower official values, referring to both the fuel economy and the emissions per traffic work (EEA, 2016b; Fontaras et al., 2017; Tietge et al., 2017).

Research have provided estimates of the divergence between the NEDC and real-world driving: By comparing over 500 000 cars, the discrepancy was under 10 percent in 2001, but up to 40 percent in 2014, here referring to the fuel consumption; the discrepancy is actually 5 percent higher for diesel cars compared to gasoline cars, whereas hybrids' CO_2 emissions were underestimated by 40-45 percent, see JRC 2011b, ICCT 2013, ICCT 2014b and ICCT 2015a cited in EEA (2016b) for more information; the given divergence is by large reflected in values given in Fontaras et al. (2017) and Tietge et al. (2017). The variability of the divergence is however large (e.g. over ten percent) between car models (Fontaras et al., 2017; Tietge et al., 2017).

Ideally, more research is needed to reduce the uncertainty when comparing test values with real-world emissions since the fuel economy depends on a wide range of factors (e.g. side wind, traffic congestion, roof boxes, auxiliary systems, ambient temperature, low friction tires, etc.) (Fontaras et al., 2017). Many of the factors display an unknown, but high variability for real-world driving (Franco et al., 2013; Fontaras et al., 2017). Likewise as with how the factors effect emissions in combinations. When over 15 million new cars were bought in 2007, likewise as in 2014, referring to the market of EU-27 (EEA, 2017), the challenge of deriving representative emissions from tests corresponding to real-world driving is hard to overestimate. Especially since test results must be repeatable as well as due to incremental technology development over time for car models (Fontaras and Dilara, 2012).

The new test cycle, Worldwide Harmonized Light Vehicle Test Procedure (WLTP), implemented in the Summer of 2017, is expected to decrease the discrepancy between tests and real-world driving, but a substantial gap will albeit remain (Pavlovic et al., 2018). As argued in Fontaras et al. (2017), no single test can ever be designed to represent real-world emissions. Most importantly, Kågeson (1998) predicted the increasing divergence as well as the infamous scandal, i.e. the Volkswagen's emission scandal discovered in 2015-2016 (EEA, 2016b; Pavlovic et al., 2018; Peitzmeier et al., 2017). And any test cycle is also susceptible for optimization efforts by car manufactures (Kågeson, 1998).

The 'prediction' by Kågeson (1998) was obviously not adhered. Instead, the divergence increased from under 10 percent in 2001 to 40 percent in 2014. EU regulations, see section 2.4, have in practice skewed the market of environmental cars as well as the emissions in Europe (EEA, 2016b; Fontaras et al., 2017; Pavlovic et al., 2018; Tietge et al., 2017). Finally, as stated in Hu et al. (2016), research results must now also be revised due to the inadequate values provided from the NEDC, thereby illustrating a waste of resources.

4.3 What impacts the magnitude of CO_2 emissions?

The magnitude of emissions is proportional to the amount of fuel combusted. For example, fuel consumption and CO_2 emissions are used interchangeably in Fontaras et al. (2017), and IPCC (2006b) recommends to only calculate CO_2 emissions with the amount of fuel combusted.

Energy- and fuel efficiency

Over 70 percent of the energy available in fuels are related to losses for a "conventional" vehicle, i.e. less than 30 percent of the energy is used for mechanical work, thereby implying the importance of the total efficiency of cars (EEA, 2016b).

The car age is a suitable proxy for the improvement of engine efficiency over time (EEA, 2017; IPCC, 2006b). Data of the fuel economy per year, see section 5.4.2, also illustrates substantial improvements of the fuel economy over time. CO_2 emissions may therefore be believed to be reduced forever and ever as long as nothing inhibits technology development. However, a combustion engine is a heat engine that must conform to thermodynamic laws and heat is not an efficient energy source to transform to mechanical work. Energy as heat is easily lost to the surroundings (Young et al., 2014) and thereby inhibits technology development.

Trade-off between human health and a reduction of CO_2

A trade-off, as implied in section 2.4, between reduced CO_2 or reduced NOx emissions (EEA, 2016b) currently puts a limit for how much emissions can be reduced. The problem is mostly related to diesel cars as they have substantially higher NOx emissions compared to other fuel technologies (EEA, 2016b; O'Driscoll et al., 2018; Fontaras and Samaras, 2010). An experiment in a German city illustrated NOx emissions to be elevated by 300-900 percent more than what EU emission limit allows for. Results which are generally reflected in other studies as well (Peitzmeier et al., 2017). NOx emissions are detrimental to human health and must come down due to health regulations. The reduction of NOx emissions is, though, currently achieved at the expense of increased CO_2 emissions due to the functioning of selective- and oxidation catalysators (EEA, 2016b; IPCC, 2006b).

The mass of cars

The mass of cars is an important factor. Mass increases do not have to coincide with an increased fuel economy since they can be counteracted by efficiency improvements. Efficiency improvements are, though, not used to improve the absolute fuel economy, rather they have benefitted the luxury of cars (e.g. air conditioning, passenger space, acceleration, etc.) (Sprei et al., 2008; Fontaras and Samaras, 2010). Technology development and its positive impact on the fuel economy have in fact been offset by increases in vehicle mass (Papagiannaki and Diakoulaki, 2009; Hu et al., 2016).

There is no standardized estimate of how much the fuel economy increase/decrease when the mass of a car changes (Fontaras et al., 2017). Increases in engine size are obviously related to acceleration, but normally also related to increases in the mass of cars (Hu et al., 2016). Thereby making it hard to determine how the fuel economy vary due to changing masses or engine sizes. Nevertheless, estimates of the impact of mass changes on the fuel economy has been acquired from literature: The fuel economy increases/decreases by 0.3-0.5 liter per 100 kilometers when the mass is increased/decreased by 100 kilo, see references 91 and 94-98 cited in Fontaras et al. (2017). The total number of passengers in a car, the occupancy rate, hence effects the fuel economy (Fontaras et al., 2017).

Diesel cars are inherently more efficient than gasoline cars due to the combustion technique, i.e. Diesel cycle versus Otto cycle (Young et al., 2014), but diesel cars have become heavier on average in later years. Compared to new gasoline cars, the average mass of new diesel cars was around 230 kg heavier in 2004 and 300 kg in 2010 where it has stayed fairly constant up until 2016 (EEA, 2017). CO_2 emissions may therefore not be reduced significantly when the share of diesel cars increases in an arbitrary vehicle fleet, they may even increase, whereas the NOx emissions will increase (Fontaras and Dilara, 2012; Fontaras and Samaras, 2010). Data of new cars registered in the EU also illustrate the improvement of gasoline cars, though less so for diesel cars: Gasoline cars, compared to diesel cars, emitted 15 percent more CO_2 on average in 2000, but only 3 and 4 percent more in 2008 and 2016 respectively (EEA, 2017).

Driving behavior and speed

The driving behavior has an effect on the fuel economy since a car has different optimal engine speeds that translate into different fuel economies for the same car. For example, a driving behavior where a lot of acceleration and braking take place increases the fuel economy compared to driving with a constant speed. Moreover, driving fast (e.g. over 90 km/h) is equivalent to higher emissions (Perby, 1989; VTI, 2017), whereas driving slow (e.g. under 60 km/h) in urban traffic also relates to higher emissions (VTI, 2017). Accordingly, speeds between 60-90 km/h result in the lowest emissions. Furthermore, in relation to the divergence between test-values and real-world driving, speeds between 60-80km/h yield lower emissions in real-world driving compared to the test-values of the NEDC (Fontaras et al., 2017). The underestimation is an exception, but it illustrates the complexity of measuring emissions due important factors such as speed. Furthermore, the driving behavior is also dependent on the specific road category (e.g. highway, urban or rural driving, the gradient, etc.) as well as on the traffic flow, i.e. congestion issues (VTI, 2017; Fontaras et al., 2017).

5. Model construction

This section beings by presenting information of an analysis of the CO_2 estimates applied in the carbon budget developed to Järfälla, referring to whether they could be exploited in the modelling. See section 2.3.2 and 3.2 for more information of the estimates.

The CO_2 emission estimates utilized in the carbon budget developed to Järfälla with origin from the NEDB could not be used in the modelling due to the following identified issues:

1) The estimates did not necessarily reflect the development of territorial CO_2 emissions in Järfälla. To illustrate, if Järfälla hypothetically has increased the CO_2 emissions from passenger cars within the municipality, while the national CO_2 emissions decrease, the emissions presented for Järfälla will paradoxically show a decrease compared to the year before, and vice versa; neither does a reduction in the share of CO_2 emissions guarantee a real-world reduction. The share depends on the development in other municipalities as well as of the quality of the traffic flow data and the simulation of traffic work for the municipal-road network. Moreover, only two allocation keys support the calculation of emissions for the period 1990-2017. Consequently, both the magnitude and trend of the estimates presented for Swedish municipalities are determined by the national emission estimates. A risk of providing an erroneous feedback if exploiting the existing estimates in local climate work was hence identified.
2) The scaling performed with the national emissions was identified to provide a connection of the national emissions to the municipal emissions, but there is no distinct connection of a municipality's emissions to the national emissions. The simulated traffic data of the municipal-road network is not utilized in the national estimate. Moreover, the traffic flow data of the state-road network, though applied in the national estimate, is not enough to guarantee a connection due to the rare update of allocation keys described in section 3.2. A reduction of CO_2 emissions in the local context was concluded to not necessarily be reflected in the national estimate.
3) CO_2 estimates were identified to change substantially from year to year due to the methodology, i.e. not because of the real-world development of emissions. The applicability of estimates was therefore reduced. For example, if the magnitude of estimates from one year is used to design a policy with the purpose to reduce emissions. And the impact of the policy is analyzed two years after, then both the initial policy as well as the following analysis risk being conducted on the basis of non-representative estimates.
4) Over 50 percent of the territorial emissions presented for Järfälla were identified to originate from the traffic work conducted on motorway E18, which is not under municipalities governing as it is part of the state-road network. It may as such be hard for the municipality of Järfälla to reduce the majority of CO_2 emissions included in the carbon budget.
5) It has not been possible to determine the uncertainty involved when the traffic work for the municipal-road network is simulated, which severely inhibited the possibility of applying the CO_2 estimates in model. Especially since information implies traffic flow data for the municipal-road network was missing. The network moreover accounts for around 30 percent of the total traffic work in Sweden, see section 3.1.1. The unknown uncertainty could possibly impact results substantially, which rendered the estimates inadequate for further modelling.

It was deemed necessary to create a model not plagued by the above issues to fulfil the objective of the modelling. The remaining part of section 5 is dispositioned as follows: A description of the model is presented in section 5.1, including the system boundaries in 5.1.1, and the model results are described in 5.2. A rationale for the model on the basis of the above identified issues is presented in 5.3. The data, the validation, the sensitivity analyses and the utilized assumptions in the model will thereafter be presented in turn order in section 5.4, 5.5, 5.6, and 5.7, respectively.

5.1 Description of the model

The modelling applied a bottom-up approach where the fuel consumption was calculated by multiplying the traffic work with the estimated fuel economy of each car. The traffic work was specified according to both the fuel technology and calendar year to enable the emission factors to be matched in fuel as well as to allow the varying carbon content over time to impact model results. The foundational equation in the model structure was a modified version of equation 1 in section 4.1. and it implied a larger uncertainty due to the inclusion of the fuel economy and traffic work data instead of fuel statistics. See equation 2 below:

$$E_{CO2} = \frac{1}{1000} * \sum_{i,j,k} \frac{FE_{i,j,}}{10} * TW_{i,j,k} * EF_{j,k} \qquad (2)$$

In equation 2, E_{CO2} is the resulting CO_2 emissions in unit [ton CO_2], FE is the fuel economy in unit [l/100km] of passenger car *i* with fuel technology *j*, TW is the traffic work in unit [10 km] conducted for passenger car *i* with fuel technology *j* in year *k* and EF is the emission factor in unit [kg CO_2/liter] for fuel technology *j* and year *k*. The fuel economy was divided by ten to mitigate the difference in units, referring to FE and TW. The scaling of 1 over 1000 was needed to present results in unit [ton]. However, the fuel economy was also weighted on the basis of the mass of cars and a correction due to car manufacturers' optimization of the NEDC was also implemented in the model. The weighting and correction, though, were not relevant for every car due to data limitations, see more information below and in section 5.4 and 5.7.

The traffic work data included the traffic work, the fuel technology, the production year and the individual mass for every car for the years 1999-2017. The elicitation of fuel economy conducted for each car was achieved by exploiting the production year of cars which was then matched to the calendar year in the fuel economy data. The calendar year highlighted the average fuel economy of new cars sold per fuel technology dating back to 1968 and a value could as such be elicited on the basis of the production year. This rather course elicitation prompted the need to weight the fuel economy according to the individual mass of a car in relation to the average mass of cars sold per calendar year. The purpose of the weighting was to approximate the unknown fuel economy of cars as specified by car manufacturers, i.e. not the real-world fuel economy. However, data of the average mass of cars sold was only available dating back to 2001 and thereby constrained the weighting to only be performed for cars with a production year of 2001 or thereafter. Anyhow, the fuel consumption was calculated by simply multiplying the traffic work of a car with the derived fuel economy, but it was then corrected to account for the skewed fuel economy data provided from car manufacturers. Emission factors specified in fuel technology and calendar year were thereafter multiplied with every car's fuel consumption in the final step to yield the resulting CO_2 emissions of the same car's traffic work. The biofuel share was manually incorporated into the emission factors to exclude biomass from CO_2 emissions and explicit assumptions were made with relevance for ethanol- and gas cars. Ethanol- and gas cars had two corresponding fuel consumptions, one for gasoline and one for E85 and vehicle gas respectively. A schematic figure of the model is presented below, see figure 6.

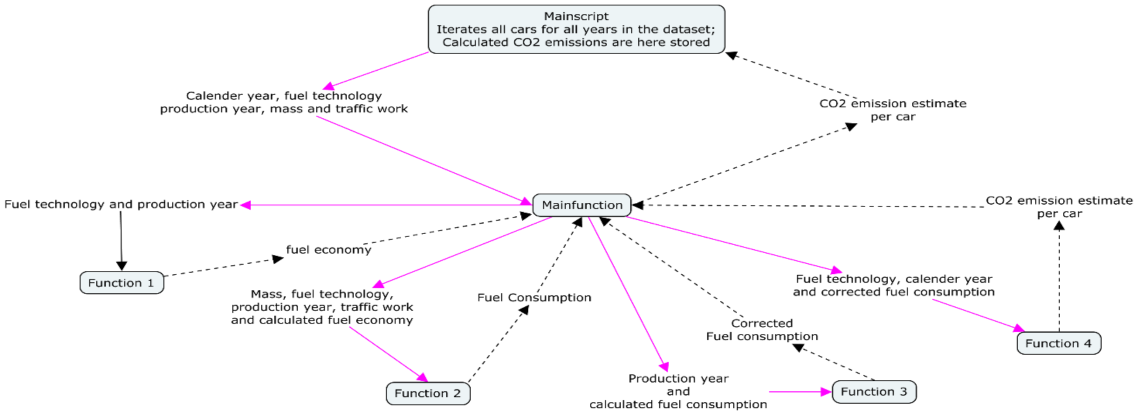

Figure 6. The texts in boxes describe scripts and functions. The text in between boxes represent input and output between functions and scripts. Input data are highlighted by ordinary arrows whereas the output with dashed arrows. In Function 1, the elicitation of the fuel economy of cars was conducted. The weighting as well as the calculation of the fuel consumption, were conducted in Function 2. The fuel consumption was thereafter corrected in Function 3. In Function 4, the calculation of CO_2 emissions per car was conducted. See text in figure for further explanation of the figure. The figure was created with CmapTools (https://cmap.ihmc.us/cmaptools/).

The modelling was performed with Matlab, whereas Excel was applied to calculate values applied in Matlab, see appendix C for the calculated values. Excel was moreover applied to create the figures used for presenting model results. Over 1500 rows of codes have been written in Matlab to calculate the CO_2 emissions of over 527 000 cars over the time period of 1999-2017 as well as to categorize the results in meaningful ways.

5.1.1 System boundaries

The CO_2 emissions per year for every passenger car in traffic per year and registered in Järfälla during the period of 1999-2017 were calculated by the model. Both juridical persons and citizens were included in the model as the owners of the modelled cars. The calculation of emissions included the fuel technologies of gasoline, diesel, electric hybrid, PHEV, ethanol and vehicle gas, by applying country specific emission factors relevant for gasoline, diesel, ethanol and vehicle gas. Only tailpipe fossil CO_2 emissions were modelled in the study since biomass was excluded from a climatic impact, simultaneously as LCA was not applied in the study. It was possible to specify where the traffic work of passenger cars have been specifically conducted. However, the estimated CO_2 emissions were approximately only emitted in Sweden since commuting to foreign countries by car should be minimal in the municipality of Järfälla due to its location, see section 5.4.1 and 5.7.1.

5.2 Description of model results

Estimates of the aggregate CO_2 emissions of all cars per year were calculated to illustrate the resulting development of emissions, i.e. total model results. Model results per Järfälla citizen was a result incorporating the aspect of population development to adhere to requirements of the municipality, see section 2.3.2. Model results were also calculated in CO_2 emissions over the car characteristics of fuel technology, mass classes and car age classes to illustrate local information with relevance for the magnitude of emissions. For example, if any shift had occurred during the study period. Mass classes were categorized into intervals in unit [kilos], e.g. 901-1000, 1501-1600, etc. Car age classes, on the other hand, were specified with 20 classes by using the production year of each car in relation to the specific calendar year relevant for the calculations. All results were relevant for the years of 1999-2017.

The model was also applied to calculate the CO_2 emissions per postal code for the year of 2017, both in absolute CO_2 emissions per postal code and in CO_2 emissions per postal code per car. The absolute result illustrated the aggregate CO_2 emissions and can be used for identifying postal codes where reductions in percent can be most efficient, referring to climate change mitigation. The relative result was more convenient when comparing results, for example, to analyze differences as one way to learn from good and bad examples. The results were presented on a map without specifying the postal codes since the results were not validated. Moreover, the result only included one postal code with less than 100 cars, whereas the majority had between 200-400 cars. See 5.7.4 for the assumptions, Appendix C for the data and Appendix D for the conducted steps in the modelling, including the cleaning of data.

The model was furthermore applied to estimate the impact of explorative scenarios on CO_2 emissions. The explorative scenarios can be compared to policy goals, as such, the results were equivalent to a quantification of the supposable impact of specified policies with the purpose to reduce emissions. The explorative scenarios were modelled as being accomplished in only one year for convenience, but could equally be viewed as being accomplished in a longer time frame as they were approximately only constrained by the scenarios' specified traffic work. The one year time step was unrealistic, and the results should be viewed as visionary. See the explorative scenarios as well as the motivations of them (in italics) below:

1. What if gasoline- and diesel cars' traffic work is reduced by 50 percent, given the constraint of travel need being constant, i.e. total traffic work between 2016 and 2017 was held static? *The motivation of this scenario was equivalent to investigate the impact of a rapid and drastic increase of the share of cars with low-emission technologies while not changing the car owners' travel need by car.*

2. What if the traffic work is reduced on average by 20 percent for the whole passenger car fleet in Järfälla? *Instead of changing the passenger car fleet composition to reduce emissions, the traffic work could instead be reduced while the car fleet would not change, and this scenario illustrated the effect of this on CO_2 emissions.*

3. What if the traffic work is reduced by 20 percent specifically for cars with individual masses over 1500 kilos? *The scenario enabled a quantification of the effect of a hypothetical and arbitrary policy goal stimulating car owners with heavier cars to reduce their traffic work.*

4. What if the traffic work is reduced by 20 percent for the ten oldest car-age classes? *The scenario enabled a quantification of the effect of a hypothetical and arbitrary policy goal stimulating car owners with older cars to reduce their traffic work.*

5.3 Rationale for model

The development of the model was guided by the universal recommendation to try simple things first. Additionally, complex models do not necessarily facilitate more accurate results (Smit et al., 2010) and especially so for CO_2 emissions from the transportation sector (IPCC, 2006b). The recommendation in IPCC (2006b) is to apply Tier 2 if country specific emission factors are available when estimating CO_2 emissions, which they are for Sweden. Tier 2 was hence decided to be the guiding equation in the model structure. Additional recommendations from IPCC were also adhered to: The exclusion of sustainable biomass from CO_2 emissions in the model; car characteristics impacted the fuel economy of cars; emission factors were specified according to the relevant fuel technology; car age, i.e. the production year, was exploited for incorporating engine improvements over time; and alternate fuels impacted the fuel economy of cars.

Driving behavior and speed were analyzed as not suitable to incorporate in the model as it would require detailed data not available for Järfälla, but even if the data were available, the accuracy of it would likely be inadequate for the model structure. Both driving behavior and speed imply an unknown variability hard to represent correctly in relation to CO_2 emissions, which could cause an unknown systematic bias in the model results. For example, mean speed data (as described in section 3.1.2) underestimated the impact of congestion issues. This reasoning is also relevant for the factors mentioned in section 4.2 (e.g. wind, tires, auxiliary systems). Most conveniently, the factors nonetheless added to the increasing divergence between real-world driving and test-values of the NEDC. The applied correction used in the model structure due to car manufacturers' optimization of the NEDC thereby implicitly incorporated the impact of factors not possible to include in the model.

The remaining part of 5.3 illustrates how the model structure mitigated the identified issues of the existing municipal CO_2 estimates in section 5. The information is presented in the same order as these issues were presented.

1) The model structure facilitated the necessary connection between the traffic work, i.e. the emitters of CO_2, with the fuel economy and the emission factors, to model the real-world development of CO_2 emissions between 1999-2017 from passenger cars. The model structure moreover facilitated technology development, biofuels and consumer preference (i.e. mass of cars and fuel technology) to impact model result. The model structure thereby incorporated essential drivers for the development of CO_2 emissions from passenger cars. Thus, if the aggregate CO_2 emissions change significantly, the model structure was most suitable to illustrate this with enough accuracy. The traffic work data as well as the other data sources are moreover updated annually, and this enabled the model structure to apply annual data instead of proxies. The model results were moreover independent of the development of national- as well as other municipal- emissions. Furthermore, model results can be updated and analyzed annually and the risk of them providing an erroneous feedback was considered minimal except in the case of economic downturns: The traffic work data can occasionally lag which make model results miss the exact timing of, for example, economic downturns. There are also uncertainties in the traffic work data, but considering the methodology in use by the data provider TRAFA, see section 5.4.1 and 5.7.1, simultaneously as it is specific to Järfälla. The data was considered to be the best data possible to acquire for the objective of the master thesis. The fuel economy data was representative for cars sold nationally, but a performed weighting nevertheless rendered the data representative for Järfälla. Moreover, a performed correction rendered the data more representative for real-world driving.
2) The application of Tier 2 in the model, the conducted validation of total model results and the data from mandatory vehicle checks guaranteed model results to be directly connected to Sweden's accounting of CO_2 emissions from passenger cars. That is, if car owners from the municipality of Järfälla hypothetically has significantly changed their CO_2 emissions from passenger cars in aggregate, it will be reflected in the NRMM, in HBEFA, in the national estimate and in the national statistics of fuel sales and in the greenhouse gas inventory. Most importantly, it will be reflected in the model results.
3) The model structure was analyzed to be sensitive to substantial changes in the traffic work data and to the applied correction due to car manufacturers' optimization of the NEDC. However, when and if improvements in traffic data or information relevant for the correction become available, model results would only be changed in a one-time event. Advantages of the data applied in the model were the relatively robust data sources, e.g. from experts and from official sources, and the data were on multiple occasion derived on a large number of cars (i.e. an adequate sample size). The exploited data thereby minimized the risk of model results to substantially vary in magnitude from year to year due to uncertain data. See more information in section 5.4, 6.1, 6.2 and 7.4.
4) The model structure was not capable of facilitating territorial CO_2 emission in the municipality to be modelled, but the model results were nevertheless specific to the municipality. The traffic work data for the model is specific to Järfälla, both in relation to the included car characteristics and the traffic work. Consequently, the

estimated CO_2 emissions by the model were specific to Järfälla and were presented in ways illustrating, for example, how the emissions had changed over time as well as over car characteristics. See section 5.2 and 6.3 for further information of the model results. Model results were therefore also suitable to the municipality's governing level since a municipal constitutes the closest governance level for citizens, see section 2.4.

5) The inherent uncertainties of the model structure were quantified where possible to increase the transparency of the model results. The largest analyzed uncertainty in the model was related to the applied correction used to correct the fuel consumption of cars. The share of gasoline fueled in ethanol-and gas cars was another unknown. The impact of the applied corrections and the gasoline share, as well as other model configurations, were however quantified in the conducted sensitivity analysis to enable the impact to be displayed and analyzed. Moreover, the conducted validation guaranteed the applied fuel economy, the calculated emission factors and the total model results to not diverge from official data and estimates, neither in magnitude nor correspondence. Also, observe the traffic word data is by large factual and not simulated, but 30-40 percent of the traffic work data is nevertheless estimated and could be subject to change. Consequently, the impact of the estimated data on model results was quantified with a share, see section 5.7.1. To summarize, considerable efforts were made in the study to specify- and also quantify- the uncertainties in the model to improve the transparency of the model.

5.4 Data

Questions in relation to any data utilized in the model can be directed to the author of the master thesis. Data, not especially analyzed or highlighted in the report, are given in Appendix C, likewise as with the values which have been recalculated to fit with the model structure. See more information below and in Appendix C.

5.4.1 Main data of the master thesis

The traffic work of cars registered in the municipality of Järfälla for the time period of 1999-2017 originate from the mandatory vehicle checks conducted in Sweden and is provided by TRAFA for the study. Between 30-41 percent of the included cars' traffic work are estimated in the dataset since cars can lack correct odometer readings due to different reasons. Cars with missing or incorrect odometer readings are classified into groups of new registered cars, direct imported cars, deregistered cars and 'other' cars. A unique model depending on the group is then used to estimate the missing traffic work. The estimation utilizes correct odometer readings of cars and their car characteristics (e.g. mass, car age, fuel, etc.), including the group, to estimate the traffic work by similarity as told by TRAFA (A Myhr, Personal Communication, 2019). As a consequence, cars can be given the same estimate if car characteristics are similar. The estimated traffic work is uncertain, but there is no quantification of the uncertainty given by TRAFA. TRAFA considers the quality of the traffic work estimates adequate enough- relative to the need for users of having the information published relatively fast- to be published just a few months after the calendar year has ended. Up to three years of delay would otherwise be unavoidable since new registered cars[7] are normally not required to check the car the first three years. Moreover, not exactly one year passes between the conducted checks and this can create a lag that, for example, make the data inadequate to accurately display the impact of economic downturns, i.e. the effect lags (TRAFA, 2011). It has been told by Anette Myhr at TRAFA that the quality of the estimations will be scrutinized during the fall of 2019 (A Myhr, Personal communication, 2019). The quality of the estimates should thus improve.

Before an odometer reading is classified as correct, it is scrutinized according to historic values to analyze whether the value is reasonable in relation to former values. With no indications of an odometer reading being faulty, the daily traffic work (e.g. 'daily kilometers') for an arbitrary passenger car is calculated as follows:

$$Daily\ kilometers = \frac{M2-M1}{\#days} \qquad (3)$$

In equation 3, M2 and M1 represent the odometers readings from two checks and #days is the number of days in between the two odometer readings. If only one odometer reading is available (e.g. the car is new), M2 takes the value of the first reading, whereas M1 take the value of zero. Equation 3 is multiplied with the number of days the car has been in traffic to give the traffic work per car for a year (TRAFA, 2011).

All cars have a corresponding traffic work, either estimated or 'real', which before of 2011 was not the case. Old estimated traffic work has been adjusted when improvements of the models have been conducted. One improvement, for example, is that passenger cars' maximum daily traffic work was set to be constrained to 600 kilometers at the most (on a daily basis). The traffic work conducted in foreign countries by Swedish cars is included in the data. Investigations imply the share is 2.5 percent in 2011, but a large part of this traffic work is related to commuting (TRAFA, 2011). The database is updated annually, and the data applied for Järfälla is also available for every other municipality in Sweden.

When analyzing the main data of the study, the occurrence of an interesting shift was identified. The traffic work by gasoline cars has been reduced substantially between 2007-2017. The reduced traffic work does not, though, coincide with an aggregate reduction of the traffic work. Other fuel technologies like diesel, ethanol, electric hybrid and vehicle gas have instead increased the traffic work more than the reduction of gasoline cars. The traffic work conducted by car owners in Järfälla had in fact increased from approximately 300 000 000 km to over 420 000 000 km in 2017, representing an increase by 40 percent. However, the number of cars had also increased, from around 23500 cars in 1999 to around 34300 in 2017 which is equivalent to an increase of approximately 46 percent. Hence, Järfälla car owners drive more on aggregate, but less per car. It was the traffic work of diesel

[7] New registered cars are defined with two conditions: No more than 4 years have passed between the registration- and calendar year; and no more than 2 years have passed between the production- and registration year.

cars that was identified to have increased the most in absolute numbers. Electric hybrid-, vehicle gas-and ethanol cars were responsible for 13 percent of the total traffic work in 2017, whereas electric- and PHEV cars only represented less than one percent in the same year. See figure 7.

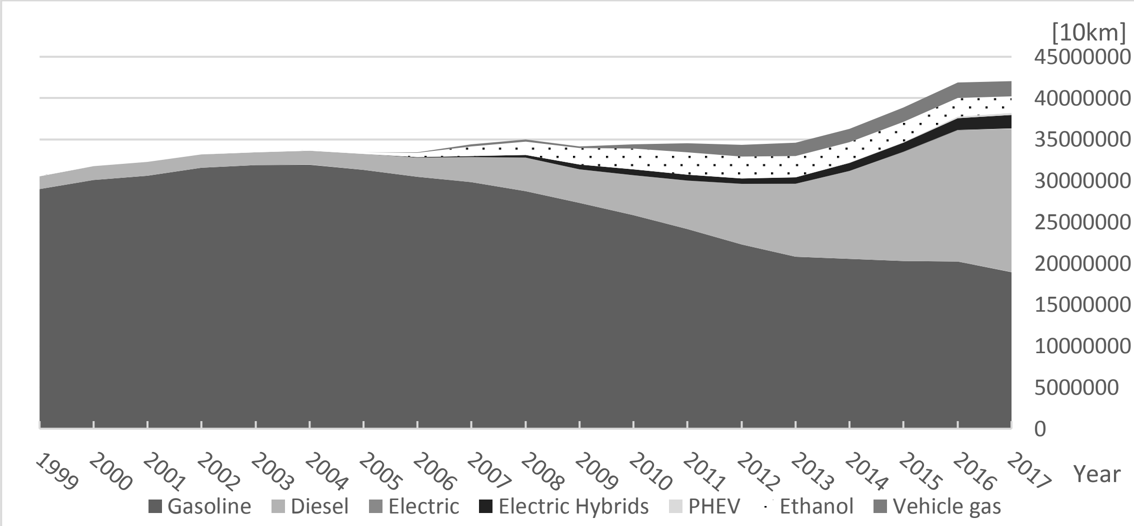

Figure 7. The included fuel technologies are described below the diagram. The figure illustrates the traffic work share of gasoline cars had been reduced substantially, whereas the share of diesel cars had increased. Moreover, the total traffic work can be observed to have increased considerably during the study period.

Cars with a mass below 500 kilos as well as cars with a fuel technology categorized as "other" were not included in the model structure. The reasons for excluding these cars related to the risk of erroneous data and the inability to assign a correct emission factor according to the fuel technology. The model results were however only marginally impacted since they represented less than 0.00001 of the total traffic work per year.

5.4.2 The fuel economy

Data of the average fuel economy dating back to 1978 had been acquired for the study. The data originated from car manufacturers as reported to the European Environment Agency and Vägverket (now part of Trafikverket), but has been compiled by Trafikverket. The given fuel economy values were viewed as rather optimistic since the data originated from car manufacturers. An equivalent dataset going back to 1968, also compiled by Trafikverket, was later identified and used to complement the first acquired data. See table 4 in Trafikverket (2018a) and table 1 in SCB (2017b). The data was specified as relevant for new sold cars per calendar year, but it has been confirmed to include older cars (e.g. ≈3 years), as measured from the production year (H Johansson, Personal communication, 2019). To illustrate, the calendar year of 2017 included fuel economy data from cars sold with production year 2017, 2016 and 2015. The share of the respective production years for a calendar year was not acquired.

The fuel economy of gas- and ethanol cars was given when driving on gasoline and needed to be transformed to when driving on vehicle gas and E85 respectively to fit with the model structure.

5.4.3 Emission factors

Emission factors of gasoline, diesel, ethanol and vehicle gas have been acquired from SEPA (2018a). For gasoline, diesel, ethanol, natural gas and biogas, emission factors have also been acquired from AoE (2015). SEPA incorporates the biofuel share in the given factors, whereas AoE provides the factors for pure fuels. Both sources provide the factors in unit [kg CO2/GJ]. The emission factors needed to be transformed to unit [kilo CO2/liter fuel] and for vehicle gas in unit [kilo CO2/kilo gas combusted). For vehicle gas, the density at atmospheric pressure and zero degrees Celsius were acquired for this purpose. It was told to be 0.75 kilo per m3, relevant for the year 2017, by AoE (J Harrysson, Personal communication, 2019). See appendix C for the calculated values applied in the model.

Emission factors in unit [g CO2/km] from HBEFA, version 3.3, have been provided by IVL with relevance for urban and rural driving on motorways and non-motorways, but they were not specified over fuel technologies. The factors from HBEFA were told to be representative for the Swedish car fleet and weighted with the traffic work on Swedish roads (M-R Yahya 2018, Personal communication 13^{th} of December).

The calculated emission factors applied in the model originated on the data from AoE (2015). The additional emission factors provided from SEPA and IVL were used to validate the calculated emission factors and the total model results respectively.

5.4.4 Fuel economy of gasoline and diesel cars used for validation

The Transportation Administration Board have provided the original data of individual fuel economy of cars that was used by SCB to derive the average fuel economy of solely gasoline- and diesel- cars for every municipality in Sweden for the years 2012-2016. However, the fuel economy is also estimated where needed and this is performed with the production year as was also performed in the study. Information of the share of estimated data is not given and no contact person is given, though SCB usually describe the quality of data, but not in SCB (2017b). The non-estimated data are considered of higher quality, but since the share is not given, the validation data was considered uncertain. See table 6 in RUS (2018) for the data.

5.5 Validation

Validation is critical to guarantee model results are accurately enough for the purpose of the modelling (Smit et al., 2010). In section 1.1, model results were specified to facilitate mitigation measures’ impact on CO_2 emissions to be analyzed, and this required the model to produce accurate results for displaying the most likely development of CO_2 emission.

The model structure included multiple data sources and configurations and the model was validated in parts to improve the interpretation of the validation results. Otherwise, a risk of not being able to improve the model, if needed, was identified since errors then could be hard to specify and correct. Nevertheless, data limitations guided the validation. The validated parts of the model were the elicitation and weighting of the fuel economy, the calculated emission factors applied in the model and the total model results. The validation data originated from official sources and built on official methods applied when estimating national CO_2 emissions to thereby provide a suitable reference context for the model results to be compared with. Observe, the real-world emissions were unknown.

The following of this section specifies the validated parts with the elicitation of the fuel economy in 5.5.1, the calculated emission factors in 5.5.2 and the total model results in 5.5.3. First observe the non-systematic errors in the model should generally average out in the results since the main data includes 23498 rows (e.g. cars) in 1999, a number that systematically grows to 34256 in 2017.

5.5.1 Validation of fuel economy

The specific fuel economies of the individual cars as given in the manuals books of cars were not acquired for the study, but the data is in part available. The validation data was only representative for gasoline and diesel cars for the years 2012-2016, see section 5.4.4. The average fuel economy of all gasoline and diesel cars, as derived in the model after the conducted weighting, was compared with the validation data. The validation had the purpose to validate the elicitation of fuel economies as well as the adequacy of the conducted weighting. An optimal result would correspond to approximately no difference between the model's applied values and the validation FE data since the weighing was conducted to compensate for the course elicitation of the fuel economy.

5.5.2 Validation of calculated emission factors

The emission factors given in SEPA (2018a), though stated to be used in Sweden's greenhouse inventory, were not possible to incorporate in the model structure. The information given in SEPA (2018a) was not specific enough to analyze whether these factors were suitable to apply in the model structure. Furthermore, the missing information also constrained model results to be analyzed with enough detail level. Specifically, the missing information related to whether technology development had impacted the derivation of the factors; hidden assumptions in the factors relevant for ethanol and vehicle gas (i.e. how are they fueled?); and how biofuels were incorporated in the factors (i.e. what share is assumed and is it sustainable?). It was not possible to acquire the missing information from SEPA. Additional emission factors were instead calculated to guarantee emission factors were suitable for the model structure and to allow model results to be analyzed more thoroughly. CO_2-estimates when applying the emission factors from SEPA and the calculated factors were then compared for gasoline-, diesel- and hybrid cars. That is, only the calculated emission factors relevant for gasoline and diesel were possible to validate. The validation result illustrated whether the calculated emission factors, including the inclusion of biomass, were adequate in relation to official emission factors used when estimating Sweden’s greenhouse gas inventory.

5.5.3 Validation of total model results

The validation models constituted of the emission factors from HBEFA and they were delivered in unit [kg CO_2 per kilometer] and required the traffic work in unit [km] for the CO_2 emissions to be calculated. Moreover, HBEFA applies Tier 3, while the model structure implemented a modified version of Tier 2 with emission factors specified in fuel technology per year specifically for Järfälla. Observe 33 percent of the data, i.e. the main data, was identical in the conducted validation. Anyhow, the validation was most relevant and beneficial to conduct since the total model results were validated with a different methodology also applied when estimating the CO_2 emissions in the national estimates. A good correspondence where shifts in estimates are reflected in both ‘methodologies’ was deemed as an adequate result of the validation. In regard to the magnitude of the estimated emissions, a ‘correct’ estimate was not available. The factors from HBEFA should not be considered more accurate than the model’s estimations for Järfälla, but differences in magnitude should nonetheless be explainable to further illustrate an adequate correspondence between the methodologies. See more information below.

An urban combination, a.k.a. Urban, was elicited as the most relevant combination to validate the model results with. The urban combination translated into a 50/50 share of traffic work between the given urban factors, see 5.7.8 for more information. To create an unrealistically low estimate of CO_2 emissions, a second combination named ‘Ideal’ was elicited. The ideal combination constituted of the two emission factors with the lowest emissions per kilometer, i.e. urban motorway and rural no motorway, each with a 50 percent share of traffic work. However, even though it was not known how and where the car owners of Järfälla drive their cars (other than in Sweden), it was unlikely to be similar to the two above presented combinations. A mix was deemed more likely and a third combination was added to the validation with the purpose to include a more varied distribution of the traffic work for Järfälla car owners. The third combination, a.k.a. Uniform, was equivalent to all provided factors being given an equal share, i.e. a 25 percent traffic work share.

The validation models and the model differed in aspects relevant for the magnitude of estimates and they were analyzed to identify whether the validation models should yield an over- or underestimate compared to the model results. The inclusion of traffic situations in HBEFA was analyzed to overestimate the result of the validation models. Moreover, the factors from HBEFA are representative for the Swedish passenger car fleet and weighted with the traffic work on Swedish roads, not Järfälla. The traffic work of the respective car fleets was therefore compared over fuel technology, car age and mass, see section 5.4.3 for data and Appendix E for the comparison. The comparison identified differences in relation to fuel technology and car age, but not for mass: Due to differences in fuel technology, referring to a lower share of diesel cars in Järfälla, the validation models were analyzed to underestimate CO_2 emissions in the beginning of the study period, but the similarity improved after 2005, so the underestimate should thus decrease. Especially so considering the larger shares of ethanol-, electric hybrid- and gas cars relevant for Järfälla at the end of the study period. The larger shares were deemed likely to cause HBEFA to overestimate emissions around 2015 due to the combined traffic work shares of these cars compared with diesel cars; in relation to differences in car age, the national car fleet was generally older than Järfälla's and the estimates of the validation models should be overestimated for all the years due to this. Accordingly, the validation models were analyzed to overestimate emissions in the end of the study period based on the comparison of the fuel technology and car age as well as the inclusion of traffic situations. However, the model structure applied a weighting and a correction with increasing impacts over the study period which complicated the validation. Sensitivity analyses of the weighting and correction were, however, performed which improved the analysis of the validation, see more information of the sensitivity analyses in section 5.6.2 and 5.6.4. Model estimates compared to the validation estimates were nevertheless analyzed to result in larger estimates over time due to the increasing impact of the correction, i.e. an increasing divergence over time. To clarify, the increasing impact of the correction was eventually assumed to outweigh the impact of traffic situations and the differences in fuel technologies and car age. Observe the correction aimed to mitigate the total discrepancy between test-values and real-world driving and not only traffic situations. A diverging result, however, cannot be said to be certain as it depended on whether the impact of traffic situations had increased over time and this information had not been acquired. Moreover, a diverging result can also be offset by the identified differences in fuel technology and car age, referring to the car fleets. Anyhow, since HBEFA underestimates the diesel consumption, see section 3.1 and due to the information presented in 4.2, the validation models may systematically underestimate emissions[8], but the relevancy of this for Järfälla was not certain. See more information of the validation in section 5.7.8.

5.6 Sensitivity analysis

Four sensitivity analyses were performed to explore model configurations' impact on total results. The purpose of the sensitivity analyses was to control for large and unexplained variances due to the applied data in the model, to analyze the sensitivity of the model due to the model structure's different configurations and to inform the validation with further information. The analysis for ethanol and gas cars had also the purpose to quantify the potential for reducing CO_2 emissions depending on how these cars were fueled.

5.6.1 The elicitation of fuel economy

The first sensitivity analysis investigated the impact on results when eliciting the fuel economy with a moving average instead of applying the production year. New car" is not explicitly defined, see section 5.4.1 and 5.4.2, and consequently, a moving average was tested. To illustrate, if the production year was 1985, the calculated moving average would

[8] It is acknowledged that HBEFA implements Tier 3 and additional factors, like hot and cold starts not specified in this section, therefore also have relevance for the magnitude of the estimated CO_2 emission. The impact on CO_2 emissions of Tier 3 was not known, but it was described to only increase the uncertainty, i.e. not necessarily the magnitude, in IPCC (2006b).

use the fuel economy data of 1985, 1984 and 1983; if the production year instead was 2009, then 2009, 2008 and 2007 would have been used. Moreover, the weighting due to mass utilized data from EEA also using the term “new car”, and this motivated the moving average to also be tested in the weighting according to the same principle as previously described though only for the production years of 2001-2017. The moving average was deemed likely to reduce the risk of a systematic underestimation due to the model structure’s elicitation of the fuel economy since older cars then were allowed to influence the elicitation. The moving averages should result in a higher accuracy of model results due to a reduced risk of a systematic underestimation of the fuel economy compared to when it was elicited with only the production year.

5.6.2 The weighting due to mass

The analysis was conducted by varying the effect on the fuel economy due to mass changes. The effect was varied over the range provided in section 4.3, i.e. 0.3-0.5 liter per 100km for every mass change of 100 kilos, by testing the values of 0.3, 0.4 and 0.5.

5.6.3 How are ethanol-and gas cars fueled?

The analysis was conducted by varying the share of gasoline fueled by ethanol- and gas cars. The analyzed shares were 0, 50 and 100 percent gasoline. As such, the potential of these cars could be illustrated, referring to lowering the CO_2 emissions for Järfälla.

5.6.4 The correction to account for real-world emissions

The sensitivity analysis investigated the impact of varying the correction applied in the model by reducing/increasing the default linear increase of 2.5 percent by 1 percent. The minimum correction applied a 1.5 percent annual increase, whereas the maximum correction applied a 3.5 percent annual increase. See all the values for the different corrections applied in the model in Appendix B.

5.7 Assumptions

Assumptions deemed of lesser interest are presented in Appendix B whereas calculated values applied in the model are presented in Appendix C.

5.7.1 Traffic work and estimated traffic work by TRAFA

Over 60 percent of the traffic work data is not estimated by TRAFA and is instead factual and thus assumed correct. The estimated data, though, is uncertain, see section 5.4.1. The share of the estimated traffic work on the estimated CO_2 emissions by the model was calculated and is here presented for convenience. The estimated data accounted for 28-42 percent of the calculated CO_2 emissions. A substantial part of the total CO_2 emissions was thus related to the estimated data which implied the importance of these being accurate enough.

The data moreover includes traffic work conducted in foreign countries, but a large part of it is related to commuting (TRAFA, 2011). The foreign traffic work conducted by Järfälla citizens was assumed negligible (< 1 percent) since commuting to foreign countries should be more prevalent in the south, west and north due to Sweden's border with Denmark, Norway and Finland respectively.

5.7.2 Fuel economy of electric hybrid, PHEV, E85 and gas cars

The fuel economy of electric hybrid- and PHEV cars are only given for gasoline in the fuel economy data, but it was assumed representative for the traffic work on average for these cars, see appendix B for a motivation. Moreover, gasoline as the second fuel was assumed representative for cars with diesel as secondary fuel due to convenience combined with the low share of traffic work for hybrids in Järfälla: Electric hybrids have a share between 2-4 percent for 2013-2017, whereas PHEV:s have a share under one percent for the whole study period.

The fuel economy of ethanol- and gas cars is also only given for gasoline in the data, but the traffic work share of these cars was substantially larger compared to the hybrids: The combined share is over five percent in 2008 and around ten percent in 2011 where it has stayed fairly constant. The significant share guided the decision to estimate the fuel economy when driving on the respective alternate fuels of E85 and vehicle gas. As such, the model structure facilitated the CO_2 emissions of ethanol- and gas cars to vary depending on the assumed share of gasoline fueled for these cars. The default configuration applied in the model was 50 percent gasoline since no information indicating the correct share was identified for the study.

To estimate a new fuel economy for when driving on E85 or vehicle gas, the NCV:s of E85, biogas, natural gas and gasoline were used in combination with the given fuel economy when driving on gasoline. The application of NCV:s was based on energy requirements since a car requires the same amount of useable energy for the same work, irrelevant of the specific fuel. The difference in energy content was exploited and quantified by calculating a scaling factor by simply dividing the NCV of gasoline with the NCV of the alternate fuels. The respective scaling factor was thereafter multiplied with the given fuel economy of the cars when driving on gasoline. The calculation was performed for every year, 1999-2017. See equation 4, 5, 6 and 7 below.

$$SF_{gasoline/E85} = \frac{NCV_{gasoline}}{NCV_{E85}} \tag{4}$$

$$SF_{gasoline/VehicleGas} = \frac{NCV_{gasoline}}{(NCV_{biogas} * x + (NCV_{natural\ gas} * (1 - x))} \tag{5}$$

$$FE_{E85} = SF_{gasoline/E85} * FE_{gasoline} \tag{6}$$

$$FE_{VehicleGas} = SF_{gasoline/VehicleGas} * FE_{gasoline} \tag{7}$$

In equation 4-7, SF represents the scaling factor for different combinations and FE is the fuel economy, see subscript for specific representation. In equation 5, X represents the bio share in vehicle gas and (1-x) represents the share of natural gas, used together to calculate the resulting NCV of vehicle gas.

5.7.3 Biomass

Biomass is categorized as not contributing to CO_2 emissions as reported to the UNFCCC (SEPA, 2017a) and was excluded from a climatic impact in the model. Biofuel shares in conventional fuels are, though, not available before 2011 in statistics. The missing values were instead specified by scrutinizing information in SEPA (2017) describing the fuel deliveries of E5, E85, natural gas, biogas and FAME, specifically for passenger cars. However, the origin of biomass should also be specified, see section 4.1, to guarantee the biomass is carbon neutral. Swedish legislation now requires biomass to be ‘sustainable’ from a life cycle perspective, or else, biomass should be categorized as the equivalent fossil fuel (AoE, 2018). Due to inadequate statistics in Sweden of the sustainable bio share in conventional fuels before 2011, it was assumed to be equal to the biofuel share. Model results may have been underestimated due to this. See applied values in Appendix C.

5.7.4 Postal Codes

The results required a rather uncertain cleaning of the applied raw data. Although the cleaning of the data can be improved, the result was deemed adequate enough to be included in the report as it illustrated a potential with the model structure. Moreover, the results seemed reasonable when illustrating them on a map. Furthermore, the minimum number of cars for a postal code to be included in the result was set to 85 to improve the quality of the result. As such, 13 postal codes were excluded to avoid errors and uncertainty caused by a too small number of cars (i.e. mitigate the impact of small sample). Additionally, the exclusion of postal codes with less than 85 cars prevented postal codes with many cars to be compared with postal codes with few cars. In sum, the results only included one postal code with less than 100 cars, whereas the majority had between 200-400 cars, but postal codes with over 1000 cars also were included. See Appendix C for more information of the data and Appendix D for a complete description of the methodology applied.

After the calculation of CO_2 emissions per postal code, each postal code’s share of the emissions was calculated to thereafter be multiplied with the model results relevant for the year of 2017. The reason to scale the results was related to the more uncertain data implying the results were less accurate. For example, missing information of the production year, simultaneously as no fuel economy value was available constrained the elicitation of the fuel economy for a significant number of cars. Furthermore, no weighting could be applied due to the data. In sum, the scaling was most relevant to apply.

The performed scaling assumed the calculated emissions of cars to be representative for the missing cars for the same postal code. The results did only incorporate the total number of cars per postal code after the cleaning of data was performed, which may be different from the real number. The population per postal codes was neither included and this reduced the potential of analyzing the results since postal codes could not be compared in relation to the population. Anyhow, it was not known to the author whether data of the population per postal code was available in Sweden. The omission of the population prompted results to also be calculated in the relative metric, i.e. in unit [mass CO_2 per postal code per car].

5.7.5 Weighting due to the individual mass

For car models of 2001-2017, the fuel economy was weighted according to an estimated mass difference to improve the representativeness of the national fuel economy data for Järfälla. The impact of the weighting on total results may as such increase over time when more cars were included in the weighting. See equation 8 below.

$$mass\ difference_{i,j} = indivudal\ mass_{i,j,k} - Swedish\ average\ mass_{j,k} \qquad (8)$$

See text in equation for an explanation of the included terms, where the subscript *i* represents the specific car weighted with fuel technology *j* and production year *k*. Ethanol-, hybrid and gas cars were however combined into one fuel technology category due to data limitations, see Appendix C. Anyhow, the weighting was only performed if the mass difference in equation 8 was greater or equal to 100 kilos, so for every change of 100-199 kilos, the fuel economy was modified by 0.3-0.5 liter per 100 km. The average of 0.4 was used as the default configuration in the model structure. The weighting moreover applied a linear formula so if the mass difference was 350 kilos, the fuel economy still changed by 1.2 liter (i.e. 3*0.4=1.2) and vice versa. The maximum *reduction* was 4.0 liter per 100 km, though for increases in mass, 8.0 liters was the maximum since passenger cars have a bigger mass range upward in relation to the average mass. The upper bound nevertheless biased the weighting to underestimate the fuel economy due to occurrence of camper vans in the data.

The weighting required the data of average masses to be adapted to Sweden. See Appendix B for the equations applied to render new average masses over fuel technologies for Sweden and table 1 in Appendix C for the resulting values.

5.7.6 The fuel economy in general

The risk of methodology changes, in relation to the two applied datasets of fuel economy, to bias the model results, was deemed as minimal since the same Government agency had compiled the data and the included values were equal for the later years. The original data from car manufacturers, however, may have been reported differently back in time. The model structure only mitigated the impact of the shift identified in the data due to car manufacturers' optimization of the NEDC, i.e. values are increasingly underestimated starting from 1999 and onwards. No information of other relevant shifts for the fuel economy data had been acquired and the data was for this reason assumed more representative on average of real-world driving before 1999, i.e. no systematic error as the above described underestimation. Possible errors in the data before 1999 were assumed to cancel out due to the large number of cars.

For older passenger cars (i.e. produced before 1968), the quality of the elicited fuel economy was worse compared to newer cars since the elicited fuel economy was assumed equal to the value of 1968. The effect on model results was negligible since the absolute majority of cars are produced after 1968.

5.7.7 The correction to account for real-world emissions

The default values of the correction were 1.025 in 1999 and 1.40 in 2014 and a linear increase for the years in between as well as up to 2017 was assumed. No correction was applied for cars produced before 1999 since relevant references indicate the problem is by large related to the 2000s. The correction, however, was assumed to be applicable solely on the basis of the production year and other car characteristics did not influence the applied correction and this reduced the accuracy in the estimates of the corrected cars. The possibility of errors possibly averaging out when all CO_2 emissions were aggregated should not, however, be excluded due to the large number of cars corrected.

5.7.8 Validation with emission factors from HBEFA

HBEFA has been credited to reflect the impact of congestion on emissions, but it seemed as if the impact of these on emissions may be underestimated, see section 3.1.2. HBEFA has further been identified to underestimate the fuel consumption for real-world driving (Peitzmeier et al., 2017). A growing divergence between the estimated diesel consumption and those derived from national statistics is also apparent in the estimates of HBEFA, though not for gasoline. Hence, even though traffic situations impact the estimates of HBEFA, they were assumed to still be underestimated. Furthermore, traffic situations were specified for HBEFA for multiple years, starting for the year 1990, but no information has been acquired of whether traffic situations' impact on emissions has increased or decreased between 1999-2017.

HBEFA emission factors are representative for the Swedish-road network, including traffic situations, and for the Swedish passenger car fleet and they were delivered in four different road types: Rural and urban motorways as well as for no motorway. The validation result would vary significantly depending on the chosen combination applied in the validation. To elicit a relevant combination, the relationship between the NEDC and the fuel economy data was analyzed: Official values of the fuel economy can represent urban-, extra urban driving or a combination of the two, where the combination represents the NEDC (Fontaras et al., 2017). The urban emission factors from HBEFA were consequently analyzed as most relevant to compare the model results with.

HBEFA specifies cars with, for example, the engine size when modelling emissions and it thereby influences the following estimates. The conducted comparison of the national car fleet's traffic work with Järfälla's fleet, see section 5.5.3, included mass classes, but not the engine sizes. The mass was nevertheless assumed to be indicative of differences in engine size. The result of HBEFA was albeit less accurate compared to if all car characteristics that HBEFA normally uses could have been exploited.

5.7.9 Emission factors and NCV:s

Emission factors in unit [kilo CO_2 per liter] were needed in the model structure and calculated for gasoline, diesel and E85 guided by unit calculations. See equation 9 for the applied unit equation:

$$[\text{kilo } CO_2/\text{liter}]=[\text{GJ/m3}]*[\text{kilo } CO_2/\text{GJ}]/1000 \quad (9)$$

Equation 9 was applied for all years 1999-2017. No further calculations were conducted for the emission factors from SEPA (2018a). The emission factors from AoE (2015), however, were modified to include the biofuel share. The inclusion was accomplished my multiplying the resulting EF after the unit transformation in equation 9 with the fossil share according to a recommendation in IPCC (2006b), see equation 10 below:

$$EF = EF_{1,i,j} * (1 - x_{i,j}) \quad (10)$$

In equation 10, EF was the final emission factor applied in the model in unit [kilo CO_2/liter], EF_1 was the resulting emission factor per fuel technology i for year j after the unit transformation in equation 9 had been conducted and the factor of (1- $x_{i,j}$) represents the fossil share for fuel technology i in year j. Equation 10 was applied for all fuels and for all years, though vehicle gas was excluded, see more information in the next paragraph.

Vehicle gas is a mixture of natural gas and biogas, and the unit given in SEPA (2018a) is [GJ/1000m^3], whereas no unit is given in AoE (2015). The missing unit was problematic for the model structure as the volume of a gas is dependent on the pressure and temperature (Young et al., 2014). Actually, as the values were given in SEPA (2018), gasoline could be interpreted as close to 1000 times more efficient, referring to the energy content per quantity. In reality, both natural and biogas have a higher energy content than gasoline. Neither contact person for the implied above references was possible to contact to acquire the missing information. The density of vehicle gas was instead acquired in unit [kilo/m3] at atmospheric pressure at zero degrees, which together with the shares of natural gas and biogas in vehicle gas, were applied to transform the unit to [GJ/kilo]. However, the density was assumed to not vary significantly over time and the effect of it on model results was most likely negligible. See equation 11 below.

$$NCV_{vehicle\ gas} = (NCV_{biogas} * X + NCV_{Natural\ gas} * (1 - X))/\rho_{vehicle\ gas} \quad (11)$$

In equation 11, NCV:s represent the net calorific values of the constituting parts of vehicle gas in unit [GJ/m^3], see subscripts for the specific meaning, X is the share of biogas, (1-X) is the share of natural gas, and the letter ρ represents the density of vehicle gas in unit [kilo/m^3]. By equation 11, the energy content for vehicle gas was calculated in unit [GJ/kilo].

The emission factor of vehicle gas was thereafter calculated with the respective bio shares from AoE (2018;2017) and the emission factors from AoE (2015). See equation 12 below:

$$NEF_{vehicle\ gas} = (EF_{biogas} * X + EF_{natural\ gas} * (1 - X)) * NCV_{vehicle\ gas} \quad (12)$$

In equation 12, EF represents the emission factors from AoE (2015) where the subscript describe the specific gas, X is the share of biogas in vehicle gas and (1-X) is share of natural gas, NCV is the calculated result from equation 11, and NEF is the resulting new emission factor for vehicle gas in unit [kilo CO_2/kilo vehicle gas combusted]. The result of equation 12 was also applied to equation 10 to exclude biomass from CO_2 emission for each year, likewise as with equation 5 and 7 where needed unit transformations also were conducted. However, the incorporation of the bio share did not make any difference between the fossil and bio origin, but the impact on results was deemed negligible.

Data of E85 and vehicle gas were not available before 2001 and 2002 respectively due to the close to non-existence of these cars. The missing emission factors of E85 and vehicle gas were chosen equal to the emission factor of gasoline for the same years due to convenience when writing the algorithm in the model structure.

NCV:s in SEPA (2018a) were analyzed to determine the likelihood of an emission factors being constant over time when only one value was available without any reference year given. This was conducted for the emission factor of ethanol relevant for all years except 2010 provided from SPBI and for the missing values of emission factors relevant for 2015-2017 from AoE (2015).

5.7.10 Explorative Scenarios

The result of the explorative scenarios was made possible by small modifications in the model algorithms where the traffic work of 2016 was modified according to the specified explorative scenarios. All the explorative scenarios applied a 50 percent share of gasoline fueled in ethanol- and gas cars. The unmodified result of 2016 was compared with the modified result of 2016 to inform of the scenarios' impact on emissions. The choice of 2016 was arbitrary and not based on any specific requirements.

The first explorative scenarios quantified the impact when 50 percent of the traffic work from gasoline and diesel cars was reduced, simultaneously as the traffic work was held static. The traffic work of electric-, electric hybrid-, PHEV-, ethanol- and gas cars was therefore increased with the equivalent traffic work. The increased traffic work of these cars can, for example, be made possible by large increases in the number of these cars. However, the result then assumed cars' individual traffic work in 2016 was static compared to the modified year of 2016 (i.e. '2017'). Consequently, the additional electric-, hybrid-, gas-, and ethanol cars needed to compensate for the reduction of traffic work for gasoline- and diesel cars were assumed to be driven equally as the 'real' cars in 2016. Furthermore, no change in the fuels was assumed between the year of 2016 and the hypothetical year of 2017.

6. Result

The results of the conducted sensitivity analyses are first presented since they were utilized when the model was validated, which in turn was used to decide on the model configurations implemented when estimating the model results. The model results are presented last in this section to allow the reader to understand how the model configurations used in the model were determined.

6.1 Sensitivity analyses

6.1.1 Eliciting the fuel economy of cars

The first sensitivity analysis investigated the impact of applying a moving average on total model results for three different configurations: When eliciting the fuel economy of cars (MAFE), when eliciting the average mass applied in the weighting (MAW) and when the two described configurations were both applied in the model (Combo). The result of MAFE was approximately 1-2.5 percent and the increase on total model results was intuitive since the fuel economy generally becomes larger for older car models. An increasing fuel economy, though, was not guaranteed, as analyzed in Trafikverket (2018) and this explained the fluctuations which was apparent in the result of MAFE. The impact of MAW was negligible for the whole period and an indication of the average masses of cars being relatively static in the data. An analysis of the applied average mass values confirmed the negligible change when calculating an average for three years, see Appendix C. The result of Combo was approximately equal to that of MAFE due to negligible impact of MAW. See figure 8 for the result of the sensitivity analysis.

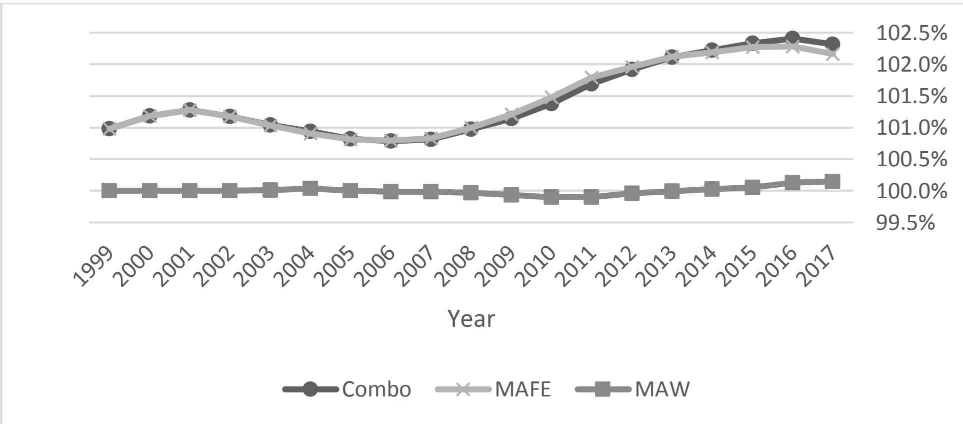

Figure 8. See the description of the included analysis below the diagram. The figure illustrates the negligible impact of MAW for the whole time period, whereas the impact of MAFE fluctuated around one and two percent between 1999–2010 and 2010–2017 respectively.

6.1.2 Weighting due to mass

The second sensitivity analysis tested the values of 0.3, 0.4 and 0.5, referring to how much the fuel economy changes in liter per 100 kilometers for every 100 kilos mass change. The 'Maximum' weight (i.e. 0.5) increased the emissions by over five percent in 2016, whereas both the 'Default' and 'Minimum' weights stayed under 5 percent for the whole series. A relatively rapid increase from 2002-2007 was moreover identified in the result which corresponded to newer and heavier cars conducting a larger share of the traffic work compared to the periods of 1999-2001 and 2007-2017. The sensitivity analysis illustrated a significant impact compared to only using the given average fuel economy data without performing a weighting, simultaneously as the model result was not sensitive to it. The significant impact was not certain on beforehand and the result showed it was relevant to weight the fuel economy according to the individual mass of cars. Only cars produced after the year of 2000 were weighted due to data limitations and consequently, over 50 percent were not weighted in 2008, one third were not weighted in 2012 and around 14 percent of the cars were not weighted in 2017. If Järfälla's passenger car fleet were likewise heavier going back in time, the increasing number of cars weighted over the study period implied the accuracy of model results improved over time and equally to be underestimated back in time. See figure 9 for the result of the sensitivity analysis.

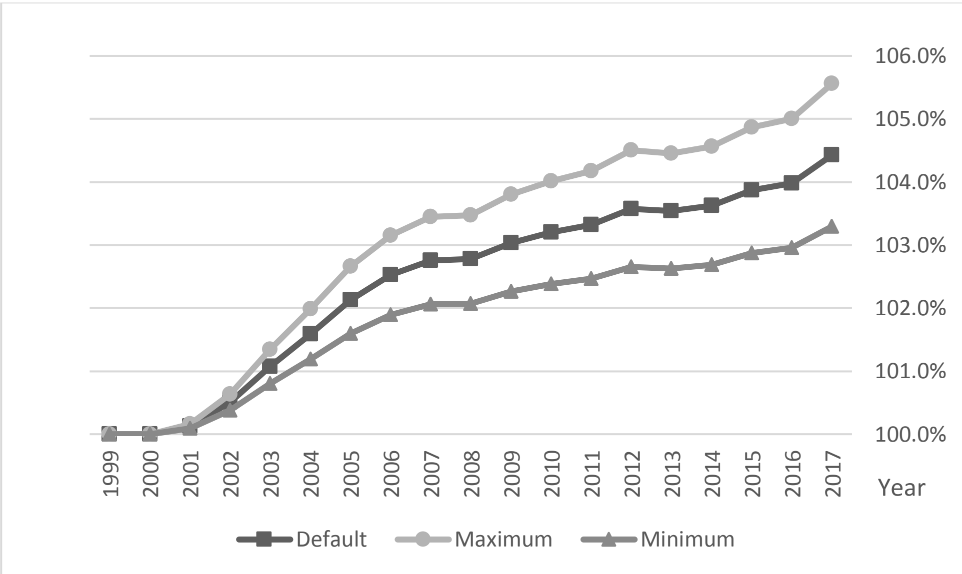

Figure 9. See description of the curves under the chart. The figure illustrates the significant impact on total model results of the weighting over time. A more rapid increase in the impact could furthermore be observed between 2002–2007.

6.1.3 The impact of how ethanol- and gas cars were fueled

The third sensitivity analysis investigated the potential of how ethanol- and gas cars were fueled on CO_2 emissions. The maximum potential when the cars drove on E85 and vehicle gas was a 5.7 percent reduction in 2010 and just over nice percent in 2017 compared to only using gasoline. The default and minimum setting had as expected proportionally smaller values. The stagnating characteristics of the curves 'Equal share' and 'Zero gasoline' for the period 2012-2017 related to ethanol cars becoming less popular during this period: Ethanol cars increased from 139 to 1663 cars during the period of 2005-2012, but the increase has nearly halted since then with corresponding reductions in the traffic work. In 2017, only 1717 ethanol cars were in traffic. Vehicle gas cars, however, have continuously been increasing in numbers, from only two cars in 2005 to 545 in 2017, though not as much in percent from 2015 and onwards. The share of traffic work for both ethanol- and gas cars has not increased significantly after 2012 compared to the other fuel technologies. The result further illustrated a missed opportunity of ethanol and gas cars for Järfälla since the impact on CO_2 emissions would have been substantially larger if the trend from 2005-2012 would have continued. That is, the potential could have increased to over 15 percent in 2017. See figure 10 for the result of the sensitivity analysis below.

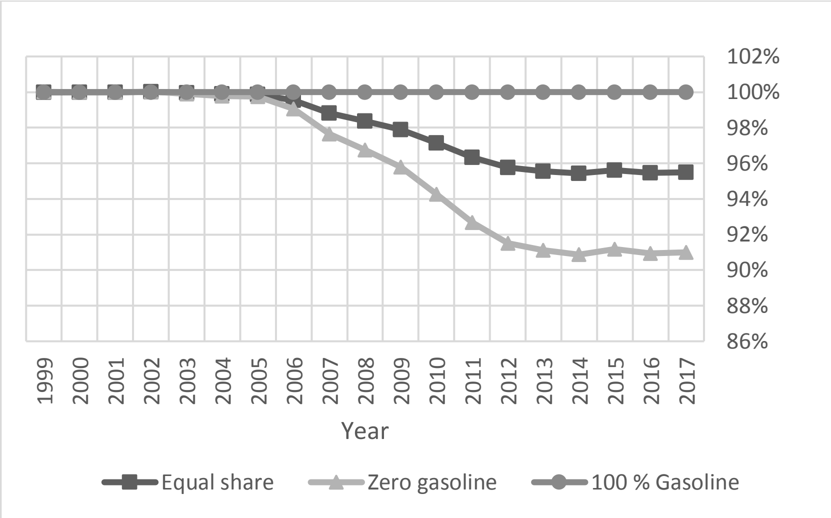

Figure 10. See description under chart for the included analyses. The figure illustrates a significant potential of how ethanol and gas cars are fueled on CO2 emissions, though the increasing potential apparent between 2005–2012 stagnated thereafter.

6.1.4 The correction due to car manufacturers

The last sensitivity analysis investigated the impact of different corrections implemented on model results. All analyzed corrections, i.e., 1.5, 2.5 and 3.5 percent annual increases, started from a correction of 2.5 percent in 1999 and the apparent lower impact in the beginning of the time series was expected. The increase on total results was large for all included corrections, 17-37 percent in 2017, between 8-16 in 2010, and between 3-5 percent in 2004. More specifically, the minimum correction (i.e. 1.5) increased results by approximately five and ten percent in 2006 and 2011 respectively. The default correction (i.e. 2.5) increased results by five and ten percent in 2005 and 2008 respectively and, finally, the maximum correction increased results in 2004 and 2007 by five and ten percent respectively. Nevertheless, the relatively large resulting interval for the impact of the corrections illustrated the model was sensitive to the applied correction and moreover to the specific correction applied.

Observe the result of the sensitivity analysis was not possible to exploit for excluding any of the applied corrections since what the optimum correction should be for Järfälla's car fleet was unknown. See figure 11 for the result of the sensitivity analysis.

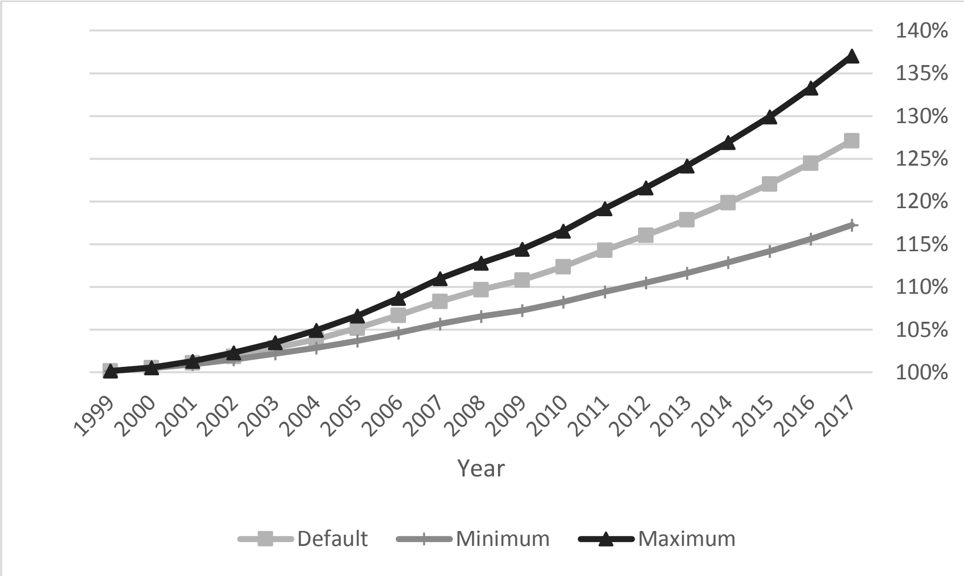

Figure 11. See description of included analyses under chart. The figure illustrates model results were sensitive to the applied correction as well as to the specific correction since the included configurations diverged substantially over time. Minimum impacted results by 1–17 percent, Default by 1–27 percent and Maximum by 1–37 percent, for the period of 2001–2017.

6.1.5 Summary of sensitivity analysis

- The modified elicitation of the fuel economy, i.e. the application of moving averages compared to only using the production year, increased results by 1-2.3 percent between 1999-2017.
- The weighting conducted increased results by 1-5.6 percent between 2003-2017.
- The share of E85 and vehicle gas, i.e. 0, 50 or 100 percent, used to propel ethanol- and gas cars was identified to decrease results by 1-9 percent between 2006-2017.
- The different corrections increased results by 1-37 percent between 2001-2017 and the model structure was identified to be sensitive of the specific correction applied in the model.

6.2 Validation result

The validation of the elicitation and weighting of fuel economy begins this section, followed by the calculated emission factors, including the incorporation of biofuels. The section ends by the validation of total model results.

6.2.1 Eliciting the fuel economy

The validation illustrated the result of comparing the average fuel economy, relevant for the years 2012-2016, of gasoline and diesel cars after the weighting had been conducted in the model, with the validation data. All tested weightings, see section 6.1.2, were included as well as the average fuel economy when no weighting was applied. Observe the no weighting was equal to the average fuel economy of Järfälla passenger car fleet when the fuel economy value was elicited with the production year. The result of the validation, though, was not expected since all weighted configurations resulted in higher averages than the validation data, whereas the no weighting yielded approximately similar values.

The result of the validation could be explained by either two things:

1. The majority of data in the validation data have been estimated according to the production year.

2. The average fuel economy of Järfälla cars was approximately identical with the the national average of new cars sold for all years investigated (e.g. 2012-2016), and for both gasoline and diesel cars.

By analyzing the result, together with the number of cars within the respective fuel technologies over mass classes for the study period, the most likely explanation could be derived: It seemed statistically unlikely that Järfälla's car fleet would be close to identical to the national average; Järfälla's gasoline car fleet had ever since 2003 become heavier in relation to the national average mass applied in the weighting. The gasoline car fleet was also significantly heavier than the national average between 2012-2016. Hence, Järfälla's average fuel economy was unlikely to be as low as the validation data indicated, especially since it was even smaller compared to the no weighting; the diesel cars of Järfälla became heavier than the national average in 2014 and this difference grows rapidly thereafter. The shift was possibly observed in the validation result as a larger divergence from the validation data for weighted diesel cars after 2014, while the no weighting had a static divergence after 2014. As such, possibly highlighting the importance of the weighting. The validation data for diesel cars, however, implied no shift in relation to the national average had taken place, which was not the case; unexplained dips were apparent for both gasoline and diesel cars irrelevant of the weighting. For gasoline, the dip increased the divergence in 2013 and for diesel the dip decreased the divergence in 2014. The different impact, the different timing of the dips, simultaneously as the relevant algorithm and the fuel economy data in the model were scrutinized, implied the two different dips were caused by the validation data. See Appendix E for the data, including some of the analysis utilized here.

In sum, explanation 2 should be seen as more unlikely than explanation 1 and the latter was concluded to be the likely cause of the result. See figure 12 for the validation relevant for gasoline cars and figure 13 for the diesel cars.

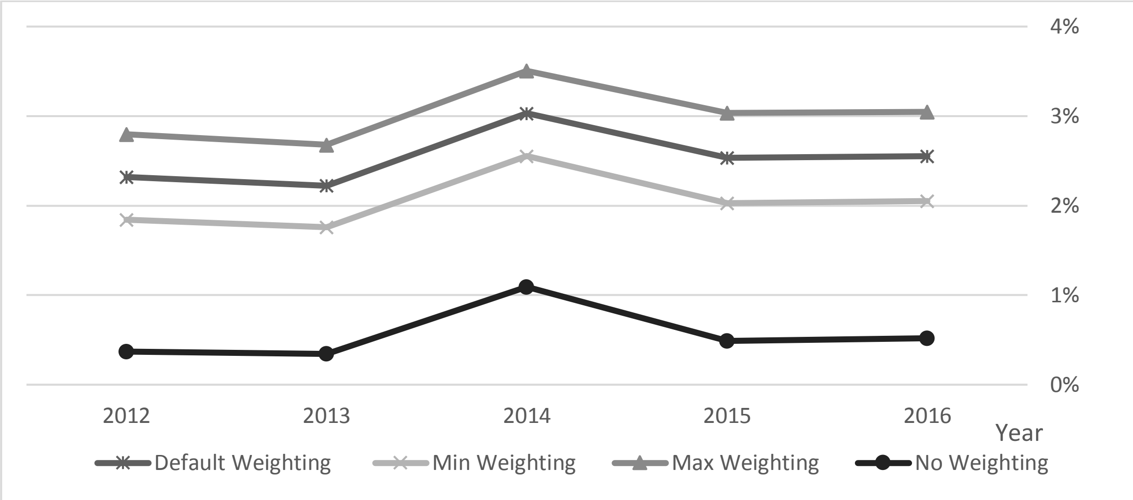

Figure 12. See description under line chart for the included analyses. The figure illustrates all weighted configurations resulted in larger values compared to the validation data, referring to gasoline cars' average fuel economy. No weighting was close to being static at 0.5 percent for all years.

Figure 13. See description under chart for the included analyses. The figure illustrates all weighted configurations resulted in larger values compared to the validation data, whereas. No weighting diverged with approximately zero percent 2014–2016, referring to diesel cars' average fuel economy.

Although the validation did not deliver the expected results, the elicitation of the fuel economy with only the production year was in fact validated instead since the no weighting resulted in approximately equal values to the validation data.

6.2.2 Emission factors

The results of the validation displayed a good correspondence between the analyzed emission factors for the whole period of 1999-2017. The characteristics of the curves were close to being identical since shifts in estimates were reflected, but differences in magnitude over two percent were observed between 2005-2008 and between 2015-2017. The divergence between 2005-2008 was explained by the emission factor of gasoline since SEPA does not vary the emission factors of gasoline significantly for any year. It has only been reduced by approximately 2.6 percent between 2002-2016. However, the *pure ethanol* share in gasoline was identified to be between 4.6-5.6 percent from the beginning of 2011 (AoE, 2018; AoE, 2017) and it was likely to be 5 percent in 2005, though the sustainable share may then be put into question. The calculated emission factor of gasoline was consequently reduced by 4.7 percent between 2002-2016, including the effect of biofuels on the fuel economy. SEPA's higher value for gasoline, combined with the relatively large share of traffic work for gasoline cars between 2005-2008, resulted in larger estimates for this period. Paradoxically, the situation is reversed for the emission factor of diesel provided from SEPA as it has been reduced by 27 percent between 2006 and 2016. The calculated emission factor of diesel, however, was only reduced by 20 percent for the same period since AoE (2017;2018) reports a sustainable biomass share between 5.2 to 21 percent for the same period of time. The divergence between the two emission factors of diesel increased substantially after 2014 and this could explain the divergence between 2015-2017. Furthermore, the differences in emission factors could have canceled out on the results between 2008-2015. The correction due to car manufacturers' optimization of the NEDC did not impact the result of the validation significantly. See figure 14 to view the correspondence of the validation and figure 15 to see the difference in percent of the magnitude over the study period. Moreover, see figure 7 in 5.4.1 for the information of gasoline cars' traffic work used above.

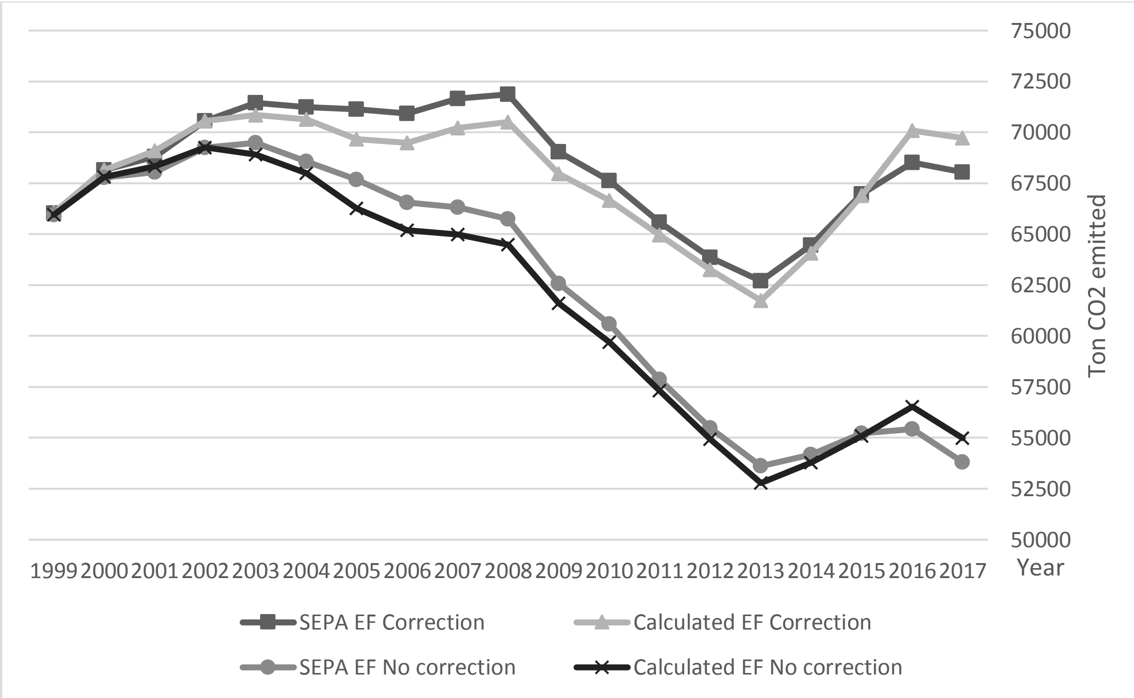

Figure 14. See description under chart for the included analyses. The figure illustrates a a good correspondence for all years 1999–2017 for the included model results and the correction did not significantly impact the validation result.

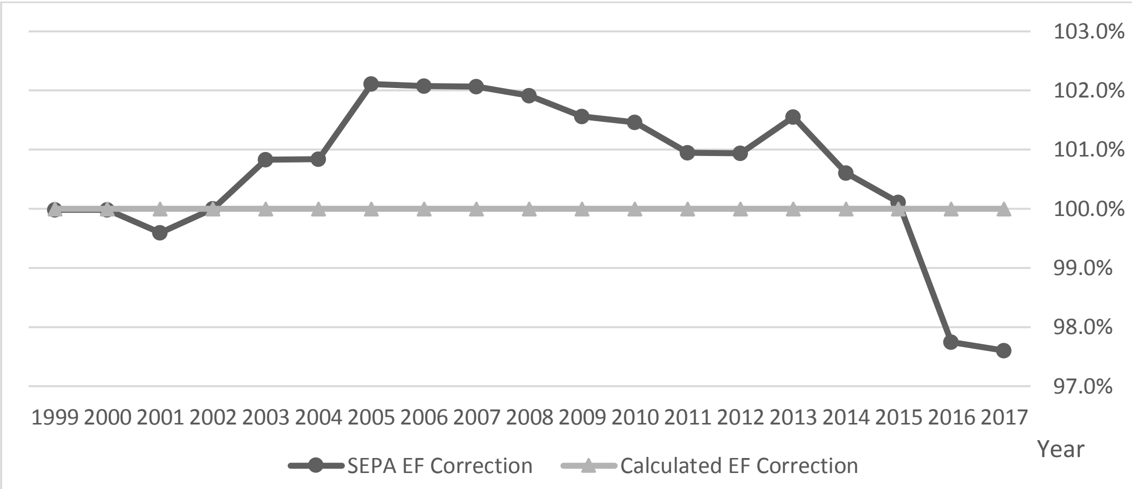

Figure 15. See description under chart for the included analyses. Calculated EF Correction was used to normalize the SEPA EF Correction and was therefore static at 100 percent for whole period. The figure illustrates a small divergence for the whole time period.

6.2.3 Validation of total model results

All model configurations assumed a 50 percent share of gasoline for ethanol- and vehicle gas cars, referring to how these cars' fuel consumption was modelled, in the validation. The result of the validation will first be presented in percent with the purpose to illustrate the difference in magnitude on the basis of the ideal combination. The result will thereafter be presented in unit [mass CO_2] with the intention to allow the reader to view the correspondence between the model and the included combinations.

The validation applied HBEFA emission factors in three different combinations, ideal, urban and uniform, and the results of these were first compared with the model results when applying the default weighting, but no correction was initially incorporated.

The first validation results illustrated model results to be larger than the estimates of the combinations up until 2004-2008; the model estimate was surpassed by the urban and uniform combinations in 2004, and by the ideal combination in 2008. A rather stable development was moreover apparent as the model result started above the ideal combination with ten percent in 1999 and ended below the same combination with ten percent; the difference was only 4-5 percent in 1999 and 19-20 percent in 2017 when analyzing the model results in relation to the urban and uniform combinations. The divergence moreover changed from positive to negative in a linear fashion. Hence, the result illustrated the increasing need to correct the fuel consumption due to car manufactures' optimization of the NEDC over time. The development of the divergence was analyzed as reasonable due to the changing car fleet in Järfälla, but the timing was unexpected. The divergence started to decrease directly after 1999 and not as expected when the similarity of the fuel technologies improved after 2005. The unexpected timing implied an unknown factor impacted earlier estimates in a rather systematic way. However, a shift in the car age relevant for the beginning of the study period was found in 6.3 which could explain the unexpected timing. The impact of the car age was there identified to be more intense in the beginning of the study period compared to the static impact derived in section 5.5.3. The linear development was moreover observed to be slightly reduced between 2005-2012 and this corresponded well to the changing composition of the car fleet in Järfälla and the new information from 6.3, especially since it picked up thereafter. Models result ended below the estimates of all combinations which was considered adequate due to the impact of traffic situations combined with the differences in car age and fuel technologies. See section 5.5.3 for more information.

Observe the relatively abrupt shift in the urban and uniform combinations between 2009-2010. The abrupt shift was believed to be related to changes in speed limits conducted in Sweden in 2008, though implemented in the traffic situations in 2010 (SEPA, 2017a). The shift, however, raises the question of why other updates with relevance for the traffic situations then could not be observed. See figure 16.

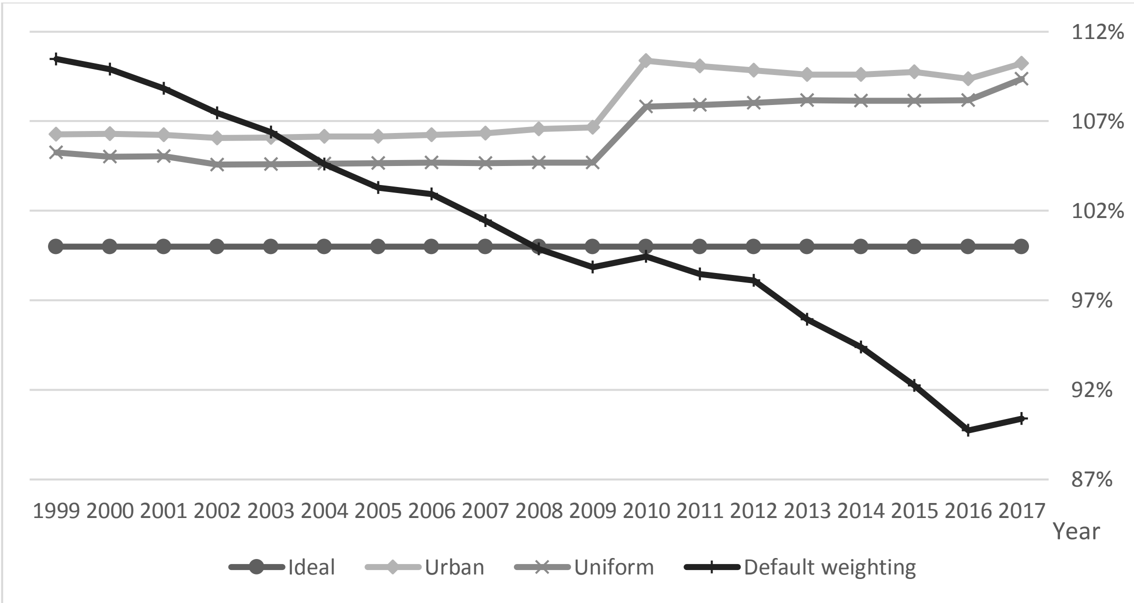

Figure 16. See the description under the chart for the included curves. The result of the ideal combination was used for normalization and it was therefore static at 100 percent for the whole series. The result of the urban and uniform combination was fairly static at 106 and 105 percent respectively up until 2010, where the difference increased with around three percent. The model results, i.e. the default weighting, started with larger estimates compared to the included combinations, but after a fairly linear development, ended with values being smaller.

The model configuration of the minimum weighting was next used in the validation of total model results and the correction was then included, though varied with the values from the sensitivity analyses in 6.1.4. The advantage of utilizing the minimum weighting in the validation was related to the convenience of analyzing the resulting minimum CO_2 estimates while still weighting the fuel economy.

The estimates of the minimum weighting-minimum correction started above the result of all combinations, but was surpassed by the urban combination in 2007 and by the uniform combination in 2010. Model results nevertheless kept above the values of the ideal combination for all years due to applied minimum correction. The minimum correction increased results by six percent in 2007, eight percent in 2010 and ten percent in 2012, see sensitivity analysis in section 6.1.4, but the impact was not enough to overshoot the urban and uniform combinations. Furthermore, the negative divergence increased between 2012-2016 as measured to the urban combination and illustrated the need of a larger correction. For the included minimum weighting-default correction, model results kept above the result of all combinations for all years. The divergence, hence, remained positive for all years, but decreased up until 2005 when the impact of the correction was five percent. The positive divergence thereafter remained fairly static albeit the year 2010 was an exception, see more information in the previous validation. The impact of the default correction in 2010 was 12 percent and it increased by approximately two percent per annum for the remaining years. Most interesting, the default correction was identified to prevent model results to further diverge from the urban combination. For the minimum weighting-maximum correction, model results were also larger for all years and the positive divergence increased for nearly all years after 2005. The increasing divergence was reasonable due to the applied maximum correction since the impact of it was already seven percent in 2005, 11 percent in 2007 and 22 percent in 2012. Judging by the result of the minimum weighting-maximum correction, it seemed as if the positive divergence would continue to increase in the future. However, all model results diverged significantly from the estimates of the validation models between 2016-2017 and thereby indicated a relatively large discrepancy in the validation result. By exploiting information from the previous validation, see figure 16, the model result of 2017 can be concluded to develop similar to the validation models' result if no correction had been applied. The result of the combinations in 2017 was therefore analyzed as a sign of discontinuity since the correction obviously cannot be excluded for a single year, while being meaningful for all other years, see more information below when the correspondence was validated. Anyhow, in 2017, the model result was around 13 percent larger than the urban estimate. See figure 17.

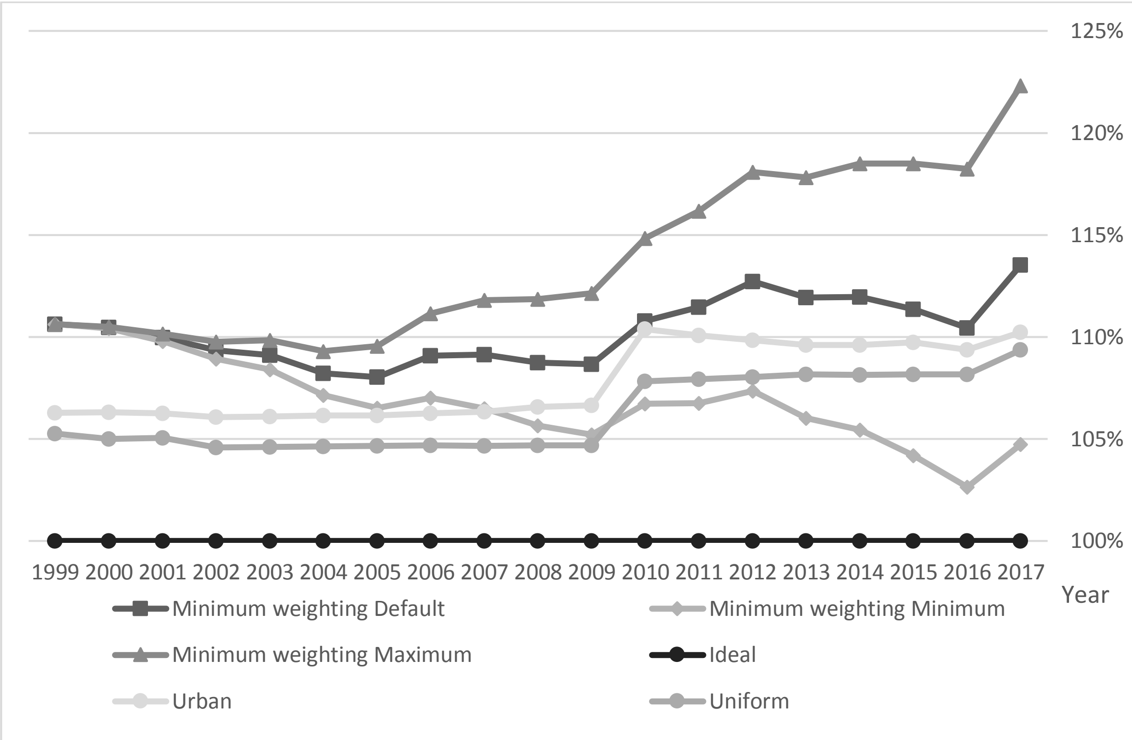

Figure 17. See the description of the curves under the chart. The result of the ideal combination was used for normalization and it was therefore static at 100 percent for the whole series. The Minimum weighting Minimum kept above the estimates of the Ideal combination for all years, but not the Urban and Uniform combinations. The Minimum weighting Default initially decreased the divergence, but nevertheless stayed above all estimates of the combinations and the divergence was close to static from 2005 and onwards. The Minimum weighting Maximum also decreased the divergence initially, but it increased for nearly all years from the year of 2005 and onwards.

The moving average for eliciting the fuel economy and the average national mass, combined with the default weighting, were next validated for different corrections. The advantage of utilizing this configuration in the validation was related to the convenience of analyzing the relatively large CO_2 estimates compared to the minimum weighting validated above.

The result was comparable with the above validation illustrated in figure 17, but three interesting differences were worth highlighting: The moving average average-minimum correction resulted in estimates approximately equal to the results of the uniform and urban combinations after 2007; the moving average-default correction (MADC) kept a more static, albeit larger, positive divergence from the urban combination after 2011; the curve of the MADC, but not the moving average-maximum correction, was slightly more smooth for all years and annual fluctuations may be less distinct for this configuration. The improved smoothness was reasonable due to the result of the sensitivity analysis in section 6.1.1, and also improved the model by making data variability between years less significant. See figure 18.

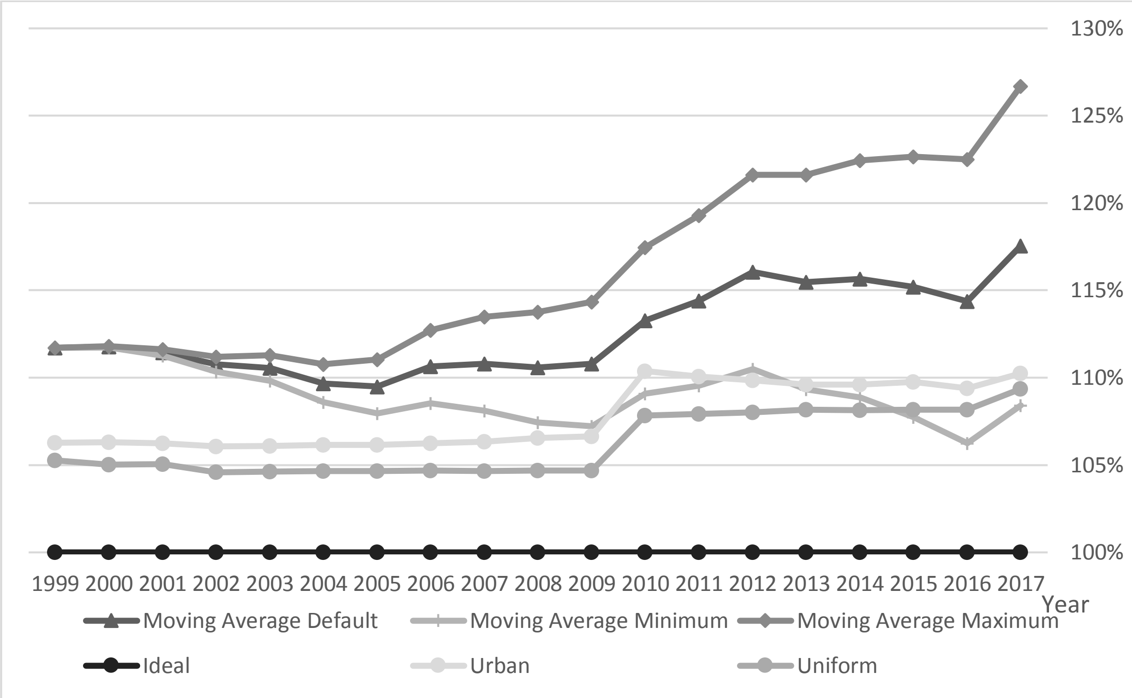

Figure 18. See the description of the curves under the chart. The result of the ideal combination was used for normalization and it was therefore static at 100 percent for the whole series. The Moving Average Minimum decreased the divergence to the urban estimates up until 2009, but the estimates were from there approximately equal until 2014 when they were surpassed. The Moving Average Default kept a fairly static divergence to the urban estimates for all years after 2005 except 2010 and 2017. The Moving Average Maximum increased the divergence for after 2004.

The static divergence of the MADC highlighted above was informing as it implied the urban and uniform combinations kept up with the default correction. In section 5.5.3, the combinations were analyzed to eventually start overestimating CO_2 emissions due to the changing composition of Järfälla's car fleet, the static difference in car age as well as the impact of traffic situations. Moreover, the analyzed underestimation in the beginning of the study period was analyzed to decrease. The validation result, combined with the new information of the shift in car age in section 6.3 described above, connect well to the fact that the divergence was halved from 1999 to 2005, and it was first after 2011 the divergence kept fairly static at 5-6 percent. The analyzed overestimation due to the emission factors from HBEFA could potentially result in the static divergence observed for MADC.

Next, the validation result will be presented in unit [mass CO_2] to illustrate the correspondence between the model- and the validation result. The included model configurations were the minimum weighting when applying both the default and maximum corrections, and the moving average when applying the minimum and default correction.

The validation result illustrated a good correspondence between the validation models and the applied models with only slight differences between 2003-2004, 2005-2006 and 2009-2010. All included configurations started significantly above the urban combination in 1999 with a positive divergence of 2600-3200 ton (i.e. 4.1-5.3 percent)[9], which was reduced for all configurations up until 2005. In 2005, results differed between 1100-2200 ton (i.e. 1.7-3.2 percent), and ended between -1200 to 7700 ton (i.e. -1.7-10.9 percent) in 2017. It was obviously the minimum weighting-maximum correction that represented the largest diverge and the smallest (though negative) diverge in the given interval for 2017 to the moving average-minimum correction. The difference between 2009-2010 was solely related to the emission factors used in the combinations already explained above. The difference between 2003-2004 was not related to the minimum weighting-maximum correction. Consequently, the maximum correction with an impact of five percent in 2004, compared to the default correction with four percent, benefitted the correspondence and, as such, illustrated how small the divergence was. No information was identified to shed light on the difference between 2005-2006. Nevertheless, the identified differences had only a marginal impact on total model results and represented a difference of around one percent. Most importantly, the differences were analyzed as negligible exceptions as they did not initiate a worsening correspondence over multiple years.

In relation to the differing result of 2017 highlighted above, the validation conducted here provided further information. It was the validation models which were reduced substantially more than the model results and, judging by the overall trend from 2013 and onwards, it was indeed a sign of discontinuity: The traffic work between 2016-2017, see figure 7 in section 5.4.1, was fairly static and this pointed to the emission factors for an explanation; the urban emission factors of HBEFA had been reduced by around 3 percent, whereas the calculated emission factors were approximately static due to a nearly static biofuel share between 2016-2017; simultaneously, the car fleet of Järfälla was analyzed to not substantially differ from 2016, though it was still likely for CO_2 emissions to be decreased since hybrid-, electric-, gas and ethanol cars increased their combined traffic work share by three percent. However, the increased traffic work share does not translate into a three percent reduction of the fossil CO_2 emissions since, for example, fossil fuels are also used as ingredients in biofuels. Additionally, the traffic work of (heavy) diesel cars also increased its share by three percent. The model estimates of 2017 were in sum analyzed as more reasonable than the validation estimates since the discontinuity was less distinct and due to the static sustainable biofuel share. See figure 19.

[9] Observe the given percentages in this paragraph cannot be compared with the result presented in figure 16, 17 and 18 as these were calculated on the basis of the ideal combination and not the urban combination as was conducted here.

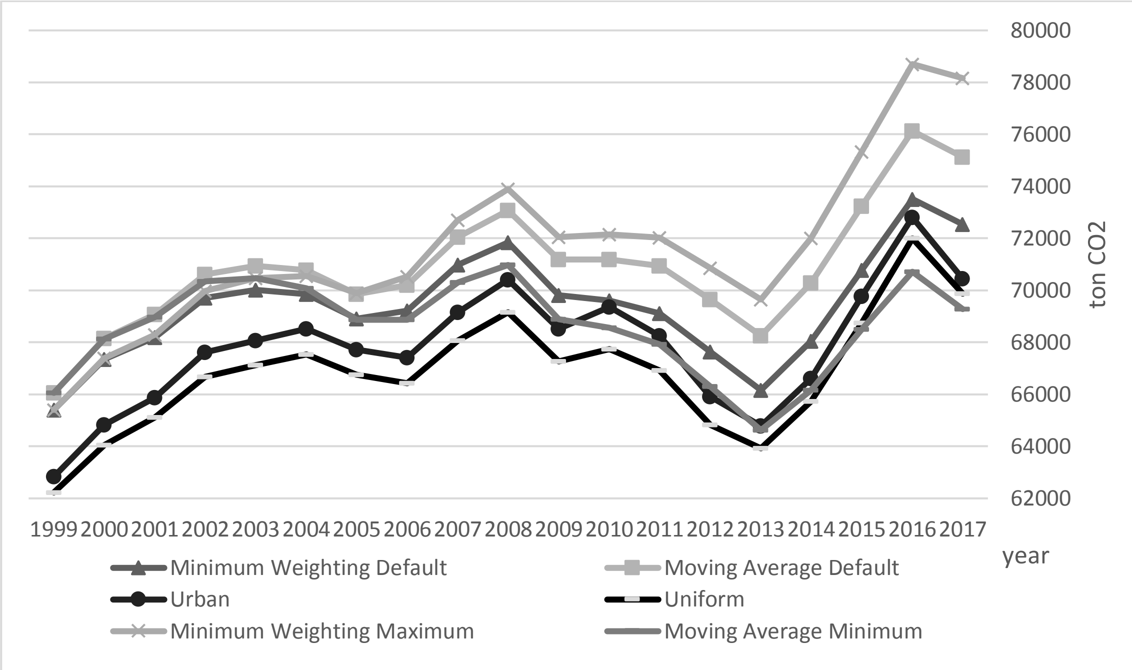

Figure 19. See the description of the included curves under the chart. The figure illustrates all included model results corresponded well with the estimates of the urban (and uniform) combination since shifts in estimates were mirrored in all curves for nearly all years and differences in magnitude were explainable.

6.2.4 Summary of validation

The calculated emission factors and their inclusion of biofuels were validated with good results as was also the performed the elicitation of the fuel economy, though not as planned. The validation of total model results could generally be explained according to the specified differences in section 5.5.3, though additionally information from 6.3 further improved the analysis. The validation of total model results illustrated an adequate correspondence; shifts were almost perfectly mirrored in the respective curves and differences in magnitude were relatively small and explainable. Furthermore, considering the adequate correspondence over time for all tested model configurations including the correction, model results were also consistent with another methodology, thus indicating the robustness of the model structure.

The minimum correction was initially assumed to be inadequate since the model results ended in smaller estimates for all configurations compared to the results of the urban combinations. Notwithstanding the risk of an underestimation, the static divergence observed for the MADC was analyzed as reasonable and information from section 5.5.3 and 6.3 hinted the emission factors from HBEFA do not necessarily underestimate CO_2 emissions in the local context of Järfälla's car fleet. The minimum correction may not be excluded without additional information. Similar to the maximum correction, which was analyzed to possibly continue to increase the divergence in the future, but no information implying the estimates to be overestimated has been acquired. All things considered, the validation result of the moving average applying the default correction was deemed the most reasonable. However, the model results presented in the next section include estimates from three configurations, the moving average when both applying the minimum-and default correction, and also the minimum weighting-maximum correction. More information should preferably be acquired before eliciting an 'optimal' model configuration, see section 7.4.

6.3 Model results

The uniform combination was identified in 6.2 to be comparable in magnitude with the urban combination, which was convenient since its distribution of traffic work should be more relevant considering the modelled cars could have been driven all over Sweden. Hence, the model results presented below were not only relevant for an urban context.

The moving average-minimum correction resulted in a range of approximately 66 100-69 300 ton, the minimum weighting-maximum correction in 65 400-78 200 and the moving average- default correction in 66 000-75 100. The CO_2 emissions were shown to have been decreased considerably between 2008-2013, but they increased substantially up until 2016 when a reduction again could be observed. See figure 20.

Figure 20. See description under chart for explanation of the included curves. The figure illustrates the CO_2 emissions from Järfälla passenger cars had increased over the study period, from approximately 66 000 ton in 1999 to between 69 000-78 000 in 2017.

When model results incorporated the effect of population development, emissions were reduced from approximately 1.10 ton in 1999 to between 0.91-1.0 ton per citizen in 2017. The moving average-minimum correction resulted in a range of approximately 1.10-0.91 ton, the minimum weighting-maximum correction in 1.10-1.02 and the moving average-default correction in 1.10-0.98. The CO_2 emissions were shown to have been steadily decreasing between 2008-2013, but not between 2013-2016. See figure 21.

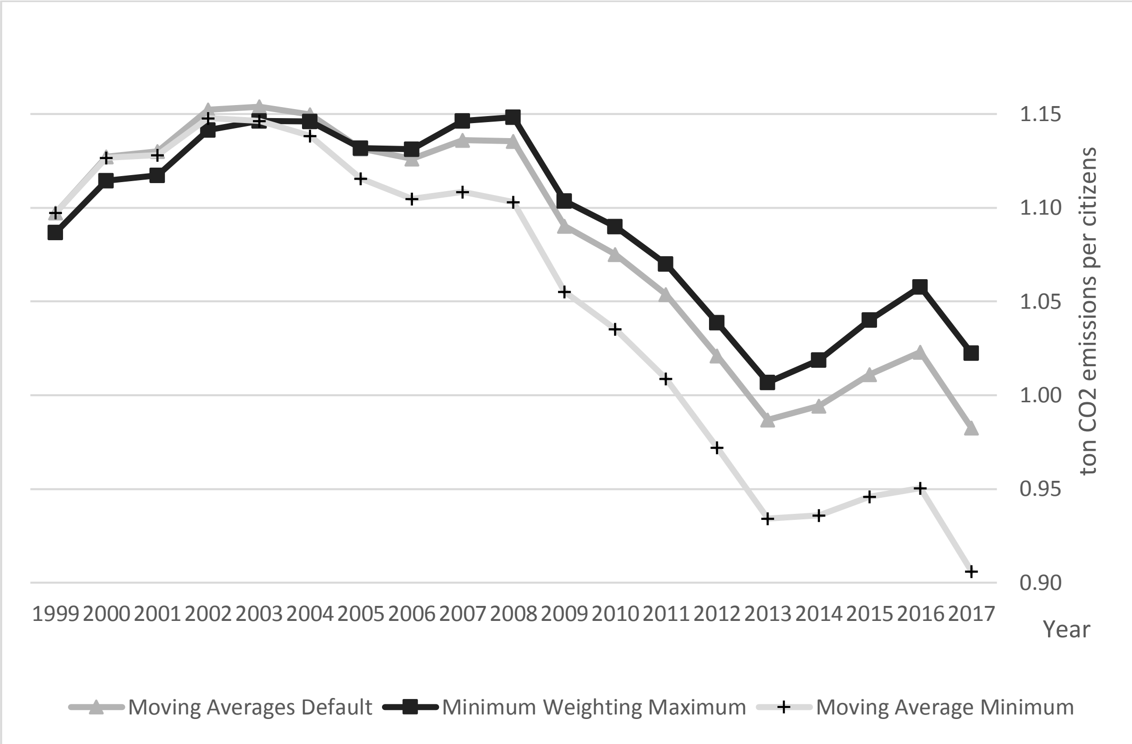

Figure 21. See description under the chart for an explanation of the curves. The figure illustrates the CO2 emissions from Järfälla passenger cars per citizens had slightly increased between 1999 to 2008 to thereafter be reduced substantially until 2013. During the study period, CO2 emissions developed from 1.10 to between 0.91-1.02 ton per citizens.

The model results presented in the remaining part of this section were calculated with the above applied model configuration of the Moving average applying the default- weighting and correction.

The model structure facilitated results to be displayed over car age- and mass classes to identify whether any shift had occurred during the study period with relevance for the CO_2 emissions from Järfälla car owners. For the car age classes, a shift was identified between 1999-2010 (though the peak was in 2003). The CO_2 emissions of the top seven classes increased for this period significantly, to thereafter be reduced to the original share in 2017. The shift identified here was referenced to in section 6.2.3. Moreover, a substantial part of Järfälla's CO_2 emissions was found to originate from newer cars. The top seven classes accounted for approximately 50 percent of the emissions for the period of 1999 and 2010-2017, but even more between 2000-2010. See figure 22.

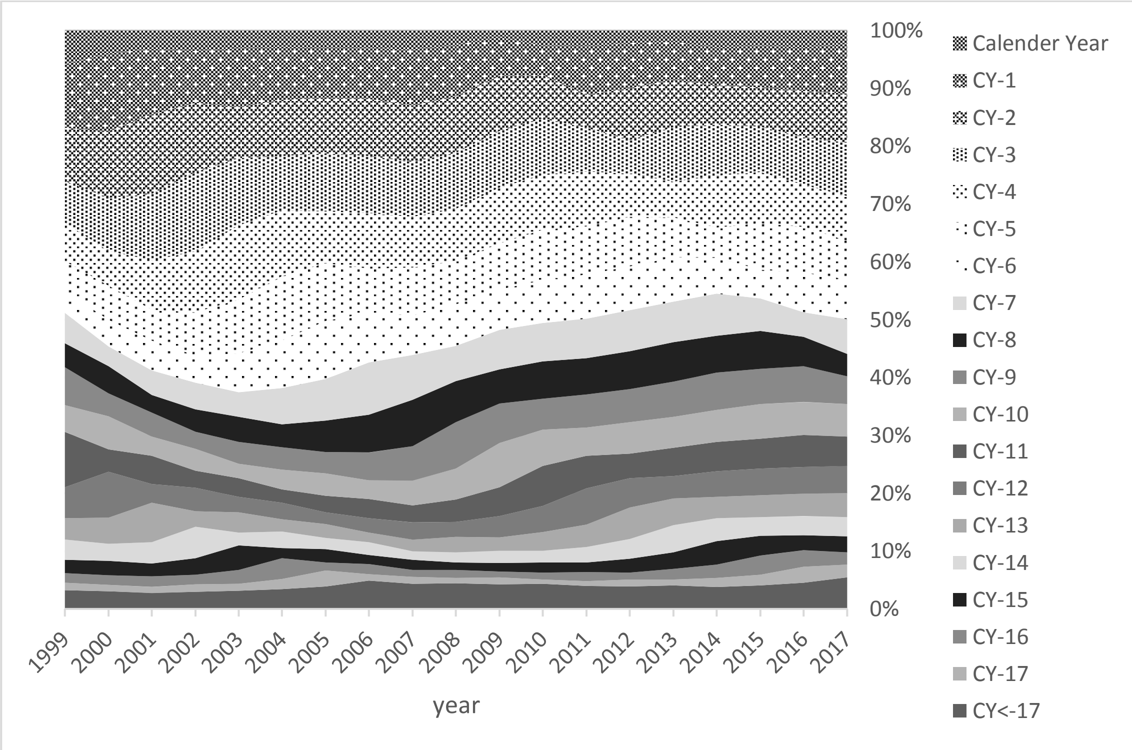

Figure 22. See description to the right in the figure for the included car age classes; CY-1 represents 'calendar year minus one year' and hence, the category CY-1 in 2013 represents all the cars produced in 2012, whereas in 2001, it represents cars produced in 2000. CY<-17 represents 'calendar year -17 years and older'. The bottom car age class in the figure is relevant to CY<-17, second from the bottom comes CY-17 and so on to the top of the figure where Calendar year is positioned. The figure illustrates the top seven newest classes, each highlighted by a different pattern of dots, dominated the CO2 emissions during the study period by a share of at least 50 percent for the whole period. Furthermore, observe the increase of the share starting from 1999 to 2003, which thereafter was slowly reduced to the original share around 2010.

A shift, though more distinct, was also identified in relation to the mass classes. In 1999, mass classes over 1500 kilos were responsible for a share of approximately 20-25 percent of the total CO_2 emissions, whereas in 2017, it had increased to 60 percent. Corresponding reductions for lighter mass classes were also observed. See figure 23.

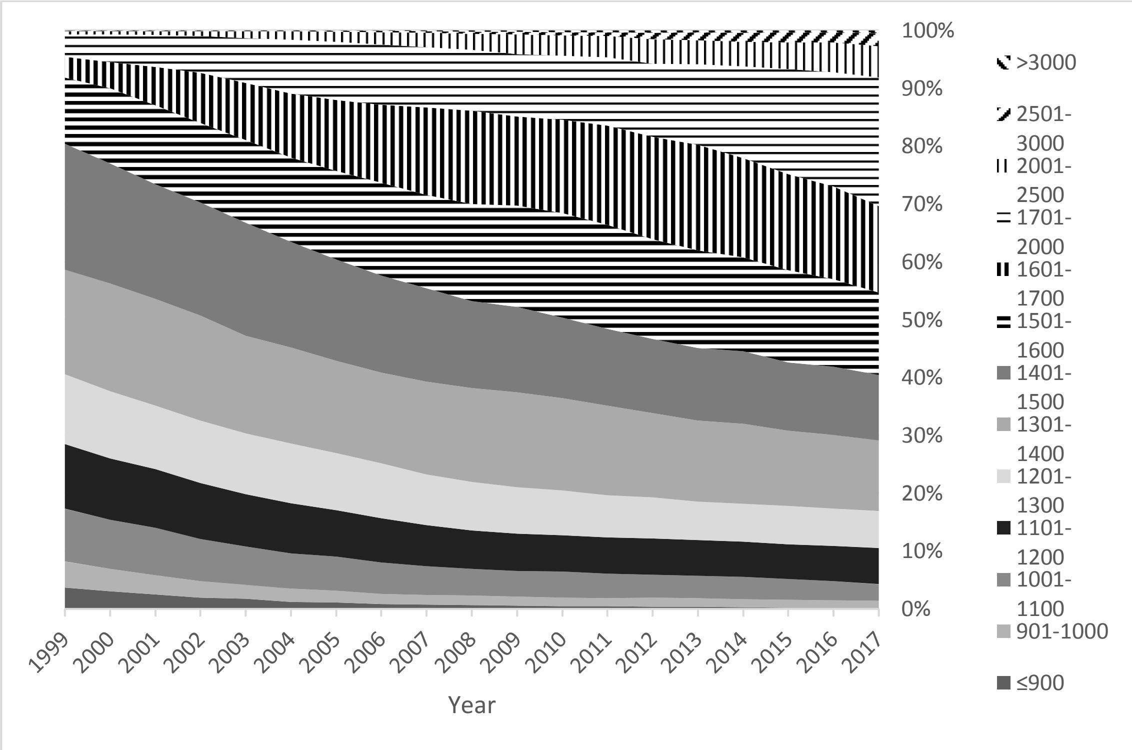

Figure 23. Mass classes are described to the right in the figure in unit [kilos]; ≤900 includes all cars lighter and equal to 900 kilos. The bottom mass car class in the diagram is relevant to the class of ≤900, second from the bottom comes 901–1000 and so on to the top of the figure. The figure illustrates mass classes over 1500 kilos, each highlighted by a different pattern of stripes, had increased the aggregate share of CO2 emissions considerably..

The CO_2 emissions could also be presented over the included fuel technologies. Gasoline cars' share of CO_2 emissions had been decreased by 40 percent over the study period, but it was still over 50 percent in 2017. Diesel cars had become much more common after 2005 in Järfälla and this was reflected in the emissions as the share had increased from 10-40 percent between 2005 and 2017. Interesting enough, the combined share of electric hybrid-, ethanol- and gas cars was relatively large since the traffic work share was 13 percent. Observe, though, the assumed 50 percent share of gasoline consumed by the ethanol- and gas cars. See figure 24 for the share of CO_2 for fuel technologies.

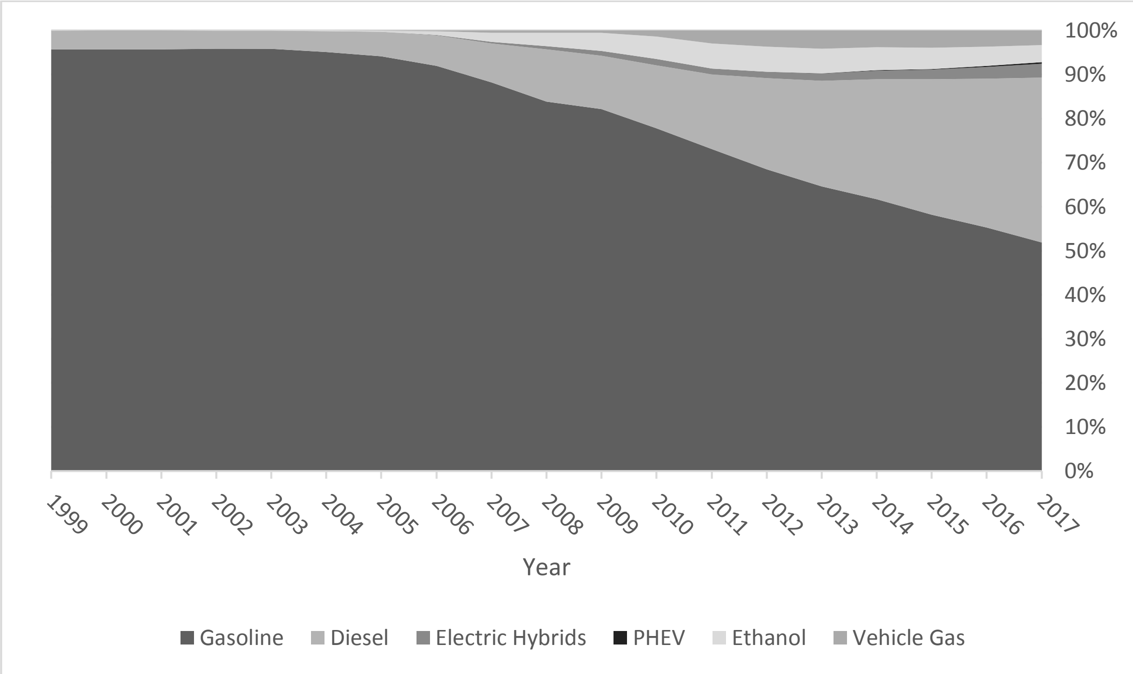

Figure 24. The included fuel technologies are described under the diagram. The figure illustrates the share of CO_2 emissions for gasoline cars had been reduced substantially on behalf of all other fuel technologies, though especially diesel cars.

6.3.1 CO_2 emissions calculated over Järfälla postal codes

The default weighting-default correction was utilized for this section.

The results were presented on a map of Järfälla in both an absolute unit [kilo CO_2] and a relative unit [kilo CO_2 per car] and the postal codes were categorized into groups illustrating whether the postal codes were large- or low- emitter of emissions. The following groups in unit [percent] were exploited: 0-11; 11-30; 30-40; 40-60; 60-70; 70-89; 89-100. To illustrate, 0-11 constituted of the postal codes representing the bottom 11 percent with the least emissions. The next group, i.e. 11-30, constituted of the postal codes representing the bottom 11-30 percent with the least emissions, and continuing so in a similar fashion up until 89-100 which constituted of the top 11 percent with the highest emissions. See section 5.7.4 for the used assumptions and Appendix D for the steps taken when cleaning the data. However, only the outer groups were displayed on the maps below.

The result when presented in absolute CO_2 emissions illustrated low emitters to be clustered in the ‘downtown’ of the municipality, whereas the larger emitters were spread outside of the center. These observed geographical differences were reduced when the results were presented in relative CO_2 emissions. Large emitters were albeit generally skewed toward the west of Järfälla, though the south of Järfälla was in part also implied as large emitters. By combining the findings of the two results, the west of Järfälla was identified to include many large emitters irrelevant of the metric results were presented in. The south of Järfälla was another region identified in both results. The result of the north of Järfälla, nonetheless, was interesting as it included five postal codes from the 89-100 group when results were presented in the absolute metric, but only one from the 70-89 group when the relative metric was used. The result may be due to postal codes with relatively large populations in the north. See figure 25.

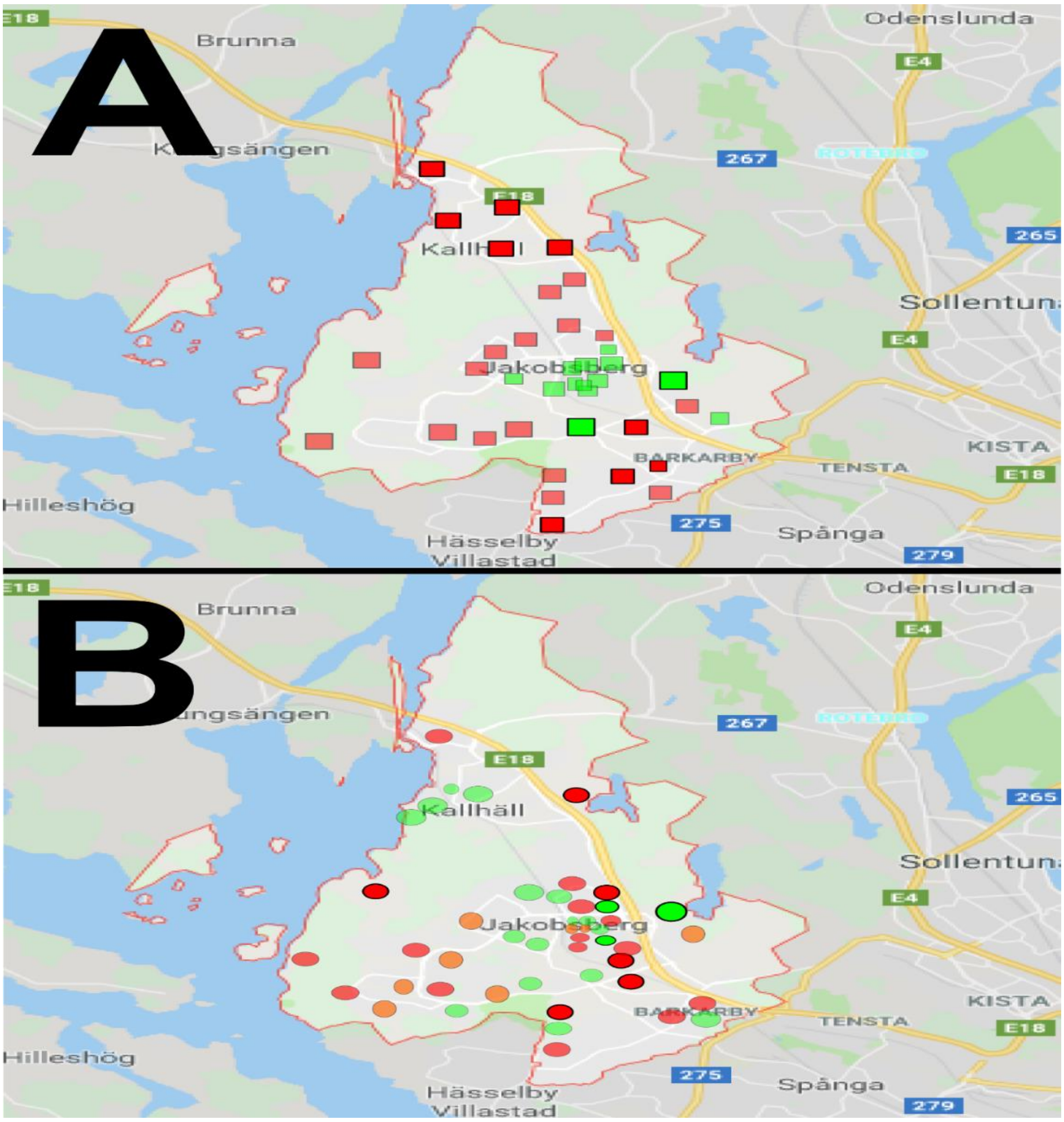

Figure 25. The top map indicated by an A displays the result in absolute CO2 where the postal codes of the top and bottom two of the emitting groups were included. In A, the sharp red squares represented the top group of 89–100, the shaded red represented the second group from the top, i.e. 70–89, shaded green represented the 11–30 percent category, whereas bright green represented the group with the least absolute emissions, i.e. 0-11. The bottom map indicated by a B displayed the result in relative emissions and included the postal codes of the top three and bottom two of the emitting groups. The sharp red circle represented the top emitting category of 89–100, the shaded red circle represented the group of 70–89 percent, the orange circle represented the group of 60–70 percent, whereas the bottom and the second from bottom group were represented by the bright and shaded green circle respectively. See figure for the result.

Anyhow, the majority of postal codes in the bottom category was not possible to identify on Google maps and the reason of why the sharp green squares and circles were relatively few in numbers. Also important to note, the locations of the postal codes in figure 25 were not exact as they were manually incorporated on the map without any software.

6.3.2 Results from the explorative scenarios

The default weighting-default correction was the utilized configuration for this section, see the result below where the scenarios also are presented for convenience.

1. What if gasoline and diesel cars' traffic work is reduced by 50 percent, given the constraint of travel need being constant?

The number of AFV:s needed to be increased by 411 percent to have a constant traffic work: Electric cars needed to increase from 37 to 152, electric hybrids from 806 to 3313, PHEV:s increased from 127 to 522, E85 from 1779 to 7309 and gas cars increased from 513 to 2109. Consequently, the traffic work of AFV:s also increased by 411 percent. However, the impact on CO_2 emissions was relatively small, only around 11 percent. The low impact on CO_2 emissions made it relevant to vary the assumed gasoline share of the *additional* ethanol- and gas cars. When the gasoline share was reduced from 50 to 20 percent, i.e. a 60 percent reduction of gasoline for these cars, the reduction approximately doubled. Observe both E85 and vehicle gas constitute of a fossil fuel share assumed as 19 and 18 percent respectively in 2016.

2. What if the traffic work is reduced by 20 percent on average for the whole passenger car fleet?

The impact on the result was a CO_2 reduction of 20 percent, i.e. the same reduction as in traffic work since, mathematically, the scenario corresponded to scaling equation 2 in section 5.1 with 0.8.

3. What if the traffic work is reduced by 20 percent specifically for cars with individual masses over 1500 kilos?

The impact on results was a CO_2 reduction of roughly 11 percent.

4. What if the traffic work is reduced by 20 percent for ten oldest car-age classes?

The impact on results was a CO_2 reduction of roughly 6 percent.

7. Discussion

Model results, with a focus on the advantages of the model are described in 7.1. Model results are discussed in the context of what the results imply to reduce emissions in 7.2. The conducted validation prompted further discussion of the methodology and the results and these are presented in 7.3. Additionally, an idea to scale up the model and apply it for every Swedish municipality is there presented in relation to HBEFA as it would provide multiple benefits. Finally, scheduled improvements in the data with relevance for the model as well as improvements are described in 7.4.

7.1 Model results

The CO_2 emissions from passenger cars registered in Järfälla were estimated to have increased during the period of 1999-2017 from at least 65 400 to between 69 300-78 200 ton CO_2. The estimated increase was most logical. The traffic work by the included cars had increased by 40 percent simultaneously as it was being conducted by a much heavier and newer passenger car fleet, including much more diesel cars. The municipality of Järfälla had during this period seen an increase in the number of registered cars in traffic from 23 498 in 1999 to 34 256 in 2017. The risk of CO_2 reductions through more efficient cars being offset by heavier cars, including diesel cars, has been identified in academic literature (Papagiannaki and Diakoulaki, 2009; Hu et al., 2016; Fontaras and Dilara, 2012). Moreover, car manufacturers' optimization of the NEDC put further doubt in emission improvements due to newer cars since the divergence between test and real-world emissions has increased to over 40 percent in 2014 (Fontaras et al., 2017; EEA, 2016b; Tietge et al., 2017). The negative effects on CO_2 emissions were shown to materialize for the municipality of Järfälla as illustrated by the model results. Moreover, the development of emissions implies support for the recommendations in 2.4 by Trafikverket (2017), referring to the needed shift of personal transportation by car to other travel modes.

The model results displayed an opposite development to the CO_2 estimates utilized in a carbon budget developed to Järfälla in the Autumn of 2017. The previous estimates originate from the National Emission Database where every Swedish municipality's territorial emissions can be acquired, whereas the model results illustrated emissions emitted over Sweden. However, due to multiple problems identified with the former CO_2 estimates, they were deemed inadequate to apply in modelling for the benefit of municipalities' climate change work. The model created during the master thesis provided a solution to the identified problems and should therefore be more suitable to exploit in local climate work. Especially since model results can be updated annually if needed due to the data applied in the model. The model's capability to utilize relevant traffic work data and car characteristics (e.g. fuel technology, the mass of cars and the car age) when estimating the CO_2 emissions facilitated a robust connection of the result to the municipality of Järfälla. Moreover, the model was shown to potentially aid municipalities to accomplish the required CO_2 emission reductions if Sweden are to live by the Paris agreement. For example, by estimating the development of CO_2 emissions accurately enough to enable a quantification of policy mitigation measures' impact on CO_2 emissions to be determined, see more examples below. Given domestic transportation's- as well as passenger cars'- dominant share of CO_2 emissions in Sweden, it further motivates the model, or rather the model results, to be incorporated in future carbon budgets developed for municipalities in Sweden.

Model results were presented on a per capita basis illustrating a reduction from approximately 1.10 ton to 0.91, and as such, an opposite trend compared to the model results in unit [ton CO_2] presented above was obvious. Hence, improvements in relation to the emissions of CO_2 were apparent for Järfälla and reductions were being accomplished, though not on the aggregate level as the other model results illustrated. The model can hence be used to present results in different metrics, and this was beneficial for the applicability of the model. Population growth is an obvious factor for increasing CO_2 emissions, but it is irrelevant for the World's climatic system. CO_2 emissions must be reduced in absolute terms to at least enable the carbon concentration in the atmosphere to decrease and to have a chance to limit global warming under 2 degrees Celsius. The model, though not implemented here, can facilitate the two metrics to yield the same required reductions to avoid confusion in the model results. For example, a ten percent reduction between 2017 and 2018 would in the absolute metric require a total emission of between 62 400-70 400 ton; on a per capita basis, using the population prognosis in section 2.3.2 with an estimated population of 79 271 people in 2018, a ten percent reduction would require emissions to be 0.79-0.89 ton per citizen in 2018. The result displayed here indicated the model was also suitable for quantifying future emissions paths.

The model was moreover applied for estimating the CO_2 emissions disaggregated over Järfälla's postal codes to possibly illustrate geographical differences between areas in the municipality. Differences were also observed in the result and illustrated further potential with the model, e.g. to identify good examples to learn from as well as postal codes where additional support should be directed. The result, though seemingly correct as interpreted from Google maps, need to be validated, see more information in section 7.4. Anyhow, the possibility to apply Geographical Information System (GIS) was considered beneficial for improving the presentation of results. GIS would be especially relevant if the result was scaled up to include every postal code in Sweden as it would not be feasible to manually incorporate the result as was conducted in the thesis. The idea to estimate CO_2 emissions for every postal code in Sweden would naturally pre-requisite improvements in the methodology. But the end result could potentially provide an indicator in climate change work with a very high detail level. Furthermore, if the Swedish postal codes were categorized into different groups of similarity, for example, population and socioeconomic data, the result would be suitable to compare postal codes, both officially and privately. The comparison should be beneficial to identify good examples, but perhaps it would provide further motivation for postal codes to reduce the CO_2 emissions.

7.2 Policy implications

Explorative scenarios were possible to investigate for Järfälla with the model, and illustrated a simple and flexible way to explore, for example, policy goals with the purpose to reduce CO_2 emissions from passenger cars for a municipality. A most interesting result was the surprisingly low reduction of roughly 11 percent when gasoline and diesel cars' traffic work were reduced by 50 percent, simultaneously as the total traffic work was held constant. That is, the traffic work of ethanol-, gas-, electric- and hybrid cars were increased by the same amount as the specified reduction of gasoline- and diesel cars. The surprisingly low reduction was mostly related to substantially higher CO_2 emissions of ethanol and gas cars since only 50 percent of their traffic work was assumed to be conducted with E85 and vehicle gas due to data limitations, whereas the other 50 percent was assumed for gasoline. Additionally, both alternate fuels constitute of significant shares of fossil fuels. The result thereby illustrated the importance of a holistic perspective for reducing CO_2 emissions since ‘environmental’ cars were identified to not guarantee substantial reductions without further assumptions. For example, car owners of ethanol- and gas cars must fuel their cars with at least 80 percent E85 and vehicle gas respectively. Additionally, the biomass in biofuels must also be sustainable to be exempt from CO_2 emissions. All results from the explorative scenarios were not as complex. The most efficient way to reduce CO_2 emissions would be to stimulate all citizens with a car to not travel by car (e.g. electric car here excluded). Two other scenarios illustrated it was more efficient to reduce the traffic work of heavier cars compared to older cars for Järfälla, referring to the reduction of CO_2 emissions. The results of the explorative scenarios could inform the municipality of the importance to motivate car owners with heavy cars to reduce their traffic work. The importance of heavier cars was also identified when displaying emissions over car mass classes. Moreover, car owners with older cars who drives significantly less (as long as they have an old car), should instead of buying a new (environmental) car perhaps be recommended and stimulated to other low carbon alternatives (e.g. carpool, public transportation, train, bicycle, walking, electric taxi, etc.). That is, be recommended to shift the travel mode. The importance of lowering the traffic work for all cars except electric cars should not be neglected, especially due to the trade-off described in 4.3 since both NO_x (and other harmful gases) and CO_2 emissions then will be reduced.

To improve the likelihood of reducing CO_2 emissions, options for a low carbon transportation lifestyle deemed as more advantageous than driving a heavy passenger car on fossil fuels, are needed. As hard as that may be it is nevertheless possible as indicated by the traffic congestions in Stockholm: 50 and 60 percent increases in travel time in morning and evening rush hour respectively should be expected, see section 3.1.2. Alternatively framed, how advantageous is it to be stuck in a car travelling 10km/h while simultaneously contributing to global warming and the deterioration of the local environment? Apparently, it is, and this should be motivation enough for decision makers to make it considerably less so. The model results were not only relevant for the municipal governing level, similar to the problem of E18 for Järfälla’s territorial emissions, as climate change work requires the whole society to cooperate to accomplish the required albeit substantial reductions.

A note on the potential, as well the issues, with biomass can here be shared. The model structure facilitated biomass to be explicitly incorporated in the model, including the sustainable share of biomass, and this was considered important due to recommendations made by IPCC (2006b). In the future, biomass was also believed to be more and more important and consequently even more important to incorporate in the model for it to be relevant for climate change work tomorrow. The increasing importance can be observed in the rapid increase of biofuels, especially those mixed in diesel, where hydrotreated vegetable oils (HVO:s) are the latest example (AoE, 2018). HVO can moreover consist of 100 percent biomass and could for this reason be completely exempt from CO_2 emissions, simultaneously as diesel engines do not have to be modified. Thereby improving the potential of biomass considerably, referring to reduced fossil CO_2 emissions. A sensitivity analysis of the potential of ethanol- and gas cars for lowering CO_2 emissions nevertheless indicated the importance of biofuels today for Järfälla. Notwithstanding the significant potential, it was dependent on whether the biomasses used in the fuels were sustainable, which they were from 2011 and onwards. Sustainable biomass may not be the normal case in the future due to the large quantities of fossil fuels consumed in the transportation sector. Additionally, the combustion of biomass results in CO_2 emissions, albeit not fossil emissions, but they still add to the carbon concentration in the atmosphere. To fulfil the potential of biomass would require the carbon cycle to dictate the consumption, which is essentially complicated considering deforestation is still on-going (FAO, 2016). Biomass look promising for cutting fossil CO_2 emission substantially, but to benefit the climate, an increased consumption of biomass necessitates absolute reductions in the combustion of fossil fuels and a halt to deforestation as well as to the exploitation of other carbon sensitive land.

7.3 Validation of model

The validation of model results was essentially complicated and, as identified from academic literature, this was no abnormality. For example, the validation of emission factors is many times costly and hard to generalize (Franco et al., 2013), whereas road traffic- and traffic emission models are seldom completely validated (Smit et al., 2010). The model was nevertheless validated, but the validation data did not include estimates of the real-world magnitude of the CO_2 emissions for the period of 1999-2017 since these were not known. Inspired by the methodologies in TRAFA (2013) and SEPA (2017a), the validation compared estimates from different methodologies. Moreover, data limitations dictated what validations were possible to conduct, and the model was validated in parts. The derived fuel economy was validated with official data and the calculated emission factors were validated with emission factors used in the greenhouse gas inventory from SEPA. Furthermore, the total model results were validated by exploiting emission factors from HBEFA also applied in the greenhouse gas inventory. These methods were not considered optimal since they were developed for a larger scale and due to data uncertainty, but they still provided a common- and meaningful- reference context for model estimates to be compared with. An advantage of the conducted validation was the connection to how CO_2 emissions are officially estimated in Sweden, thereby making the model results relevant to the national scale as well. All validation results were also adequate and illustrated the suitability to apply the model for estimating CO_2 emission from passenger cars for a municipality while still being connected to the national scale.

Multiple model configurations' impact on the model results were also analyzed with sensitivity analyses. The model structure was then found to be sensitive to the applied correction which was no surprise considering the estimated divergence between real-world driving and test-values was as much as 40 percent for cars produced in 2014. Nonetheless, the sensitivity analyses indicated the adequacy of the model structure's different configurations for the purpose of estimating CO_2 emissions from passenger cars. An advantage of the model structure was the flexibility it provided. Model configurations could be adjusted with ease in the model during the master thesis and additional configurations can be added to improve the model if new data or information become available. The sensitivity of the model structure could as such be mitigated.

A most relevant and intriguing idea for improving the validation would be to apply the model for each municipality in Sweden and thereafter aggregate the results and analyze the divergence with the national estimate by HBEFA. It would for example be interesting to see whether the model results, though corrected, would yield underestimates compared to HBEFA due to a lighter passenger car fleet in other municipalities. Results, which could be used to improve the model. The algorithms developed for the model can facilitate the required calculation by simply switching the data to another municipality, and so on for all municipalities in Sweden. Alternatively framed, the model structure was suitable for estimating the CO_2 emissions of every car in Sweden! HBEFA is nevertheless most suitable to apply on the national scale, though less so for specific municipalities due to uncertain input data and the smaller scale relevant for municipalities. The developed model could thus potentially complement HBEFA with a cost-effective additional bottom-up approach for both the local and national scale.

7.4 Model improvements

TRAFA will scrutinize the estimated traffic work data in the fall of 2019 and the quality of them should improve. The potential of improvement, though, implied a weakness of the model results since these could be subject to an implicit methodology change. However, the scrutinization of TRAFA is a onetime 'event' and the majority of the traffic work data is not estimated. Moreover, the methodology, which have been applied for the estimates, is moreover reasonable, see section 5.4.1. Thus, model results would most likely change for Järfälla due to the scrutinization, but the risk of substantial changes were nevertheless reduced. Considering the onetime occurrence of the scrutinization, the model if applied for other municipalities will result in more certain estimates compared to Järfälla

The fuel economy of the cars was another uncertainty factor and therefore also analyzed considerably in the study, both with a sensitivity analysis as well as with validation data. Nevertheless, if the individual fuel economy as given from manufacturers per car were available, this would reduce the uncertainty in the model results. TRAFA has been consulted about the individual fuel economy of cars and they are told to be uncertain (A Myhr, Personal Communication, 2019). The highlighted uncertainty fits nicely with the validation result in 6.2.1. The applied fuel economy data in the model, combined with the conducted elicitation and weighting, may be the most adequate option when in need of the individual fuel economy for many passenger cars, for example, a car fleet.

Information needed to fully exploit the validation of total model results was missing in the report. The missing information related to the unknown values of what the applied correction should ideally be modelled with for Järfälla's car fleet. The correction was derived with information provided from academic literature where the discrepancy between real-world driving and the test-values of the NEDC was specified. The applied correction is nevertheless based on research applicable for the EU in general and not Sweden (or Järfälla) specifically. The uncertainty in model results should improve considerably if similar data, as used by Tietge et al. (2017) for German passenger cars, was available for the Swedish passenger car fleet. For example, a correction specified over fuel technologies, production year and mass. Factors highlighted in 4.2 and 5.3 were implicitly included in the model due to the applied correction, but they should preferably be specified in future modelling to further reduce the uncertainty. However, the NEDC was replaced in the summer of 2017 with a new driving cycle, the WLTP, and this has a most important consequence for future modelling. Passenger cars tested with the WLTP show CO_2 emissions can increase by more than 20 percent and this is equivalent to a reduction in the discrepancy between test-values and real-world driving (Pavlovic et al., 2018). Future modelling would consequently require two different corrections in the same model depending on the production year to enable model results to reflect real-world driving.

To further improve the analysis of the total model results, the emission factors from HBEFA should have been specified more thoroughly. For example: What is the impact of traffic situations per year and per emission factor; and why was there a shift between 2009-2010, but not for any other years, see figure 16 in section 6.2.3. Moreover, when the maximum correction was applied in the model, model results diverged from the validation estimates, which was not the case when the moving average-default correction was applied, simultaneously as the impact of both the corrections increases every year. The emission factors from HBEFA therefore seemed to keep up with the increasing impact of default correction, which was surprising. Other factors could, though, influence the emission factors of HBEFA to partially make up for the correction, which combined with a too low correction would result in a static divergence. Anyhow, with the benefit of hindsight, the author should have contacted IVL to see whether they could help fill in the missing information of for example traffic situations, but observe the complexity involved. For example, traffic situations are just one factor adding to the divergence between test and real-world values and the Tier 3 applied in HBEFA was described to increase the uncertainty in CO_2 estimates (IPCC, 2006b).

Motor specialist should be consulted with the purpose to improve the incorporation of the biofuels' impact on the fuel economy as this can be of increasing importance in the future due to an increased biofuel consumption. The model structure solely utilized the energy content, but there may be other factors to consider, or perhaps, a more suitable equation than the scaling applied. Additionally, the weighting due to mass should further be investigated to possibly incorporate other factors, for example the engine size, though attention should be given to avoid the inclusion of large uncertainties.

More attention should be given to the cleaning of the postal code data to improve the results. The estimation models applied by TRAFA for estimating data of cars without odometer readings for different reasons, would be one way to improve the cleaning. However, observe the author of the study has not been in contact with the original data provider (though attempts were made), see Appendix C.

8. Conclusion

CO_2 emission estimates of the transportation sector, including passenger cars, were included in a carbon budget developed to the municipality of Järfälla, but these did not necessarily reflect the real-world development of emissions. Instead, the national development of CO_2 emissions dictates the local development and on only two occasions has the municipal shares of emissions been specifically estimated. A model created during the work of the master thesis provided solutions to these and other identified issues with the above described estimates. The model was applied for a case study, the municipality of Järfälla.

The developed model estimated the annual CO_2 emissions from passenger cars in traffic for the time-period of 1999-2017, where the cars were owned by citizens and juridical persons in the municipality of Järfälla. Model results illustrated emissions had increased for the period of 1999-2017, but when results were presented in unit [ton CO_2 per citizens of Järfälla], emissions were instead down over the time period. Shifts in relation to how the CO_2 emissions had developed in Järfälla were moreover identified. For example, an increasingly larger part of Järfälla's emissions were being emitted by diesel cars as well as by heavier cars. For the year of 2017, CO_2 estimates were furthermore calculated for the relevant postal codes in Järfälla. Results illustrated geographical differences, and these were presented on a map, but observe the results, although reasonable, were not validated. Finally, the model structure allowed for a simple and flexible way to explore explorative scenarios. The scenarios can be compared with policy goals with the purpose to reduce CO_2 emissions from passenger cars for a municipality. A most interesting result was identified when the traffic work of gasoline and diesel cars were reduced by 50 percent, simultaneously as the total traffic work was unchanged. CO_2 emissions were then only reduced by 11 percent when ethanol- and gas cars were assumed to consume 50 percent gasoline and 50 percent E85 and vehicle gas respectively. Perhaps less surprising, the most efficient way to reduce CO_2 emissions was by a reduction of total traffic work, irrelevant of fuel technology. The model results, as such, illustrated the CO_2 emissions from passenger cars with different, but relevant, perspectives, all possible to exploit when planning for how emissions can be systematically reduced in a relatively short time.

The traffic work data for the model originated from mandatory vehicle checks conducted in Sweden. Other important input data were the mass, production year and fuel technology of each car, national fuel economy data, sustainable biofuel shares, country specific emission factors as well the NCV:s of different fuels. The model structure applied a novel approach using four calculated emission factors specified over fuel technology in unit [kilo CO_2 per liter fuel] as well as in unit [kilo CO_2 per kilo vehicle gas]. National fuel economy data was weighted according to the mass of cars to make the national data representative for Järfälla. The model structure incorporated the biofuel share as well as how ethanol and gas cars were fueled (i.e. with 0-100 percent E85 or vehicle gas respectively). A correction due to car manufacturers' optimization of the NEDC was needed and rendered the model results more representative for real-world driving. Furthermore, the effect of biofuels on the fuel economy was calculated and incorporated in the model structure. In sum, the model adhered to recommendations from the IPCC guidelines for estimating CO_2 emissions from passenger cars.

The model was validated according to methods applied when estimating Sweden's national emissions as reported to the UNFCCC. Total model results were validated by utilizing emission factors from an emission model, HBEFA. Moreover, the calculated emission factors of gasoline and diesel were validated with emission factors from SEPA and the elicitation of the fuel economy of cars was validated with data from the national car register. Validation results were good and considered an indication of robust results in relation to official data and national estimates. The model structure was thus considered adequate to apply for other Swedish municipalities in need of information to exploit for reducing CO_2 emissions from passenger cars. Furthermore, given domestic transportation's- as well as passenger cars'- dominant share of CO_2 emissions in Sweden, the model has the potential to aid municipalities to accomplish the substantial reductions required in the future if Sweden are to live by the Paris agreement. Hence, the model should be exploited in future carbon budgets developed for municipalities in Sweden.

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Appendix A

Table 1. Calculation of Järfälla's share of Swedish total CO2 emissions from passenger cars.

Year	**A** Dataset 2014 CO2 [ton]*	**B** Dataset 2016 CO2 [ton]*	**C** National total of CO_2 [kilo ton] **	**D=A/C** Share Dataset 2014	**E=B/C** Share Dataset 2016
1990	52 570	52 640	12 453.9	0.4221	0.4227
1991	NA	NA	12 641.8	NA	NA
1992	NA	NA	12 956.6	NA	NA
1993	NA	NA	12 299.8	NA	NA
1994	NA	NA	12 479.9	NA	NA
1995	NA	NA	12 689.5	NA	NA
1996	NA	NA	12 604.2	NA	NA
1997	NA	NA	12 426.4	NA	NA
1998	NA	NA	12 270.4	NA	NA
1999	NA	NA	12 435.4	NA	NA
2000	52 000	52 120	12 340.8	0.4214	0.4223
2001	NA	NA	12 483.3	NA	NA
2002	NA	NA	12 756.1	NA	NA
2003	NA	NA	12 761.5	NA	NA
2004	NA	NA	12 713.8	NA	NA
2005	53 160	53 280	12 619.9	0.4213	0.4222
2006	52 550	NA	12 479.4	0.4211	NA
2007	53 080	NA	12 596.7	0.4214	NA
2008	51 080	NA	12 116.1	0.4216	NA
2009	50 970	NA	12 086.5	0.4217	NA
2010	36 920	44 530	11 838.9	0.3118	0.3761
2011	35 770	43 170	11 477.6	0.3117	0.3761
2012	33 940	40 930	10 880.7	0.3119	0.3761
2013	33 210	39 970	10 627.4	0.3125	0.3761
2014	32 860	39 640	10 537.5	0.3118	0.3761
2015	NA	39 880	10 601.7	NA	0.3761
2016	NA	38 570	10 253.9	NA	0.3761

* Data acquired from the National Emission Database. Acquired in 2018 from: http://www.airviro.smhi.se/cgi-bin/RUS/apub.html_rusreport.cgi

** Data from Statistics Sweden produced by the Swedish Environmental Protection Agency. Acquired in 2018 from: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0107/MI0107InTransp/?rxid=c37818a7-f98f-40c3-8db4-be52e0cc310f in 2018. The dataset applied was last updated in 20171130.

Table 2. A simplified calculation of the emissions from E18 passing through the municipality of Järfälla.

A*** Emission Factor [kg CO_2 per kilometer]	**B****** Length of E18 passing through Järfälla	**C****** Average vehicles per day passing through Järfälla	**D=[B*C*365*A]** CO_2 emissions from E18 in Järfälla per year [kg]
0.1685	≈11 km	≈52 000	≈35 200 000

*** Provided from the Swedish Environmental Institute, IVL.

**** See references in the report section 3.2.

Appendix B

The references used here refer to the reference list in the main report.

Fuel economy of electric hybrids and PHEV:s

Hybrid vehicles have two engines, one that runs on fossil fuels, whereas the other runs on electricity. For PHEV:s, the assumption was motivated by the considerably lower values for PHEV cars compared with all other fuel technologies, simultaneously as the electric battery have relatively low capacity, thereby constraining the use for longer travel needs. For electric hybrids, the battery is only recharged when braking and acceleration occurs (EEA, 2016b), thus constraining the electric drive considerably. For both electric hybrids and PHEV:s, the electric engine complements the combustion engine. Hence, the electric engine was assumed to be the reason to the low fuel economy when driving on gasoline and, as such, the fuel economy was assumed to relevant for driving these cars on average.

Biofuels in gasoline and diesel

The fuel economy of diesel cars was not modified to incorporate the effect of biofuels due to a negligible effect and data limitations: Given a 10 percent share of the biofuel Fatty acid methyl ester (FAME) and since diesel has 7 percent more energy per volume quantity than FAME, the impact on the fuel economy was negligible (i.e. less than one percent). However, larger bio shares for diesel are now available (AoE, 2018; AoE, 2017), for example, a sustainable share of biofuels of 21 percent in 2016 and 2017, but these are related to the biofuel of Hydrogenated vegetable oils (HVO:s). But no information regarding NCV:s for HVO fuel had been acquired for the study which most likely was related to the variability of HVO, referring to what it is constituted of.

For gasoline cars the effect of biofuels on the fuel economy was over one percent from 2004 and onwards due to a larger difference in the energy content between gasoline and ethanol where the former has more than 50 percent more energy per volume quantity. The fuel economy of gasoline cars was therefore modified according to the bio share. See table 5 in Appendix C for the derived scaling factor.

Weighting due to mass

An implicit assumption of the performed weighting was that mass differences influence passenger cars equally irrelevant of other car characteristics like the original weight, car model, fuel technology, etc. Nevertheless, the assumption originated on Newton's second law, see equation 1 below, thereby relevant for all vehicles.

$$\sum \boldsymbol{F} = m * \boldsymbol{a} \tag{1}$$

The summation of **F** represents the net force in unit [Newton] acting on a body, m is the mass in unit [kilos] of the body, whereas **a** represents the acceleration in the same direction as the net force in unit [m/s^2] (Young et al., 2014). If the mass m is increased/decreased in equation 1, a proportionally larger/smaller force is required to balance the equation, given that the required acceleration is the same. For a passenger car, the need of a larger/smaller force is fulfilled by a change in the consumed energy for the car, which most often translates into the fuel economy and ultimately to the fuel consumption. That is, the fuel consumption per driven distance increases or decreases, depending on how the mass changes.

Linear extrapolation was exploited to mitigate the missing values of average masses per fuel technology for the Swedish passenger car fleet for 2001-2003 as well as for 2017. The extrapolation was made possible due to data being available on average for Sweden back to 2001, whereas the specific fuel technologies from the EU only dates back to 2004.

Mass differences were calculated based on the years of 2004-2016 to quantify how much in kilos that separated the Swedish average mass with the average mass of specific fuel technologies in the EU. An average of five kilo per year for 2001-2004 (e.g. a decrease) and for 2017 (e.g. increase) was estimated and applied for gasoline cars, 1.75 was estimated for diesel and 3.9 kilos for AFV. The values enabled the mass difference to be extrapolated back in time, which in turn, enabled an estimation of European average masses per fuel technology for 2001-2003 and 2017 to be derived. Extrapolation is associated with an increased uncertainty in calculations, but considering the few years estimated in this way, the approach was deemed adequate here. The exploitation of extrapolation nevertheless assumed the mass differences observable in the data were indicative of future and backward differences as well.

A scaling factor was estimated to enable the calculation of average masses per fuel technology with relevance for Sweden, see equation 2 and 3 below.

$$SF_{per\ year} = \frac{Swedish\ mass\ average_{per\ year}}{European\ mass\ average_{per\ year}} \qquad (2)$$

$$Swedish\ mass\ average_{per\ FT\ and\ year} = SF_{per\ year} * European\ average\ mass_{per\ FT\ and\ year} \qquad (3)$$

The indexation, FT, represent the fuel technologies included. For all other years than 2001-2017, no weighting was performed due to data limitations. The elicited fuel economy for older cars in the model should therefore be considered of lesser quality compared to newer cars. The scaling factor was assumed to quantify the mass difference between passenger cars in Sweden and the EU, relevant for gasoline-, diesel- and AFV cars. Observe that no consideration was given to market shares of different fuel technologies when calculating the respective Swedish mass averages. On the plus side, however, the scaling factor was not dependent on a specific fuel technology, thereby possible including the market share. Anyhow, the scaling factor calculated in equation 2 was multiplied with the respective European averages of the fuel technologies in equation 3**,** including the extrapolated values, and the result was the average Swedish mass of the same fuel technologies for the period of 2001-2017.

Finally, the weighting applied a strict distinction of 100 kilos, which could be problematic, but this was assumed to average out simultaneously as the impact of it on model results was negligible.

Missing values of 1999 or 2017

When a needed value was missing for the year of 2017, though available for the period of 1999-2016, the missing value was assumed equal to the year of 2016 if the available data did imply relatively static values. Likewise as when the value of 1999 was missing. The effect on model results was most likely negligible since values, as observed, do not vary drastically between years.

Appendix C

The references used here refer to the reference list in the main report.

Comparison of the national passenger cars fleet's traffic work with Järfälla's

The data of traffic work for the Swedish national passenger car fleet specified according to mass, car age and fuel technology, originate from TRAFA (2018). The data were modified (e.g. not recalculated), referring to the car age classes, to accomplish a comparison over time since the specific classes in the national data were changing depending on the calendar year.

Information of the average mass of passenger cars

The conducted weighting of the study exploited the annual average mass of cars sold in Sweden irrelevant of fuel technology acquired from EEA as well as the average mass for gasoline-, diesel- and AFV cars in the EU, also acquired from EEA. The AFV category consists of E85-, natural gas-, biodiesel-, liquified petroleum gas (LPG)-, battery electric- and hybrid cars (EEA, 2017). LPG-, biodiesel- and electric cars were not relevant when estimating the CO_2 emissions for for Järfälla car owners, but the data relevant for AFV:s was nevertheless assumed representative for E85, vehicle gas and hybrids. The Swedish average masses are given for the years 2001-2016, whereas the averages relevant for sold cars in Europe are given for the years of 2004-2016. See table A1.2 and 3.5 respectively in EEA (2017). Furthermore, see table 1 for the estimated average masses of Swedish passenger cars per fuel technology and the estimated scaling factor between Swedish and European passenger car fleets.

Table 3. Calculated average masses for Swedish passenger cars per fuel technology and scaling factor.

Year	Average Mass Gasoline [kilo]	Average Mass Diesel [kilo]	Average Mass AFV [kilo]	Scaling factor
2001	1344	1580	1535	1.09
2002	1345	1584	1537	1.09
2003	1359	1602	1552	1.09
2004	1347	1593	1541	1.0891
2005	1339	1603	1522	1.0841
2006	1343	1628	1510	1.0845
2007	1346	1646	1385	1.0899
2008	1331	1634	1341	1.0838
2009	1344	1669	1303	1.1144
2010	1332	1654	1319	1.0975

2011	1327	1657	1382	1.0879
2012	1329	1679	1354	1.0856
2013	1332	1683	1415	1.0935
2014	1328	1670	1478	1.1004
2015	1342	1685	1579	1.1058
2016	1344	1676	1549	1.0939
2017	1345	1683	1550	1.09

Emissions factors

The emission factors calculated according to data from SEPA (2018a) are provided below in table 2. The emission factors calculated according to data from AoE (2015) are provided in table 3.

The biofuel shares for different year relevant for gasoline, diesel, vehicle gas and ethanol were acquired from AoE (2018;2017) as well as interpreted from SEPA (2017b). Values applicable before 2011 were missing in AoE (2018;2017) which is the reason of why the latter SEPA (2017b) was investigated. Information of the sustainable shares of biofuels per year of different biofuels in conventional fuels were also acquired in AoE (2018;2017) though only for 2011-2017. See table 4 below for the applied values in the model.

Table 4. Calculated emission factors with data from SEPA.

Year	Gasoline [kilo CO2/liter]	Diesel [kilo CO2/liter]
1999	2.36	2.54
2000	2.36	2.54
2001	2.35	2.54
2002	2.34	2.54
2003	2.33	2.54
2004	2.29	2.54
2005	2.29	2.54
2006	2.29	2.50
2007	2.29	2.47
2008	2.29	2.45
2009	2.28	2.43
2010	2.28	2.42
2011	2.28	2.39

2012	2.28	2.34
2013	2.28	2.26
2014	2.28	2.16
2015	2.28	2.04
2016	2.28	1.82
2017	2.28	1.82

Table 5. Calculated emission factors with data from AoE with the incorporation of the share of biomass.

Year	Gasoline [kilo CO2/liter]	Diesel [kilo CO2/liter]	E85 [kilo CO2/liter]	Vehicle Gas [kilo CO2/kilo gas]
1999	2.36	2.55	2.36	2.36
2000	2.36	2.55	2.36	2.36
2001	2.36	2.54	2.36	2.36
2002	2.34	2.54	2.34	1.96
2003	2.31	2.54	0.47	1.82
2004	2.27	2.54	0.47	1.72
2005	2.24	2.54	0.47	1.62
2006	2.24	2.50	0.47	1.29
2007	2.24	2.46	0.47	1.29
2008	2.24	2.46	0.47	1.29
2009	2.24	2.43	0.47	1.29
2010	2.24	2.43	0.47	1.29
2011	2.25	2.41	0.47	1.29
2012	2.25	2.35	0.47	0.99
2013	2.24	2.24	0.47	0.97
2014	2.24	2.21	0.45	0.71
2015	2.24	2.11	0.45	0.80
2016	2.24	2.01	0.45	0.49
2017	2.23	2.01	0.45	0.27

Table 6. Share of biomass with data from AoE and SEPA.

Year	Gasoline [%]	Diesel [%]	Ethanol/E85[%]	Vehicle Gas [%]
1999	0	0	0	0
2000	0	0	0	0
2001	0	0	0	0
2002	0.01	0	0	0.33
2003	0.02	0	0.8	0.37
2004	0.04	0	0.8	0.4
2005	0.05	0	0.8	0.43
2006	0.05	0.015	0.8	0.54
2007	0.05	0.03	0.8	0.54
2008	0.05	0.03	0.8	0.54
2009	0.05	0.045	0.8	0.54
2010	0.05	0.045	0.8	0.54
2011	0.047	0.052	0.8	0.54
2012	0.046	0.075	0.8	0.64
2013	0.051	0.12	0.8	0.65
2014	0.05	0.13	0.81	0.74
2015	0.049	0.17	0.81	0.71
2016	0.05	0.21	0.81	0.82
2017	0.056	0.21	0.81	0.90

Net calorific values

Net calorific values (NCV:s) of gasoline and diesel were acquired from SEPA (2018a) whereas the NCV:s of natural gas and biogas from AoE (2015). The NCV:s given in the different references were approximately equal. Additionally, for E85 the composition of the fuel changes between summer (E85) and winter (E75), so values from the Swedish Petroleum Biofuel Institute where both fuels are presented were applied (SPBI, 2017). See table 5 for the scaling factors derived with the NCV:s for gasoline, ethanol and vehicle gas to adjust the fuel economy due to biofuels. See table 6 for the calculated NCV:s for gasoline and vehicle gas in unit [GJ/kilo] exploited to derive the emission factor for vehicle gas in unit [kilo CO_2/kilo vehicle gas combusted].

Table 7. Scaling factors derived and applied to adjust the fuel economy due to biofuels.

Year	Gasoline	Ethanol/E85	Vehicle Gas
1999	1	NA	NA
2000	1	NA	NA
2001	1	1.41	NA
2002	1.004	1.41	0.8521
2003	1.007	1.41	0.8576
2004	1.014	1.41	0.8630
2005	1.018	1.41	0.8674
2006	1.018	1.41	0.8800
2007	1.018	1.41	0.8794
2008	1.018	1.41	0.8805
2009	1.018	1.41	0.8809
2010	1.018	1.41	0.8809
2011	1.017	1.41	0.8809
2012	1.017	1.41	0.8908
2013	1.019	1.41	0.8918
2014	1.018	1.41	0.9010
2015	1.017	1.41	0.8979
2016	1.018	1.41	0.9093
2017	1.020	1.41	0.9178

Table 8. Calculated NCV:s for gasoline and vehicle gas

Year	Gasoline [GJ/kilo]	Vehicle gas [GJ/kilo]
2002	0.0437	0.05130
2003	0.0437	0.0510
2004	0.0437	0.0506
2005	0.0437	0.0504
2006	0.0437	0.0497
2007	0.0437	0.0497
2008	0.0437	0.0496
2009	0.0437	0.0496
2010	0.0437	0.0496

2011	0.0437	0.0496
2012	0.0437	0.0491
2013	0.0437	0.0490
2014	0.0437	0.0485
2015	0.0437	0.0487
2016	0.0437	0.0481
2017	0.0437	0.0468

Correction due to car manufacturers

The applied correction for the study origin from the information given in section 4.2, where information from EEA (2016b), Fontaras et al. (2017) and Tietge et al. (2017) have been analyzed. See table 7 for the applied values in the study.

Table 9. Applied correction in the study

Year	Default	Minimum	Maximum
1999	1.025	1.025	1.025
2000	1.05	1.04	1.06
2001	1.075	1.055	1.095
2002	1.10	1.07	1.13
2003	1.125	1.085	1.165
2004	1.15	1.10	1.2
2005	1.175	1.115	1.235
2006	1.20	1.13	1.27
2007	1.225	1.145	1.305
2008	1.25	1.16	1.34
2009	1.275	1.175	1.375
2010	1.30	1.19	1.41
2011	1.325	1.205	1.445
2012	1.35	1.22	1.48
2013	1.375	1.235	1.515
2014	1.4	1.25	1.55
2015	1.425	1.265	1.585
2016	1.45	1.28	1.62

2017	1.475	1.295	1.665

Postal codes

The data constituted of values from the mandatory vehicle checks before TRAFA has modified it according to their estimation models. The data is therefore more uncertain than the main data of the study. The data originated from the Transportation Administration Board though provided from Martin Wetterstedt at Climate Change Leadership (CCL) that currently create carbon budgets in Sweden. To display the postal codes on the map, Google maps were exploited (https://www.google.com/maps), where the postal code under investigation was googled for. The information was thereafter manually transformed to the result presented in 6.3.1.

Population development in Järfälla

The data have been acquired from SCB (2019).

Fuel economy for gasoline-, ethanol and vehicle gas cars

Table 10. Fuel economy for gasoline-, ethanol and gas cars adjusted to account for the effect of biofuels.

Year	Gasoline [liter/100km]	Ethanol/E85 [liter/100km]	Vehicle Gas [kilo/100km]
2002	8.4	9.7	6.2
2003	8.4	9.7	5.9
2004	8.4	9.7	5.8
2005	8.2	11.1	5.7
2006	8.0	11.5	6.1
2007	7.9	11.3	6.1
2008	7.4	11.23	5.6
2009	6.9	11.1	4.8
2010	6.7	10.7	4.8
2011	6.5	10.1	4.9
2012	6.2	9.8	5.0
2013	5.9	9.1	4.8
2014	5.8	8.3	4.4
2015	5.6	7.6	4.0
2016	5.6	7.5	4.0
2017	5.7	7.5	4.0

Appendix D

The information presented here originates from TRAFA (2011) described in section 5.4.1.

Pre-requisites:

1) It was only the year of 2017 that was of interest in the model results and it was therefore critical to exploit the data to compile the traffic work of 2017 for all the included cars possible, including car characteristics needed for calculating the following CO_2 emissions.
2) If only one odometer reading is available it could imply the car is new registered, if so, M2 takes the value of the first reading, whereas M1 take the value of zero.
3) New registered cars are normally exempt from mandatory vehicle checks the first three years in traffic, which in 2017 was relevant for cars with a production year of 2018, 2017, 2016, 2015 and 2014. Cars produced between 2014-2018, while also having one mandatory vehicle check simultaneously as they have not been deregistered, were assumed directly imported or new depending on specific value. The traffic work in 2017 of these cars was estimated.
4) In general, deregistered, new registered, imported and cars with erroneous data are estimated by TRAFA. These cars, irrelevant of the exact classification, were problematic since they were missing the data of traffic work. Moreover, these cars constituted a too big part of the data file (e.g. >30 percent) and could therefore not be excluded. The traffic work in 2017 of these cars was estimated if possible, that is, if information of the production year was included.
5) All passenger cars produced before 1997 (e.g. older than 20 years) are missing from the file. These cars are believed to be given the production year of zero.
6) Cars can have multiple checks in one year since, for example, a car does not ‘pass’ the first check and has to fix the car and control the car a second time. If the number of days in between checks was less than 100, it was assumed to imply an abnormality with the car (e.g. checked multiple times during the year). The traffic work of these cars was then estimated instead of using the data from the odometer readings.
7) The traffic work of these cars was not assumed representative for the whole year of 2017 and were instead estimated.
8) Fuel technologies are specified in three columns: First fuel, secondary fuel and ‘third’ fuel though the last column is set to zero for all cars in the dataset. The fuel technologies are specified as: 1- gasoline, 2-diesel, 1-3-Electric, 2-3-hybrids (i.e. electric hybrid and PHEV), 1-7-E85 and 1-16-vehicle gas. The much valuable information was provided by Anette Myhr at TRAFA (A Myhr, Personal Communication, 2019). To separate PHEV from electric hybrid in the data, car models and other data need to be scrutinized. But due to the low number of PHEV:s in the main data of the thesis, they were assumed as electric hybrids here.
9) The traffic work was analyzed as given in unit [km].

10) Finally, the author of the study has not been in contact with the data provider as it was provided from Climate Change Leadership, which in turn had it delivered from the Transport Administration Board.

Cleaning of data

11) The methodology presented below should not be considered optimal in any way. Results were therefore compared with the estimate of 2017 calculated on the basis of the main data and additional quality checks were also performed, and are presented next:
    a. The estimate of 2017 was calculated on the basis of 34256 cars, whereas the results here included 26422 cars after all modifications; 26121/34256≈76 percent. The estimate of 2017 was calculated on the basis 420 574 220 km, whereas the result here included 372 668 146 km; 374 369 010/420 574 220≈89 percent. Hence, more cars in percent were missing than for the traffic work and this could imply the traffic work for the included cars was overestimated though not certain.
    b. The number of cars produced before 1997 was assumed to be given the production year zero in the postal code data. However, only 3641 cars in the main data were produced before 1997, while a total of 7834 cars were missing in the postal code data. Thus, another 4200 cars were missing. The performed cleaning removed 9260 rows (i.e. cars), 26 percent compared to the number in the original data. Thus, the cleaning of data could be improved, see point 19 further below.
    c. Post codes included; 85 postal codes were included after the first cleaning, a number that was after the cleaning reduced to 82. Hence, 82 out of 101-103 postal codes were included when estimating CO_2 emissions over postal codes in Järfälla.

The steps taken when the data was cleaned will next be presented.

12) Only rows relevant for Järfälla were of interest and other rows were removed; 35276 out of 35681 rows in the dataset remained.
13) The postal codes with relevance for Järfälla were identified from PostNord[10] with their search engine. The numbers of 17502, 17533, 17536, 17537, 17540, 17572, 17575, 17577, 17579 and 17710, i.e. ten numbers, were not relevant for Järfälla and therefore removed. 85 out of 101-103[11] postal codes were identified to be included in the data. It was assumed that no passenger cars were available for the postal codes not included in the data, but no knowledge of relevance had been acquired to support this.
14) Cars included, but deregistered before 2017-01-01 were removed; 1909 rows

[10] https://www.postnord.se/vara-verktyg/sok-postnummer-och-adress [2019-03-20].

[11] There are 100-102 postal numbers relevant for Järfälla, but no investigation of the correct number or the reason of why two different ranges are available, have been conducted.

15) For cars that were deregistered in 2017, the number of traffic days in 2017 was calculated as the difference between the deregister date and 2016-12-31.
16) Other cars, certain not to have been in traffic 2017, were removed according to the registration date. 1819 rows were removed due to a registration date after 2017-12-31. As such, cars produced in 2016, 2017 and 2018 with one mandatory vehicle check before 2018, though no value given there, were then also removed. These cars may have been in traffic 2017 and perhaps later sold, but these were still removed due to convenience.
17) Cars without two mandatory vehicle checks, simultaneously as the production year is zero, were removed since no traffic work could then be estimated; 34 rows were removed.
18) Cars without one odometer reading or without a datum for the mandatory vehicle check, simultaneously as they were given the production year zero, were removed since the traffic work could then not be estimated; 396 rows were removed.
19) Cars with less than 100 days in between checks were considered abnormal as well as the traffic work in between checks was assumed inaccurate for estimating traffic work of 2017; 4201 rows were removed due to this. With the benefit of hindsight, this point was analyzed as most relevant to improve.
20) Cars with a negative traffic work between checks imply an error with the odometer, and were instead given the value of zero to thereafter be estimated. However, cars with an erroneous traffic work between checks (e.g. zero or minus), simultaneously as the production year is zero, was removed since no estimation was possible; 71 rows were removed due to this.
21) For cars with a non-zero production year, while the odometer readings are missing was estimated according to the main data of the thesis. That is, cars produced in 2017 had a daily average traffic work in 2017 of 22km/day; 2016-45km/day; 2015-49km/day; 2014-50km/day; 2013-45km/day; 2012-42km/day; 2011-39km/day; 2010-35km/day; 2009-34km/day; 2008-33km/day; 2007-32km/day; 2006-30km/day; 2005-28km/day; 2004-27km/day; 2003-25km/day; 2002-24km/day; 2001-22km/day; 2000-21km/day; <2000-15km/day.
22) For cars with a larger value than 600km/day, the traffic work was set to the maximum value, i.e. 600km/day.
23) All values below one kilometer were assumed faulty (e.g. since the car need to be driven to the mandatory vehicle check) and instead estimated where it was possible according to the production year and otherwise removed; 288 rows were removed due to this.
24) The number of days in traffic in 2017 was calculated with the registration date, the deregistration date (where needed) and by the datum of 2016-12-31 and 2017-12-31.
25) The average traffic work per day was calculated by diving the total traffic work per car with the number of days in traffic or estimated where needed.
26) The CO_2 emissions were calculated by the exploiting information of the fuel technology, the fuel economy or, alternatively, the production year to elicit a value of the fuel economy (as conducted in the main model of the thesis). Cars with neither were excluded from the CO_2 calculation. The production year was also exploited for

eliciting a correction due to car manufacturers optimization, but cars without a production year was not corrected. The share of CO_2 emissions per postal codes were calculated to enable a scaling with the total CO_2 emissions calculated with the model structure with the primary data.

To conclude, the performed scaling was conducted to mitigate the non-optimal cleaning and any errors included in the results was therefore believed to possibly cancel out. However, the results must still be considered uncertain, for example, the missing postal codes in the original dataset may not be especially reasonable. Hence, results must therefore be validated with additional resources, e.g., local expertise or with expertise knowledge from TRAFA.

Appendix E

First, the information of the conducted validation of total model results is presented. Thereafter, the information exploited in the conducted validation of the fuel economy is presented.

The traffic work of Järfälla cars were disaggregated over mass-and car age classes as well as the fuel technology of cars. For this purpose, the cars' traffic work from Järfälla was categorized equally as the national data. The national traffic work per class were thereafter divided with the corresponding value for Järfälla to yield a relationship: If the value was over 100 percent, the national class conducts a higher traffic work compared to the corresponding class for Järfälla, and vice versa. Electric cars and PHEV:s were not included since their share of traffic work is under one percent for the whole timeseries. Finally, the year of 1999 was not included due to the data in TRAFA (2018).

Starting with the comparison of traffic work over fuel technologies. Gasoline and diesel cars combined conduct the dominant part of the traffic work in Järfälla and Sweden. For example, approximately 86 in Järfälla and 92 percent in Sweden in 2015, and 98 and 98 percent in 2006, respectively. Gasoline cars in 2006 represented 91 and 87 percent of the traffic work for Järfälla and Sweden respectively and in 2000 the equivalent values were 95 and 91 percent and thereby illustrate gasoline cars dominance back in time. In 2015, however, the share of diesel cars amounted to around 34 for Järfälla and 40 percent for Sweden as a whole. The importance of diesel cars in the comparison therefore increased over time. The comparison illustrated that Järfälla for the whole study period had a lower share of diesel cars, but a higher share of gasoline cars up until 2015. Diesel cars have substantially lower CO_2 emissions per kilometer driven than gasoline cars as analyzed from official data of the fuel economy (Trafikverket, 2018a; SCB, 2017b) and the emission factors given in SEPA (2018a). The emission factors from HBEFA were analyzed to underestimate CO_2 emissions between 1999-2014, but due to the increasing similarity of diesel cars over time, the underestimation was assumed to decreases over time. In 2015, the difference between diesel cars for Järfälla and Sweden was approximately compensated by higher shares of ethanol-, gas- and electric hybrid cars for Järfälla. The traffic work of these alternating cars implied the possibility of factors from HBEFA will overestimate emissions after 2015. See figure V for the comparison of fuel technology below.

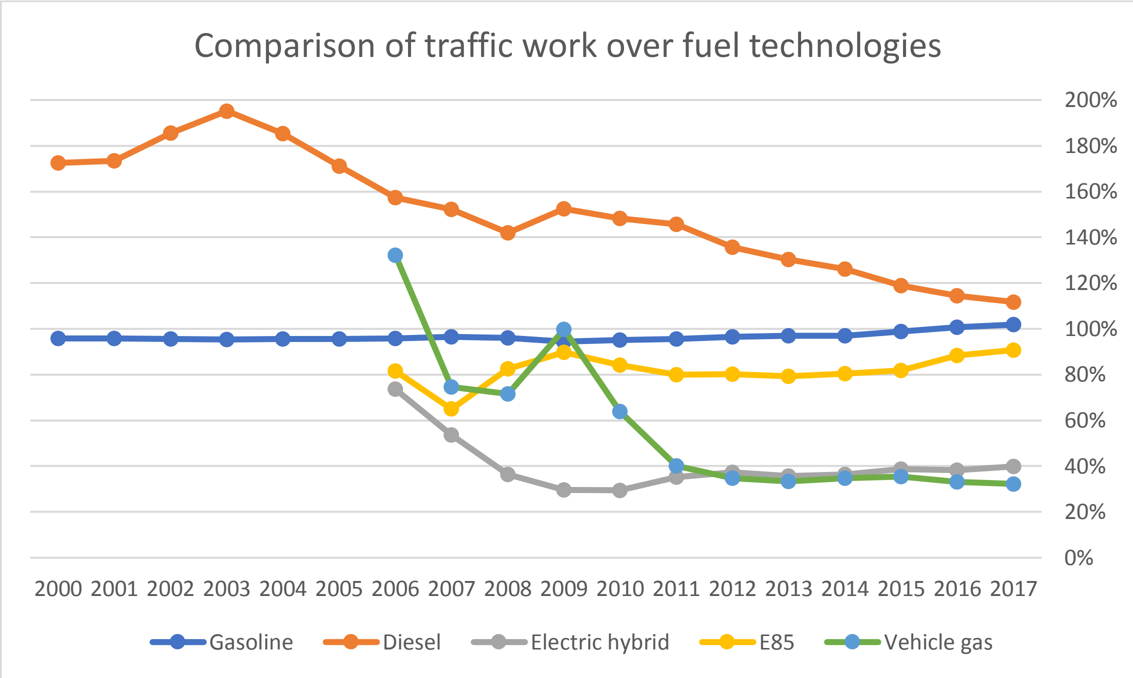

Figure V. Comparison of traffic work over fuel technologies. See description under chart for description of the included curves. Diesel cars had decreased the difference, from over 160 percent in 2000 to a little over 110 percent in 2017, though observe the difference was 195 percent in 2003. Gasoline cars started in 2000 with a similarity of 96 percent, which have increased to 102 percent in 2017. The similarity of E85 cars varied between 2006 and 2009 (e.g. 82-90 percent), though fairly static thereafter to 2017, the similarity was 91 percent in 2017. Electric hybrids have diverged from the national fleet, from 74 percent in 2006 to 40 percent in 2017. Finally, vehicle gas started at 132 percent in 2006, but decreased to 32 percent in 2017. The data originated from TRAFA (2018a) and TRAFA (2018b).

Newer cars have lower CO_2 emissions compared to older cars (VTI, 2017; EEA, 2017b). The comparison of traffic work over car age classes illustrated clearly how a larger share of the traffic work of cars from Järälla was conducted by newer cars compared to the national average. A trend indicating a higher similarity over time was also identified. HBEFA was therefore analyzed to overestimate results for the whole period, but with a smaller impact over time. Observe, though, that newer cars which are heavier than older cars, may still result in larger emissions per kilometer. See figure W below.

	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
CY<-17	168%	171%	171%	171%	158%	165%	167%	161%	158%	160%	168%	167%	173%	180%	184%	184%	214%	180%
CY-17	128%	132%	133%	129%	150%	139%	151%	160%	146%	146%	160%	156%	144%	148%	178%	172%	189%	177%
CY-16	128%	117%	124%	130%	132%	150%	126%	145%	134%	148%	138%	148%	156%	141%	140%	165%	157%	156%
CY-15	123%	123%	111%	117%	121%	123%	138%	127%	139%	139%	145%	132%	136%	149%	141%	140%	150%	143%
CY-14	121%	119%	113%		112%	119%	124%	129%	122%	130%	145%	134%	128%	130%	139%	130%	128%	135%
CY-13	109%	118%	112%	108%		106%	116%	117%	128%	110%	127%	142%	144%	130%	124%	134%	117%	121%
CY-12	107%	107%	106%		109%			109%	115%	125%	110%	115%	137%	137%	118%	115%	122%	112%
CY-11	106%					107%				116%	117%	108%	110%	131%	132%	116%	107%	115%
CY-10	108%							92%		107%	112%	116%			128%	122%	108%	
CY-9		106%							88%			107%	110%	110%		120%	115%	
CY-8					94%	93%		90%	91%	89%	92%	94%		108%			116%	106%
CY-7						94%	92%		89%	91%	83%	86%	92%		107%		94%	106%
CY-6	91%	94%	88%	92%		91%	90%	91%		88%	85%	81%	84%	87%			93%	90%
CY-5	84%	85%	85%	85%	86%	90%	87%	82%	87%	90%	82%	81%	75%	81%	83%	92%	94%	88%
CY-4	76%	83%	83%	84%	82%	87%	90%	85%	84%	85%	91%	81%	78%	74%	79%	81%	86%	89%
CY-3	75%	76%	86%	90%	84%	89%	91%	92%	86%	85%	90%	88%	83%	81%	77%	79%	80%	89%
CY-2	92%	86%	93%			87%	92%	93%		86%	90%	88%	90%	87%	86%	76%	80%	80%
CY-1							94%				91%			93%	82%	84%	77%	81%
Calender Year	123%			87%	114%	110%	110%	110%	157%	114%	120%	115%	114%	116%	107%	89%	91%	83%

Figure W. The figure was used in the comparison of traffic work over car age classes, referring to Järfälla's passenger car fleet with the national car fleet. The top column represents the calendar year, where the left column represents the car age classes. The green squares represent fairly equal values, i.e. they do not diverge by more than five percent. The figure clearly illustrated values over 100 percent was biased to the top and vice versa.

There were noticeable differences in relation to differences in relation to the mass, but the comparison was less distinct compared to the car ages above due to a more spread result. There were differences relevant for both lighter and heavier classes not possible to analyze in combination and no overarching systematic difference possible to exploit was identified. See figure X

Similarity	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
≤900	123%	114%	121%			106%	107%	112%	111%		111%	118%	116%	123%	107%	112%		
901-1000	93%	93%	91%	90%	92%	91%		94%	94%	94%					110%	112%	116%	111%
1001-1100		93%	91%	91%	93%		93%	91%										
1101-1200	93%		93%	90%	90%	91%	93%											
1201-1300												94%						
1301-1400	94%	94%	94%	92%	94%	93%	90%	90%	89%	91%	94%							
1401-1500			107%		107%	108%	108%	107%		107%								
1501-1600	109%	107%		107%	106%					107%	108%						93%	93%
1601-1700	109%	106%	106%													92%	94%	
1701-2000					109%	110%	110%					91%	90%	88%	91%	93%	91%	88%
2001-2500	91%	89%	91%		93%	87%				113%	114%	116%	117%	119%	120%	130%	124%	134%
2501-3000	52%	58%	53%	54%	58%	65%		117%	129%	139%	134%	88%	89%				90%	85%
>3000	172%	211%	184%	152%	149%	131%	157%	126%	133%	123%	120%	117%	208%	245%	218%	234%	243%	211%

Figure X. The figure was used in the comparison of traffic work over mass classes, referring to Järfälla's passenger car fleet with the national car fleet. The top column represents the calendar year, where the left column represents the mass classes. The green squares represent fairly equal values, i.e. they do not diverge by more than five percent. No significant pattern was identified in the figure.

The identified difference in car age was however assumed to be of lesser importance than the identified difference in fuel technology since it also depends on the fuel technology. To elaborate, if an arbitrary car is replaced by a newer car while the mass is equal, the fuel economy may not be reduced if the fuel technology changes to gasoline. Additionally, the fuel economy also depends on how new the car is relative to the older one since improvements cannot be taken for granted over small time periods like three years; but if the fuel technology of an arbitrary car is changed from gasoline to diesel, given that the mass is equal, the fuel economy will be reduced more certainly. The more certain impact can be understood since diesel cars then, due to the combustion technique, are more efficient than gasoline cars, and, it is more prevalent to switch to newer cars compared to switching to (much) older cars. Hence, the impact of car age was analyzed as more dependent on the fuel technology than what the latter is of the former, referring to the impact on CO_2 emissions.

Validation of fuel economies:

Järfälla's car fleet was heavier than the average national mass and especially so for gasoline cars. Diesel cars were heavier starting from 2014, though the masses of the increment of diesel cars for 2012-2016 were heavier than the average mass. Järfälla's new gasoline and diesel cars were therefore deemed likely to be heavier on average compared with the national data of new cars. Moreover, it seemed unlikely that the individual fuel economies for a specific municipality like Järfälla would be identical to the national average. See figure Y, Z and Å below.

# Gasoline	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999
<=900	148	157	186	212	232	255	271	289	319	399	425	485	558	633	749	851	986	1165	1287
901-1000	710	709	685	687	687	698	682	700	706	717	723	766	853	876	963	1088	1218	1337	1460
1001-1100	1510	1614	1677	1721	1725	1798	1827	1957	1993	1991	2019	2084	2176	2276	2359	2480	2635	2591	2626
1101-1200	2632	2584	2492	2468	2406	2365	2421	2480	2455	2495	2534	2613	2705	2779	2820	2829	2892	2897	2936
1201-1300	2346	2339	2354	2252	2253	2313	2426	2531	2622	2721	2767	2865	2932	3017	3028	3005	2943	3011	3029
1301-1400	3408	3492	3471	3485	3536	3707	3883	4000	4107	4237	4270	4271	4358	4437	4386	4607	4478	4471	4213
1401-1500	2699	2811	2871	2929	3108	3281	3486	3681	3938	4066	4211	4266	4349	4447	4547	4446	4259	4190	4136
1501-1600	3112	3345	3354	3409	3437	3553	3785	3803	3761	3692	3566	3494	3314	3070	2868	2648	2408	2196	1953
1601-1700	2127	2196	2232	2242	2282	2342	2366	2339	2352	2343	2299	2227	2077	1923	1676	1405	1079	816	565
1701-2000	1333	1370	1431	1491	1540	1615	1666	1703	1715	1666	1666	1641	1572	1463	1311	1159	994	857	676
2001-2500	358	384	406	369	363	393	393	382	403	346	319	287	275	250	212	161	138	124	121
2501-3000	28	31	30	30	25	30	28	28	31	25	33	27	27	27	25	19	11	9	12
>3000	2	2	3	3	2	3	4	4	4	5	3	0	0	0	0	0	0	0	0

Figure Y. The figure illustrates the number of gasoline cars over mass classes. The top column represents the calendar year and the left column represents the mass classes. By comparing the development of cars above and below the mass class of 1301-1400, the figure was analyzed as gasoline cars had become heavier since 2003.

# Diesel	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999
<=900	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
901-1000	2	3	4	4	3	4	4	10	11	12	9	8	8	8	6	8	12	11	15
1001-1100	9	11	7	8	11	15	15	11	7	3	4	9	7	4	7	7	9	9	7
1101-1200	115	127	123	130	137	138	105	65	59	38	36	25	25	28	30	33	36	33	32
1201-1300	163	167	138	127	104	93	81	62	54	55	45	34	27	25	31	35	37	42	36
1301-1400	633	626	607	517	409	391	303	194	134	87	71	52	46	47	64	68	64	62	62
1401-1500	1244	1257	1002	941	699	549	444	277	201	187	145	93	99	85	77	90	93	93	91
1501-1600	1205	1131	981	793	703	576	470	390	326	221	155	115	104	100	83	109	93	88	74
1601-1700	1850	1713	1498	1239	1090	893	722	620	447	417	316	191	99	82	77	79	74	80	73
1701-2000	4014	3321	2536	1856	1393	1097	840	659	444	392	298	205	152	141	122	97	84	71	69
2001-2500	815	660	479	376	311	253	219	257	216	130	115	73	55	41	35	31	27	24	13
2501-3000	213	157	137	125	101	92	60	56	37	30	23	14	14	5	4	4	5	4	5
>3000	138	123	104	100	91	74	61	56	41	32	22	7	1	1	1	1	1	1	1
unknown																			

Figure Z. The figure illustrates the number of diesel cars over mass classes. The top column represents the calendar year and the left column represents the mass classes. By comparing the development of cars above and below the mass class 1601-1700, the figure was analyzed as that diesel cars started becoming heavier in 2014 and onwards.

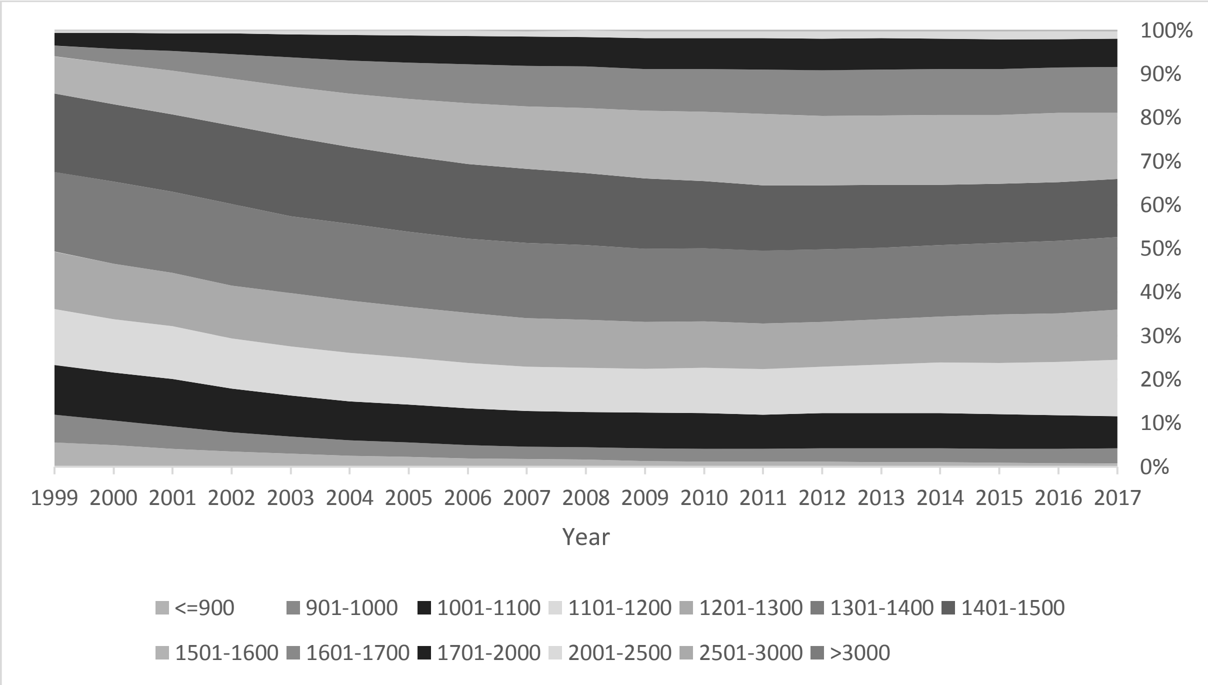

Figure Å. The figure illustrates gasoline cars, with masses over the national average mass (i.e. 1310-1346 kilos for gasoline cars) had increased its share of the traffic work during the study period. From around 35 percent in 1999 to over 45 percent in 2017.