

Achieving Zero Emission Transportation in a Regional Perspective

Addressing Municipal Climate Goals in Umeå

Master's thesis in Master Programme Sustainable Energy Systems

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Cover: A complex transportation system transforming from polluting fossil based cars to greener alternatives. What changes until 2040? Made by Joel Amrén and Johannes Hedfors.

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Abstract

Climate goals have been adopted on multiple different levels in society to limit global warming according to the Paris Agreement. The municipality of Umeå has set a goal of reaching net zero emissions by 2040, where 41 % of the current emissions come from the transportation sector. Even though the municipality has set the goal of mitigating emissions, only a fraction of the emissions is directly emitted by the municipality organization. Abatement measures must be implemented to reach the climate goal, but the understanding of their impact on the system is lacking. In the thesis, abatement measures for the transportation sector in Umeå are identified and characterised based on their cost, abatement potential, and how they abate the emissions. The dynamics between the measures are visualised in Marginal Abatement Cost curves. The visualisation highlights that the conditions of abatement measures are impacted depending on which other measures have been implemented and in what manner they reduce the emissions. This highlights the importance of the order of implementation as well as the allocation of abatement potential to reduce the risk of double counting, especially when a combination of abatement measures is implemented. Furthermore, it is difficult to quantify the cost and abatement potential of measures that depend on a change of behaviour due to the uncertainty of the impact, but the abatement potentials of these measures are generally smaller in comparison to cost-driven measures. Other dimensions can however make behaviour change measures important to invest in. The municipality has to motivate other actors to reduce their emissions while simultaneously reducing the emissions of the municipality's own organisation, in order to reach its climate goal.

Keywords: Abatement measure, MAC-curve, Transportation, GHG emissions, Governance, Municipality, Measure dynamics, Complexity, Climate goals.

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Johannes Hedfors & Joel Amrén, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AD	Average distance
BEV	Battery electric vehicle
E	Emissions
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gases
HDV	Heavy duty vehicle
ICEV-d	Internal combustion engine vehicle - diesel
ICEV-g	Internal combustion engine vehicle - gasoline
LDV	Light duty vehicle
MAC	Marginal abatement cost
MM	Mopeds and motorbikes
PC	Passenger car
PHEV	Plug-in hybrid electric vehicle
TCO	Annualized total cost of ownership
TD	Transportation demand
TES	Transport efficient society
vkm	Vehicle kilometer
VT	Vehicle type

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1

Introduction

1.1 Background

Global warming is a problem that has gained attention during the last few decades. Humans produce Green House Gas (GHG) emissions at a rate that increases the temperature of the planet, rapidly approaching the limit of 1.5 °C of the Paris Agreement [1]. To tackle this problem, many countries have endorsed environmental goals to limit their emissions. Sweden has adopted the goal to reach net zero emissions by 2045 [2]. However, on a local scale, many municipalities have adopted climate goals of their own to act as front runners against climate change, ahead of the national goals (e.g. Gothenburg [3], Lund [4] and Uppsala [5]). The municipality of Umeå has established a goal to reach net zero emissions within the geographic area of the municipality by 2040 [6], 5 years ahead of the Swedish national goals. The municipality also has a vision that the population will reach 200 000 by 2050 [7] compared to roughly 129 000 inhabitants in 2019 [8]. Thus, the municipalities have to address how to reach their climate goals while still reaching their growth targets.

Both globally and locally in Umeå, the transportation sector account for a big part of the total GHG emissions at 15-20% globally [9]–[11] and 41% in Umeå 2020 [12]. Emissions from transportation are difficult to reduce due to their diffuse nature, which means that the emissions are spread out in numerous diluted sources. This is unlike point sources, such as industries, that have a high concentration of GHG emissions in a few sources, and therefore easier to capture. The combination of diffuse emissions with a big overall share of the total emissions makes the transition of this sector problematic and therefore important to study.

The challenge with the environmental problem is further magnified by being a societal problem, which by definition is classified as wicked [13]. Wicked problems exist in systems that consist of interconnected pieces, pieces that change the dynamics of the whole system over time. The relationships between the pieces are also not linear which makes solving and mapping of the system nontrivial.

An important aspect that municipalities need to consider in their work toward reaching their climate goals is governance. Governance means how a municipality or company can create change. There are four different modes of governance according to

Bulkeley and Kern [14]. Firstly, self-governance. This is where the municipality has total control of the actions since it is within its own operation. Secondly, governing by provision, which is when the entity provides services and resources that enable the public to make better choices. Thirdly, governing by authority, which is the creation of rules and regulations to steer the public and companies. Finally, governing through enabling means that the municipality uses information or persuasion to steer the choices of another actor.

The challenge of municipal governance has been brought forward by multiple municipalities. The lack of governance within measures that try to change behaviour is highlighted by the municipality of Malmö [15]. The municipality of Umeå points out that there exists a big challenge in the fact that the governance of measures is spread out between many stakeholders [16]. A report that was prepared on behalf of the municipality of Norrköping highlights the challenge of where emissions are accounted for compared to what actor can change the emissions in terms of governance [17]. The topic of governance is therefore highly important for the environmental work of municipalities and a topic where more knowledge is needed.

Another challenge that exists is that the definition of emissions can vary. For example, it can include only CO₂ or all GHG emissions (CO_{2e}). It can also be defined as scope 1-3 [18] or life cycle analysis (LCA) emissions [19]. *Scope 1* includes direct GHG emissions from the source, such as the combustion of fossil fuel [18]. *Scope 2* includes the indirect emissions coupled to the use of energy, an example of this is the GHG emissions from electricity production when using an electric appliance. *Scope 3* includes all other GHG emissions that arise from an action, such as trash created by a company which later will cause emissions when combusted. Lastly, LCA emissions, include the GHG emissions of the entire life cycle of a product [19]. For example, the life cycle of an electric vehicle, where the emissions of the material used, production phase, use phase, and end of life of the vehicle are accounted for. A conscious choice of what emissions a municipality should include in its environmental goals is therefore highly important.

There are a number of tools that municipalities utilise in their work with their environmental goals. Tools that are publicly available are for example *ClimateOS*, *Kolada*, and *Klimatkollen*. These specific tools are all used by Umeå [20]–[22] but also many others (e.g. Borås [23] and Helsingborg [24]). *ClimateOS* is a tool that is used to visualize the current emissions of the municipality and the goals as well as different actions that are taken towards these goals [20]. *Kolada* is a database which catalog environmental key values of municipals [25]. The database also includes a tool that can be used to compare different key values between municipalities. *Klimatkollen* provides municipal carbon budgets for all municipalities in Sweden based on national and environmental data from national databases [26]. However, the tools and methods used by municipalities today do not help them prioritize between measures.

One method that does focus on measures is Marginal Abatement Cost-curves (MAC-

curves), but this method has not been used on a municipal level in Sweden before. MAC-curves has been used as a policy tool on both national and city scale [27]–[31]. The function of MAC-curves is to identify emission abatement measures as well as costs and abatement potentials for these measures [27], [28], [30]–[34]. MAC-curves were popularized by McKinsey in 2007 [31], [33] who made one expert-based MAC-curve on a global scale and 14 on a national scale [32]. Expert-based MAC-curves are based on expert assumptions for the input data [35], examples of expert-based MAC-curves are [28], [29], [36]. The abatement measures of expert-based MAC-curves are summarized under one average price and do traditionally not include factors such as behaviour change and interactions between measures. This leads to simplification of the measures as it is presented under a single cost which in reality is far from the truth [33].

In 2021, Evolved Energy Research (EER) created a model-based MAC-curve (MAC 2.0), which focused on catching the dynamic of the measures and the synergies between sectors [31]. The system investigated was the energy sector of the USA. Model-based MAC-curves use a model to calculate the costs and emission reduction potentials [30], [31], [33]–[35]. To incorporate the dynamics of the system EER created an iterative process with how the system changed after implementing the least cost measure [31].

The municipality organisation has set up ambitious climate goals, which require a transition to sustainable transportation. However, the transition is a wicked problem with multiple actors and abatement measures. Prioritisation between measures is essential to reach the goal. Therefore, MAC-curves could be a part of the prioritisation by visualising the potential of different measures.

1.2 Aim

The aim of the study is to identify and analyse abatement measures to highlight the complex connections between them. Furthermore, the outcome of the thesis provides insights into the consequences of different choices a municipality like Umeå can make in their work towards reaching their climate goals.

The methodology used in the thesis will be applied to a specific climate goal, which in this thesis is the goal of reaching net zero emissions within the geographic area of the municipality of Umeå by 2040 [6]. The methodology will focus on reducing scope 1 emissions within the transportation sector. This includes the tailpipe GHG emissions from the combustion of fossil fuels.

Therefore, the research questions that will be answered are:

1. How can different abatement measures be characterised, summarised, and visualised in a way that also includes outlining the dynamics between them?
 - What abatement measures are available?

1. Introduction

- What are the abatement potentials for the measures?
 - What is the cost of implementing the measures?
 - Which emissions do the measures affect?
 - In what manner does the measure affect the system?
 - How can the potentials and costs of abatement measures be comparably summarised with regard to their characteristics?
 - How can the measures be visualised in a way that is easily understood?
2. What challenges do municipalities face in their work toward reaching their climate goals?
- How does the choice of system boundaries and investigated dimensions affect the result?
 - What role does the governance of the municipality organisation have in achieving the climate goals?

2

Method

This chapter describes the general approach of the methodology to summarise, visualise (Section 2.1) and characterise (Section 2.2) abatement measures for the transportation sector of Umeå. Furthermore, this is followed by a list of identified measures (Section 2.3). The specific data, assumptions, and calculations made for the case of Umeå are described for the identified measures (Section 2.4). The measures are compiled in the List of Abatement Measures (Section 2.5). Finally, a scenario analysis to visualise the dynamics between measures in the system is described (Section 2.6).

2.1 Summarisation and Visualisation

The summarisation and visualisation of the abatement measures were done by utilising the construction of MAC-curves. The MAC-curves that were constructed in this thesis are expert-based. However, the measures were investigated as if they were implemented by themselves. Therefore the cumulative abatement potential of all measures was not limited by the total emissions of the system. Furthermore, inspiration of the iterative process of MAC 2.0 [31] was used to visualise the measure dynamics through scenarios.

Two specific values are required to construct a MAC-curve. The general equations of these are shown below.

$$MAC_i = \frac{\Delta C_i}{\Delta E_i} = \frac{(C_i - C_{ref})}{(E_{ref} - E_i)} \quad (2.1)$$

$$\Delta E_i = E_{ref} - E_i \quad (2.2)$$

Equation 2.1 is the basis for the y-axis of each abatement measure. Here, C_i refers to the annualized total cost of ownership (TCO) of abatement measure i . C_{ref} refers to the annualised TCO of the system if the measure would not be implemented. All of the costs are from a system perspective, and thus the costs of for example a citizen

and the municipality are not separated. E_{ref} is the emission of the system before a measure is implemented, and E_i refers to the emissions left in the system when measure i has been implemented. Equation 2.2 is used as the basis for the x-axis of the MAC-curve. When MAC_i and ΔE_i have been calculated, a MAC-curve is created by sorting the measures from lowest to highest MAC , creating a curve as shown in Figure 2.1. A negative MAC means that the measure would result in cost savings while a positive MAC indicates that implementation of the measure would lead to additional cost compared to if no change was made to the transportation system.

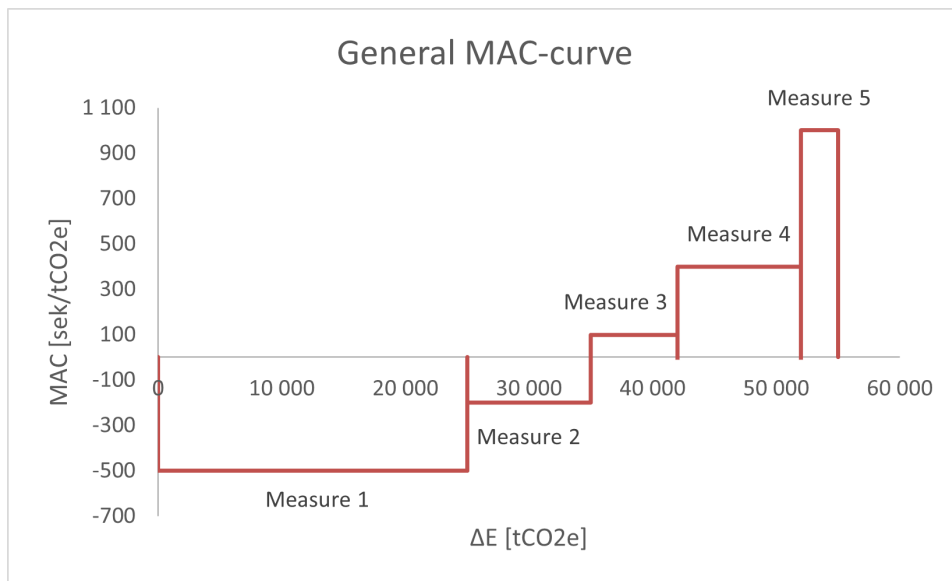


Figure 2.1: General appearance of an expert-based MAC-curve

2.2 Characterising Abatement Measures

However, to be able to calculate the MAC_i and ΔE_i of the measures, the characterisation of the measures has to be performed. In the following subsections, the methodology of the characterisation will be described more in detail. The 3 main parts of the characterisation of abatement measures were:

- Mapping of the Current System
- The Reference system
- List of Possible Abatement Measures

2.2.1 Mapping of the Current System

The current system is used as the basis of the calculations. It is important to get an understanding of how the system is built today in order to find what measures can be used and what the costs and abatement potentials for these measures are.

Three main key values were identified for the transportation system that acts as the foundation for the current system. These are Vehicle type (VT), Emissions (E), and Transportation Demand (TD). Respectively, the key values explain the composition of the vehicle fleet, the amount of direct emissions in the geographical area chosen in the thesis, and the yearly vehicle kilometers (vkm) driven by each vehicle type. These key values were chosen to describe the current system by highlighting how the different measures interact with the transportation system. Each of these key values can be further expanded by adding layers of detail to more accurately describe the current system.

TD and E are connected using emission factors (EF) which describe the amount of emissions a vehicle produce per distance traveled. This connection is illustrated in Equation 2.3.

$$TD_{VT} = \frac{E_{VT}}{EF_{VT}} \quad (2.3)$$

2.2.2 The Reference System

The reference system is a description of the system at a specific point in time, typically the point in time where the environmental goal that is studied is set to. Assumptions are made of how the system changes from the current system until this point in time to construct the reference system. Different scenarios can then be constructed by adding, removing, and adjusting the assumptions.

The reference system is the foundation that the measures are compared to. For example, a measure like the electrification of passenger cars requires the number of cars that can be electrified. Thus, an assumption can be done of how many diesel or gasoline cars exist in the reference case, typically by finding the number of existing cars in the current system and adjusting this number as seen fit. The cost of replacing these cars can then be calculated by comparing the investment cost of electric cars to the fossil cars defined by the reference system.

Creation of the reference system in this way is an iterative process. It changes as more dimensions of the measures and more complexity is added or removed. Thus, it should be seen as moldable to the needs that arise, while the current system is static.

2.2.3 List of Potential Abatement Measures

The list of potential abatement measures shows all identified measures in the scope of the thesis that can be applied in the system. It is used to store the data and characteristics of the measures that are required to construct the MAC-curve and to analyse the results. Table 2.1 list the characteristics that were identified as useful for this process.

2. Method

E_{VT} *affected* denotes the vehicle emissions which each measure affects, and together with *Maximum abatement potential* acts as the basis to calculate ΔE_i . *How it affects* E_{VT} is used to describe how the measure changes the system when it is implemented.

Table 2.1: Categories and parameters that are used to characterise abatement measures.

Category name	Category parameter
Abatement measure	Name of measure
E_{VT} affected	Passenger cars (PC) Heavy duty vehicle (HDV) Light duty vehicle (LDV) Busses Mopeds and motorcycles (MM) Domestic civil seafaring Domestic flight Railway traffic
How it affects E_{VT} [37]	Improve - Decrease EF Shift - TD shift between two VT Avoid - Decrease TD
Governance	Direct governance Indirect governance No governance
Maximum abatement potential	% of emissions that the measure can abate
ΔE_i	Amount of emissions that measure i can abate tCO _{2e}
MAC _{i}	Abatement cost of measure i sek/tCO _{2e}

The categories of *Improve*, *Shift* and *Avoid* were chosen to describe the effect that the measures have within the model of the thesis. These categories are adapted from Martin et al. [37], but slightly modified to fit the model of the thesis. Within the categories, different types of measures are lumped together in what ways they affect the system of the thesis. These lumps and what measures they include are presented below.

Improve:

- Technology switch - Replacement of fossil-based technology by renewable alternative. E.g. switch to electric or hydrogen vehicles from diesel/petrol.
- Energy efficiency - Increase in the energy efficiency of engines or general mode of transfer. E.g. through improved aerodynamics or improved engine design.
- Fuel switch - Replacement of fossil fuel with a renewable alternative without switching technology. E.g. switch to HVO100 from diesel.

Shift:

- Modal shift of transportation demand between two different vehicle types. E.g. shift from passenger cars to busses.

Avoid:

- Transportation need - Reduction of the overall need for transportation. E.g. through working from home or densification of cities.
- Occupancy rate - The occupancy rate of vehicles increases, thus the same amount of people or goods are transported but with fewer total vkm. E.g. Ridesharing and carpooling or logistics solutions for HDV.

The final part of the characterisation was an evaluation of what type of governance the municipality organisation has of each measure. Three different levels of governance were defined for the thesis based on the four modes of governance put forward by Bulkeley and Kern [14]; direct, indirect, and no governance. Direct governance includes self-governance, and thus all measures that affect only the municipality organisation's own operations. Indirect governance includes the last three modes; governing by provision, governing by authority, and governing through enabling. Thus, indirect governance means generating emission reduction outside of the municipality organisation itself. Finally, no governance includes the measures that the municipality organisation cannot affect in any way.

2.3 List of Identified Abatement Measures

The list below shows the identified abatement measures that are available for the transportation sector. The measures were identified by brainstorming between the authors of the thesis with the exception of the measures *Densification*, *Enforcing speed limits*, and *Logistics solutions*, which were found in literature.

The measures are divided into the three types of effects a measure has on the system, *Improve*, *Avoid*, and *Shift*. The amount of data found differed greatly between measures as indicated by the column *Successfully connected to data?*. Furthermore, the time for gathering data was a limiting factor. The measures limited by time are denoted *out of scope*. Therefore, only the measures that were successfully connected to data are further presented.

Table 2.2: Identified abatement measures for the transportation sector.

Abatement measure	E_{VT} affected	Successfully connected to data?
Improve		
BEV _{Aircraft}	Domestic flight	Out of scope
BEV _{Busses}	Busses	Out of scope
BEV _{HDV}	HDV	Yes
BEV _{LDV}	LDV	Out of scope
BEV _{MM}	MM	Out of scope
BEV _{PC}	PC	Yes
FCEV _{HDV}	HDV	Yes
FCEV _{LDV}	LDV	Out of scope
FCEV _{PC}	PC	Yes
PHEV _{PC}	PC	Yes
Biofuel (HVO100)	ICEV-d PC	Yes
Enforcing speed limits [38]	HDV	Out of scope
Improved efficiency of aircraft	Domestic flight	Out of scope
Improved efficiency of busses	Busses	Out of scope
Improved efficiency of MM	MM	Out of scope
Improved efficiency of PC	PC	Out of scope
Improved efficiency of vehicle	LDV, HDV	Out of scope
Avoid		
Ridesharing and carpooling	PC	Yes
Densification [39]	PC	Yes
Logistics solutions [40]	LDV, HDV	No data
Working from home	PC	Yes
Shift		
Busses to Bicycling/walking	Busses	No data
Domestic flight to train	Domestic flight	Out of scope
LDV/HDV to train	LDV, HDV	Yes
PC to biking/walking	PC	No data
PC to busses	PC	No data

Abbreviations: Battery electric vehicle (BEV), Fuel cell electric vehicle (FCEV), Plug-in hybrid electric vehicle (PHEV), Heavy duty vehicle (HDV), Light duty vehicle (LDV), Mopeds and motorbikes (MM), Passenger cars (PC), Internal combustion engine vehicle diesel (ICEV-d).

2.4 Assumptions & Data

This section describes the assumptions, data, and equations that were used to find MAC_i of the identified abatement measures for the reference case of Umeå.

2.4.1 The Current System of Umeå

The main assumptions of the current system were:

- The emissions and vehicle kilometers of pre-covid are used to reflect the current system, emissions data from the turn of the year 2019/2020 has been used.
- Diesel and gasoline cars are assumed to account for all registered emissions of the municipality (90% of registered passenger cars in Umeå are diesel or gasoline cars [41]).
- The yearly vehicle kilometers of Umeå registered vehicles is applicable for all emissions. Bypassing traffic is assumed to be driven the same way as Umeå registered vehicles.
- Heavy duty vehicles (HDV) are limited to ICEV-d. (97% of registered HDV in Umeå are ICEV-d [41]).

Data was used from SMED and HBEFA to describe VT, E, and EF for Umeå [12], [42]. These key values were used to calculate TD for each VT using Equation 2.3. The results can be seen in Table 2.3.

Table 2.3: Data for Emissions (E), Transportation Demand (TD), and Emission Factors (EF) for the current system.

Vehicle type	E [tCO _{2e}] [12]	TD [vkm] Eq. 2.3	EF [gCO _{2e} /vkm] [42]
Passenger cars	96 659	652 347 321	Diesel: 134 Gasoline: 165
Heavy duty vehicle	25 132	39 869 711	634
Light duty vehicle	13 062	92 353 782	141
Busses	2 245	9 876 847	227
Mopeds and motorcycles	788	7 547 945	104
Domestic civil seafaring	6 538	-	^a
Domestic flight	16 627	-	^a
Railway traffic	171	-	^a

^aEF excluded due to not existing in the HBEFA database [42]. Complementary calculations of the emissions from these vehicle types were not performed since measures for these vehicles were not explored.

To achieve further resolution of the current system, the passenger cars were split up into gasoline (ICEV-g) and diesel (ICEV-d). The split was done by using local data from passenger cars registered in Umeå [41] which can be seen in Table 2.4. The following equations were used to define the total yearly kilometers (*TYK*) and the average distance per individual vehicle (*AD*).

$$TYK = \frac{FPC * P}{F} \quad (2.4)$$

$$AD = \frac{TYK}{n_{PC}} \quad (2.5)$$

Here, FPC is the fuel consumption per capita, P is the population size, F is the average fuel consumption of diesel or gasoline cars in l/vkm and n_{PC} is the number of passenger cars in Umeå.

With the calculated data for Umeå registered PCs, it was applied on the total emissions of PCs shown in Table 2.3. This was used in combination with the equations 2.6 & 2.7 to find E_{ICEV-g} and E_{ICEV-d} respectively. Furthermore, TD was calculated using Equation 2.3. The result of these calculations is listed in Table 2.3.

$$E_{ICEV-g} = \frac{E_{PC}}{\left(\frac{TYK_d}{TYK_g} * \frac{1}{EF_g}\right) * EF_d + 1} \quad (2.6)$$

$$E_{ICEV-d} = E_{PC} - E_{ICEV-g} \quad (2.7)$$

Table 2.4: Data from Umeå registered gasoline (ICEV-g) and diesel (ICEV-d) passenger cars (PC).

Metric	Abbreviation	ICEV-g _{PC}	ICEV-d _{PC}	Unit	Source
Population	P	128 901		pop	[8]
Average fuel consumption	F	0.077	0.055	l/vkm	[43]
Fuel consumption per capita	FPC	172	146	l/pop	[43]
Passenger cars	n_{PC}	30 504	20 129	car	[41]
Total yearly kilometers	TYK	287 934 701	342 173 563	vkm	Eq. 2.4
Average distance per passenger car	AD	9 439	16 999	vkm/car	Eq. 2.5
Emissions	E	49 319	47 339	tCO _{2e}	[12]
Transportation demand	TD	298 097 075	354 250 245	vkm	[12], [42]
Transportation demand of the municipality organisation	TD _{MO}	2 344 978	2 016 151	vkm	[44]

2.4.2 Construction of the Reference System

The main assumptions of the reference system were:

- The entire vehicle fleet will be exchanged until 2040 because the average life span of cars in Sweden is 17 years [45].

- The Vehicle types, Emissions, and Transportation need is identical to the mapping of the current system, seen in Table 2.3 and 2.4.
- Old vehicles will be replaced by new vehicles of the same type unless otherwise stated.
- The fuel and technical costs are based on the yearly price of 2022.

To explain the investment cost of different vehicle types of the same segment, the vehicles had to be comparable in relation to each other. Therefore, the investment cost of PCs was based on the mid-size car alternative defined by Grube et al. [46] in an extensive study of the total cost of ownership of PCs. Furthermore, Grube et al. identified the manufacturing costs of the PCs. In the thesis, the relative manufacturing costs were assumed to be equal to the relative investment cost. The investment costs of the different vehicles were calculated using an ICEV-g mid-class vehicle as a reference, with a price of 282 900 sek which is the cost of the most common mid-size gasoline car in Sweden [47], [48]. Thus, the investment cost of each PC vehicle type could be calculated using Equation 2.8.

$$IC_{VT} = r_{VT} * IC_{ICEV-g} \quad (2.8)$$

Here, IC is the investment cost and r is the relative investment cost. The coefficients and the calculated investment costs for PCs can be seen in Table 2.5.

Table 2.5: Cost parameters for the different types of passenger cars (PC).

Vehicle type (VT)	Relative Investment Cost (r) [-]	Investment cost (IC) [sek]
ICEV-g	1	282 900
ICEV-d	1.22	344 000
PHEV	1.38	392 200
BEV	1.66	470 400
FCEV	2.06	583 400

Abbreviations: Internal combustion engine vehicle diesel/gasoline (ICEV-d/-g), Battery electric vehicle (BEV), Fuel cell electric vehicle (FCEV), Plug-in hybrid electric vehicle (PHEV).

2.4.3 Adapting Values from Literature

The measures BEV_{HDV} , $FCEV_{HDV}$, *Densification*, *Ridesharing and carpooling*, and *Shift from HDV/LDV to train* was based on literature studies describing the effect of the measure or the cost of it. These values were directly applied to the reference system. This section will describe the assumptions required to apply this input data to the method. Finally, the input data is visualised in Table 2.6.

Assumptions for TCO of HDV based on IVA [49]:

- All HDV was assumed to be of the same size at 40 tonnes with a yearly AD of 130 000 km.
- The TCO includes the total cost of the Fuel and Investment cost of the vehicle.
- The costs refer to a system in 2030.

The TCO values shown in Table 2.6, were used directly and compared to the reference systems TCO to find ΔC_i . ΔE_i was based on the assumption that the entire vehicle fleet would be replaced until 2040.

Densification:

- An increase in population density of a general region by 10% is assumed to lead to a 3% reduction of vkm of PC, adapted from Litman [50].
- The amount of vehicles in the system is assumed to remain constant. Thus, the reduction in vehicle kilometers results in a decrease in AD.

Only ΔE_i could be identified for the measure Densification. This was done by applying the effect described by Litman [50]. ΔE_i is based on how much the city is densified and results in reducing the emissions of the PCs by reducing TD and AD. A 10% increase in population density leads to a reduction of TD and AD for PC by 3% respectively, which in turn reduces 3% of the reference system emissions.

Ridesharing and carpooling:

- The abatement potential is 5% of the total emissions from PC, adapted from Bieser et al. [51].
- Ridesharing increases the number of people per car trip, which leads to a reduction in total TD.
- carpooling was assumed to have the effect of reducing TD by reducing unnecessary trips due to the reduction of accessibility of the car.
- The amount of vehicles in the system is assumed to remain constant.
- The total vkm reduction is implemented by reducing the TD of PCs.

Ridesharing and carpooling were summarised as one measure since it was described this way in the literature. The potential of the measure was assumed to be 5% as the source describes the abatement potential is within 1-8% of the GHG emissions of PC [51].

Shift from HDV/LDV to train:

- 13% of the GHG emissions from LDV/HDV can be abated, assuming that the potential identified nationally by Trafikverket [52] is applicable on the local scale of Umeå.

The measure Shift from HDV/LDV to train was based on the national scale potential of 13% reduction of HDV/LDV by shifting to train identified by Trafikverket [52]. This data was implemented on the vkm of the respective vehicle and it was assumed that no new vkm of the train was required, but rather the utilisation of the trains was increased in terms of tonnes of goods transported. This results in a reduction of ΔE_i by 13% of $E_{HDV,LDV}$. A summary of the data that has been adapted from literature is shown in Table 2.6.

Table 2.6: Data gathered from literature that was used for the case of Umeå.

Data gathered	Value	Unit	Source
BEV-HDV TCO	4.35	kr/vkm	[49]
FCEV-HDV TCO	6.63	kr/vkm	[49]
ICEV-d-HDV TCO	6.95	kr/vkm	[49]
Densification	10% increase in population density decreases PC vkm by 3%	-	[50]
Ridesharing and carpooling	5% decrease of PC GHG emissions	-	[51]
Shift of HDV/LDV to train	13% decrease of HDV and LDV vkm	-	[52]

Abbreviations: Battery electric vehicle (BEV), Fuel cell electric vehicle (FCEV), Internal combustion engine vehicle diesel (ICEV-d), Heavy duty vehicle (HDV), Light duty vehicle (LDV), Total cost of ownership (TCO), Passenger car (PC).

2.4.4 Calculations of Abatement Measures

The amount of data available differed between the abatement measures, therefore more detailed calculation has been done where extensive data were found. The detailed calculations were done for the *Improving* PC measures and for the measure *Working from home*. The data used for the calculations can be seen in Table 2.8 and 2.9, and the respective assumptions required can be seen in the lists below.

The C_i of the *Improving*-measures were calculated in a comparable manner, where the first step was to find the cost per vkm. However, the PHEV measure required an extra equation to describe the fuel cost as it has 2 motor types. The extra equation is presented along with the assumptions of the measures.

The sub-costs included in the TCO for the *Improving* PC measures can be seen in Table 2.7.

Table 2.7: Data included in the total cost of ownership of passenger cars.

Vehicle Type (PC)	Investment	Fuel	Infrastructure	Repair	Maintenance
BEV	Yes	Yes	Yes	Yes	Yes
FCEV	Yes	Yes	-	Yes	-
PHEV	Yes	Yes	Yes	Yes	Yes
Biofuel	^a	Yes	-	^a	^a

^aThe relative cost is zero due to the assumption that the same car would be bought as in the reference system.

Abbreviations: Passenger car (PC), Battery electric vehicle (BEV), Fuel cell electric vehicle (FCEV), Plugin hybrid electric vehicle (PHEV).

For the investment cost to be included in the cost breakdown, the cost was annualised and based per vkm using Equation 2.9.

$$\Delta c_{i,investment} = \frac{(IC_i - IC_{ref}) * A}{AD_{ref}} \quad (2.9)$$

Here, $\Delta c_{i,investment}$ is the relative annualised investment cost per vkm compared to the reference system, IC is the investment cost, A is the annuity factor based on a lifespan of 17 years together with a 5% discount rate, and AD is the average yearly distance driven by the vehicle.

The following sub-cost to consider is the fuel cost which can be seen in Equation 2.10.

$$\Delta c_{i,fuel} = (F_i * FC_i) - (F_{ref} * FC_{ref}) \quad (2.10)$$

Where $\Delta c_{i,fuel}$ is the relative cost per vkm compared to the reference system, F is the fuel consumption per vkm, and FC is the fuel cost per energy. Both the repair and maintenance cost was found from a literature study which already summarised it on a cost per vkm unit [53]. Therefore, the relative cost $\Delta c_{i,repair}$ and $\Delta c_{i,maintenance}$ could be calculated using Equation 2.11 and 2.12 respectively.

$$\Delta c_{i,repair} = RC_i - RC_{ref} \quad (2.11)$$

$$\Delta c_{i,maintenance} = MC_i - MC_{ref} \quad (2.12)$$

For the new infrastructure only BEV and PHEV were calculated, which were done in the following steps in Equations 2.13 and 2.14.

$$\Delta C_{i,infrastructure} = \frac{(IC_{public} * CC_{public} + IC_{private} * n_{private}) * A}{AD_{ref}} \quad (2.13)$$

$$CC_{public} = EUD_i * n_{PC,i} - CC_{ref} \quad (2.14)$$

Where, $\Delta C_{i,infrastructure}$ is the relative infrastructure cost per vkm in comparison with the reference system, assuming ICEV-g/d requires no new infrastructure. IC_{public} is the investment cost per kw capacity, CC_{public} is the public charging capacity that is needed, $IC_{private}$ is the investment cost per home charger and $n_{private}$ is the required home chargers per electric vehicle. In Equation 2.14 EUD_i is the EU-directive of capacity required per vehicle and $n_{PC,i}$ is the number of cars.

The total annualised costs were then summarised by the following equation.

$$\Delta C_i = \sum_j \Delta C_{i,j} * TD_{ref} \quad (2.15)$$

The assumptions for the calculation-based measures are presented below:

BEV_{PC}:

- Electricity consumption for all BEV are assumed to be 0.153 kwh/km which is the average of BEV-owned vehicles in Umeå 2019 [43].
- The cost of fuel is based on the electricity spot price of electricity in SE2 2022, 0.69 kr/kwh [54], an electricity grid fee of 0.729 kr/kwh and an electricity tax of 0.296 kr/kwh [55].
- All cars can be replaced with BEV and the supply of BEV will never limit deployment.
- 1 kW of public charging capacity is needed for each BEV in the system based on proposed EU-directive [56].
- Each BEV requires installing one home charger of 5 kW [57].
- The cost of installation of 1 kW of charging capacity is 5000 sek [57].
- Repair cost is assumed to be 0.033 \$/vkm (≈ 0.218 sek/vkm) based on Burnham et al [53].
- Maintenance cost is assumed to be 0.101 \$/vkm (≈ 0.657 sek/vkm) based on Burnham et al. [53].

- All BEV:s in the system are assumed to have a range of 300 km [46].

FCEV_{PC}:

- All hydrogen used as fuel is assumed to be produced through electrolysis. Thus, the price can be calculated based on the price of electricity. However, no costs for the electrolyzers were included.
- The consumption of fuel is 0.5 kWhel/km [58].
- Repair cost is assumed to be 0.033 \$/vkm (≈ 0.22 sek/vkm), the same as for BEV_{PC}, based on Burnham et al. [53].

PHEV_{PC}:

- The fuel used is assumed to consist of Electricity and HVO100.
- The overall consumption of diesel of PHEV is 0.038 l HVO100/km [59].
- The consumption of diesel during purely diesel drive is assumed to be 0.55 L/km based on Umeå PC diesel consumption 2019 [43].
- The consumption of electricity during pure electrical drive is assumed to be 0.153 kWh/km based on BEV consumption in Umeå 2019 [43].
- Each PHEV requires installation of one home charger of 5 kW [57].
- 0.66 kW of public charging capacity is needed for each BEV in the system based on proposed EU-directive [56].
- Repair cost is assumed to be 0.043 \$/vkm (≈ 0.280 sek/vkm) based on Burnham et al. [53].
- Maintenance cost is assumed to be 0.09 \$/vkm (≈ 0.59 sek/vkm) based on Burnham et al. [53].

As the PHEV_{PC} is driven with 2 engines, diesel, and electricity the amount of specific fuel per vkm had to be calculated. This was done in Equation 2.16.

$$F_{PHEV,Electricity} = \left(1 - \frac{F_{PHEV,HVO100}}{F_{ICEV-d}}\right) * F_{BEV} \quad (2.16)$$

Here, F is the fuel consumption for the different engine types, $F_{PHEV,HVO100}$ is based on a study by Plötz et al. [59] investigating the actual fuel consumption of fossil fuel used for PHEVs per vkm.

Biofuel, ICEV-d_{PC}:

- Supply of biofuel is unlimited.
- Biofuel is considered to be HVO100 only. Thus, this measure only covers diesel cars.
- The price of biofuel is 28.5 sek/l, in line with the price in 2022 [60].
- The car that is bought new is the same as the old one, thus the difference in investment-, repair- and maintenance costs will be 0.

Working from home:

- Currently people work from home 0.8 days a week in Umeå if they have the possibility [61].
- Assume that 36.1% is the maximum % of work that can be done from home in Umeå [62].
- All trips mentioned in Umeå resvanor is assumed to have the same distance, i.e. 25% of working trips = 25% of TD, i.e. 25% of TD_{ICEV-g} and 25% of TD_{ICEV-d}.
- Assume a feasible maximum of 40% of the total working time occurs from home, i.e. 2 days a week.

Based on the assumptions in the list and the data from Table 2.8 and 2.9 the calculation for the abatement potential of working from home was done as shown in Equation 2.17.

$$\Delta E_{WFH} = E_{PC} * WFH_{Population} * TW * \frac{d_{WFH,40\%} - d_{WFH,ref}}{d_{WFH,100\%}} \quad (2.17)$$

Here, ΔE_{WFH} is the abatement potential of working from home, E_{PC} is the emissions of passenger cars, $WFH_{Population}$ is the share of people that has the possibility to work from home, TW is the total share of vehicle kilometers made for work and d_{WFH} the days per week that is worked from home. The result of the equation can be seen in Table 2.10.

2. Method

Table 2.8: List of input data used in calculations of parameters for the Umeå-specific abatement measures.

Metric	Abbreviation	Value	Unit	Source
General				
Annuity factor	A	0.09	-	
Fuel cost, HVO100	FC_{HVO100}	28.5	sek/L	[60]
Fuel cost, Electricity	$FC_{Electricity}$	1.72	sek/kwh	[55]
General maintenance cost ICEV PC	MC_{ICEV}	0.66	sek/vkm	[53]
General repair cost ICEV PC	RC_{ICEV}	0.33	sek/vkm	[53]
Charging capacity available today	CC_{ref}	5042	kw	[63]
ICEV-d_{PC}				
Investment cost	IC_d	344 000	sek	Tab. 2.5
Transportation demand	TD_d	354 250 245	vkm	Tab. 2.4
Fuel cost	FC_d	24.45	sek/L	[60]
Average distance per diesel car	AD_d	16 999	vkm/car	Tab. 2.4
Reference emissions	E_{ICEV-d}	47 339	tCO _{2e}	Tab. 2.4
Fuel consumption	F_{ICEV-d}	0.055	L/vkm	[43]
Passenger cars	n_{PC}	20 129	car	Tab. 2.4 [41]
ICEV-g_{PC}				
Investment cost	IC_g	282 900	sek	Tab. 2.5
Transportation demand	TD_g	287 934 701	vkm	Tab. 2.4
Fuel cost	FC_g	20.53	sek/L	[60]
Average distance per gasoline car	AD_g	9 439	vkm	Tab. 2.4
Reference emissions	E_{ICEV-g}	49 319	tCO _{2e}	Tab. 2.4
Fuel consumption	F_{ICEV-g}	0.077	L/vkm	[43]
Passenger cars	n_{PC}	30 504	car	Tab. 2.4 [41]
BEV_{PC}				
Investment cost	IC_{BEV}	470 400	sek	Tab. 2.5
Fuel consumption	F_{BEV}	0.153	kwh/km	[43]
Investment cost public charger	IC_{public}	5 000	sek/kW	[57]
Investment cost private charger	$IC_{private}$	25 000	sek/charger	[57]
EU directive charging capacity BEV	EU_{BEV}	1	kW	[56]
Private chargers per BEV	$n_{private}$	1	charger/car	[57]
Maintenance cost	MC_{BEV}	0.39	sek/vkm	[53]
Repair cost	RC_{BEV}	0.22	sek/vkm	[53]

Abbreviations: Internal combustion engine vehicle diesel/gasoline (ICEV-d/-g), Passenger cars (PC), Battery electric vehicle (BEV), Fuel cell electric vehicle (FCEV).

Table 2.9: Continued list of input data used in calculations of parameters for the Umeå-specific abatement measures.

Metric	Abbreviation	Value	Unit	Source
FCEV_{PC}				
Investment cost	IC_{FCEV}	583 400	sek	Tab. 2.5
Fuel consumption	F_{FCEV}	0.5	kwhel/km	[58]
Repair cost	RC_{FCEV}	0.22	sek/vkm	[53]
PHEV_{PC}				
Investment cost	IC_{PHEV}	392 200	sek	Tab. 2.5
Fuel consumption, HVO100	$F_{PHEV,HVO100}$	0.038	l/km	[59]
Fuel consumption, Electricity	$F_{PHEV,Electricity}$	0.047	kwh/km	Eq. 2.16
Investment cost public charger	IC_{public}	5 000	sek/kW	[57]
Investment cost private charger	$IC_{private}$	25 000	sek/charger	[57]
EU directive charging capacity PHEV	EUD_{PHEV}	0.66	kW	[56]
Private chargers per PHEV	$n_{private}$	1	charger/car	[57]
Maintenance cost	MC_{PHEV}	0.59	sek/vkm	[53]
Repair cost	RC_{PHEV}	0.28	sek/vkm	[53]
Working from home				
Days working from home today	$d_{WFH,ref}$	0.8	d/week	[61]
Share that worked from home Q2 2021	$WFH_{Population}$	0.36	-	[62]
Total share of trips to work	TW	0.25	-	[61]

Abbreviations: Passenger cars (PC), Fuel cell electric vehicle (FCEV), Plug-in hybrid electric vehicle (PHEV).

2.5 List of Abatement Measures

A summary of the abatement potential and marginal abatement cost of the measures in the reference case was done in Table 2.10. The measures were also categorised based on how they were added, either by multiple calculations based on Umeå specific conditions (c) or by one value from literature that was adapted upon the reference system (l).

Table 2.10: Identified abatement measures from the transportation sector of the reference case. c and l in column 4 denote the source of the data. c = multiple calculations based on Umeå-specific circumstances. l = a value from literature, adapted upon the reference system.

Abatement measure (i)	Abatement potential (ΔE_i) [tCO _{2e}]	Marginal abatement cost (MAC _{i}) [sek/tCO _{2e}]	Data source
Improve			
BEV _{HDV}	25 132	- 4 103	l
BEV _{PC}	96 659	- 1 934	c
FCEV _{HDV}	25 132	- 505	l
FCEV _{PC}	96 659	16 131	c
PHEV _{PC}	96 659	2 197	c
Biofuel _{PC} (ICEV-d)	47 340	1 667	c
Avoid			
Ridesharing and carpooling	4 833		l
Densification	2 900		l
Working from home	2 967		c
Shift			
LDV/HDV to train	4 965		l

Abbreviations: Battery electric vehicle (BEV), Fuel cell electric vehicle (FCEV), Plug-in hybrid electric vehicle (PHEV), Heavy duty vehicle (HDV), Light duty vehicle (LDV), Passenger cars (PC), Internal combustion engine vehicle diesel (ICEV-d).

2.6 Scenarios

The scenarios are theoretical and chosen based on different perspectives. The first three scenarios are used to visualise the dynamics between different measures by changing the reference system or applying one measure at a time and observing how the MAC-curve changes based on the characterisation of the abatement measures. The fourth scenario answers the question of whether it is possible to reach the net zero emission goal using the identified measures.

In Table 2.11 the parameters that were changed in the different scenarios are summarised. This is followed by a more detailed explanation of the reasoning behind each scenario.

Table 2.11: A summary of the first three scenarios analysed with how the data was changed in comparison to the reference case.

Scenario name	Base	Population increase	Densification	60% BEV _{PC}
Population	128 901 pop	+36%	-	-
E _{PC}	96 659 tCO ₂	+36%	-3%	-60%
TD _{PC}	652 347 321 vkm	+36%	-3%	-60%
AD _{PC,ICEV-d}	16 999 vkm/PC	-	-3%	-
AD _{PC,ICEV-g}	9 439 vkm/PC	-	-3%	-

Population Increase

Population increase was based on the vision of reaching 200 000 people by 2050. The assumption was made that the population increase was linear and that the total *TD* is increased by the same % as the population increase. This results in a population of 176 300 people in 2040 and an increase of the *TD* of all vehicles by 36.7%.

Densification

Densification highlights the effect of an *Avoiding*-measure. In the scenario, it was assumed that the population density of the municipality increased by 10% which results in a decrease of *TD* of PCs in the reference system by 3% based on FFF [50]. The decrease of *TD* was applied by reducing *AD* of PCs.

60% BEV_{PC}

60% BEV_{PC} highlights the effect of an *Improving*-measure. In the scenario, it was assumed that 60% of the fossil passenger car fleet were replaced by BEV_{PC}. This was implemented by reducing *EF* to 0 for 60% of the PC fleet. The consequence this has on the reference system is that there is only 40% of the initial *TD* from PCs left to abate.

Goal fulfilling

The goal fulfilling scenario differentiates from the other scenarios in the manner that it is retrospective rather than a foresight. Rather than looking at what different choices there are to reduce the emissions, the goal fulfilling scenario investigates if the emission goal of reaching net zero emissions can be reached using the identified abatement measures. This was implemented by assuming the cheapest alternatives were implemented fully.

3

Results

The following chapter presents the results of the thesis. First, the visualisation of the identified abatement measures including governance for different measures is presented. Second, a detailed visualisation of the sub-costs of BEV_{PC} is shown. lastly, the dynamics between measures are visualised by four scenarios, three of which show foresight MAC-curves and lastly a retrospective MAC-curve.

3.1 Visualisation of Abatement Measures

Figure 3.1 shows the foundation of the visualisation, which highlights the different abatement measures as if they were implemented by themselves to reduce the reference system emissions. Therefore, the abatement measures have a total emission potential larger than the total emissions of the reference system which is highlighted in Figure 3.1 as a vertical line. Based on the methodology and data & assumptions BEV_{PC} as well as BEV_{HDV} are the most cost-effective measures in comparison to other *Improving* measures. Furthermore, the abatement costs of these measures are negative, which means that they result in cost savings in comparison to the reference system.

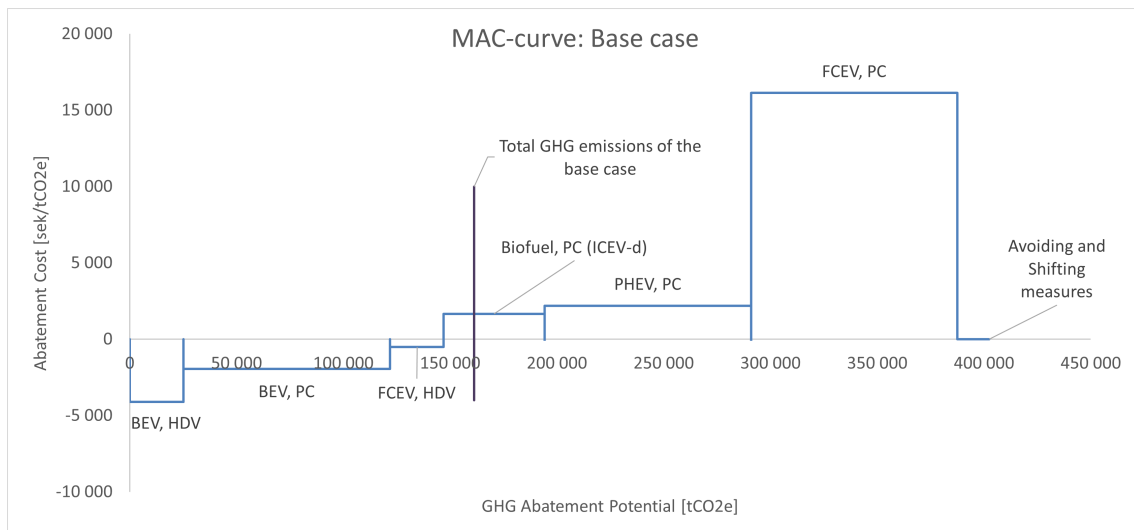


Figure 3.1: Visualisation of the MAC-curve of the base case.

The end of the MAC-curve consists of the *Shifting* and *Avoiding* measures where abatement potentials but no costs could be identified. Noticeable is the total size of the abatement potential of these categories which is small in comparison to the *Improving*-measures of BEV, PHEV, FCEV, and Biofuel. This is partly due to a lack of understanding of how big of an impact *Avoiding* and *Shifting*-measures can have. For example, Bieser et al [51] highlight that the difficulty of understanding the effects of working from home might be due to possible rebound effects of the measure. Furthermore, the costs of these measures could not be identified as these measures are not driven.

An example of how abatement measures can be visualised based on the level of governance from the perspective of a municipality organisation is shown in Figure 3.2. Note that the direct governance of the organisation is only part of the abatement measures which reduce emissions from the PC fleet. In the figure, the direct governance is not included for the *Avoid*-measures such as working from home. However, in reality, the organisation has direct governance by having employees working from home rather than commuting by car, though the size of the abatement potential of this is so small that it can not be visualised. Furthermore, the size of the direct governance is 0.4% of the total GHG emissions. The remaining 99.6% of the GHG emissions the municipality has indirect or no governance of. For indirect governance, both the cost and emissions are highly dependent on other actors making the final decision. The municipal organisation can create a foundation to enable these actors to transition, both investment based such as infrastructure but also knowledge-based such as spreading information.

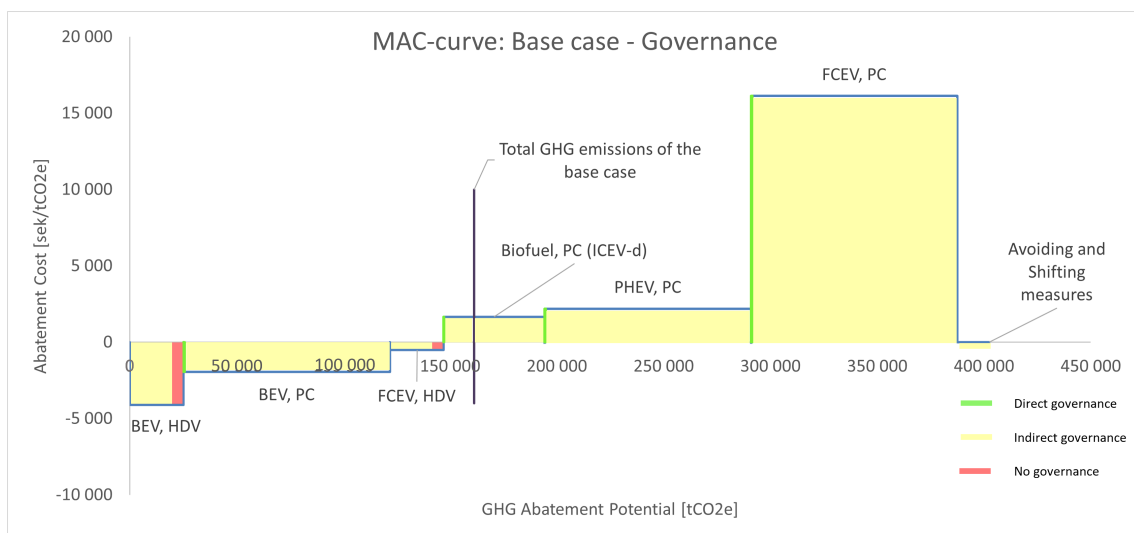


Figure 3.2: Visualisation of the base case with color coding for the level of governance of the abatement measures from the perspective of the municipality organisation.

For the HDV measures, there are parts of indirect and no governance, where the decision of local and national hauling contractors can be indirectly governed by

3. Results

enabling the transition by investing in charging/fueling stations in close proximity to the highways. The emissions of which the organisation has no governance are that of foreign hauling contractors. Even though the municipal organisation could enable a transition of the geographic area, this does not impact a decision of an HDV owner that is stationed in a country where the infrastructure for the transition is underdeveloped.

Zooming in on BEV_{PC} from the MAC-curve as an abatement measure, figure 3.3 shows the cost breakdown of the measure. This illustrated the different sub-costs that are part of the whole measure. Furthermore, it highlights the cost and abatement difference of BEV_{PC} as a measure based on if it abates emissions from ICEV-d or ICEV-g.

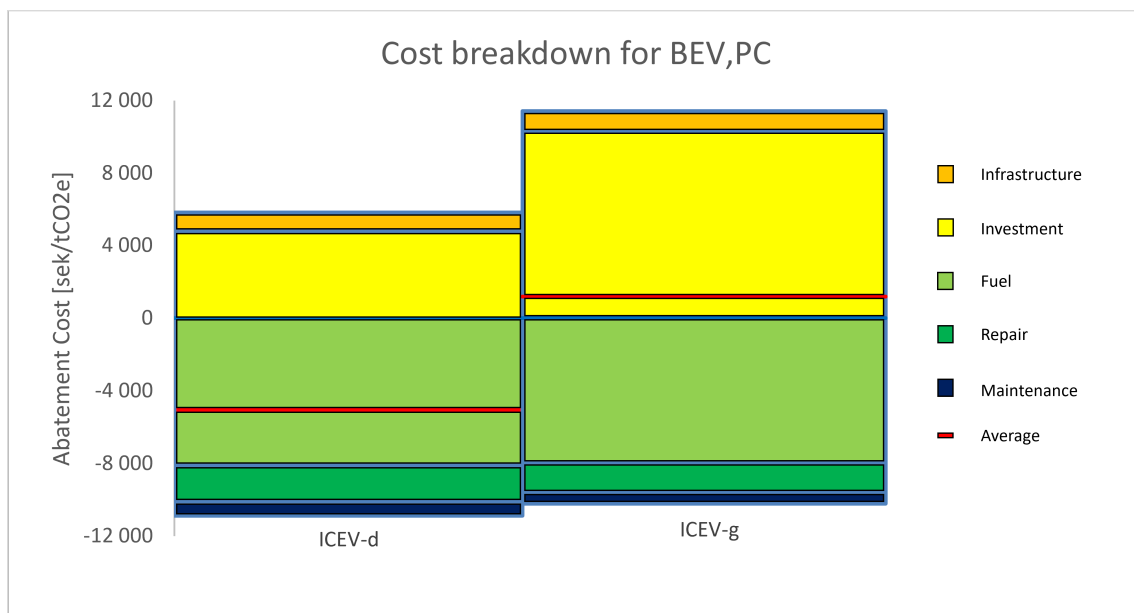


Figure 3.3: Illustration of cost breakdown of the battery electric vehicle, personal car (BEV_{PC}) measure. The left column represents the cost of replacing diesel cars, while the right part represents the cost of replacing gasoline cars.

For BEV_{PC} the total cost of the measure was negative in comparison with ICEV-d, meanwhile positive in comparison with ICEV-g. However, sub-costs such as investment cost and infrastructure were positive. This indicates that even though some costs are more expensive in comparison with the reference system, the overall cost for the measure is cheaper than the reference system. The figure also shows that it is more expensive to switch to BEV_{PC} from an ICEV-g. This is partly due to the investment cost of ICEV-g being less than ICEV-d, but the largest factor is the AD of the vehicle type, as ICEV-g only has 9 439 vkm/yr/car in comparison to ICEV-d 16 999 vkm/yr/car. Therefore, fewer vehicles have to be replaced for the same amount of GHG abated which leads to a cheaper investment cost on a system level.

3.2 Visualisation of Measure Dynamics

Figure 3.4 shows a comparison of the base case and the scenario, where the total GHG emissions of the base case and scenario are highlighted in two separate vertical lines. In the scenario with increased population shown in Figure 3.4 the total GHG emissions of the reference system increases. Furthermore, the GHG abatement potential of each abatement measure increases. However, the abatement cost of the measures remains the same as the reference MAC-curve. This indicates a clear connection between a population increase and an increase in emissions. This means that if no other measures are made in the transition of the transportation system, the municipality could face even more emissions which need to be abated by 2040.

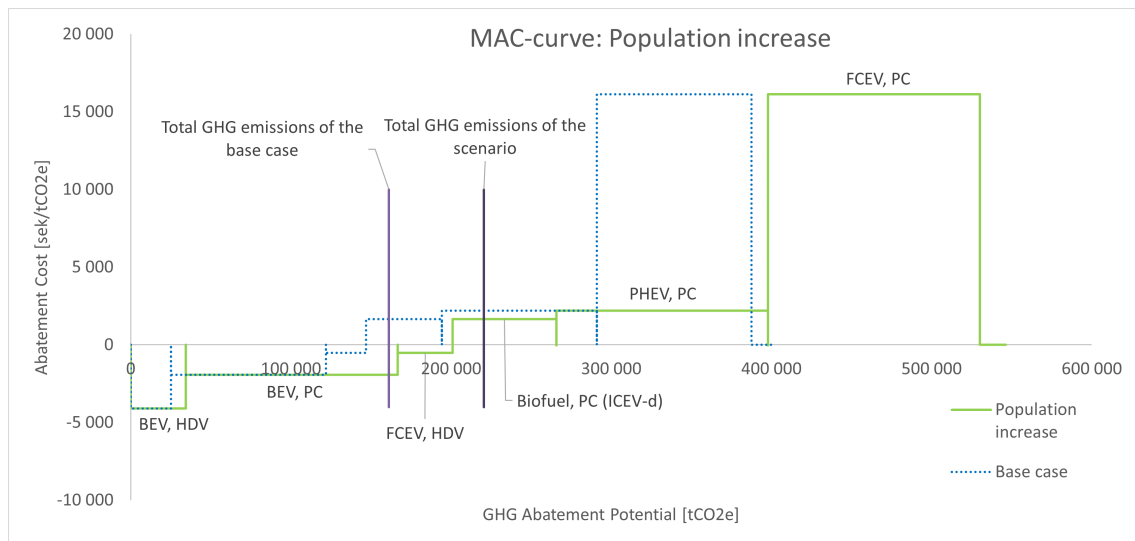


Figure 3.4: Resulting MAC-curve in the case where the population increase in accordance with the vision of the municipality.

In Figure 3.5 a 10% increase in the population density of the municipality is assumed to take place. This decreases the total emissions of the reference system, as well as the potential of the remaining abatement measures. The cost of the abatement measures increases due to the decrease in AD . However this is barely visible as 10% densification only decreases the total transportation need of PCs by 3%.

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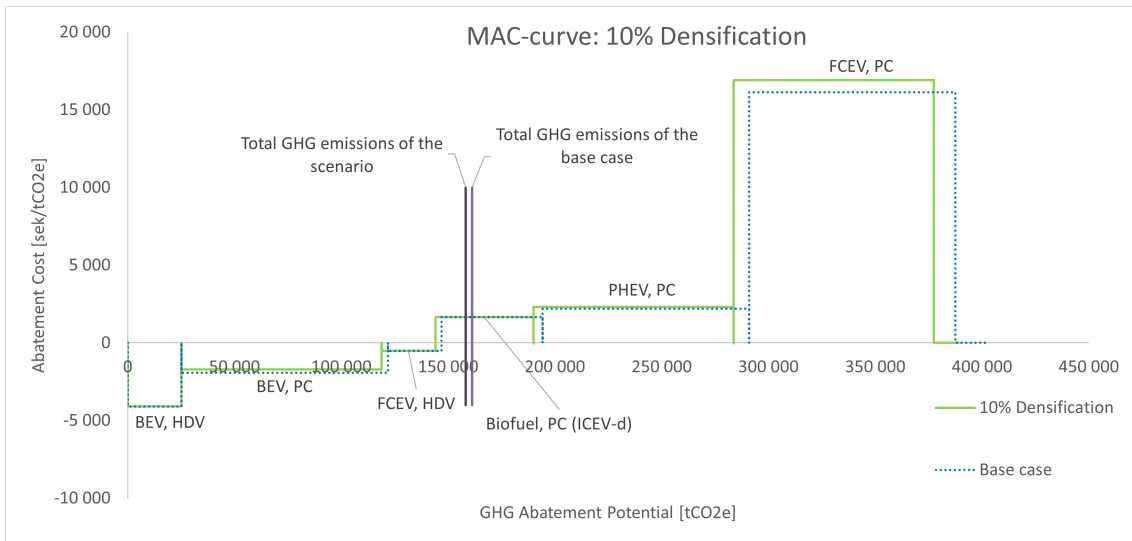


Figure 3.5: Resulting MAC-curve of scenario where the density of the municipality increases by 10%.

Figure 3.6 shows the MAC-curve of the scenario where 60% of the fossil PC travel distance is replaced with BEV. Noticeable is that the abatement potentials of the remaining abatement measures which affect PCs decrease. However, the cost of these measures remains the same.

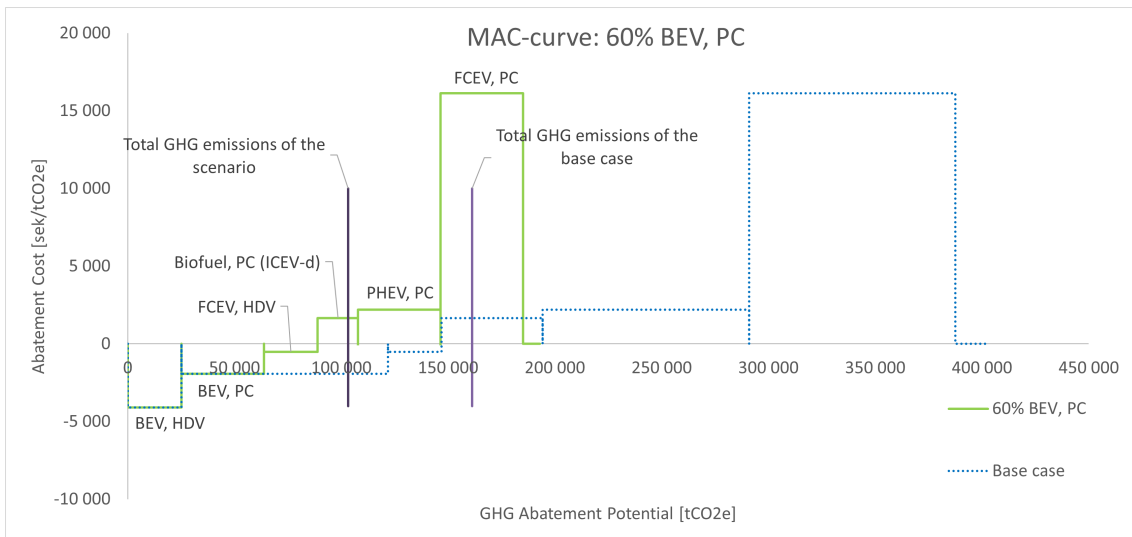


Figure 3.6: Resulting MAC-curve of the scenario where 60% of the fossil PC travel distance is replaced by BEV.

When trying to achieve the climate goal of net neutrality until 2040, a selection of two improving measures were selected which can be seen in Figure 3.7. The combination of a fully electrified PC and HDV vehicle fleet would result in 75.5% abated emissions of the total emissions from transportation. In this selection, there

are no other abatement measures to decrease the emissions further due to PCs and HDVs having already been reduced. Therefore the rest of the emissions are coupled to other vehicles types, whereas this thesis did not identify abatement measures, which is highlighted in Figure 3.7 between the 2 vertical lines *PC and HDV GHG emissions* and *Total GHG emissions*. Furthermore, the green area in Figure 3.7 represents the direct governance of the municipality organisation. It accounts for 0.4% of the total emissions in the transportation sector.

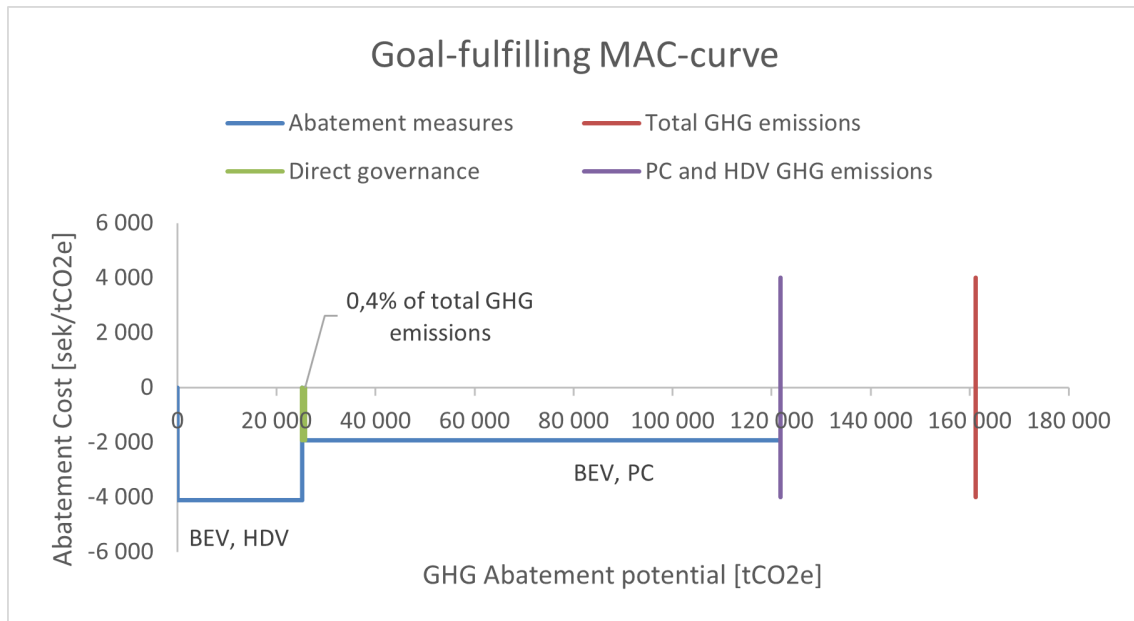


Figure 3.7: An attempt of a goal fulfilling MAC-curve, where no population increase is considered. The emissions included in the total GHG emissions are from the following vehicle types: Passenger cars (PC), Heavy duty vehicles (HDV), Light duty vehicles, Busses, Motorcycles and mopeds, domestic civil seafaring, domestic flight, and railway traffic.

4

Discussion

In the following chapter, a discussion of how the methodology can be used to help municipalities towards reaching their climate goals. This includes outlining the challenges which arose during the characterisation of the abatement measures, the impact of different system delimitations, and how the municipal organisation can handle measures at different levels of governance.

4.1 Challenges with Measure Characteristics

There are a lot of assumptions that were required to fit the data with the reference system in order to characterise the abatement measures. The assumptions differ greatly in scope and severity of simplification and are the only way to make the data workable. It does however create a simplification of reality which creates inaccuracies if the measures and numbers extracted from the thesis would be compared to the same measures in reality. This is important to keep in mind when choosing assumptions but also when interpreting and using the results as a basis to make decisions on what measures to invest in.

An assumption that would have a big impact is the assumption that all cars are driven the same distance each year. This results in a yearly driving distance for gasoline cars being 9 400 km/year and for diesel cars being 17 000 km/year. However, there are vehicles in the system that are not driven at all. These cars can for example be classic cars that are only driven once or twice a year and that presumably use mainly gasoline as fuel. They are unlikely to be replaced, and if they would be replaced it would be at a high cost. Removing these cars from the total vehicle pool would then increase the yearly driving distance of gasoline cars overall, which in turn would decrease the relative investment cost. The measure can therefore in reality be assumed to have a lower cost than what the results show.

Another assumption that could be significant is the assumption that all BEV cars are the same type of car of the same cost, size, and range. The car chosen in the study was a mid-class vehicle, and the BEV had a range of 300 km. In reality, there would exist a wide range of cars of different sizes and at different price levels. A modification of this assumption to better match reality could lead to either an

increase or a decrease in the costs. This would depend on the distribution of car size that is assumed.

While this shows two examples of assumptions that have a big impact on the results, there are also those that have a small impact. One of these is the cost of electricity for BEV. Doubling this cost would not make a big impact since the costs are relative. The relative cost makes the higher cost more significant, which in this case is the cost of gasoline or diesel. These costs are around 20 times as big as the cost of electricity and thus are the dominant factor in fuel cost calculations.

The abatement potential of the *Improving*-measures can cover large parts of their respective vehicle type. The *Avoid* and *Shifting* measures potentials are comparably smaller, which is partly due to a lack of understanding of their actual potential and effect on other abatement measures but also due to rebound effects. Furthermore, these measures have a discrepancy in the literature, where FFF [39] and Trafikverket [52] state it can account for around 20% reduction of *TD*, while other studies such as Kågesson [38] and Merkel [64] argue that the potential is in the range of 1%. These conflicting studies highlight the uncertainty of the outcome of these measures, which in turn makes them unreliable to lean on when trying to fulfill a climate goal of reducing GHG emissions. However, most of these measures have other benefits that can make them beneficial to invest in, such as reduced risk of accidents by building bicycle roads, saved time by working from home, improved health from more biking and walking, etc.

It is difficult to identify both the abatement potential and cost of *Shifting*-measures. This is due to the existing data and local specific conditions. Even though the vehicle kilometers of busses increases there is nothing guaranteeing that vehicle kilometers of PCs will decrease, as it could be causing new transportation demand rather than creating a shift from cars. Therefore, a more detailed level of data and follow-up of this data would be needed to make reasonable assumptions about the potential of these measures. Furthermore, the sub-measures for this category are hard to grasp. What contributes to an increase of the shift and what are their potentials? For example, a sub-measure to shift from PC to bus is to build bus lanes. This decreases the time the bus is stuck in traffic which reduces the total transportation time of the commuter. However, how this impacts the transportation demand of the car fleet is unclear. It could be argued that the transportation demand for passenger cars will be reduced, but it could also be argued that this would not impact the transportation demand as the saved time from the trip with the bus is not the swaying factor for the commuter to decide if they will shift their behaviour. As the measure is not cost driven, it becomes speculative which parameters and sub measures that will be needed for a specific amount of abatement. The reason for this difficulty is that the *Shifting*-measures require behaviour change at a higher degree than *Improving*-measures.

This highlights a characteristic of measures that were not considered in the thesis. The saving of time by constructing bus lanes makes it easier for people to choose an

environmentally friendly mode of transportation. However, this measure also might lead to fewer car lanes, which in turn makes it more difficult to keep doing the more polluting activity. This can create pushback from people that do not want to or do not have the possibility to be part of the change, slowing down or stopping progress toward the goal. Keeping these effects in mind is therefore important when choosing what measures and sub-measures to invest in.

The effect the measures have on the other abatement potentials and costs becomes dependent on which order they get applied, as well as in what manner the effect takes place since the measures affect the reductions of emissions in different ways. As an example, implementing the *Avoid*-measure of densification, which has the effect of a 10% increased population density leads to a reduction of 3% of the total PC vkm. This measure indirectly reduces the emissions from PCs in the reference system by having shorter *AD* but the amount of cars in the system remains the same. This has further implications on the cost of the remaining PC measures where shorter *AD* makes *Improving*-measures with cheap fuel and high investment costs such as BEV and FCEV become more expensive in comparison to the reference system of ICEVs. However, the abatement potential of densification can not alone reduce all emissions to reach carbon neutrality. Therefore, additional abatement measures have to be included to reach further, such as an *Improving*-measure as BEV_{PC}.

Including both *Avoiding* and *Improving* measure types in a system leads to allocation difficulties. As densification reduces the vkm of the system, the abatement potential of this measure is highly dependent on the emissions in the system. If the vehicle fleet were to be fully electrified there would no longer be a relation between vkm and emissions. However, if an *Shifting* or *Avoiding*-measure can decrease the number of vehicles in the system, it would not impact the cost for the *Improving*-measures. Thereby, depending on how the reduction of *TD* is introduced, this will impact the cost and allocation of abatement potential of the remaining measures.

4.2 System Delimitations

The methodology of this thesis is based on multiple system delimitations, which all impact the results. An example of system delimitations is which emissions the characterisation includes. If all scopes of 1-3 or a LCA perspective would be included rather than just scope 1, this would impact the total GHG emissions of the reference system as well as available measures and the potential of each measure. For example, the BEV measure would have emissions coupled to how the electricity is produced, as well as the emissions coupled to the production of the vehicle. Therefore, the identified measures in the thesis could not alone reach net zero emissions in the transportation sector. Thereby being dependent on other sectors such as electricity producers as well as negative emissions to compensate for the LCA emissions of production and recycling of the vehicles.

Another system delimitation is the geographical and time aspects of the climate goal which has consequences on the outcome of the methodology. For example the climate

goal of reaching carbon neutrality of the geographical area of the city of Umeå until 2030. For the geographical area of the city, the total distance per trip is presumably shorter which is beneficial for shifting measures. Thereby, it could be argued that most of the transportation in the city can be done by bicycling/walking/busses. However, it is important to remember that although the system boundary for that goal is the city, that does not mean that all trips have their starting and end points inside the geographical system boundary. Consequently, the total distance travelled per trip may extend beyond the city limits, emphasising the need to consider the overall travel distance of vehicles entering the city. Furthermore, this highlights the importance of understanding the interaction between the inside and outside of the system boundary to avoid sub-optimisation.

If this becomes the case for the city to reach its goal by 2030 that would impact the conditions for the upcoming goal of 2040 for the geographical area of Umeå. As the geographical area of Umeå still would be dependent on longer distances with PCs, measures to reduce emissions would most likely still be *Improve*-based. Here the time aspect of 2030 comes into play for the potential abatement measures, mainly the assumption of how vehicles would be completely replaced is no longer the case for a 2030 scenario due to the average lifetime of 17 years of PCs. Thereby, only about 40% of the PC fleet would be replaced naturally in the span of 7 years. In order to achieve the climate goal, the 60% of vehicles that have not yet reached the end of their lifespan would also need to be replaced, resulting in a significantly higher investment cost. For this scenario, an alternative fuel that matches the current system vehicles can play a bigger role to reach the 2030 goal, such as biofuel.

The methodology used in this thesis limits the effects of the measures on the transportation sector in Umeå. However, in reality, the effect of implementing these measures would stretch across multiple sectors and also geographically outside of Umeå. For example, broad adoption of the BEV measures could require an extension of the electricity system in regard to both transmission capacity and production. Similarly, a big reliance on biofuel could require an increase in production capacity and price on a national level. These effects can in turn affect the measures in different feedback loops which constantly change the conditions of the investigated system. From this, multiple questions arise. Is the maximum potential of BEV limited due to the speed at which the infrastructure can be expanded? Is it possible to produce the quantities of biofuel that are required for broad adoption of the biofuel measure? These effects and arising questions make the system difficult to accurately model. It also illustrates two things. Firstly, the importance of choosing system boundaries and delimiting the work to a reasonable size. Secondly, it illustrated the wickedness of the system.

4.3 Direct, Indirect and No Governance

For the transportation sector, the municipal organisation has direct governance of the vehicle kilometers driven by the ICEVs of their organisation. These emissions could be reduced by a technology switch from ICEV-g/d to BEV, resulting in a

reduction of 0.4% of the emissions of the whole transportation sector. Therefore, reducing the emissions of transportation from the organisation alone would not suffice to reach the geographical goal of net zero emissions. However, this does not make these emissions irrelevant in the work towards reaching the climate goals. Rather the opposite, it can be seen as of high importance to act as front runners in the transition to indicate to other actors that it is possible to reduce their emissions. This can in turn lead to a snowballing effect of the transition. This means by transitioning with measures where the organisation has direct governance can impact the rest of the system indirectly to go in the same direction.

This sparks the question of how the municipal organisation can further reduce the emissions of the transportation sector to reach the climate goal. Here, indirect governance has a big part of the work. How the municipal organisation can work with indirect governance is coupled with which measure the focus is, as the implications of making people shift from PCs to busses differ from making people switch to BEV_{PCs}. Therefore, this discussion will focus on what options an organisation has to indirectly impact the switch. In the cost breakdown of BEV one of the additional costs in comparison with the reference system was the infrastructure cost. The infrastructure for BEV is necessary for the transition to take place. The owner of a car need to feel like it is possible to fulfill the transportation need without being afraid of getting stuck on the road due to a lack of charging points. Therefore, the additional cost of the infrastructure could be invested in by the municipal organisation to enable the transition, making it easier for the other actors to choose BEV over ICEV. Even though this is a cost in comparison to the reference system it could be argued that the infrastructure could get paid off by charging more for the electricity compared to the price of electricity when charging from home. From the perspective of the municipal organisation, the investment then becomes both an enabler for the transition and at the same time becomes a foundation for long-term profits.

Outside of the cost of the infrastructure, there is direct governance in creating suitable locations for charging infrastructure at the parking spaces owned by the municipal. Furthermore, information could play a big role to highlight the benefits of the transition to BEV for other actors, such as the cost savings found in the thesis. The municipal organisation can also work with the urban planning of roads, creating a lane for non-fossil transportation only, to create an incentive to switch vehicles for time-saving purposes.

However, here other aspects of sustainability come into play, such as the socio-economical aspects. The high investment cost of BEV can be a barrier for a lot of actors during the time span the transition from ICEV to BEV takes place. Not everyone will be able to invest in a new vehicle which leads to the transition from ICEV to BEV has to come from the used-car market. If the system then creates more beneficial aspects such as BEV-only lanes this could further widen the rift in society based on income.

Lastly, there are factors that the municipal organisation has no governance of at

all. However, these factors can have big impacts on the emissions in the system and if the climate goal will be achievable or not. One example of these factors is "Reduktionsplikten", how much biofuel is diluted into gasoline and diesel, which is set by the politicians at a national scale. For Sweden, the dilution was 30,5% for diesel by 2022, but a decision made in 2023 changed it to 6% starting from 2024 [65]. This is out of the hands of the municipal organisation but still has a large impact on the emissions from ICEVs. Thereby, it is a factor that needs to be considered even though the municipal organisation can not affect it. Another example is which vehicle types are actually produced and what efficiencies they have, these are also important parameters but yet again the municipal organisation can not affect them.

5

Conclusion

5.1 Conclusions from the Method

The presented method can be used to characterise abatement measures. However, the method is more appropriate to use for some types of measures than others. *Improving*-measures are to a higher extent easier to characterise since abatement potentials and costs for a majority of these measures could be gathered. Measures of this category are less reliant on behaviour change which makes their effects easier to predict compared to *Shifting*- and *Avoiding*-measures. Finding data for these two types of measures proved difficult. However, measures of these types do generally have a lower potential than *Improving*-measures, based on the data that was found.

The assumptions that were used had a significant impact on the results. Assumptions like all cars drive the same distance each year and that all cars are of the same model and size are two examples of assumptions that make a big difference. These assumptions strongly diverge from reality. The calculated costs and abatement potential can therefore be expected to not line up to reality and should be seen more as an estimate on an order of magnitude level. The assumptions were however vital for being able to implement the found data into the model, despite this vital flaw.

It is possible to summarise and visualise measure dynamics by utilizing MAC curves and constructing scenarios used comparatively. However, the limitations of using MAC curves make illustrating dimensions that are not limited to cost and abatement potentials difficult. This problem can somewhat be circumvented as it has been shown that governance can be illustrated in the MAC curve. This limitation disfavors measures that are not cost-driven or where the correlation between action and abatement potential is uncertain.

The implementation order of different measures plays a big role in the result of the scenarios. Different sequences of implementation create different results which affect the allocation of the abatement potential of each measure in major ways. This creates a risk of double counting which should be avoided.

5.2 Conclusions for the Municipality of Umeå

The fraction of the total emissions that the municipality organisation has direct governance of is 0.4%. Furthermore, the vision of a population increase to 200 000 by 2050 has a big impact on the total emissions that need to be abated in order to reach the 2040 climate goal of net neutrality.

Of the identified abatement measures, the *Improving*-measures are the most "effective" measures to implement both in respect of total abatement potential and also of reliability of their effect. For example, the cheapest *Improving*-measures are BEV_{PC} and BEV_{HDV} which can abate their entire vehicle fleet at a negative cost compared to the reference system with an exception for replacing ICEV-g PCs. The focus of the municipality should be to facilitate the implementation of the technical measures through switching their own vehicle fleet to BEV which indirectly can impact other actors. Furthermore, the municipality can enable the transition to BEV by investing and facilitating space for the charging infrastructure. Non-cost-driven actions such as informing actors of the benefits of BEV can also be done to indirectly impact other actors. However, other aspects of sustainability have to be taken into consideration when impacting other actors by indirect governance, such as socio-economical aspects.

It is difficult to quantify abatement potentials and costs for the *Shifting*-measures and the effect on other measures are highly uncertain due to the lack of found data. Therefore, these measures are risky to rely upon when trying to fulfill a set climate goal. However, just because these measures are not well suited to analyse in the context of abatement potential and cost, does not make them unnecessary to invest in as they have benefits in other dimensions such as health and degree of governance.

It is important to understand how the decrease of vehicle kilometers is implemented when adapting *Avoid*-measures to Umeå, as it has consequences on the remaining abatement measures. Furthermore, the abatement potential of the *Avoid*-measures can not alone reduce all emissions to reach carbon neutrality. Therefore, additional abatement measures have to be included to reach further, such as an *Improving*-measure. Including both of these measure types in a system leads to allocation difficulties as emissions and vehicle kilometers get decoupled. Therefore, the municipality organisation has to discuss; Which abatement measure can take credit for the emission reduction?

5.3 Future Research

- Investigate abatement measures for more vehicle types, such as Light duty vehicles, Domestic seafaring, and Domestic flight.
- Further analyse the effect of non-cost driven measures to get a deeper understanding of what their impacts could be.

5. Conclusion

- Go into further detail about what is needed in order for an abatement measure to take place, for example, the infrastructure of battery electric vehicles, where should the charging posts be placed in order to for them to be used efficiently.
- Include other sectors to the visualisation in the MAC-curve, will there be cross-sectional dynamics that can be explained and highlighted?
- Apply the method to another municipality, to investigate how locally specific the abatement potential and costs are.
- Investigate what effect different types of emissions can have on the different measures, eg. what happens if LCA or Scope 2 emissions are considered?

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