The environmental impact of e-moped sharing

A quantitative study into the environmental impact of e-moped sharing at city level

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by

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Abstract

E-moped sharing is a relatively new transport alternative. Its environmental impact is often questioned in news articles. In addition, there is no consensus in scientific literature whether it has a positive impact on greenhouse gas (GHG) emissions in a city. In this papers first a conceptual model was developed, integrating shared e-moped adoption factors and factors influencing their environmental impact at city level. Subsequently, the conceptual model, data from literature studies and the Ecoinvent database were used to developed a quantitative environmental impact model. This model was used to determine the environmental impact of e-moped sharing for a specific city. In this model, city and country specific characteristics can be defined making the model applicable to every city in the world. The GWP of shared e-moped was calculated to be 34.9 g CO_2-eq/pkt using Dutch characteristics. Further application of the model to an average city in the Netherlands, resulted in 77.5 g CO2-eq avoided emissions per shared e-moped pkt. The relative impact is however limited, total transport GHG emissions in a cities are affected by less than 0.01 % by the introduction of shared e-mopeds. Scenario analysis showed that the environmental impact of e-moped sharing will decrease in the future, but is expected to remain positive until at least 2040.

Preface

Dear reader,

The thesis in front of you concludes my master's degree in Transport, Infrastructure, and Logistics. Over the last 7 months, with much pleasure I did research into the *Environmental impact of e-moped sharing* which resulted in this report.

In October 2021, I had to write a research proposal as an exercise and preparation for my master's thesis. In the search for a topic, I had a discussion with my brother about the sustainability of shared e-mopeds, which led me to choose this interesting and relevant topic. I would like to express my gratitude to my brother for his contribution on finding this topic.

Half a year later, I was searching for a definitive thesis topic when I came across a report by CE Delft who, in the meantime, published a research on this topic. In their recommendations for further research, I found the perfect topic for my master thesis, as it is presented to you here. I would like to thank CE Delft for this opportunity, the warm welcome and the enjoyable time I had while working at their office. In particular, I would like to express my appreciation to Roy van den Berg for his guidance, trust, and for giving me the freedom to conduct the research in my own way and his pleasant personality.

Furthermore, I would like to thank my university supervisors, Adam Pel, Jan Anne Annema and Bert van Wee, for their enthusiasm on the topic and constructive feedback on my research. Finally, I would like to thank my parents for giving me the opportunity and supporting me to go to university.

M. K. Heijink
Delft, March 2023

Summary

The transportation sector is one of the biggest contributors to global warming. It accounts for 24 % of CO2 emissions, of which more than 40 % is caused by passenger road vehicles. Next to the environmental concerns, cities faces challenges with rising traffic volumes and congestion. Shared micromobility is a potential (partial) solution to these problems. Shared micromobility is often an on-demand and free-floating service, which increases the flexibility and accessibility of these new transport modes. Shared e-mopeds are a relatively new, but rising type of shared micromobility.

Shared e-moped operators tend to emphasize that shared e-mopeds are a green mobility solution. This is however frequently questioned by the media. Multiple articles on news sites have doubted whether shared e-mopeds just replace bicycle and walking trips, and thus what the environmental impact of this new mobility form is. In addition, there is no consensus in the scientific literature on whether shared e-mopeds have a positive environmental impact in terms of GHG-emissions. This lack of consensus is caused by a discrepancy in the environmental impact of shared e-moped themselves, mainly caused by the assumed occupancy, lifespan and vehicle type used for operations.

The objective of this paper is to provide a scientific based statement on whether e-moped sharing brings a positive impact on the environment in terms of GHG emissions in a city. The main research question of this research is:

What is the environmental impact of e-moped sharing in a city in terms of GHG emissions?

To answer the main research question, factors that affect the adoption of e-moped sharing, as well as factors influencing the environmental impact of e-moped sharing in a city were identified via a literature study and semi-structured interviews with municipalities and shared e-moped operators. A conceptual modal was developed integrating both type of factors, for a visual representation of these factors and their interrelations. The conceptual model served as a guideline for constructing the quantitative environmental impact model that can be used in three ways. First, the model can be used for evaluation purposes to determine the environmental impact of e-moped sharing at a specific city. Second, it can provide insight in the impact of shared e-mopeds prior to introduction, using default values for important parameters obtained from literature and current practices. Finally, the modal can provide insight into factors that have a high influence on the environmental impact of e-moped sharing.

In order to determine the environmental impact of each transport mode, an extensive literature review was conducted in combination with data from the Ecoinvent database. The climate change impact was selected as the environmental impact category in this study. The global warming potential (GWP) is selected as an indicator to represent this environmental impact. The GWP is a comprehensive indicator that accounts for the impact of all greenhouse gas (GHG) emissions, expressed in CO_2-eq. To evaluate all emissions related to a transport mode, a life cycle assessment (LCA) approach was used which considers all life cycle emissions of a transport mode. In this research, the LCA consists of a vehicle, battery, maintenance, fuel and operational service component. To allow for a fair comparison between transport modes, the GWP was expressed in CO_2-eq per passenger kilometer travelled (pkt), to account for lifespan and occupancy of the vehicle.

The GWP of a shared e-moped was calculated at 34.9 g CO_2-eq/pkt, assuming a lifespan of 50,000 km, an occupancy of 1.3 passengers and an electric service vehicle. The results show that 24 % of the GWP comes from vehicle production and disposal, 18 % from battery production and disposal, 7 % from maintenance, 27 % from fuel emissions and 24 % from operational service emissions.

Compared to other urban passenger transport modes, shared e-mopeds contribute less to global warming than shared e-bikes, private petrol mopeds, public transport, cars and taxis, while having a comparable impact to its private counterpart.

A Monte Carlo analysis was conducted to account for the uncertainty in input variables used to calculate

the GWP of shared e-mopeds. A triangular distribution was selected for all input variables, with lower and upper bounds obtained from the literature review.

The input variables considered were the shared e-moped lifespan, shared e-moped occupancy, vehicle production emissions per kg, battery production emissions per kWh, battery vehicle ratio, battery range, and service distance per shared e-moped kilometer. Results indicate that there is a low level of uncertainty associated with the GWP of shared e-mopeds. There is a 90 % probability that the GWP of shared e-mopeds ranges from 35.7 and 37.9 g CO_2-eq/pkt. In addition, the GWP calculated and used in this research is only 2.6 % lower than the mean value obtained from the Monte Carlo simulation, 35.9 g CO_2-eq/pkt vs. 36.4 g CO_2-eq/pkt.

To demonstrate the environmental impact of e-moped sharing in a city, the model is applied to four case studies: Amsterdam, Groningen, Rotterdam and an average Dutch city. City-specific factors that the model takes into account and can be specified are modal shift, public transport availability and usage, fleet size, frequency of use, and average trip distance. These variables result in variations in the GWP of public transport, modal shift, and shared e-moped kilometers between cities.

The findings indicate that the use of shared e-mopeds has a positive impact per kilometer driven independent of a city, although the extent of this impact varies between cities depending on factors such as the presence of a tram and metro systems, the sustainability of the bus fleet, and the transport mode being replaced. In the average Dutch city, per shared e-moped pkt, on average 77.5 g CO_2-eq is avoided, while for Amsterdam, Groningen and Rotterdam this is respectively 46.1, 45.9 and 79.2 g CO_2-eq/pkt. To contextualize this impact, the equivalent of 1.0 pkt CO_2-eq by car is saved for every 3.0 pkt travelled with a shared e-moped, based on average Dutch city values.

To determine the absolute environmental impact of e-moped sharing, the city-specific impact per shared e-moped pkt is multiplied with the total number of shared e-moped kilometers within a city. In Rotterdam, the introduction of shared e-mopeds has resulted in the avoidance of approximately 630,000 kg of CO_2-eq per year, making it the city with the highest positive environmental impact. In other cities this value is lower. In Groningen, the lowest amount of CO_2-eq emissions are avoided, around 91,000 kg per year. To gain more insight in the impact of e-moped sharing on a cities transportation GHG-emissions, the relative impact is calculated. The results indicate that e-moped sharing has a very small impact, reducing a city's transportation-related greenhouse gas emissions by less than 0.01 %.

The future environmental impact of e-moped sharing was explored by developing two scenario, for 2030 and 2040. Developments in bus fleet, car fleet, taxi fleet, electricity emission factor and battery production emissions per kWh were considered in the scenario analysis. These are all factors that can be changed in the model to address a specific city worldwide. Prior to the scenario analysis, a sensitivity analysis was conducted for each of these factors. The results revealed that, with the exception of battery production emissions, all factors had a significant impact on the environmental impact of e-moped sharing. The future scenario analyses suggests that the environmental impact of shared e-mopeds decreases over time but still has a positive impact in 2040, for all cases considered. This can be explained by the positive impact of future developments on the GWP of shared e-mopeds, but the positive impact on the GWP of the average repladed transport mode is even greater due to the electrification and the decrease of the electricity emissions factor.

Overall, it can be concluded that e-moped sharing has a positive environmental impact on a city's GHG emissions. However, the environmental impact of e-moped sharing is only one aspect of this new transportation alternative. To fully assess the overall impact of e-moped sharing in a city, additional research is needed to investigate other implications e-moped sharing brings in a city.

Contents

List of Figures

List of Tables

1 Introduction

The transportation sector is one of the biggest contributors to global warming. It accounts for 24% of CO_2 emissions due to fuel combustion: nearly 8.5 Gt CO_2 in 2019, of which more than 40% is caused by passenger road vehicles (IEA, 2022) [1]. Next to the environmental concerns, cities face challenges with rising traffic volumes and congestion. To reduce the impact of the passenger transportation sector, (new) sustainable transportation is needed. Sustainable transportation is defined as the capacity to support the mobility needs of a society in a manner that is the least damageable to the environment and does not impair the mobility needs of future generations (The Geography of Transport Systems, 2022).

Shared micromobility is a potential (partial) solution. Micromobility is defined as the use of small, low speed, lightweight vehicles with a design speed up to 45 km/h, a mass of less than 350 kg and are mainly electric (Schelte et al., 2021). Shared mobility is the concept of vehicle sharing instead of traditional vehicle ownership, resulting in less vehicles needed. The three main modalities of micromobility are e-bikes, stand-up e-scooters (in Dutch: step) and moped e-scooters. In this paper a moped e-scooter is referred to as e-moped and a stand-up e-scooter as e-scooter. New shared micromobility services have specific features which makes them a popular option when traveling in urban areas. Instead of traditional public transport which is fixed-route and fixed-schedule, shared micromobility is an on-demand service and often free-floating, which increases the flexibility and accessibility of these new transport modes (Aguilera-García, Gomez, Sobrino, & Díaz, 2021). Free-floating means that a vehicle can be picked up and left within a geo-fenced service area. Shared e-mopeds and e-scooters are in almost every city free-floating, while shared e-bikes are more often station-based (Aguilera-García et al., 2021).

Moped sharing was first introduced in San Francisco in 2012, since then the business has been rapidly growing. Currently moped sharing is available in more than 175 cities spread over 27 countries, with over 12 million users worldwide in 2021. In 2021, the total number of shared e-mopeds rose up to 110.000 worldwide (Howe & Gmeling, 2021). However, the number of scientific publications into this new transport mode is falling behind. Especially compared to the amount of research that has been performed into the other micromobility sharing modes like e-bikes and e-scooters (Aguilera-García et al., 2021). Therefore, this paper proposes a research that focuses on e-moped sharing.

Even though shared e-moped operators tend to emphasize that shared mopeds are a green mobility solution, not everyone is positive about this new mode of transport. In addition to the increased flexibility and accessibility, the emergence of shared e-mopeds brings implications for public health, safety, street scenes, congestion, air quality and the overall accessibility of a city (Fiorini, Ciavotta, Joglekar, Šćepanović, & Quercia, 2022). Especially non-users are concerned about the parking, safety and driving style of the riders. Sometimes the sustainability is also questioned. Multiple articles on news sites have doubted whether shared e-mopeds just replace bicycle and walking trips, and thus how sustainable this new mobility form is (AD, 2022a) (AD, 2022b) (Volkskrant, 2022) (NU, 2021) (Trouw, 2020).

[1]The numbers from 2019 have been used because due to the COVID-19 pandemic, it fell with 10 % to 7.2 Gt in 2020 (IEA, 2022)

These statements and questions often do not have a scientific basis, which endorsed the importance of sound scientific research into this topic.

Three goals micromobility should achieve in order to be considered sustainable are reducing GHG-emissions, operating reliably and equitably and enhancing the human experience. This study focuses on the first goal, the environmental impact of shared e-mopeds in terms of GHG-emissions. As a consequence, the environmental impact on for instance air quality and noise pollution is not considered in this study. Mechanisms to achieve this first goal are to enable the mode shift from automobiles, to avoid the mode shift from transit and walking and to complement and encourage new transit ridership (McQueen, Abou-Zeid, MacArthur, & Clifton, 2021).

Three parts are of great importance when determining the environmental impact of e-moped sharing. The GWP [2] of the e-moped itself, the environmental impact of the replaceable transport modes and the modal shift shared e-mopeds cause in a city. Additionally, the adoption and consequently the usage of e-moped sharing is essentual to determine the impact on city level.

Five scientific papers and one report [3] assessed the first part using a life-cycle assessment (LCA) (ITF, 2020) (Felipe-Falgas, Madrid-Lopez, & Marquet, 2022) (Schelte et al., 2021) (Wortmann, Syré, Grahle, & Göhlich, 2021) (de Bortoli, 2021). A LCA not only considers the emissions from fuel extraction and combustion, but also from vehicle production, maintenance and disposal in addition to operational services, thus the emissions from a vehicle entire life. The studies show a wide range of the GWP of shared e-mopeds expressed in CO_2-eq per passenger kilometer travelled. The GWP of a shared e-moped ranges from 34.0 to 80.0 g CO_2-eq/pkt. The differences are quite large due to differences research design, average occupancy, vehicle lifetime, sources used for the LCA and the electricity mixes in countries used as a case study. The same holds for the GWP of the replaced transport mode. Some of the studies mentioned above also determined the GWP of those transport modes using a LCA methodology, which also shows a wide range in GWP between the studies.

For the modal shift, limited data is available. The data that is available mainly comes from Spanish cities, the country with the biggest e-moped sharing market. This data shows that in general only 20% of the shared e-moped trips are a substitute for a private vehicle, while the shared e-moped was 50% of the time a substitute for PT and 18% for walking or cycling (Aguilera-García et al., 2021).

To date, only one research to the full environmental impact that incorporates these three aspects has been performed. Schelte et al. (2021) solely calculated the GWP of shared e-mopeds and not the replaced transport mode. In the research of Wortmann et al. (2021) the LCA on shared e-mopeds is only a small part of the entire research, and no GWP calculation of replaceable transport modes is done and modal shift data is incorporated to assess the impact at city level. de Bortoli (2021) compared all shared (electric) micromobility modes in terms of GWP, but not of all transport modes and the modal shift to determine the environmental impact on city level. The study of Christoforou, De Bortoli1, and Christoforou1 (2020) comes closest to the research done here. The GWP of transport modes in Paris is determined. Modal shift data is also used to determine the city wide impact in terms of GHG emissions. Shared e-scooters are however the starting point, and not shared e-mopeds. ITF (2020) performed a LCA on all urban passenger transport modes, but did not include the modal shift to determine the change in emissions in a city. Felipe-Falgas et al. (2022) is the only study in which incorporates all three aspects. The results did show that in Barcelona shared e-mopeds are causing an actual increase in GHG emissions, but not in which extend. For shared e-scooters this kind of research has been conducted a couple of times. These studies rather indicated that the shared e-scooter have a negative impact on the environment than a positive Moreau et al. (2020) Hollingsworth, Copeland, and Johnson (2019) Badia and Jenelius (2023). Besides that, these papers concluded that the environmental impact strongly depends on city characteristics, which causes big differences in the prior modal split and thus the caused modal shift. Especially between US and European cities due to cultural and spatial differences. Although there are differences between shared e-mopeds and e-scooters, it is nevertheless very likely that these city characteristics also have a significant impact on the modal shift of shared e-

[2] The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different greenhouse gases (GHG). It is an indication of the extent to which a greenhouse gas can contribute to global warming. Specifically, it is a measure of how much energy the emissions of a greenhouse gas will absorb over a given period of time, relative to the emissions of the same mass of carbon dioxide (CO_2)" (US EPA, 2022b)

[3] The study of ITF (2020) is not a scientific paper but a Corporate Partnership Board Report

mopeds. Since the only research to the full environmental impact of shared e-mopeds in a city is done for one particular city - and obtaining a negative result - it is important this is done for multiple cities. Moreover, the constructed model in this research will be applicable to cities all over the world if data is available by adjusting a few parameters.

CE Delft [4] performed, commissioned by Felyx, a research into the effect of shared electric mopeds on CO_2-eq emissions (CE Delft, 2021). Using Rotterdam as a case study, they found that after introducing shared e-mopeds, almost 500 tonnes of CO_2-eq were avoided in the period from October 2020 to September 2021. However, they only took the emissions during the use phase into account. Use phase emissions [5] account for 28.7 % of the total GWP, which shows the importance of incorporating vehicle emissions since these account for 71.3 % of the total life cycle emissions according to this particular research (Christoforou et al., 2020). This is similar to the 75 % contribution of the vehicle stage found by de Bortoli (2021). In Barcelona, around 40 % of the GWP of shared e-mopeds comes from vehicle production, maintenance and end-of-life treatments (Felipe-Falgas et al., 2022). These percentages of contribution of the vehicle stage of shared e-mopeds shows that it is essential a life-cycle approach is used when determining the environmental impact of this new transport mode.

This paper aims to fill this gap and contribute to the knowledge about the environmental impact of this new shared transport mode. A quantitative approach is proposed, to determine the environmental impact of shared e-mopeds at city level. To able to do so, a quantitative environmental impact model is developed. In some way it is quite similar to the one already developed by CE Delft, however it is extended with multiple parameter to make it applicable to every city. Furthermore, life cycle emissions and not solely the emissions during the use phase are considered for all transport modes. This enables a more accurate estimation of the GHG-emissions change shared e-mopeds cause.

The proposed developed model can be used for three manners. First, it can be used to evaluate the impact of shared e-mopeds on a cities GHG emissions. Furthermore, using default values for parameters and modal shift patterns derived from literature and other cities, it can be used to assess the effect of shared e-moped in a city prior to introduction. This way it can for example give a substantiation on the decision of municipalities to allow shared e-mopeds in its city. Lastly, the model can give insight into factors that have a high influence on the environmental impact of shared e-mopeds. Using this knowledge, municipalities can for instance make tailor-made policy for a particular city to stimulate certain behaviour which result in (higher) emission reduction. This information can also be used by shared e-moped operators to change their operation or to reduce the GWP of shared e-mopeds and its environmental impact by gaining insight in which emissions contribute the most the GWP of shared e-mopeds .

1.1. Research objective and questions

The aim of this research extends beyond the mere comparison of life cycle emissions between shared e-mopeds and other transportation modes. The objective is to assess the environmental impact of shared e-mopeds on transportation emissions in a city, while taking into account the unique characteristics of the city and the modal shift resulting from the introduction of shared e-mopeds.

What is the environmental impact of e-moped sharing in a city in terms of GHG emissions?

To answer this main question, five sub-questions are defined:

1. What are the factors that influence the impact of shared e-mopeds on GHG transportation emissions in a city considering life cycle emissions?
2. What is the environmental impact of a shared e-moped using a LCA methodology?
3. What is the environmental impact of all replaceable transport modes using a LCA methodology?
4. What is a suitable model based on the conceptualisation that can estimate the environmental impact of shared e-mopeds in different cities?

[4] CE Delft is an independent research and consultancy firm, specialized in developing innovative solutions for environmental and sustainability issues

[5] Here fuel and infrastructure emissions

5. What is the impact of the introduction of shared e-mopeds on GHG transportation emissions in a city considering different (future) scenarios?

Firstly, the factors that influence the impact of shared e-mopeds on GHG transportation emissions in a city considering life cycle emissions will be identified. This identification process includes an examination of factors related to the adoption and usage of e-moped sharing, as well as factors that determine the environmental impact of both shared e-mopeds and its replaceable transport mode. A conceptual model will be developed that integrates both types of factors and provides a visual representation of the relationships between them. Secondly, the environmental impact of a shared e-moped using a Life Cycle Assessment (LCA) methodology will be quantified. Thirdly, the environmental impact of all replaceable transport modes using a LCA methodology will be assessed to provide a baseline for comparison. Fourthly, a suitable model based on the conceptualization will be developed to estimate the environmental impact of shared e-mopeds in different cities. This model will take into consideration various city-specific characteristics and factors that influence the environmental impact of shared e-mopeds. Finally, the impact of the introduction of shared e-mopeds on GHG transportation emissions in a city considering different (future) scenarios will be evaluated. Next to current potential benefit, this will provide valuable insights into the future potential environmental benefits of e-moped sharing and enable informed decisions to be made regarding the environmental impact of this new mobility alternative.

1.2. Scope

Geographical location case study - The Netherlands

Parameters that vary among countries and can have a significant impact on the GHG emissions of different transport modes include the electricity mix, occupancy rates of transport modes, electrification of public transport, and modal split (which affects the modal shift that shared e-mopeds cause. This study is conducted in the Netherlands, and thus the country is initially chosen as the default value for these important parameters. However, the environmental impact assessment model can be easily adjusted to reflect values from other cities and/or countries. The Netherlands is an interesting case due to several factors, such as the cycling culture, which makes cycling one of the primary transportation modes, particularly in urban areas where shared e-moped services operate. This also means that there is an extensive cycling infrastructure network that can also be utilized by shared e-mopeds. In addition, the cities in the Netherlands are located relatively close to each other, making it possible to travel between them with shared e-mopeds. Other countries may not have these unique characteristics, and thus the environmental impact of shared e-mopeds may differ there, making it interesting to study the impact of shared e-mopeds in those countries as well.

Environmental impact categories

For the evaluation of a transport mode using LCA approach, various environmental impact categories can be considered. Typically, the climate change environmental impact category is used, and to represent this impact, the Global Warming Potential (GWP) indicator is selected. The GWP is a comprehensive indicator that accounts for the impact of all greenhouse gas (GHG) emissions, expressed in CO_2-eq. Although particulate matter and NO_x-eq emissions have direct negative effects on public health, this study focuses specifically on the impact of shared e-mopeds on climate change and therefore does not consider these factors.

Infrastructure emissions

In a life cycle assessment (LCA) approach, infrastructure emissions refer to the emissions associated with the construction, maintenance, and end-of-life management of the infrastructure required for vehicle operations. However, the definitions of infrastructure life cycle emissions can vary between studies, which can make fair comparisons difficult. While some studies include infrastructure emissions of road or track for public transport, such as metro and train tunnels, stations, docks, and roadway earthwork emissions, most studies only consider road wear emissions.

In this study, infrastructure emissions are not taken into account since the introduction of shared e-mopeds does not have an impact on the construction of existing bicycle roads or urban rail tracks. These roads and infrastructures already exist, and the mobility system will not change significantly enough to influence existing or future infrastructure. This claim is supported by the number of shared e-moped trips on an average working day in Amsterdam, which only contribute to a small extent to all passenger trips, accounting for 0.32 % (6,000 of 1,900,000 total trips) according to Gemeente Amsterdam (2022).

Transportation emissions
Transportation emissions refer to emissions generated during the transportation of vehicles from the production site to their usage location. In an LCA approach, including this component can significantly affect the environmental performance of the analyzed vehicle. However, the results show that transportation emissions do not have a significant impact on the GWP if transportation is done by sea, road, and/or rail. For instance, transporting shared e-mopeds from China to Europe increases the carbon footprint by only 2 to 3 %. In contrast, air shipping has a major impact on the carbon footprint of shared e-mopeds, which can increase by 96 % due to the high weight of an e-moped (de Bortoli, 2021). It is however unlikely that shared e-mopeds are shipped by air. Therefore, the impact of transportation emissions on the GWP of shared e-mopeds is expected to be low. However, the fact that transportation emissions are low is not a sufficient argument for not considering them since the replaced transport mode may have significant transportation emissions. Despite this, it is decided not to consider transportation emissions in this study due to the difficulty in obtaining information on the production location of all vehicles analyzed.

1.3. Relevance

This research provides a significant contribution by offering a scientifically-sound statement regarding the environmental impact of shared e-mopeds in an indefinite particular city.

The first academic contribution this research provides is the integration of shared e-moped adoption factors as well as factors that influence the environmental impact of e-moped sharing into a conceptual model. This conceptual model gives insight into relevant factors that need to be considered when addressing the environmental impact of introduction of shared e-mopeds in a city. In addition, it gives insight into the interrelations between these factors and how they influence each other.

The quantitative environmental impact model created for this study contributes to knowledge about the environmental impact of e-moped sharing in a indefinite city. The environmental impact of shared e-moped and its replaceable transport modes are calculated considering a LCA approach. The model is adaptable to country and city-specific characteristics and factors, making it applicable to cities worldwide.

Dutch country characteristics are used as default values for calculating the environmental impact of e-moped sharing. Although the model is applied to the Dutch case, the results include findings that can be generalised beyond the Dutch case, as the results show that e-moped sharing has a positive environmental impact in a city, independent of the chosen case study. The Monte Carlo analysis further showed that there is a low uncertainty around the GWP of shared e-mopeds, meaning it the study provide a reliable estimate of the environmental impact of shared e-mopeds. This information can be used by shared e-moped operators and (local) policy makers to highlight the favorable environmental profile of shared e-mopeds compared to more harmful modes of transportation.

Furthermore, this research offers valuable insights into key factors that significantly influence the environmental impact of shared e-mopeds. Shared e-moped occupancy, the vehicles lifespan, service vehicle type and the service distance play a crucial role when calculating the environmental impact of shared e-mopeds. Based on this information, policymakers can make better informed decisions to promote the positive environmental impact this new mobility alternative.

1.4. Report structure

This report is structured in the following manner. Chapter 2 outlines the research methodology used in this study. In Chapter 3, the conceptual model is illustrated, and the factors and their interrelationships from the conceptual model are explained. The conceptual model serves as a benchmark for the subsequent chapters. Chapter 4 provides background information on shared e-mopeds, including modal shift, user characteristics, and usage patterns. In Chapter 5, the global warming potential (GWP) of shared e-mopeds and their replaced transport modes are determined, while Chapter 6 explains the construction of the environmental impact model used in this study. Chapter 7 presents the main results, including the GWP of all transport modes, a Monte Carlo uncertainty analysis on the GWP of shared e-mopeds, and the environmental impact at the city-level of shared e-mopeds for three case studies, as well as the application of future scenarios and their results. Chapter 8 draws final conclusions by addressing the main research question and its sub-questions. Finally, Chapter 9 provides a discussion of the findings, limitations of the research and suggestions for future research.

2

Research methodology

This chapter provides detailed information about the methodology used to answer the main research question in this research. A graphic representation of the methodology is presented in Figure 2.1. Section 2.1 justifies the use of interviews and outlines the usage of these interviews. Section 2.2 provides an overview of the literature study, including the search method for relevant papers and selection criteria. Section 2.3 explains the process of developing the conceptual model and the input used in this process. Finally, section 2.4 details the construction of the quantitative environmental impact model and the collection of input data.

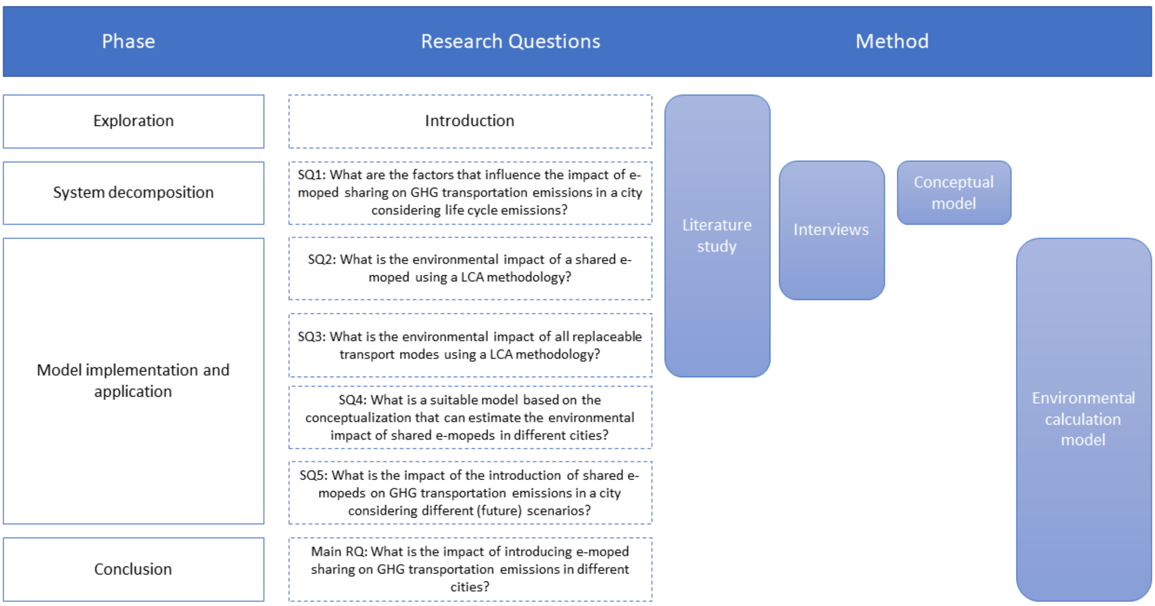


Figure 2.1: Research Flow Diagram

2.1. Interviews

Semi-structured Interviews were conducted to gather contextual information around the e-moped sharing system. Semi-structured interviews combine structured and unstructured approaches, with predetermined questions that are not necessarily asked with certainty or in a predetermined order. Interviews were conducted with both shared e-moped operators and municipalities to obtain input from both perspectives. To ensure a comprehensive view, interviews were conducted with all three shared e-moped operators, while municipalities in Breda and Utrecht were chosen for their contrasting policies towards shared e-mopeds. Utrecht has recently banned shared e-mopeds in their city, while Breda promotes shared mobility. Interviews with municipalities provided greater understanding of the role and place of shared e-mopeds in the current and future mobility system, as well as their views on the environmental sustainability of this new transport alternative. Interviews with e-moped service providers provided insight into the environmental sustainability and adoption of the e-moped sharing system in different cities. The interviews were used as input for the conceptual model, where they, along with a literature study, helped to determine the factors and interrelationships included in the model. In addition to input for the conceptual model, interviews with e-moped service providers were used to gather information on e-moped characteristics for calculating the GWP (Global Warming Potential) of shared e-mopeds. The interviews are summarized in Appendix B.

2.2. Literature Study

A literature study is conducted to gain insight and knowledge on the e-moped sharing system. To be more specific, into the environmental impact of e-moped sharing, and the adoption of this new transport mode. To literature study was first used to determine the factor influencing these two factors, in combination with the relations between them. The second purpose of the literature study was collection data and input for the environmental impact calculation of e-moped sharing. The first purpose provided input for the conceptual model, while the second provided input for the quantitative environmental impact model.

Google Scholar, Scopus and ScienceDirect were used to find the scientific literature using a combination of the following keywords: *Shared e-mopeds*, *E-moped sharing*, *Moped e-scooter*, *Environmental impact*, *Shared e-moped usage*,*Adoption*, *Modal shift*, *LCA*, *Sustainability*. Furthermore, forward and backward snowballing was used in search of other articles that had been overlooked. Research on e-moped sharing is currently limited. Therefore, to the best knowledge, all papers up to 2023 were analyzed and summarized in table format in Appendix A. Since this study covered both the adoption and environmental impact of shared e-mopeds, the studies that focused on identifying optimal parking locations and analyzing motorcycle sharing systems in multiple Spanish cities were deemed irrelevant and excluded from this research.

2.3. Conceptual model

The conceptual was developed to provide a visual representation of the e-moped sharing system regarding the environmental impact. It integrated both factors related to shared e-moped adoption and factors that influence the environmental impact of e-moped sharing. This was done to identify factors that are important and relevant to consider when addressing the environmental impact of e-moped sharing for the quantitative environmental impact model. The factors and their interrelationships that were included in the conceptual model were obtained from the literature study. Technical reports and shared e-moped evaluation reports from municipalities were used to supplement the literature review on user and trip characteristics of e-moped sharing, which is related to the adoption of e-moped sharing.

2.4. Quantitative environmental impact model

The quantitative environmental impact model was constructed to be able to make a statement on the environmental impact of e-moped sharing in a city. A conceptual model was developed using factors obtained from the literature study and interviews as a guideline for developing the quantitative environmental impact model.

First, the global warming potential (GWP) - which is used as an indicator of the environmental impact of a transport mode - of all transport modes was calculated using a life cycle assessment (LCA) approach. Section 5.1 expounds more on the LCA methodology. To do so, default values for essential parameters needed to be determined. Literature studies that calculated the GWP of shared e-mopeds were analyzed and decomposed. The values in the studies were first corrected for different lifespans and occupancy's to enable comparison. Emissions were decomposed to LCA components considered in this study. Together with the Ecovinvent database and data from shared e-moped operators obtained in the interviews, default values for parameters were specified. Each LCA component was individually calculated per transport mode. Fuel emissions of all transport modes were obtained from the STREAM study of CE Delft. Subsequently, a default GWP was calculated for each transport mode.

The quantitative environmental impact model furthermore includes a Monte Carlo analysis of the GWP of shared e-mopeds. Section 7.2 expounds on the methodology of a Monte Carlo analysis. The lower and upper bounds required for the included independent variables were obtained from the literature review, where values for these variables were compared between studies.

Three case studies and a city with average Dutch characteristics [1] were applied to the model to gain insight in the absolute environmental impact of e-moped sharing. Data for these four cases on shared e-moped usage in a city was thus required. City specific data on the modal shift, average trip distance, fleet size, and frequency of use are essential for a reliable calculation of the environmental impact of shared e-mopeds. For the case studies, this data was obtained using evaluation reports from municipalities. Specific city data regarding public transport was obtained from yearly reports from the relevant public transport companies.

To gain insight into the future environmental impact of e-moped sharing, the model includes a scenario analysis. Policies and expected developments were used as input data, and a sensitivity analysis was performed for each factor individually. Two scenarios were created for 2030 and 2040, which included all the factors.

Chapter 6 provides a more detailed explanation on the development of the model and how all the environmental impact indicators were calculated.

[1] This is a city with average values of Amsterdam, Rotterdam and Groningen, thus not really an average Dutch city

3

Conceptual model

This chapter presents a conceptual model that shows the environmental impact in a city after introduction of shared e-mopeds. Starting-point is the introduction of shared e-mopeds and end-point of the model is the environmental impact. The conceptual model provides new insights into e-moped sharing by integrating information and factors related to the adoption and environmental impact of this new mobility alternative. The factors and their relationships are mainly identified through a literature study on the e-moped sharing system, supplemented by technical reports, interviews with scooter operators and municipalities, conversation with experts from CE Delft and the researcher's own knowledge and experience. To the best knowledge, the study and thus conceptual model uses all relevant papers on e-moped sharing published before 2023. However, the findings from two papers are not incorporated as they were deemed irrelevant to the conceptual model presented in this study. The first focused on a methodology for finding optimal parking spaces and the other analyzed the motorcycle sharing system in multiple Spanish cities.

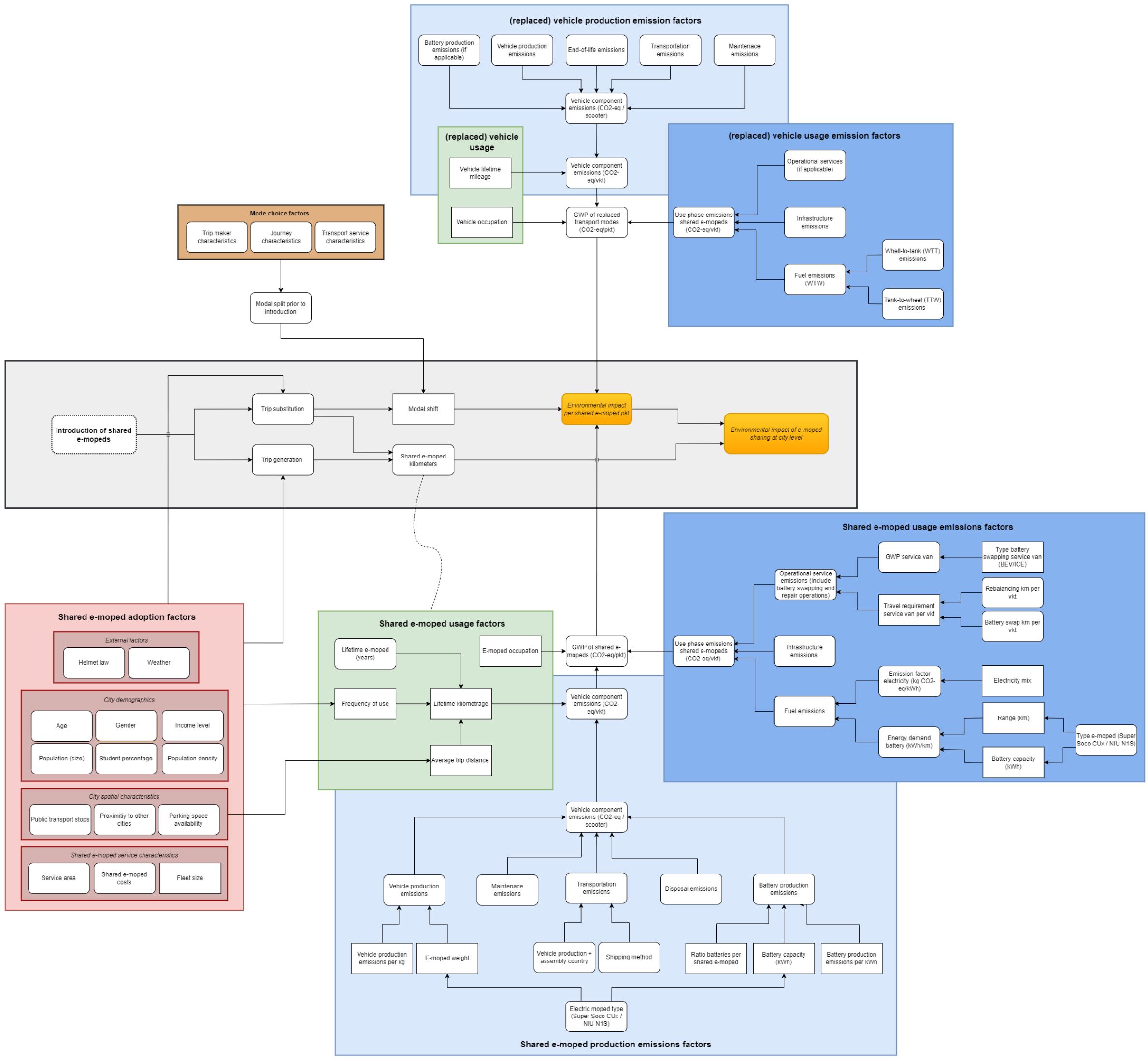
The section comprises an examination of the mobility effects arising from the use of shared e-mopeds (section 3.1.1), the modal shift induced by this new mode of transportation (section 3.1.2), and the factors influencing the adoption of shared e-mopeds (section 3.1.3), structured to the different components in the conceptual model. In addition, section 3.1.4 provides a brief description of the method for calculating the environmental impact of a transport mode, while section 3.1.5expounds concisely on the environmental impact in a city resulting from the use of shared e-mopeds.

3.1. Conceptual model explanation

Figure 3.1 shows the created conceptual model. Factors in the model can have two different shapes: rectangular and rounded. Rectangular factors represent parameters in the quantitative environmental calculation model which can be adjusted, while rounded factors represent calculated variables or factors that influence the environmental impact of e-moped sharing but are not included in the calculation model.

The central light grey box provides a broad overview of the impact of introducing shared e-mopeds in a city. The model starts with the introduction of shared e-mopeds in a city. The boxes that are illustrated are explained and discussed below in general, in order of occurrence. Shared e-moped adoption factors are discussed more extensively below, while the subsequent chapter delves into shared e-moped usage (represented by the green box in the lower part), modal shift and modal split prior to introduction. In addition, chapter 5 expounds more on the light and darker blue boxes, the environmental impact of shared e-mopeds and its replaceable transportation modes. The two orange factors in the model represent the main results indicators. Chapter 6 explains the calculation of these indicators, and their results are discussed in chapter 7.

Figure 3.1: Conceptual model



3.1.1. Mobility effects

Introduction of shared e-mopeds in a city cause mobility effects. These effects are two-sided, on the one hand is causes trip substitution and on the other hand trip generation. Trip generation is the concept that a new mobility form creates more trips than prior to introduction in a city. These are extra trips and thus kilometers driven with a shared e-moped which would not have been made otherwise. It is also called induced demand. For shared e-scooters, induced demand is more dominant in trips for fun, while it is minimal for commuting trips. The same observation is likely to apply for shared e-mopeds, indicating that these extra trips are primarily trips for fun (Weschke, Oostendorp, & Hardinghaus, 2022). A literature review of shared e-scooters indicates that induced demand is generally low and ranges from 2 % to 6 % of all trips (Weschke et al., 2022).

Trip substitution is the phenomena that travellers take a shared e-moped instead of another transport mode. Substituting one mode for another is called modal shift and results in a change in the modal split in a city. This modal shift is a crucial aspect when determining the environmental impact of shared e-mopeds, since it is desired that a mode which causes more damage to the environment in terms of GHG-emissions is replaced.

3.1.2. Modal shift

The modal shift shows which transport modes are replaced by a shared e-moped. It is important to remember that the decision of taking a shared e-moped at all, is already made. The decision whether a shared e-moped is taken, which thus determines the usage or adoption of shared e-mopeds at city level, is explained in the lower red part of the conceptual model. The main indicator for modal shift is the modal split prior to introduction in a city. The modal split already accounts for factors like car ownership. If in a city the car ownership per household is very low, it is expected that the car substitution rate is lower than in a city with higher car ownership. However, this also applies to the modal split prior to introduction since a low car ownership leads to a lower car share in the modal split. The next chapter elaborates a bit more on the modal split and mode choice factors which determine this modal split.

It is noteworthy that some of the factors influencing mode choice and consequently modal split also influence the adoption of shared e-mopeds. However, these factors are separated in the conceptual model as it is uncertain whether all mode choice factors apply to shared e-moped adoption. The factors that indeed influence the adoption of shared e-mopeds - confirmed by scientific research - are categorized in the red box *shared e-moped adoption factors*.

3.1.3. Shared e-moped adoption

The left red part below the environmental impact calculation determines the adoption of shared e-mopeds. This adoption influences both trip substitution and trip generation. Trip substitution and generation combined gives the total shared e-moped kilometers. Theoretically, shared e-moped kilometers can be calculated by multiplying the average trip distance, frequency of use and fleet size. Shared e-moped adoption factors also influence shared e-moped usage, specifically the vehicles lifespan, which can be calculated by multiplying the frequency of use, average trip distance and lifetime in years. In this subsection, factors influencing shared e-moped adoption are examined and substantiated.

A more general conclusion - which is not covered by any of the subsections - is that only a few factors differ between occasional and frequent users (Aguilera-García, Gomez, & Sobrino, 2020). This could indicate that the main barrier to adopt e-moped sharing is related to having a first experience with a moped-sharing system. This conclusion is very important for policy makers, since it is thus more important to target non-users than trying to shift users from occasional to frequent ones - if the goal it to increase shared e-moped usage in a city.

Shared e-moped service characteristics

Service area

If it is desired that shared e-mopeds become a regular transport option, it is important that a vehicle is located within walking distance. 84.3 % of the users would walk less than 500 m to pick up an e-moped, and nearly half of the users are not willing to walk beyond 200 m (Aguilera-García et al., 2021). Expanding the fleet and service area increases the reliability of shared e-moped service and can thus increase the usage and shared e-moped kilometers.

Shared e-moped costs

The rate of shared e-mopeds is based on the trip duration in minutes, though a fixed starting rate is always present. Lower trip costs is expected to result in a decrease in shared e-moped usage.

Fleet size

The frequency of use however does not increase linearly with a larger fleet size, the only certainty is that the total shared e-moped kilometer increase. The expectation is that the relationship between the factors has a sort parabola shape. In the beginning, increasing the fleet size results in a higher frequency of use. However, at one point it is no longer beneficial to add mopeds since the market is then saturated.

City demographics

Socio-demographic factors that influence the adoption of shared e-mopeds are discussed here. Factors that influence the decision of shared e-moped scooter operators to operate in a city are city size (measured by number of inhabitants), population density, car ownership and demographics. A scientific basis for these relationships is given here, if investigated or present in scientific literature.

Age

People aged between 26 and 35 have a higher probability of being a frequent shared e-moped user (Aguilera-García et al., 2020). The higher penetration of e-moped sharing in this age group can be explained by more familiarity with new technologies in this age group compared to older people. Above 50 years, there a smaller chance of ever using a shared e-moped. It is worth noticing that there is also penetration in the middle-aged adult group - 35 to 49 years old - however, at a lower intensity than the group of younger adults (Aguilera-García et al., 2021) (Aguilera-García et al., 2020).

Gender

In addition, gender is a critical variable that determines the usage of shared e-mopeds. Male are also more likely to be frequent user of shared e-moped compared to females (Aguilera-García et al., 2020). Furthermore, in the research of Aguilera-García et al. (2021) there is a significantly higher share of males that ever used e-moped sharing compared to females, 30.4 % vs 14.0 %.

Students

Students present a higher probability of adoption shared e-mopeds compared to employees (Aguilera-García et al., 2020). Additionally, Fiorini et al. (2022) found that an increase in education index leads to an increase in shared e-moped use. The education index is measured in share of gratitude's, which is used as a proxy for the average socio-economic status of an area. It is assumed that higher education is related to a higher income level and greater economic and social well-being (Fiorini et al., 2022).

Aguilera-García et al. (2020) explored the influence of education level and income level on shared e-moped adoption separately and found two different relations. Higher Education level increases the likelihood of being a frequent user with 400 % having a university degree compared to non-university (Aguilera-García et al., 2020). In addition, a higher education level has a higher proportion of users in this new mobility alternative (Aguilera-García et al., 2021). An explanation is the higher proportion of young people among students, along with the faster tendency to adopt new innovative technical services among highly-educated people (Aguilera-García et al., 2020).

Income level

On the contrary, income level significantly reduces the likelihood of being a frequent users, but shows not to have an impact on occasional users (Aguilera-García et al., 2020). Wealthy people have a higher use of private vehicles for daily mobility, which can be an explanation for this relation.

However, individuals who own a private vehicle have a higher probability of having adopted e-moped sharing. Only 20 % of the individuals without a private vehicle declared having adoption e-moped sharing (Aguilera-García et al., 2021). Moreover, people who used car-sharing or have ever driven a motor/scooter are significantly more likely to ever use a shared e-moped (Aguilera-García et al., 2020).

No research is yet done into the influence of population size and density and the adoption of e-moped sharing. The expectation is that both population density and population size are expected to have a positive relation with shared e-moped usage.

Population size

Generally, city size (measured by resident population) has a positive association with public transport share, actives modes share (for distances under 1.5 km) and a negative association with private car share (Susilo & Maat, 2007) (Scheiner, 2010). This means that if a cities growth in size, more public transport and less private car will be used. Shared e-mopeds are complementary with pedestrian and bike mobility and they seem to substituted private car (there are no clear effects on public transportation). Theoretically, less car trips are thus substituted in larger cities, where the car share is lower.

Population density
Population density has a positive relation with public transport share and a negative one with car share. The relation between walking and cycling share and population density differs between studies. Shared e-moped trips are often commuting trips. In Groningen, 46.3 % of shared e-mopeds trips are for commuting or travelling to an educational institution (Gemeente Groningen, 2022). In Amsterdam this is 36 % and in Eindhoven 47 % (**?**) (Gemeente Amsterdam, 2022). For commuting journeys Susilo and Maat (2007) and Pinjari, Pendyala, Bhat, and Waddell (2007) found a positive association between active mode share and population density. However, not all studies endorse this relation. Phanie Souche (2010) found that the population density has a negative association with active mode choice.

City spatial characteristics
Public transport stops
The factor public transport stops relates to the accessibility to PT stops in a city. Shared e-mopeds are often used in combination with other transport modes, in Eindhoven, 75 % of the users combines shared mobility with the train, meaning shared e-mopeds are often used as first- and last-mile transport option for public transport. More public transport stops can on one side increase shared e-moped usage since these are often used as first- and last-mile transport option. The other side is however that a extensive public transport network decreases the need to use shared e-mopeds.

Proximity to other cities
Proximity to other cities increases the usage of shared e-mopeds. If two cities are located relatively close to each other, a shared e-mopeds becomes an option for travel between the cities. Next to inner-city trips, inter-city trips become an option resulting in a higher shared e-moped usage. Empirical data also endorses the fact that the average trip distance increases when cities are located close to each other. In Rijswijk, the average trip distance lies between 4.5 - 5.0 km, which is significantly higher than the Dutch average (3.7 km). Rijswijk, is a (small [1]) city located between The Hague and Delft is a perfect example where inter-city travel with a shared e-moped is possible. From the center of Rijswijk to Delft's city center the distance is around 4 km, and to the Hague it is around 5 km. These distance can easily be undertaken with a shared e-moped which is also showed by the higher average trip distance.

Parking space availability
Shared e-mopeds are a more convenient option for travelling to a city center compared to a car. The benefit of shared e-mopeds is that parking is free compared to car parking (close to the city center) and a shared e-moped can almost always be parked closer to the city center than a car (Aguilera-García et al., 2021). In addition, parking availability is one of the significant decision factors that differed between non-users, frequent users and occasional users (Aguilera-García et al., 2021). Hence, less parking space availability for cars is expected to increase shared e-moped usage.

External factors
Helmet law
From the first of January of this year, it is required by law tho wear a helmet on both 25 km/h and 45 km/h mopeds (Rijksoverheid, 2023). Since this law only applies for two months now, it is hard to make a statement on the impact of this law of the usage of shared e-mopeds. The expectation is shared e-mopeds become less popular due to this helmet obligation. People can find it unsanitary and in general the threshold to quickly grab a shared e-moped is raised.

Weather
The weather is also a factor that influence shared e-moped usage. In bad weather - rain and cold - a shared e-moped is a less comfortable way to travel than the private car, taxi or public transport where a person is inside a vehicle and thus dry and less cold. This statement is endorsed by seasonal shared e-moped usage data, where the total number of trips is lower in winter months than in summer months (Gemeente Eindhoven, 2023). This trend can however also be caused by COVID-19 measures, which often applied in winter months and less restrictions were present in summer months. It is however still likely that the cold and rain has a negative impact on the number of shared e-moped trips. This is

[1]Compared to The Hague, Rotterdam and also Delft

confirmed by the research of Arias-Molinares, Romanillos, García-Palomares, and Gutiérrez (2021). In Spanish cities, in warmer month - from March to October - shared e-moped usage is higher compared to winter months. From March there is a peak related to a rising temperature which make shared micromobility more attractive. The research furthermore showed that holidays have a negative impact on shared e-moped usage, endorses by a shard rise in September and October when people return from holidays and going back to their daily routines.

3.1.4. GWP shared e-mopeds and its replaceable transport modes

The GWP of both shared e-mopeds and its replaceable transport modes is determined by two bigger components - vehicle and use phase - which can both be decomposed to smaller components. Chapter 5 will elaborate in detail on these component and the influence of the other factors illustrated in the conceptual model. It is important to note that the GWP of both shared e-mopeds and their replaced mode of transport is expressed in CO_2-eq/pkt. The emissions in the use phase do not depend on the usage of shared e-mopeds, since these emissions increase with every driven kilometer. The vehicle production emissions do depend on the vehicle usage, since these emissions are divided by the vehicle lifetime mileage. In addition, the vehicle occupancy is taking into account by dividing the emissions per vehicle kilometer with the average occupancy rate to obtain the emissions per passenger kilometer travelled. Although the GWP of each replaced mode of transport must be calculated separately, here it is shown as one to keep it as clear as possible.

3.1.5. Environmental impact

The difference between the *GWP shared e-mopeds* and *average GWP replaced transport mode* gives the environmental impact per shared e-moped pkt. The average GWP of a replaced trip per pkt is calculated using the modal shift en the GWP of all substituted transport mode. Combining the environmental impact per shared e-moped pkt and the total shared e-moped kilometers in a city, results in the environmental impact of introduction of shared e-mopeds at city level.

4

Background information on shared e-mopeds

The preceding chapter presented a graphical representation of the environmental impact of introducing shared e-mopeds in a city, inclusive of factors that influence the adoption of e-moped sharing and, consequently, shared e-moped usage. This chapter expounds upon usage characteristics of shared e-mopeds. Section 4.1 delves further into the modal shift shared e-moped cause. Empirical data is presented, followed by an explanation of factors that can affect or determine this modal shift. Section 4.2 discusses user and trip characteristics of shared e-mopeds.

4.1. Modal shift shared e-mopeds

The indirect environmental impacts of transportation disruptions are frequently overlooked (Christoforou et al., 2020). There are limitations when only the LCA of an e-scooter is assessed. Simply said, an e-moped only contributes to more sustainable transport when it replaces a trip that was otherwise made with a modality with a higher GWP. Therefore, the modal shift that shared e-mopeds causes must be determined. This section first shows insights from modal shifts in Europe in section 4.1.1 followed by current practice in the Netherlands in section 4.1.2.

4.1.1. Modal shift insights from the literature

In the study of Aguilera-García et al. (2021) using survey data from Spain, the main transportation mode that was previously used instead of a shared e-moped scooter were investigated, differentiated by occasional and frequent users. Approximately 50% of the trips were a substitute for public transit, around 20% for a private vehicle and 18% for walking or cycling (Aguilera-García et al., 2021). Frequent shared e-moped users replace a private vehicle much more often than occasional users: 26.3 % against 14.3 % (Aguilera-García et al., 2021). On the contrary, public transit is more often replaced by occasional users than frequent users (55.4 % vs. 44.7 %). To ensure that car trips are replaced more often, it is thus important to encourage that shared e-moped becomes a regular (daily) mode of transport. There is still room for improving this because leisure is the main trip purpose, which is not a regular trip compared to for instance a commuting trip. Currently around 32 % of the shared e-moped trips are for shopping, visiting friends and/or family and day trips in Amsterdam (Gemeente Amsterdam, 2022).

To investigate the share of car trips that could be substituted by a shared e-moped, Wortmann et al. (2021) created a sharing simulation model. In the base case with a fleet size of 2500 e-mopeds, 1.95% of the car trips in Berlin can be substituted. Evidently, the larger the fleet, the more and longer the trips are that can be substituted. For a fleet size of 10,000 and 50,000 e-mopeds respectively, up to 7.1 and 23.3 % of all car trips can be replaced. However, a larger fleet size increases the street nuisance and decreases the efficiency in terms of frequency of use per e-moped per day (Wortmann et al., 2021). A fleet size of 50,000 e-moped is unlikely due to municipal restricts and the economic side for an operator. A fleet size of 10,000 is also generally deemed as very high, however, Berlin is one of the biggest European cities with 3.6 million inhabitants and a surface of around 890 square kilometer. Compared to another large European capital city, Madrid with a population size of 3.2 million, surface of around 600 square kilometer and fleet size of 3,600 e-moped 10,000 e-moped is probably too high, but possible.

Schelte et al. (2021) stated based on a study from 2013 that in 81% of the time e-mopeds substitute transport modes with a similar or higher GWP, like private cars, conventional scooter or public transport. This research is however outdated and based on stated preference, since in 2013 no e-moped sharing was introduced yet.

4.1.2. Current practice in the Netherlands

Table 4.1 displays the modal shift in Amsterdam, Groningen and Rotterdam. These are trip-level substitution rates, meaning shared e-moped users are asked which mode they replaced per trip. It is however plausible that the trip distance differs per substituted transport mode. This is elaborated upon in section 4.2.2.

General observations from table 4.1 are that the three most common replaced transport mods are cycling, BTM and car. In Rotterdam, these are approximately equally substituted, while in Groningen cycling is substituted twice as often as the car and bus [1]. In Amsterdam, car replacements is relatively low compared to Groningen and Rotterdam where this percentage approximately doubles. On the contrary, BTM replacement is very high in Amsterdam compared to the other two cities.

	Amsterdam		Groningen		Rotterdam
	2022	2021	2021	2020	2020
Walking	7 %	7 %	7 %	16 %	10 %
Cycling	30 %	32 %	48 %	51 %	23 %
Moped	1 %	2 %	3 %	2 %	5 %
Train	1 %	0 %			
BTM	41 %	29 %	21 %	11 %	27 %
Car	10 %	15 %	19 %	18 %	23 %
Taxi	5 %	9 %	1 %	2 %	7 %
Induced demand	4 %	6 %	2 %	0 %	3 %

Table 4.1: Modal shift in three Dutch cities (Gemeente Groningen, 2022) (Gemeente Rotterdam, 2021) (Gemeente Amsterdam, 2022). The numerical values have been scaled due to their failure to sum up to 100 % in the survey. Subsequently, they were rounded to whole numbers, thereby explaining why they do not add up to 100 % here. BTM in Amsterdam also includes ferry.

There is a limitations when comparing this data between the cities. The measured year differs between the cities. Normally this would not impose a big problem since the years are close to each other, however, the COVID-19 pandemic makes it more difficult. Daily activities and consequently mobility and in particular public transportation reduced drastically during lockdown and the curfew. It could for instance be that more public transportation was substituted in these years to avoided physical human contact.

The statement above is endorsed by the change in Modal shift in both Amsterdam and Groningen in two consecutive years. What stands out is the increase in BTM substitution and decrease in car and taxi replacement in Amsterdam in 2022 compared to the year before. Substitution rates of the other transport modes stayed about the same. In the beginning of 2022, all COVID-19 measure were abolished, while in 2021 there were multiple lockdown and a curfew. As mentioned above, people were discouraged to use public transport and avoided physical human contact. As a consequence, PT is assumed to be used more often in 2022 resulting in the fact that more PT trips can be replaced. In Groningen bus replacement increased in 2021, which was at the expense of replaced walking trips.

Induced demand

As mentioned before in section 3.1.1, induced demand is the phenomena that individuals would not have made the trip at all without a shared e-moped available. Induced demand is actually trip generation, which is graphically visualized in the conceptual model in the previous chapter. In the modal shift

[1] There is no metro or tram network in Groningen

percentages displayed in table 4.1, the induced demand indicates the proportion of additional trips generated. In the case of the three Dutch cities analyzed, 0 % to 6 % of all shared e-mopeds trips is induced demand, similar to shared e-scooters, where it ranges from 2 - 6 % (Weschke et al., 2022).

Most recent modal shift data from Rotterdam shows the percentage of trips which would not have been made otherwise is 3 %, while in Amsterdam this is 4 % (Gemeente Rotterdam, 2021) (Gemeente Amsterdam, 2022) and in Groningen 0 % (although the year before it was 2 %). One possible explanation for variation could be that Amsterdam is more of a tourist city than Rotterdam and Rotterdam is a more tourist city than Groningen, resulting in more fun trips, which have a higher probability of being induced demand as discussed in section 3.1.1.

Modal split

Table 4.2 shows the modal split prior to introduction of e-moped sharing. A cities modal split gives the distribution of trips by mode of transport. Modal split shares are for travel inside the city, thus excluding travel to and from the city. Amsterdam and Rotterdam modal split data is from 2015. More recent data could not be found. Data for Groningen is from 2018/2019. 2020/2021 data is available, but was not chosen due to the influence of the COVID-19 pandemic.

The modal split prior to introduction in a city can give insights in the modal shift shared e-mopeds cause. Shared e-moped service providers mentioned that the decision to start to operate in a certain city depends on - among others - car ownership or whether a city is car oriented play a role. The modal split in a city already gives insight in this car ownership. Higher car ownership results in higher car share in the modal split (Santos, Maoh, Potoglou, & von Brunn, 2013). The relationship between car share and car replacement by a shared e-moped is two-sided. High car ownership results in less tendency to use a shared e-mopeds. However, in an absolute sense, more car trips can be replaced if a city has a higher car share.

	Amsterdam		Groningen		Rotterdam	
	Modal Shift	Modal Split	Modal Shift	Modal Split	Modal Shift	Modal Split
Walking	7 %	31 %	7 %	24 %	10 %	34 %
Cycling	30 %	36 %	48 %	51 %	23 %	23 %
Moped	1 %	2 %	3 %		5 %	1 %
Train	1 %	1 %				
BTM	41 %	10 %	21 %		27 %	11 %
Car	10 %	19 %	19 %	20 %	23 %	31 %
Taxi	5 %		1 %		7 %	
Other		1%		3 %		1 %

Table 4.2: Modal shift and split in three Dutch cities (Gemeente Rotterdam, 2016) (CBS, 2022d)

Patterns in the relation between modal split and modal shift are observable. It is however impossible to make a hard statement about these, since no statistical analysis is done and only three cities are considered. A quick look results in the following observations:

- Cities with a high share of cycling, have a higher substitution rate of cycling trips
- Cities with a higher car, tend to have a higher car substitution rate

Mode choice factors

The mode choices of travellers for all trips determines the modal split in a city. Multiple factors influence the mode choice of a traveller. These factors can be classified into three categories: user characteristics, trip characteristics and transport facility characteristics (Ortúzar & Wilumsen, 2011). All factors are shown below. It is important to note that these factors could also influence the choice for a shared e-moped. However - as mentioned before - limited research is yet done into shared e-mopeds. The findings on factors that do influence shared e-moped usage are included in the conceptual model.

- Trip maker characteristics
  - Car ownership

- Income
- Driver license possession
- Household structure
- Residential density
- Decisions made elsewhere

- Journey characteristics
  - Trip purpose
  - Alone trip or with others
  - Time of day
- Transport service
  - Quantitative factors
    - Travel cost components
    - Travel time components
    - Parking availability and costs
    - Travel time reliability and regulatory of service
  - Qualitative factors
    - Driving task demands
    - Comfort and convenience
    - Opportunity to undertake other activities during travel
    - Safety, protection and security

4.2. Shared e-moped usage

This section examines shared e-moped usage. The section is divided into two subsections. First, in 4.2.1 the user characteristics of shared e-mopeds in terms of age, gender and student percentage are explored. Subsequently, in section 4.2.2 trip characteristics in terms of trip distance of e-moped sharing are explored.

4.2.1. Shared e-moped user characteristics

Age

Shared e-moped users tend to be millennial's, students, tourists, expats, are often male and between 18 and 34 years old (KiM, 2021) (Howe & Gmeling, 2021) (Gemeente Rijswijk, 2021). Moped Sharing (2021) held a survey in Barcelona, Berlin and Paris (the three biggest cities in terms of shared e-mopeds usage and fleet sizes). In these cities the average age of shared e-moped users is 32 years old. In Zwolle the average age is 28 years old, while in Groningen this is even lower with 26 years old (Gemeente Zwolle, 2021) (Gemeente Groningen, 2022). According to Felyx, the average age of shared e-moped users is 29.4 years CE Delft (2021). In Spain, almost half of the users is between 18 to 25 years old, namely 47.5 %. 24.3 % is between 26 and 34 years old, 17.9 % 35 to 49 and only 10.3 % is older than 49 years old. In Berlin, the average shared e-moped user is 33.7 years old.

Gender

The municipality of Amsterdam states that a majority of the users is male. In Spain, 67.5 % of the users is male, almost the same as in Paris where 66 % of the users is male (Aguilera-García et al., 2021) (Moped Sharing, 2021). In Berlin, this percentage is even higher. 80 % of the shared e-moped users is male in the capital of Germany (Moped Sharing, 2021). In Groningen, 58.9 % is male (Gemeente Groningen, 2022).

Students
Furthermore, shared e-moped user are often well educated and a high percentage is student (Gemeente Amsterdam, 2021). In Spain, 34.6 % of the e-moped users are currently (part-time) students and 83.5 % completed a university degree (Aguilera-García et al., 2020). In Groningen, half of the users is student (50.3 %) (Gemeente Groningen, 2022).

4.2.2. Shared e-moped trip characteristics

Shared e-moped trip distance in the Netherlands
Shared e-moped trip distances can give insight in transport modes that can be replaced by shared e-mopeds. Moreover, it is used calculation of total shared e-moped kilometers is a city together with the fleet size and frequency of use. Each city has is own (spatial) characteristics and thus a specific average trip distance of shared e-mopeds. A review of all publicly available data from literature, web articles and reports of average trip distances in Dutch cities is shown in table 4.3. Rijswijk, a small village in between The Hague and Delft, has the highest average trip distance. This can be explained by the favorable location of Rijswijk as connection to surrounding municipalities (Gemeente Rijswijk, 2021). According to a study of KiM Netherlands Institute for Transport Policy Analysis the average trip distance with a shared e-moped is only 2.3 km (KiM, 2021), which is significantly lower than the values found by municipalities themselves.

Table 4.3: Average trip distance with a shared e-moped in the Netherlands (Gemeente Groningen, 2020) ("Tussentijdse rapportage Deelvervoer in Amsterdam: deelscooter en deelauto", n.d.) (Gemeente Utrecht, 2022) (Gemeente Rotterdam, 2021) (Gemeente Rijswijk, 2021) (Hendriks, 2020) (Gemeente Den Haag, 2021)

City	Trip distance
Rijswijk	4.5-5.0 km
Amsterdam	4.0 km
Utrecht	3.7 km
Den Haag	3.6 km
Breda	3.5 km
Groningen	3.5 km
Rotterdam	3.1 km
Average	*3.7 km*

Comparison with European cities
Arias-Molinares et al. (2021) analysed a dataset of multiple Spanish cities consisting of the average trip distances and vehicle rotation per day. These results are shown in table 4.4. Shared e-mopeds are mostly used for short urban trips, between 1 and 3 km. Cities with large metropolitan areas as Madrid, Valencia and Seville contain a considerable number of longer distance trips (Arias-Molinares et al., 2021). Furthermore, travel distance may be highly influences by the size of a scooter operators service area in a city. Evidently, an expansion of service areas can lead to longer travel distances.

In a unspecified German city, the average distance per scooter is 4.9 km (Schelte et al., 2021), which is quite higher than the averages from the Netherlands and Spain.

Table 4.4: Average trip distance and vehicle rotation per day in Spain (Arias-Molinares et al., 2021)

City	Trip distance	Vehicle rotation per day
Malaga	3.68 km	1.84
Madrid	3.49 km	1.08
Saragossa	3.42 km	2.24
Seville	3.23 km	2.15
Valencia	3.18 km	2.02
Cadiz	2.73 km	2.37
Cordova	2.67 km	1.80
Average	*3.20 km*	*2.04*

Trip distance to replaced transport mode
Assuming the trip distance does not depend on the replaced transport can be viewed as too short-sighted. It is plausible that the previously taken mode of transport influence the trip distance. This can be illustrated by giving an example. If previously a car would have been used instead of a shared e-moped, the trip distance would probably be higher than if previously a person would have walked to their destination. Felipe-Falgas et al. (2022) asked shared e-moped users which mode they substituted in combination with the trip duration. Using the average shared e-moped speed the trip distance per substituted mode was calculated. The results are shown in table 4.5.

Table 4.5: Trip distance per substituted transport mode (Felipe-Falgas et al., 2022)

Substituted transport mode	Trip duration	Trip distance
Car	15.77 min	6.28 km
E-scooter	15.00 min	5.98 km
Train	14.78 min	5.89 km
Bus	14.23 min	5.67 km
Motorcycle	13.53 min	5.39 km
Private traditional bike	12.30 min	4.90 km
Induced trip	12.20 min	4.86 km
Walking	11.90 min	4.78 km
Shared traditional bike	10.63 min	4.23 km
Shared electric bike	10.00 min	3.98 km
Private electric bike	6.50 min	2.59 km

Observing these results, it stands out that the trip distance of all substitute transport modes are very high. The average trip distance in the Netherlands 3.7 km, which is lower than all the replaced trip distances in Felipe-Falgas et al. (2022). In Spain, the average trip distance is 3.2 km, and the highest is 3.68 km (in Malaga). The trip distance per replaced transport mode in Barcelona is higher for each mode than the average trip distance in the other Spanish cities - except the private e-bike which is implausible low -, it is thus plausible that the average trip distance to replaced transport mode is overestimated. One of the causes could be the average speed of a shared e-moped used for calculation of the trip duration to trip distance. At first glance, the average e-moped speed of 23.9 km/h used seems as a decent representation. However, when considering time to put on a helmet, taking it off the stand, stop time at traffic lights, parking time and the time to take and upload a photo of the parked vehicle the average speed could be overestimated. Another possible explanation for the high trip duration and thus trip distances is the city size. The survey was held among users in Barcelona, a large Spanish city. The statement that city size influence trip distance is also endorsed by a Dutch shared e-moped operator, who mentioned that the average trip distance in Amsterdam is 4 km, while in Leeuwarden this is only 2.4 km. However, Malaga and Madrid are also very large cities. Cities in the Netherlands where e-moped sharing is available tend to me smaller than Barcelona, confirmed by the lower overall average trip distance. The trip distances from table 4.5 are used as a guideline for the order of transport mode to trip distances for determining the values for the Dutch case.

The values for the average Dutch city are shown in table 4.7. A replaced walking trip is assumed to be 2 km. For an average walking speed of 5 km/h, this means that on average a walking trip of 24 minutes is replaced. Value for private traditional bicycle is 3.0 km and for an electric one 4.0 km, as the distance travelled with a e-bike is assumed to be a bit higher than for a traditional bike. This would however here be a too large difference, which is why the stated values are used. The distance of a private moped is determined by adding the average walking distance to a shared e-moped (200 m) to the average shared e-moped trip distance. For the train, the average distance between two train stations in Amsterdam is taken, which is 4.7 km. The average trip distance when replacing a BTM trip is assumed to be 4.5 km. For taxi, the same distance as for a car is taken, which is 4.5 km. Induced trip argumentative has the same value as the average shared e-moped trip distance.

The values are calibrated for Amsterdam, Groningen, Rotterdam and the average Dutch city [2] using the following formula. It is desired that the results approximately matches the average trip distance of that

[2] Modal shift trip-level of the average Dutch city is the average of Amsterdam, Groningen and Rotterdam

city.

$$\sum X_{tm} * Y_{tm} \approx TD_{city} \tag{4.1}$$

Table 4.6: Mode substitution from trip-level to km-level

Variable	Description	Unit
X_{tm}	Modal shift on trip-level	%
Y_{tm}	Average trip distance when replacing this particular transport mode	km
TD_{city}	The average shared e-moped trip distance in a particular city	km

Table 4.7: Trip distance per substituted transport mode in the Netherlands

Substituted transport mode	Average trip distance inside city center
Walking	2.0 km
Private traditional bicycle	3.0 km
Private electric bicycle	4.0 km
Shared electric bicycle	3.7 km
Private moped (either electric or ICE)	3.9 km
Train	4.7 km
BTM	4.5 km
Car	4.5 km
Taxi	4.5 km
Induced trip	3.7 km

5

Life cycle emissions of urban passenger transport

This chapter elaborates on the life cycle emissions of urban passenger transport modalities. First, the method used for assessing the environmental impact of a transport mode is explained in section 5.1. Second, in section 5.2 the life cycle emissions of shared e-mopeds are examined. Multiple studies which use LCA methodology are compared and their research methods and assumptions are discussed. In addition, the most important factors influencing the GWP of shared e-mopeds are discussed, as illustrated in the conceptual modal. For all factors a default value is given to be able to come up with a default value for the GWP of shared e-mopeds. The same is done for all replaceable transport modes in the next section (5.3), however slightly less extensive. Lastly, an overview of the GWP of all transport modes is given in table format and things that stand out are discussed.

5.1. LCA methodology

Life Cycle Assessment (LCA) methodology is used to evaluate the environmental impact of a service or product during its entire life cycle. When following a cradle-to-grave approach, it identifies and calculates the emissions related to production, usage and disposal of transport mode (Muralikrishna & Manickam, 2017). A LCA can have different environmental impact categories, this research focuses on climate change impact category. This impact category indicates the (potential) global warming impact due to emissions of greenhouse gasses (GHG) to air (Ecochain, 2022). The most well-known Greenhouse Gases are carbon dixoide (CO_2-eq), methane (CH_4), nitrous oxide (N_2O) and fluorinated gasses (US EPA, 2022a). Emissions levels of GHG are converted into CO_2-equivalents to allow combining the global warming impact of the gasses (CBS, 2022a). This is based on the Global Warming Potential (GWP) [1] of a greenhouse gas, where one kg of CO_2 equals to the effect of one kg CO_2 emissions on the global warming. One kg of N_2O emissions has an equal impact on the global warming as 298 kg CO_2-equivalents. The emission of one kg of CH_4 equals 25 kg CO_2-equivalents. The GWPs of fluorinates gases vary significantly, but levels can have a substantial impact of the global warming. Greenhouse Gas Protocol provides standards for the GWPs of all GHG (Greenhouse Gas Protocol, 2014).

The total life cycle emissions are always expressed in CO_2-eq per passenger kilometer travelled (pkt) and not per vehicle kilometer travelled (vkt). This allows for a fair comparison between of all modes of transport considering the occupation of a transport mode.

5.1.1. LCA for shared e-mopeds

The LCA production (also: manufacturing) component consist of (raw) material extraction, vehicle component production and vehicle assembling. Transport is the distribution of an e-moped from the

[1] "The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2)" (US EPA, 2022b)

manufacturing location to the city where the e-mopeds are introduced. Fuel emissions can be divided into well-to-tank and tank-to-wheel emissions. The first are the emissions that are emitted during the generation of electricity, the second are emissions that are emitted during vehicle usage (which is zero at electric vehicle). Disposal emissions arise from the recycling or treatment of the vehicle components at the end-of-life. Infrastructure life cycle emissions can relate to construction, maintenance and end-of-life management of infrastructure. The definitions of infrastructure life cycle emissions can differ between studies which makes it hard to make a fair comparison. Most studies only consider road wear emissions, while some also take infrastructure emissions of road construction - or track in case of rail public transport - into account, while the construction of metro and train tunnels, station and docks for shared vehicles or roadway earthwork emissions can still be neglected at the same time. Operational services are a relative new LCA component since they are only applicable to shared mobility services. The consist of the battery swap operation (BSO) emissions and if applicable the re-balancing of the e-mopeds. BSO and re-balancing emission are the electricity needed to charge the batteries and the life cycle emissions emitted by the (electrical) vans used for these operations. E-moped maintenance is often integrated in the operational services. The maintenance emissions therefore often only relate to new e-moped component production.

All LCA components are illustrated in Figure 5.1. Some studies consider all these factors, while others neglect a few, see table C.1.

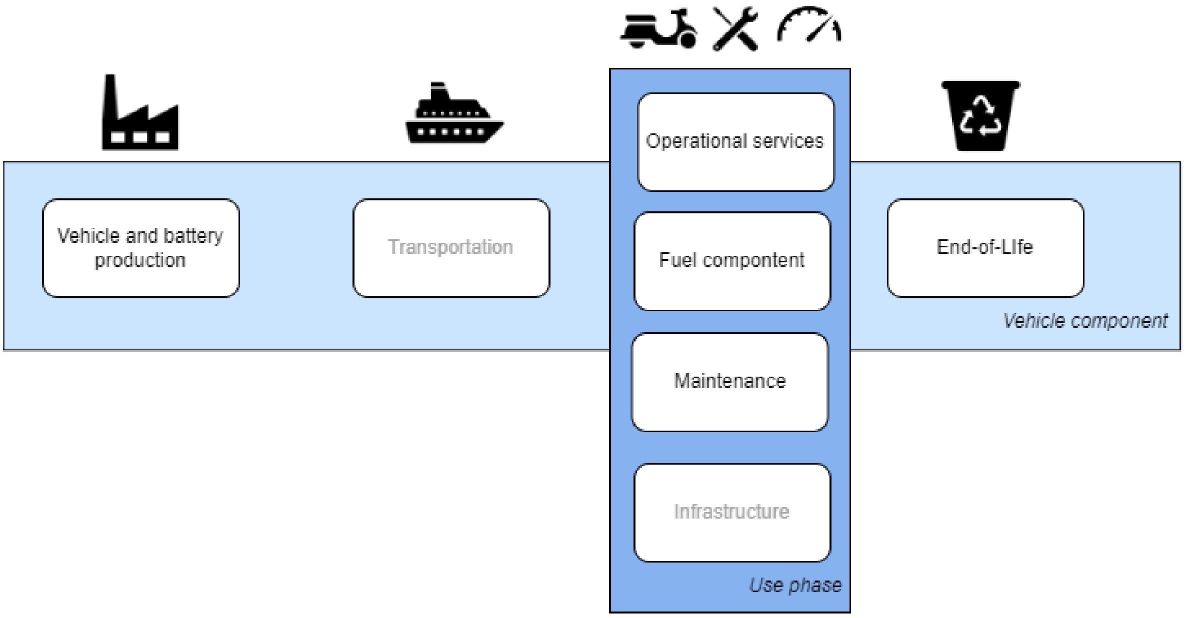


Figure 5.1: LCA components for shared e-mopeds. Light grey boxes - transportation and infrastructure - are neglected in this study. Own illustration based on all reviewed papers

5.2. Life cycle emissions of shared e-mopeds

A total of six studies have been performed on the environmental sustainability of shared e-mopeds using a LCA. All studies take different LCA components into account and use different research methodology methods and input data (see table C.1 and C.2). As stated and explained in section 1.2, infrastructure and transportation emissions are not considered here.

When having a first quick look at the GWP of shared e-mopeds, the CO_2-eq emissions per passenger kilometer travelled differ substantially between the studies. The GWP lies between 34 and 80 g CO_2-eq/pkt (bron). This wide range can be explained by the fact that all studies use different assumptions, input data and calculation methods (for example different databases). It is therefore important that the studies are reviewed in detail to gain insight into these different assumptions and research methodologies.

This section first elaborates upon the most important factors influencing the life cycle emissions of shared e-mopeds, which can also be seen in the conceptual model. For every factor a default value or assumption corresponding to the Dutch case is given at the end of the paragraph.

After that, the different LCA component (split up into a vehicle component en use phase section) are addressed and operationalised for the Dutch case, meaning the default values and assumptions stated before are used to determine the GWP of the different LCA components for shared e-mopeds in the Netherlands. It is important to remember that these are default values and can thus be adjusted in the eventually developed environmental impact calculation model.

Table 5.1: Input data per reviewed study

Paper	Case location	Occupancy rate	E-moped lifespan	BSO vehicle type
ITF (2020)	Global	1.0	19,610	van ICE
Felipe-Falgas et al. (2022)	Barcelona	1.07	50,000	electric LCV
Schelte et al. (2021)	Germany	1.3	50,000	Diesel
de Bortoli (2021)	Paris	1.0	48,000	electric LCV
Christoforou et al. (2020)	Paris	1.0	50,000	electric vehicle
Wortmann et al. (2021)	Berlin	1.0	89,846 [2]	-

5.2.1. Factors influencing life cycle emissions of shared e-mopeds

The subsections below elaborate on the impact of these factors on the GWP of shared e-mopeds. The values and assumptions used in the six above mentioned studies are discussed where after the value or assumption that matches the Dutch case the most is given as a default value. These assumptions and default values are needed for calculations to obtain the GWP of shared e-mopeds in the Netherlands in the next sections.

Shared e-moped lifetime mileage

The total number of kilometers driven over a shared e-mopeds lifetime influence the LCA vehicle components. The components are static emissions, however expressed per kilometer driven. To obtain the value per kilometer driven, the static CO_2-eq emissions must be divided by the kilometer lifespan of the vehicle, which shows why this factor has such a big influence.

Schelte et al. (2021), de Bortoli (2021) and Felipe-Falgas et al. (2022) all used around the same lifetime of a shared e-moped, about 50,000 km. The study from ITF (2020) however, states that a shared e-moped only lasts around 3.7 years, which results in a moped kilometrage of less than 20,000, which is less than half the kilometrage used in the other studies (see table C.2. The lifetime of a shared e-moped is determined by using a sharing correction factor of 0.4, which is multiplied by the lifetime in years of a private moped. Thee idea behind this sharing correction factor is that is accounts for tampering and vandalisation which arises from the fact that the mopeds are not privately owned and the assumption that people are less careful with the not privately owned vehicles. If this factor is not applied, the lifetime mileage equals around the value used by the other studies, namely 48,760 km.

[2]For a fleet size of 2,500 e-mopeds. Lifetime mileage decreases to 84,732 for a fleet size of 10,000 and to 61,826 for a fleet size of 10,000 e-mopeds

The lifespan of a shared e-moped in the study where a simulation model using Berlin as a case study was constructed differs a lot compared to the other studies. Multiple fleet sizes were used and the impact was evaluated. In the base case with a fleet size of 2,500, the average utilization rate per e-moped is 18.45, while for fleet sizes of respectively 10,000 and 50,000 vehicles this reduces to 16.91 and 11.08 trip per e-moped per day. Compared to real observed data, this is very high. In the Netherlands, according to one of the shared e-moped operators a vehicle is on average used six times day (B), while in Spain this is for example only about twice a day Arias-Molinares et al. (2021). The founded utilization rate per day is an explanation for the high vehicles lifetime mileage.

A Dutch shared e-moped service provider states that on average a shared e-moped is used six times, with an average trip length of 3.5 km. Most shared e-moped service providers started operating around 5 years ago. The majority of the e-mopeds are still in operation. Thus assuming a lifetime of 5 years (which tends to be an underestimation, but also used in other studies) results in the lifespan of around 40,000 km.

All in all, a default value of 50,000 km is used for GWP calculation of shared e-mopeds in this research. This value corresponds to most scientific papers (which are often based on shared e-moped operators data) and a quick calculation of Dutch shared e-moped operators.

Shared e-moped occupancy
The average number of people on an e-moped has a major impact on the GWP. All life cycle CO_2-eq emissions per vehicle kilometer travelled (vtk) are divided by this occupancy rate, to obtain the CO_2-eq emissions per pkt (see the conceptual model). As can be seen in table C.2, the literature and technical reports show no consensus about this occupancy rate. The researches from ITF (2020) and de Bortoli (2021) Wortmann et al. (2021), Christoforou et al. (2020) all use an occupancy rate of (almost) 1.0. The municipality of Amsterdam did a research where the scooter operator claim that approximately 30 % of the shared e-moped trips have two people on an e-moped (Gemeente Amsterdam, 2021). According to Moped Sharing (2021), the average number of passengers per vehicle kilometer is even higher, namely 1.46. A default value of 1.3 passenger per vehicle is used, similar to the one found in the survey in Amsterdam. To date, this is the most recent and reliable survey [3].

Operational service
Operational service can be divided into two parts: the battery swap operation (BSO) and the re-balancing of vehicles. The BSO also includes the possible repair of a shared e-moped, which eliminates the need for extra kilometers for this operation. Relocation of shared e-mopeds may be required to balance vehicle supply and demand in different service regions of shared e-moped sharing (Jin, Wang, Lim, Pan, & Shen, 2023). Two options for repositioning are available: (1) offering financial incentives for rides for certain vehicles parked at low-demand locations, and (2) using a service van to relocate the e-mopeds (Jin et al., 2023). Interviews with three Dutch shared e-moped operators revealed that almost no re-balancing with service vans is required, hence it is not considered in this study.

The studies by ITF (2020) and Christoforou et al. (2020) assumed that e-mopeds with empty batteries are picked up, charged at a central location, and distributed in the city. However, e-moped service operators report that almost empty batteries are swapped on-site using electric vans, which reduces the distance traveled by the service vehicle. Additionally, all operational service vehicles in the Netherlands are electric, as confirmed by the three e-moped service providers. Section 5.2.3 will provide a detailed description of the GWP calculation for shared e-moped operational services.

Shared e-moped type and characteristics
Three shared e-moped operators are present in the Netherlands: Check, Felyx and GO Sharing. The e-moped GO Sharing fleet consist of the Supoer Soco CUx. Check and Felyx both offer the NIU N1S electric moped. Check also offers the Segway E110 L. Currently there exists two versions of an e-moped, a 25 km/h and 45 km/h model. From January 1 2023, a helmet is mandatory for 25 km/h mopeds. The expectation is that the ratio between the two models shift more to the 45 km/h type due to this helmet obligation. Although the e-moped versions differ in maximum speed,the shared e-moped operators state that there is no significance difference in energy consumption between them. The battery type

[3]The survey was held between April - June 2022 (N=420)

used in electric mopeds are lithium-ion ones. The three electric mopeds weight between 65 and 85 kg excluding the batteries.

Batteries
Most e-mopeds have room for two batteries, also referred to as 1 battery pack. Over a shared e-moped lifetime, the studies of de Bortoli (2021) and Felipe-Falgas et al. (2022) assume that the battery pack (two inside the e-moped) must be changed once. ITF (2020) and Schelte et al. (2021) both assume that an e-moped requires 1.25 battery packs over its lifetime. They calculated this using a battery and vehicle lifetime of respectively 40,000 km and 50,000 km.

It is important to note that a shared e-moped operators possess more batteries than that can fit in the total e-moped fleet. This way the operator can ensure that there are always fully charged batteries available. Currently, Dutch shared e-moped service providers possess on average 3 batteries (thus 1.5 battery packs or sets) per e-moped (Appendix B). The battery and e-moped ratio thus lies between 2.5 and 4 batteries per e-moped (or 1.25 and 2.0 battery packs per e-moped). As a default value, 3 Li-ion batteries or 1.5 battery packs per e-moped are assumed.

Electricity mix
The electricity mix gives the percentage of sources as fossil fuels, solar energy, wind energy etc. used to generate the electricity. An electricity mix results in greenhouse gas emissions intensity of electricity generation (or carbon intensity of the power sector), expressed in CO_2-eq/kWh. Electricity mixes differ between countries and/or regions. Since this research focuses on the Dutch case and the reviewed (scientific) papers use either the average world or a country specific electricity mix, it is important to gain insight in the impact the electricity mix has on the GWP of shared e-mopeds. The electricity emissions factor mainly influences the emissions from the use phase, the fuel and operational service emissions since these a shared e-moped and operational service van are both electric powered.

Schelte et al. (2021) determined that when shared e-mopeds are charged with solar power only the GWP reduces with 20 %. de Bortoli (2021) calculated that using the electricity mix of Norway and Denmark, shared e-moped emit 32 CO_2-eq/pkt, while in China this would increase to 78 CO_2-eq/pkt. When the electricity mix of the Netherlands is used, the GWP of shared e-mopeds is 55 CO_2-eq/pkt instead of 34 in the France case.

The next subsection goes into more detail on the vehicle component life cycle emissions and the assumptions made and data used for the calculation. After that, the use phase emissions are elaborated upon. For both aspects, values for important factors and consequently a bandwidth and default GWP value for the Dutch case is given.

5.2.2. Vehicle component emissions

The emissions that arise from the vehicle component are static and thus do not change with increased usage of a shared e-moped. To obtain the vehicle component life cycle emissions per pkt, the total static vehicle emissions must be divided by the lifetime mileage and average occupancy. Vehicle and battery production and disposal emissions are addressed separately, to for the most accurate calculation.

Vehicle production emissions
Appendix C shows the vehicle production emissions and database used in all six studies which investigated the environmental performance of shared e-mopeds using a LCA methodology. Multiplying the GWP of the vehicle component with the kilometrage and the average occupancy gives the static CO_2-eq emissions released during the manufacturing and assembling of one e-moped. These emissions lie somewhere between 293 kg CO_2-eq and 725 kg CO_2-eq per e-moped, excluding battery. This range seems quite wide, this is however caused by the very low emissions of the ITF (2020) study and the very high emissions of the Christoforou et al. (2020) study, also caused by a large spread in e-moped weight.

As a default value, 655 kg CO_2-eq emissions per e-moped is used here (Schelte et al., 2021). The reasons for this is that it is the only study which performed an own LCA on a particular e-moped type - the

Kumpan 1954 i. As can be seen in appendix C, all the other studies used the Ecoinvent database process ”Electric scooter, without battery, GLO”. An electric scooter is however different than an electric moped, thus using the vehicle production emissions from Schelte et al. (2021) is considered to be the most accurate.

Compared to the e-moped used by Check, Felyx and GO Sharing, the e-moped type used in Schelte et al. (2021) is a bit heavier (92 without battery vs. 68 kg for the Super Soco CUx and 85 kg for the NIU N1S (*Super Soco CUx – ☐ Elektrische Scooters 2022*, n.d.) (NIU, n.d.). To account for this weight difference, the average weight of the Super Soco CUx and NIU N1s is used, and the vehicle production emissions are scaled down to this weight (76.5 kg). This results in a vehicle production emission for the average Dutch shared e-moped without battery production of 544 kg CO_2-eq, thus 7.1 kg CO_2-eq per kg produced e-moped without battery.

Battery production emissions
The comparison table in Appendix C presents a wide range of production emissions per kWh for batteries. A default value of 72.9 kg CO_2-eq/kWh, sourced from Dai, Kelly, Gaines, and Wang (2019) and also used in the Ecoinvent database, is assumed for battery production. This default value falls in the middle of the range of 25.8 - 119.5 kg CO_2-eq/kWh. A single battery has an electric potential of 60 V and capacity of 29 Ah, resulting in an capacity of 1.74 kWh. As mentioned in section 5.2.1, three single batteries are assumed for each e-moped, resulting in a total of 381 kg CO_2-eq emissions for battery production. It is important to note that the same source and values are used for calculating the production (and disposal) emissions of all electric vehicles.

Maintenance emissions
Maintenance or repair emissions are important to consider for shared e-mopeds, since it is plausible people are less careful because the vehicle is not theirs. Most repairs are done on-street, in combination with the battery swap operation. It is therefore assumed no extra emissions are released due to driving to the shared e-moped. According to the Ecoinvent V3.6 database, a total of around 306 kg CO_2-eq emissions arise from the maintenance of a 144 kg electric scooter. This service includes material replacement (mainly plastic and steel parts), water, waste and emissions. The average weight of a shared e-moped in the Dutch fleet is used to down scale these emissions to 163 kg CO_2-eq. No maintenance emissions for the batteries are taken into account, since this is accounted for by needing 3 batteries per e-moped over its lifetime.

End-of-life emissions
As indicated in most interviews, several parts of an e-moped are recycled and reused. Although the recycling process consumes energy and initially increases emissions, it ultimately reduces total emissions by decreasing the need for new raw materials for future vehicles (Transport & Environment, 2022). The extent to which a shared e-moped is recycled is uncertain; thus, the assumption is made that a shared e-moped is shredded, based on Schelte et al. (2021) research. The energy consumption for this end-of-life process is 15 kWh (Schelte et al., 2021). The electricity emissions factor used in this study is 344 g CO_2-eq/kWh, as used in stream and applied for fuel emissions of all transport modes (CE Delft, 2023). This results in 5.2 kg CO_2-eq for the disposal emissions of one e-moped. For a lifetime mileage of 50,000 km and an average occupancy of 1.3 passengers, this results in approximately 0.079 g CO_2-eq/pkt, which is less than 1 % of the total GWP. This estimate is lower than the end-of-life emissions in Wortmann et al. (2021) study, which equates to roughly 0.41 g CO_2-eq/pkt, corrected using a vehicle lifetime mileage of 50,000 km and an occupancy of 1.3 passengers. Assuming that a shared e-moped is shredded instead of recycled is not a significant issue since the emissions have a negligible impact on the total GWP of a shared e-moped.

For battery disposal emissions, a value of 1.35 kg CO_2-eq per kg of produced battery is assumed, based on Puig-Samper Naranjo, Bolonio, Ortega, and García-Martínez (2021). According to Dai et al. (2019), one kWh produced battery weighs around 7 kg. Although three batteries are assumed per e-moped, only 1.25 batteries are needed over the shared lifetime of the e-moped. Therefore, for disposal emissions, the assumption is made that 1.25 batteries are disposed of, since the other batteries can be used for other applications or new vehicles. The total battery disposal emissions are estimated to be 20.6 kg CO_2-eq.

Vehicle component emissions - default value

Transportation and end-of-life emissions are neglected in this study, therefore the vehicle component emissions only exist of the vehicle manufacturing and assembling emissions (including battery production emissions). The default value for vehicle without battery is 657 kg CO_2-eq, 241.8 kg CO_2-eq for three single batteries and . Adding these two up results in a GWP of 898.9 kg CO_2-eq emissions per shared e-moped for the vehicle component. Dividing this over the default value for the vehicles lifetime mileage and occupancy results in a GWP of 13.8 g CO_2-eq/pkt.

Table 5.2: Default values used for vehicle component emissions calculations

Characteristic	Value
Lifetime mileage	50,000 km
Shared e-moped occupancy	1.3 pkt/vkt
Battery e-moped ratio	3.0 batteries per e-moped
Battery capacity	1.74 kWh
E-moped weight without batteries	76.5 kg
Vehicle component emissions of a shared e-moped	1114 kg CO_2-eq
Vehicle production emissions	655 kg CO_2-eq
Vehicle maintenance emissions	163 kg CO_2-eq
Vehicle end-of-life emissions	5.2 kg CO_2-eq
Battery production emissions	381 kg CO_2-eq [4]
Battery end-of-life emissions	20.6 kg CO_2-eq
GWP of vehicle component shared e-mopeds	**17.2 g CO_2-eq/pkt**

5.2.3. Use phase emissions

Use phase emissions consists of infrastructure, fuel and operational service emissions. All these emissions have a linear relationship with the number of driven kilometer and therefore do not depend of the vehicles lifetime mileage and only on the occupancy of a shared e-moped. The three use phase emissions components are discussed below and the default value is given in CO_2-eq/pkt.

Fuel emissions

Fuel emissions or whell-to-wheel (WTW) emissions consist of whell-to-tank (WTT) and tank-to-wheel (TTW) emissions. WTT emissions are emissions released during the transport and refining process of fuels or transport and generation of electricity. TTW emissions emergence from fuel combustion during vehicle usage. TTW emissions are zero for electric driven vehicles, and thus for e-mopeds. Shared e-moped operators claim that the e-mopeds are charged with 100 % renewable electricity, which leads to less CO_2-eq emissions, however they are still not zero. The emissions released during the generation of electricity are expressed in CO_2-eq/kWh. As mentioned in section 5.2.1, this emission factor differs between countries and is 344 g CO_2-eq/kWh for the Netherlands. To obtain the emissions per driven kilometer of an e-moped, first the consumption in kWh per kilometer is needed where-after this can be multiplied with the emissions factor.

$$EC_{\text{moped}} = \frac{V * q * 1000}{R} \tag{5.1}$$

$$E_{\text{WTT}} = EF_{\text{NL}} * EC_{\text{moped}} \tag{5.2}$$

$$E_{\text{WTW}} = E_{\text{WTT}} + E_{\text{TTW}} \tag{5.3}$$

[4] For the production of three batteries

Table 5.3

Variable	Description	Unit
E_{WTW}	Whell-to-wheel emissions	*g CO2-eq/pkt*
E_{WTT}	Well-to-tank emissions	*g CO2-eq/pkt*
E_{TTW}	Tank-to-wheel emissions	*g CO2-eq/pkt*
EC_{moped}	E-moped energy consumption	*kWh/km*
V	Electric potential	*V*
q	Battery capacity	*Ah*
EF_{NL}	GHG emissions intensity of electricity generation	*g CO2-eq/kWh*
occupancy	Average number of passengers	*pkt/vkt*
R	Actual range of an e-moped	*km*

Table 5.4: Shared e-moped characteristics required for energy consumption calculations

Characteristics	Value
Electric Potential	60 V
Battery capacity	29 Ah
Actual range	50 km
Occupancy	1.3 pkt/vkt

The energy consumption of shared e-mopeds is 0.035 kWh/pkt, resulting from a calculation using the values in table 5.4 and the formulas above. This value almost similar to the ones found on the internet and the value of 0.04 kWh/pkt stated by a shared e-moped operator in a mail correspondence and therefore used as a default value (Sprintmonitor.de, n.d.) (Spritmonitor.de, n.d.). Using this default value and the current GHG emissions factor of 344 g CO_2-eq/kWh resulting from the Dutch electricity mix leads to a GWP of 12.3 g CO_2-eq/vkt. To obtain the emissions per passenger kilometer travelled, this value is divided by the average occupancy which results in a GWP of 9.5 g CO_2-eq/pkt for the fuel component.

Operational service emissions

The second use phase component that causes CO_2-eq emissions arise from operational services, which are in this study assumed to be done with an electric van. This deviates from several scientific papers previously cited, which considered petrol or diesel operational service vehicles, or did not take into account operational service emissions at all (ITF, 2020) (Schelte et al., 2021) (Wortmann et al., 2021). To calculate the GWP of operational services, two aspects must be known: the distance driven with the service vehicle per shared e-moped driven kilometer, and the GWP of the service vehicle in g CO_2-eq/km. In this study, operational service only includes the Battery Swapping Operations (BSO) and not the relocation of shared e-mopeds, as discussed in section 5.2.1. The GWP of an electric service van consist, similar to the GWP of an e-moped, of both vehicle component emissions and use phase (fuel) emissions. The studies that did not assume an electric service vehicle are still used as a benchmark to determine the first aspect, the service distance. Table 5.5 provides an overview of the BSO emissions calculation components across all considered studies. The study of CE Delft is included as they calculated the service distance for the case of Rotterdam (CE Delft, 2021).

Service vehicle driven kilometers

Not only the van used for the operational services, but also the frequency of battery swapping and the resulting service kilometer per shared e-moped driven kilometer are important to consider when calculating the operational service emissions. In Rotterdam, the total distance driven per day for the battery swap operation is 640 km, equipping 240 e-moped with new batteries (of the total fleet of 1,200 e-mopeds) (CE Delft, 2021). This results in 2.67 km per equipped e-moped per day or 0.53 km per e-moped considering the entire fleet. The entire fleet must be considered here since the battery of an e-moped is on average only swapped every 5 days (CE Delft, 2021). The average daily distance driven per e-moped is around 13 km, which thus results in 41 m service per e-moped vehicle kilometer (CE Delft, 2021). In the study of ITF (2020) it assumed that per vkt of an e-moped 60 service vehicle meter is needed. Both de Bortoli (2021) and Felipe-Falgas et al. (2022) assume only 20 m service kilometer per

Study	Service distance	BSO vehicle type	GWP BSO vehicle	GWP BSO
ITF (2020)	60 m	ICE	245	13.5
Schelte et al. (2021)	83 m	Diesel	386	24.6
Christoforou et al. (2020)		Electric	52	
de Bortoli (2021)	20 m	Electric	125	2.5 g
Felipe-Falgas et al. (2022)	20 m	Electric		35.5
CE Delft (2021)	41 m	Electric		3.0

Table 5.5: Christoforou et al. (2020) did quantify the carbon footprint of a shared two-wheeler (battery charged). However, in the results no servicing emissions are considered for this transport mode, while for shared e-scooter and shared e-bikes service emissions are considered. The GWP of the electric van used for servicing of the e-scooter and e-bike is stated in the table. GWP of the electric service van in de Bortoli (2021) is calculated by dividing the BSO emissions with the service distance, since the occupancy is assumed to be 1. In the study from CE Delft (2021) no LCA approach is used, only fuel emission from the service van are considered, resulting in a lower GWP of the BSO

e-moped kilometer travelled. The last study assumed 83 m servicing needed per e-moped vkt (Schelte et al., 2021). Concluding from the literature, the range of service vehicle distance per e-moped kilometer driven lies between 20 - 83 meter. As default value 50 m servicing per e-moped kilometer is taken, which is in the middle of the range and almost matches the average from the five studies (46.6 m).

GWP of the service vehicle

The electric LCV used by the major moped sharing operator in Paris consumes 0.25 kWh/km in the use phase, while this is 0.19 kWh/km for the electric service vans in Barcelona de Bortoli (2021) Felipe-Falgas et al. (2022). The electric vans used by Felyx consumes 0.27 kWh/km CE Delft (2021), which is used as a default value for energy consumption of the electric service van due to the scope of this study being the Netherlands where Felyx is one the main shared e-moped operators.

The production, disposal and maintenance emissions of an electric service van are obtained using the Ecoinvent database process "market for passenger car, electric, without battery GLO" and "market for maintenance, passenger car, electric, without battery GLO". The process for an electric passenger car is used, since no data is available for electric vans. This values for electric car are expressed in kg CO_2-eq per kg van and must thus be multiplied by the weight of the van. Battery production emission per kWh battery (weighing 7 kg per kWh) are used from the same source as for shared e-mopeds and electric cars (Dai et al., 2019). Battery disposal emissions are taken from Puig-Samper Naranjo et al. (2021), just as for shared e-mopeds, e-bikes and electric cars. An electric van weighs 1250 kg, and two Li-ion batteries of 350 kg are needed over its lifetime (de Bortoli, 2021). Considering these three processes results in 18640 kg CO_2-eq emissions for production, maintenance and disposal of the entire electric service van. An electric service van has a lifetime mileage of 150,000 km, leading to a GWP for the vehicle component of the service van of 124.2 g CO_2-eq/vkt (de Bortoli, 2021).

The calculation for the emissions of the battery swap operation differ a lot between studies. Although diesel vans are assumed (which in-evidently do much more harm to the environment than electric vans), the BSO in the study of Schelte et al. (2021) only has a GWP of 24.6 g CO_2-eq/pkt. In the study of Felipe-Falgas et al. (2022), this is 35.5 g CO_2-eq/pkt, while electric vans are assumed. At first glance, it is implausible that the BSO where electric vans are used has a higher GWP than the BSO where a diesel van is used. However, when decomposing these calculations in detail, this difference can be explained, which is essential to do since BSO emissions have a large share (48 %) in the total GWP (Felipe-Falgas et al., 2022).

The first study assumed a GWP of the diesel van of 386 g CO_2-eq/vkt (Schelte et al., 2021). The service distance per e-moped kilometer travelled is 83 m, resulting in 32 g g CO_2-eq per e-moped kilometer. Dividing this with the occupancy of 1.3 leads to a GWP of 24.6 g g CO_2-eq per passenger kilometer travelled with an e-moped (Schelte et al., 2021). This is the same calculation method used in this study, as can be seen in the next paragraph.

The second study assumes electric vans including a trailer and uses the Ecoinvent database to determine the GWP of this electric service vehicle. The service distance per shared e-moped kilometer is assumed smaller, only 20 meter (Felipe-Falgas et al., 2022). Note that a smaller service distance per shared e-moped kilometer (20 m vs. 83 m) and using an electric operational service vehicle instead of a diesel one should inevitable lead to less CO_2-eq emissions for the BSO per shared e-moped passenger kilometer. This is however not the case, since the GWP of the battery swap operation in Felipe-Falgas et al. (2022) is calculated at 35.5 g g CO_2-eq/pkt, which is more than 10 g CO_2-eq/pkt higher than in the study of Schelte et al. (2021). In Barcelona, the case of the study, 30 electric service vans are in operation each day. For calculation of the BSO emissions, the GWP of a service vehicle in CO_2-eq/vkt was multiplied with the number of service vans (Felipe-Falgas et al., 2022). Calculation the GWP of a service van in this way is incorrect, because this indicates that 30 service vehicles drive to one e-moped to swap its battery. Doing the calculation in this way causes the GWP of a service van having a linear relationship with number of service vans used in a city, which is logically not the case. It may sound logic to take the number of service vans needed in a city into account, this is however not necessary. Using the vehicle lifetime mileage, this in (indirectly) accounted for. The emissions of a service van are expressed in driven kilometer and is therefore not influence by the number of vans. Correcting for this mistake would theoretical decrease the BSO emissions with a factor 30 (the number of service vehicles), thus concluding that this mistake has a significant impact on the total GWP of shared e-mopeds.

Operational service emissions - default value

The formula for calculating the operational service emissions per shared e-moped pkt is shown below. Using the values for an electric service van, results in a GWP of the operational service of 8.4 g CO_2-eq/pkt.

$$E_{\text{os}} = \frac{VP_{\text{sv}}}{LM_{\text{sv}}} + EC_{\text{sv}} * EF_{\text{NL}} * SD * \frac{1}{occupancy} \tag{5.4}$$

Table 5.6: Operational service emissions formula

Variable	Description	Unit
occupancy	average number of people on an e-moepd	pkt/vkt
LM_{sv}	Lifetime mileage of service van	km
EF_{NL}	GHG emissions intensity of electricity generation	g CO2-eq/kWh
EC_{sv}	Energy consumption electric service van	kWh/km
SD	Service distance per e-moped kilometer	km/vkt
VP_{sv}	Vehicle component emissions of the service van	g CO_2-eq

Table 5.7: Electric service van characteristics for calculating the operational service emissions

Characteristics	Value
Vehicle weight	1250 kg
Battery weight	350 kg
Vehicle production emissions	18640 kg CO_2-eq
Vans lifetime mileage	150,000 km
Service distance per e-moped kilometer	50 m per shared e-moped vkt
Energy consumption service van	0.27 kWh/km
Emission factor electricity generation	344 g CO_2-eq/kWh

5.2.4. GWP of shared e-mopeds - default value

Combining the default values calculated and stated in the previous subsections, the total GWP of shared e-mopeds can be calculated, which equals 36.9 g CO_2-eq/pkt. This value is in line with the GWP found by a shared e-moped operator [5] itself, which was 33.0 g CO_2-eq/pkt.

[5] The operator commissioned a company to do a LCA on the shared e-mopeds. This research is however not publicly available. In the interview this value was given

Table 5.8: GWP of shared e-mopeds to LCA component

LCA component	GWP (g CO_2-eq/pkt)	Percentage contribution
Vehicle component	17.1	
Vehicle emissions	8.5	24 %
Battery emissions	6.2	18 %
Maintenance emissions	2.5	7 %
Use phase	17.8	
Fuel emissions	9.5	27 %
Operational service emissions	8.4	24 %
Total GWP of shared e-mopeds	**34.9 g CO_2-eq/pkt**	

5.3. Life cycle emissions of the replaced mode of transport

In order to determine the environmental sustainability of e-moped sharing, it is crucial to have knowledge of the GWP of the replaced transportation modes. However, comparing life cycle emissions of transportation from various studies is challenging, as numerous aspects and parameters in the operational stage are highly sensitive to specific cases, such as a country's electricity mix, electrification of public transport, and vehicle occupancy rates (Spreafico & Russo, 2020). For instance, due to the low carbon-intense electricity in France and the electrification of most public transport, the carbon footprint of the metro and RER train in Paris is lower than that of shared e-scooters and shared bicycles. In contrast, in the US, public transport modes have a higher modal carbon footprint than shared mobility (de Bortoli, 2021).

Not all modes of passenger transportation are relevant to consider since some cannot be replaced by a shared e-moped. Based on modal shift data and the permitted vehicles in the Netherlands, the following transport modes are taken into account: passenger cars, taxis, trains, buses, trams, metros, private (e-)mopeds, shared and private (e-)bikes, and walking. The modal shift often combines buses, trams, and metros into a single replaced mode of transportation. However, these modes are separately evaluated before being combined into an average bus, tram, and metro (BTM) mode. If more detailed modal shift data becomes available in the future, or if the distribution of modes in terms of usage expressed in total passenger kilometers changes, it will be easy to adjust. The same applies to private and shared (e-)bikes. Different types of cars, taxis, buses, and mopeds in terms of fuel or propulsion are also addressed separately, to account for future changes in their respective fleets.

To ensure a fair comparison of different transportation modes in terms of GWP, it is crucial to consider the same LCA components as for shared e-mopeds. It should be noted that since shared e-mopeds are a new shared mobility option, the operational service component is considered for shared e-mopeds, but this does not exist for traditional transportation means.

Calculating the GWP involves two parts: the vehicle component and the use phase. Since the GWP is expressed per passenger kilometer traveled, emissions from the use phase have a linear relationship with the distance driven. The emissions of the vehicle component are fixed but divided over the vehicle's lifetime kilometrage and occupancy rate to ensure a fair comparison by expressing the emissions per passenger kilometer traveled.

The following subsections will provide a more detailed explanation of the GWP for each replaceable transport modes. However, before this, a general overview of the vehicle component and use phase emission calculation method and sources is given.

General information of GWP calculation of replaceable transport modes

First, for all transport modes a default value for the vehicle lifespan in total kilometers and the average occupancy is - retrieved from a small literature review - given since these two factors determine the CO_2-eq emissions per passenger kilometer travelled. Using these two values, a default value for the GWP vehicle component can be calculated. In combination with the Ecoinvent database and the values from the different papers, a default value will be given for the vehicle component emissions. There are two ways the vehicle component emissions are calculated. If the emissions are expressed per kg vehicle, this is multiplied by the assumed or default value of the vehicle weight. When the emissions are given for a certain vehicle weights, this scaled up or down to the assumed vehicle weight in this research.

Maintenance emissions from the Ecoinvent database, are a static CO_2-eq value for a certain vehicles lifespan. It is logic that if a vehicle has a longer lifetime, the maintenance emissions increase. However, since these emissions are divided over the vehicles lifespan to be able to express them per passenger kilometer travelled, the maintenance emissions in CO_2-eq/pkt remain the same if the lifespan of a vehicle increases.

Recently, CE Delft performed a study called STREAM (Study on TRansport Emissions of All Modes) which gives an overview of the use phase emissions of all transport modes. Fuel emissions consisting of WTT (whell-to-tank) and TTW (tank-to-wheel) emissions are calculated and added up to obtain the WTW (whell-to-wheel) emissions. For fuel emissions the values from STREAM are thus used. No shared micromobility modes are present in STREAM, thus the same operational service emissions as for shared e-mopeds are used for the shared e-bikes.

STREAM contains data on the average fuel emissions per kilometer travelled, but it also contains data on fuel emissions broken down to road type (city roads, suburban roads and highways). For e-bikes, e-mopeds and the electrified urban rail transport modes there is no distinction between these road types. Shared e-mopeds trips mostly take place in urban areas, which is why for passenger car, public transportation bus and mopeds the value for city roads is assumed. The city roads CO_2-eq emissions value for the fuel component for mopeds is lower than the average, this also applies to plug-in hybrid passenger cars. While for fully electrified, petrol and diesel passengers and all bus types, more CO_2-eq per kilometer driven is emitted on city roads compared to the average road type.

The studies used as a source or benchmark for the life cycle emissions of the replaced transport modes are the same ones used in the previous section for addressing the GWP of shared e-mopeds complemented with the Ecoinvent database and a few recent published studies when the previous used studies are not sufficient enough. Appendix C gives are more detailed substantiation for default values on occupancy and lifespan and the used source by reviewing and comparing different scientific papers. Furthermore, the calculated GWP of each transport mode is compared to the GWP determined in other studies. In addition, in some cases a more detailed description is given on how the GWP is calculated.

5.3.1. Walking

As stated in section 4.1, walking is often replaced by a shared e-moped. Walking is the only transport mode which does not require a vehicle. Still one can argue that emissions are emitted in two ways. The first one are extra emissions as a result of a person's breathing (which is higher when walking than when sitting on a vehicle). The second one are the emissions required for the infrastructure needed for walking (sidewalks and lights). Both are however not considered in this study and therefore the GWP of walking is zero.

5.3.2. Cycling

Three different bicycle types are considered. Private traditional bike, private electric bike and shared electric bike.

Private traditional bicycle

The use phase emissions for a traditional bicycle are zero, and thus only the vehicle component emissions consisting of bicycle production and maintenance must be considered. A private traditional bicycle has a lifespan of 15,000 km and an average occupation of 1.0 persons. Production of a normal bicycle, weighing 17 kg emits around 141 kg CO_2-eq. Maintenance emissions over a bicycles entire lifetime (15,000 km) are in total 16.7 kg CO_2-eq. No fuel emissions are present, which results in a GWP of 10.5 g CO_2-eq/pkt, which is used as a default value for calculations in this study.

Private e-bike

Compared to traditional bicycles, electric ones emit more emissions due to battery charging and the corresponding emissions from electricity production. Similar to the traditional personal bicycle, the average occupancy on a private e-bike is 1.0 person. Furthermore, all reviewed studies assume the same lifetime in kilometer as for private bicycles (ITF, 2020). Therefore, a lifespan of 15,000 km - equal to the traditional private one - for the private e-bike is assumed here.

For vehicle production and maintenance emissions the emissions of the traditional bicycle is used, scaled to a higher e-bike weight (without battery). Battery production emissions are calculated in the same manner as for the batteries for e-mopeds and (partially) electric driven cars. The emissions of a traditional bicycle from the Ecoinvent database are chosen because the electric bicycle emissions from the database combines vehicle and battery emissions. The batteries lifetime in the Ecoinvent database is only 4,000 km, which is too low compared to the calculation here and the value used in STREAM (CE Delft, 2023). Since these vehicle and battery production (and disposal) emissions are combined, it is impossible to only derive the e-bike vehicle production emissions. Therefore, the emissions of a traditional bicycle are used as benchmark, scaled to a e-bicycle weight of 23 kg (Gazelle, n.d.).

The method described above results in respectively around 191 kg CO_2-eq and 29 kg CO_2-eq emissions for vehicle production and disposal and battery production and disposal. Maintenance emissions are equal as for a traditional bicycle, battery maintenance emissions are included in the battery component. Where the number of batteries required over the vehicles lifetime is considered. For the average electricity mix in the Netherlands, the fuel emissions are 3.2 g CO_2-eq per passenger kilometer travelled. Combining all these components results in a default value for the GWP of a private e-bike of 19.1 g CO_2-eq/pkt.

Shared electric bicycle
For shared electric bicycles, the free-floating option is assumed. In the Netherlands, the ”PT-bike” (in Dutch: OV-fiets) is very popular, and which is also sort of a bike sharing system. Shared e-mopeds are commonly used as first and last-mile solution to public transport. The first mile trip (way to the train station) can not be done with an PT-bike, contrary to the last-mile trip, which is often done by PT-bike and thus likely to be replaceable by a shared e-moped. However, since PT-bikes are station-based at mainly (main) railway stations which are often not located in a city center, this bike sharing system is neglected here.

There are three differences between a shared and private electric bicycle. The first one is the vehicles lifetime mileage, which is lower for a shared e-bike compared to a personal one. In addition, the batteries in shared e-bikes must be swapped by the service providing company, which causes extra CO_2-eq emissions due electricity needed for these operational services (assuming this is done with electrical vans). Lastly, more batteries are required to ensure that there are always fully charged batteries available for the battery swap operation. Here, two batteries per shared e-bike are assumed.

A lifespan of 9,000 km is assumed for shared e-bikes. The battery swapping operation (BSO) is assumed to be comparable with the BSO for shared e-mopeds. The occupancy of shared e-bikes are lower than shared e-mopeds. As a consequence, the BSO emissions per passenger kilometer travelled are slightly higher than for shared e-mopeds, namely 10.9 g CO_2-eq/pkt. The total GWP of shared e-bikes is calculated at 44.4 g CO_2-eq/pkt.

5.3.3. Private moped
According to modal shift data, there are people who shift from a personal (e-)moped to its shared (electric) counterpart. It is therefore necessary to calculate the GWP of private (e-)mopeds.

Private e-mopeds
Private e-mopeds have the same lifespan as their shared counterpart, 50,000 km. For private mopeds, the average occupancy is 1.1 persons (CE Delft, 2023).

The vehicle component emissions are equal for the private as the shared e-moped. The only difference is that less batteries are needed since the vehicle is privately owned and no extra batteries are needed to ensure that there are always fully charged batteries available. Instead of 3 batteries per e-moped, 1.25 batteries are required over the vehicles lifetime. This leads to approximately 180 kg CO_2-eq for the battery component and 670 kg CO_2-eq for the vehicle component, combining these gives a GWP of 15.5 g CO_2-eq/pkt. Correcting the same maintenance emissions with a different occupancy for shared e-mopeds to private ones results in 3 g CO_2-eq/pkt. Fuel emissions are 14.6 g CO_2-eq/pkt. Combining all the LCA component results in a default value for the GWP of private e-mopeds of 33.0 g CO_2-eq per passenger kilometer travelled.

Private petrol mopeds
Private petrol mopeds have the same average occupancy and lifespan as electric ones, thus 1.1 persons and 50,000 km. Per passenger kilometer, fuel emissions are 71.3 g CO_2-eq (CE Delft, 2023).

The most two bought petrol mopeds in the Netherlands have an average weight of 97.5 kg. This weight is used to scale up the production and maintenance emissions obtained from the Ecoinvent database. Leading to a GWP of 8.5 and 4.6 g CO_2-eq for the vehicle component and maintenance respectively. Adding all the LCA components, results in a default value for the GWP of a private petrol moped of 84.4 g CO_2-eq/pkt.

5.3.4. Public transport

The modal shift causes by shared e-mopeds often combines all public transport modes in one replaceable mode. It is however more common that shared e-mopeds replace a BTM trip compared to a train trip, as explained in 4.1. Moreover, all public transportation have different characteristics and thus a divergent impact on the environment. Therefore the environmental impact of in terms of GWP is determined per public transportation mode. Assessing the GWP of all public transportation individually, ensures that when more detailed information becomes available about the replaced mode of transport, it is easy to account for because the GWP of all public transport modes separately is then already known. Furthermore, it gives the possibility to account for different BTM divisions in a city. For example, some cities only have a bus network, thus the total BTM consists of bus trips and thus the GWP of a bus is required. While other cities own a bus, tram and metro network and in addition the usage of these modes in terms of passenger kilometer travelled can also differ between cities. This is all accounted for by determined the GWP of bus, tram, metro and train individually.

Urban rail transport services

Three urban rail passenger transport modes are considered; (regional) train, tram and metro. It is important to know that trains [6], metros and trams are electrically powered vehicles, thus only indirect emissions from generating electricity are relevant.

Tram

The tram (also referred to as streetcar) has a lifespan of 1,120,000 km and average occupancy 23 passengers (ACM, 2021). This average occupancy is derived from the tram in in Rotterdam, Amsterdam and The Hague. The tram production and maintenance process from the Ecoinvent database is scaled up to the average Dutch tram weight of 38 ton resulting in a GWP of 5.2 g CO_2-eq for vehicle production and 11.8 g CO_2-eq for maintenance.

Fuel emissions from STREAM are already expressed in CO_2-eq per passenger kilometer travelled, resulting in 65.3 g CO_2-eq/pkt. Note that in the model this value can change when a different occupancy rate is filled in. A ratio of the average Dutch occupancy rate (35.8 %) and the ratio filled in for a particular city is then determined and used to scale the CO_2-eq emissions per passenger kilometer travelled.

Combining the production, maintenance and fuel emissions results in a GWP of 82.4 g CO_2-eq/pkt for travelling in the average Dutch tram.

Metro

There are only two cities in the Netherlands which have a metro system: Rotterdam (with extensions to The Hague and Hoek van Holland) and Amsterdam. A metro has a lifespan of 4,000,000 km and is on average occupied with 82 passenger in the Netherlands.

The same Ecoinvent process for vehicle production and maintenance as for the regional train are used, since no metro process is present in the Ecoinvent database. Scaling the emissions to a metro weight of 52 ton, results in a GWP of 0.52 and 0.07 g CO_2-eq/pkt for vehicle production and maintenance.

The average Dutch metro has a seat occupancy of 84.3 % and fuel emissions are 42.6 g CO_2-eq/pkt (CE Delft, 2023). In Appendix D, a more accurate calculation is done to account for the case studies of Amsterdam and Rotterdam to account for different metro occupancy rates.

Combining the vehicle production, maintenance and fuel emissions results in a total GWP of 43.2 g CO_2-eq/pkt for the average Dutch metro.

Train

It is not common that a train trip is replaced by a shared e-moped trip. If this however is the case, the replaced train is considered to be a regional (in Dutch: sprinter) train, thus no high-speed or long-distance trains are assessed here.

[6] There are still a small number of diesel trains in operation on the regional train network in the Netherlands. However, these are limited and on the main rail network where the Dutch Railways (NS) operates, only electric trains are in operations, resulting in the fact that only electric trains are considered here.

A NS sprinter weights on average 135 ton and has a capacity of 376 passengers. The same values for production and maintenance of a regional train as for the metro are used here, which results in 441,316 kg Co_2-eq for production and 57,474 kg CO_2-eq emissions for maintenance over its lifetime. Using a lifespan of 6,000,000 km and occupancy rate of 23.8 % this results in 0.8 g CO_2-eq/pkt for vehicle production and 0.1 g CO_2-eq/pkt for vehicle maintenance.

Fuel emissions are 41.7 g CO_2-eq per passenger kilometer travelled. Combining the different LCA components results in GWP of 42.6 g CO_2-eq/pkt.

Bus

In contrast with the train, metro and tram busses are not fully electrified. Although the share of electric and hybrid busses in the Netherlands is increasing, still the the majority (more than 75 % in 2021 (CBS, 2021b)) runs on diesel. Since it is plausible that the share of electric buses will keep increasing in the future, it is important to address the different bus types individually, to be able to cope with a different bus type division in the future. The share of bus types is a parameter in the model to cope with future developments. The current bus type distribution is shown in table 5.9, weighed to its share in the total transport performance. In this research, the GWP of a hydrogen bus is not determined since it does not (yet) play a role in the passenger bus transport.

Bus type	Share
Diesel	56 %
HVO	3 %
CNG	29 %
Electric	12 %
Hydrogen	0 %

Table 5.9: Bus type shares in 2020 of the total bus traffic volume (CBS, 2021b)

Full LCA on public transportation busses which considered all types are limited. Therefore, a few studies are combined. Three sources are used for bus GWP calculation. Vehicle production emissions come from Gabriel et al. (2021), vehicle maintenance and end-of-life emissions come from Nordelöf, Romare, and Tivander (2019) and fuel emissions are taken from STREAM (CE Delft, 2023). A more detailed description of the calculation which resulted in the GWP of each bus type can be found in Appendix C.

The lifespan of a bus is calculated at 897,600 km and there are on average 7.19 passenger in a bus. The lifespan and occupancy is assumed to be equal for all bus types.

Diesel bus has a GWP of 173.2 g CO_2-eq/pkt, HVO-diesel bus of only 51.4 g CO_2-eq/pkt. This difference is caused by the very low fuel emissions of HVO-diesel. The CNG bus has a GWP of 170.0 g CO_2-eq/pkt, while the electric bus has a GWP of 91.3 g CO_2-eq/pkt. Using the bus share data from table 5.9, results in a GWP of an average Dutch bus of 158.8 g CO_2-eq/pkt.

5.3.5. Car

A variety of cars exists nowadays and they differ much in terms of environmental impact. The fleet division to car types is changing and expected to keep changing in favor of more environmental friendly options. It is therefore important to address all car types individually and not only determine the environmental impact of an average car.

Table 5.10 shows the share of each car type in the total car fleet. It is more accurate to use the share of each car on the total passenger car traffic volume, which is displayed in table 5.11. LPG, CNG and Hydrogen cars are neglected in this study. They only cover a very small share in the total passenger kilometers driven. Above that, as can be seen in table 5.10, the share of LPG and CNG is decreasing.

An overview of the vehicle component emissions (vehicle production, battery production, vehicle maintenance, vehicle end-of-life and battery end-of-life) for three reviewed studies and the Ecoinvent database used to come to a default value for different passenger car types is given in Appendix C. Fuel emissions are again taken from STREAM.

Car type	Share in 2022	Percentage change
Petrol	79.6 %	0.6 %
Diesel	11.0 %	-8.9 %
Electric (incl. hybrid)	8.2 %	37.8 %
LPG	1.1 %	-4.8 %
CNG	0.1 %	-5.3 %

Table 5.10: Car type shares in 2022, the development relative to 2021 (CBS, 2023)

Car type	Share
Petrol	71.6 %
Diesel	23.3 %
Electric	2.3 %
LPG	1.4 %
CNG	0.2 %
Plug-in hybrid	1.1 %

Table 5.11: Car type shares in 2020 of the total passenger car traffic volume

Battery disposal and vehicle weight, production, disposal and maintenance emissions are taken from Puig-Samper Naranjo et al. (2021), while battery production emissions are taken from the same source as for e-mopeds and e-bikes (Dai et al., 2019). The different car types differ in vehicle weight, maintenance emissions and vehicle production and disposal emissions per kg vehicle. Battery capacity of a BEV is 66.8 kWh and for a PHEV the battery has an average capacity of 14.9 kWh.

Diesel car has the highest GWP of 244.3 g CO_2-eq/pkt. The GWP of a petrol car is slightly lower, 231.3 g CO_2-eq/pkt. PHEV only has a GWP of 186.4 g CO_2-eq/pkt, mainly caused by the lower fuel emissions compared to ICE cars. Although having the highest GWP for the vehicle component - battery and vehicle combined - the full electric car has the lowest GWP of 118.0 g CO_2-eq/pkt, mainly caused by low fuel emissions. Further decomposition of GWP of each LCA component and detailed description of source choice and calculation is given in Appendix C.

Taxi
A special urban passenger car transport mode is the taxi. Modal shift data indicates that a significant share of shared e-moped trips replace taxi trips. The only difference for calculation the GWP of taxi types is the occupancy rate and vehicle lifetime mileage. Taxis are assumed to have a longer lifetime than private passenger cars, 300,000 km vs 240,000 km. In addition, the vehicle occupancy can differ between a private passenger car and taxi. Here, an average taxi occupancy of 1.1 persons is taken as reference. Next to these difference, the car fleet division to vehicle type is different than for private passenger cars. Limited data is available, therefore data from Paris, Madrid and the average taxi of ITF (2020) is used to determine a default value for taxi fleet division. Doing so, 80 % diesel, 10 % petrol and 10 % electric taxi is assumed, which is a plausible distribution of the taxi fleet in the Netherlands since currently 5 - 10 % of the Dutch taxi's is electric (Rijksoverheid, 2021a).

Finally, the GWP of different taxi types is as follows: 280.7 g CO_2-eq/pkt for diesel taxi, 265.9 g CO_2-eq/pkt for petrol taxi, 211.3 g CO_2-eq/pkt for a plug-in hybrid taxi and 126.6 g CO_2-eq/pkt for a full electric taxi. Using the taxi fleet division above, results in a GWP of 268.0 g CO_2-eq/pkt for an average taxi.

5.4. GWP comparison between transport modes

Table 5.12 shows the default values used for the GWP calculation of all transport modes and the calculated GWP. Chapter 6 graphically shows this overview of the GWP of all transport modes, there the results are also discussed and compared. As mentioned before, vehicle lifespan and average occupancy is not static and has a significant impact on the GWP, which is why it can be easily adjusted in the constructed model. Note that metro and tram is the occupation rate per seat kilometer, and not total capacity. Furthermore, BTM consist of 68.7 % bus, 12.7 % tram and 18.7 % metro (CE Delft, 2023).

Table 5.12: Comparison of the GWP of all transport modes. VL = vehicle lifespan. OC = occupancy. VC = vehicle component emissions including vehicle production, maintenance and disposal and battery production and disposal. UP = use phase emissions including fuel and operational service emissions.

		VL [km]	OC [pkt/vkt]	VC [g CO_2-eq/pkt]	UP [g CO_2-eq/pkt]	GWP [g CO_2-eq/pkt]
Walking				0	0	0
Cycling	Private traditional	15,000	1.0	10.5	0	10.5
	Private electric	15,000	1.0	15.9	3.2	19.1
	Shared electric	9,000	1.0	30.4	14.1	44.4
Moped	Private petrol	50,000	1.1	13.1	71.3	84.4
	Private electric	50,000	1.1	18.5	14.6	33.0
	Shared electric	50,000	1.3	17.1	17.8	34.9
Tram	Electric	1,120,000	35.8 % - 23	17.0	65.3	82.4
Metro	Electric	4,000,000	84.3 % - 82	0.59	42.6	43.2
Bus	Diesel	897,000	8.1	16.8	156.3	173.2
	CNG	897,000	8.1	20.5	149.4	170.0
	Electric	897,000	8.1	25.1	66.2	91.3
	HVO-diesel	897,000	8.1	16.8	34.6	51.4
	Average bus			18.9	139.8	158.8
BTM	Average BTM			15.2	112.3	128.5
Train	Electric (sprinter)	6,000,000	23.8 % - 83	0.9	41.7	42.6
Car	Petrol	225,000	1.31	32.0	199.3	231.3
	Diesel	225,000	1.31	34.5	209.8	244.3
	PHEV	225,000	1.31	36.0	150.4	186.4
	BEV	225,000	1.31	47.0	71.0	118.0
	Average car			32.9	198.2	231.2
Taxi	Diesel	300,000	1.1	30.8	249.9	280.7
	Petrol	300,000	1.1	28.5	237.4	265.9
	PHEV	300,000	1.1	32.2	179.1	211.3
	BEV	300,000	1.1	42.0	84.6	126.6
	Average taxi			31.1	236.8	268.0

6

Quantitative environmental impact model

This chapter elaborates on the developed quantitative environmental model. The methodology for determining the GWP of each transport mode is already elaborated upon in the previous chapter. Section 6.1 expounds on the method used for calculating the environmental impact of e-moped sharing. Next, section 6.2 provides an overview of all input parameters in the model. Third, insection 6.3 model assumptions are discussed. Lastly, in section 6.4 model verification and validation is explained.

6.1. Environmental impact calculation

The process for determining each environmental impact indicator is presented in Figure **??**. The first step involves calculating the GWP of all replaceable transport modes, including shared e-mopeds, which was described in the previous chapter. The next step is calculating the environmental impact per shared e-moped passenger kilometer driven. This indicator - which is already city specific - can then be used to calculate the city wide impact of shared e-mopeds by first determining the shared e-moped kilometers in a city. The resulting absolute city-wide impact can be compared to the total transportation GHG emissions of the city to determine the relative impact of shared e-mopeds. The concept of marginal emissions, depicted in the figure, will be further discussed in the discussion.

6.1.1. Environmental impact per pkt calculation

First, the modal shift must be converted from trip-level to km-level substitution rate, to account for a discrepancy in trip distance per replaced transport mode. After that, combining the GWP of all transport modes and the km-level substitution rates results in the environmental impact of shared e-mopeds per pkt, expressed in +/- g CO_2-eq/pkt.

Modal shift trip-level to km-level

Mode substitution is often given in percentage per replaced trip. It is however more accurate if the model substitution is given in percentages per replaced kilometer. The following method is used to change the modal shift from trip-level to km-level (Felipe-Falgas et al., 2022). Table 4.7 shows the trip distance per substituted transport mode, which are used as default values for the calculation.

$$D_{tm} = \frac{X_{tm} * Y_{tm}}{\sum X * Y} \tag{6.1}$$

Environmental impact per pkt

The environmental impact of shared e-mopeds is determined by subtracting the average impact per pkt (GWP) of the replaced modes of the GWP of shared e-mopeds. The average GWP of the replaced transport mode is determined by multiplying the GWP of each replaceable transport mode with the replacement share (in km-level percentage), presented by the following formula:

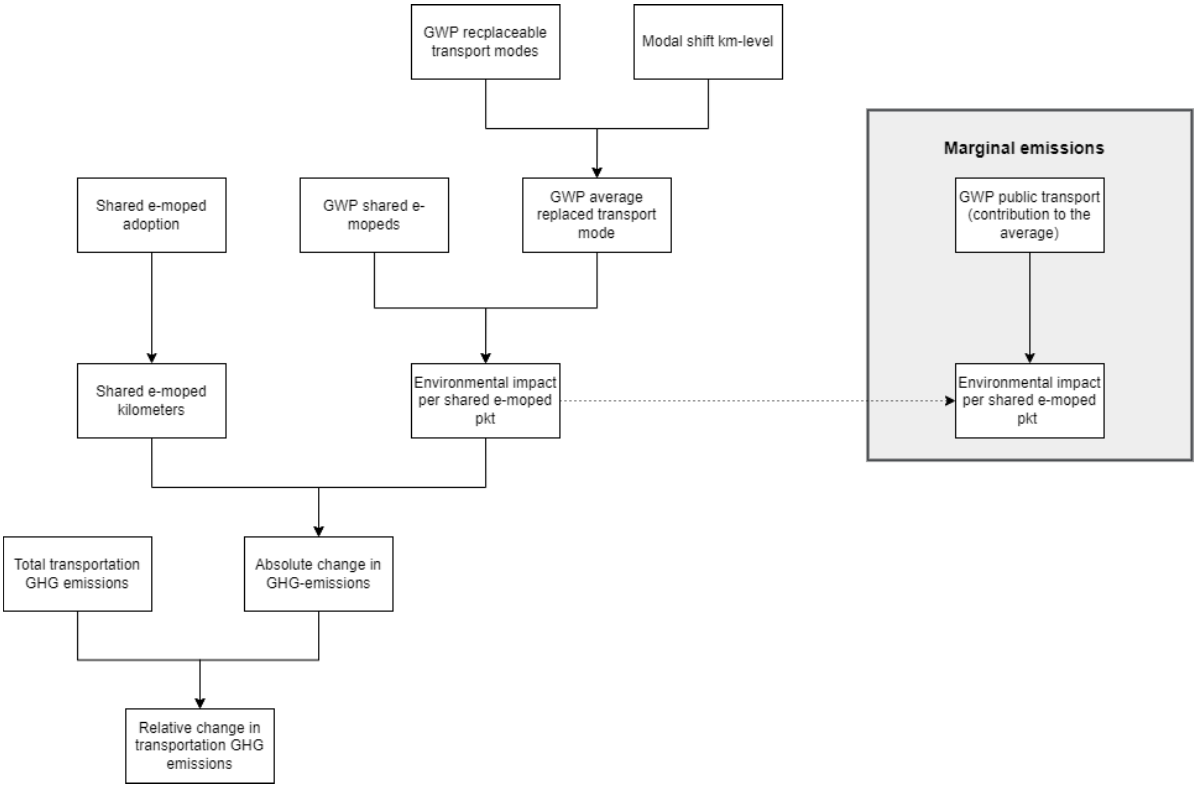


Figure 6.1: Graphic overview of results for each environmental impact indicator

$$EI_{\text{s.e-moped}} = GWP_{\text{s.e-moped}} - \sum D_{\text{tm}} * GWP_{\text{tm}} \tag{6.2}$$

Table 6.1: Mode substitution from trip-level to km-level formula input

Variable	Description	Unit
X_{tm}	Modal shift on trip-level	%
Y_{tm}	Average trip distance when replacing this particular transport mode	km
D_{tm}	Travelled distance where a substituted mode represents one substituted pkt [1]	km
$EI_{s.e\text{-}moped}$	The environmental impact of shared e-moped per pkt	g CO2-eq/pkt
GWP_{tm}	The GWP of a transport mode	g CO2-eq/pkt
$GWP_{s.e\text{-}moped}$	The GWP of a shared e-moped mode	g CO2-eq/pkt

6.1.2. Environmental impact city level calculation

To determine the city wide impact of shared e-mopeds, first the total number of shared e-moped kilometers must be calculated. Three - city specific - factors are essential to calculate this: fleet size, frequency of use and average trip distance. Frequency of use is often given in number of rentals per moped per day, thus multiplying this with the other two factors results in the total shared e-moped kilometers in a city per day. The total number of shared e-moped kilometers can then be multiplied with the environmental impact per shared e-moped pkt - but first dividing it by shared e-moped occupancy - which leads to the avoided or extra CO_2-eq per day due to introduction of shared e-mopeds in a city.

Relative impact

The relative impact of e-moped sharing on a cities GHG transportation emissions is expressed as a percentage of the total GHH transportation emissions. The transportation GHG emissions of a city are

[1]For example, if 30 % of new shared e-moped pkt travelled by car before, D_{car} will be 0.3

obtained from the CEREM [2] model, developed by CE Delft. The modal includes total transportation emissions from rail, bus, passenger car and two-wheelers per year for each Dutch city. It should be noted that only well-to-wheel (WTW) emissions are considered in CEREM and not all life cycle emissions. Therefore, for calculating the relative impact, the calculation of the avoided CO_2-eq per year only includes fuel and BSO emissions, resulting in slightly different avoided emissions values than considering a LCA approach.

6.2. Model parameters or input

In the constructed model, many parameters are included which can be change to represent a certain city. The next chapter performs a sensitivity analysis for most of these input parameters, where the sensitivity of (future) values to the model KPI's is examined. Here, all input decision than can be made are explained and whether these are city and/or country specific.

6.2.1. GWP input parameters

The conceptual model displayed in chapter 3 already provided insights in the adjustable parameters in the model by giving those factor rectangular corners. There are two input parameters which can be filled in for all transport modes. A vehicle lifespan in km and the average occupancy - or occupancy rate for urban rail transport modes - are the two most influential parameters for GWP calculation. For shared e-mopeds the most parameters can be filled in, which is logic since the focus of this research is on shared e-mopeds. The input that can be filled in for each transport is illustrated in Figure 6.2

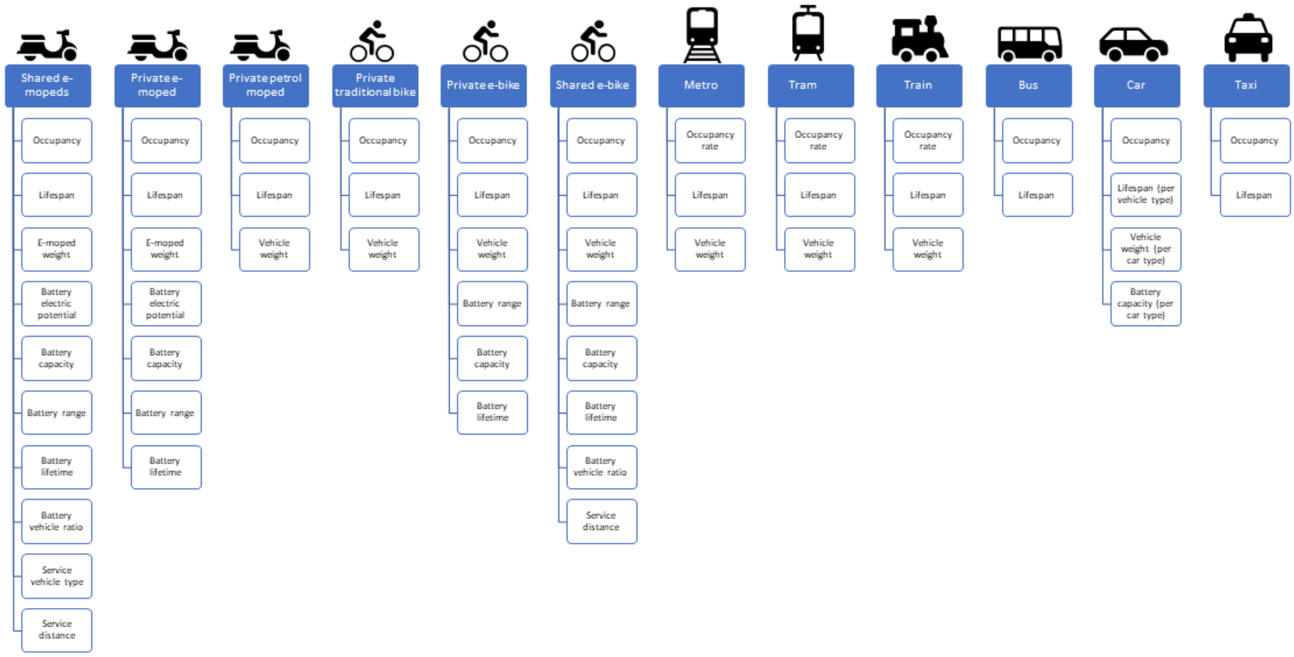


Figure 6.2: GWP input parameters for each transport mode

6.2.2. City specific input

City specific variables contain variables that influence GWP calculation of transport modes, but also influence environmental impact per shared e-moped pkt. The city specific variables and how these influence the environmental impact indicators is conceptually illustrated below. The *average impact replaced transport mode* in-evidently depends on the GWP of all replaceable transport mode, however, these are not city specific and thus not included in this figure. Purple factors illustrate city specific factors which can be changed in the model to match a specific city, white cells represent a calculation in the model which eventually results in the blue environmental impact indicators. One can argue that

[2] CEREM stands for CE - Regional Mobility Effects Calculation

taxi fleet is city specific. This is partially correct since also for six large municipalities the desire is that from 2025 all new taxi are emission free, while this will not apply to the rest of the Netherlands until 2030. Here it is chosen to state is as a country specific input since no data is available on taxi fleet division for specific cities, however when creating or representing a specific city, it is possible to specify the taxi fleet that matches that specific city.

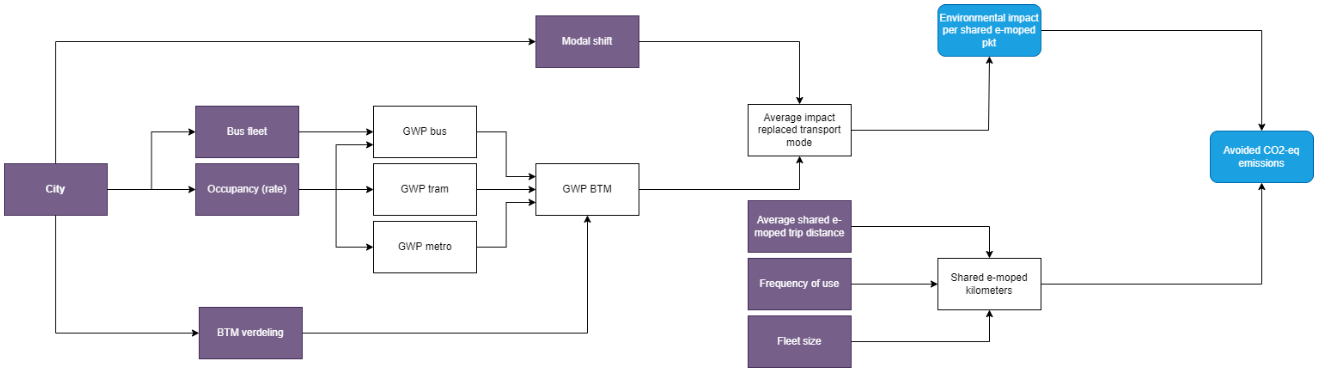


Figure 6.3: City specific variables

Non-specified location

One can select four 'locations', Amsterdam, Rotterdam, Groningen or the so-called *Non-specified location*. If the *Non-specified location* is selected, the purple city specific factors illustrated in figure 6.3 can be specified to match the desired city. As a base, average Dutch values are used for these factors, meaning shared e-moped environmental impact results are given for an average Dutch city. Input data for the average Dutch city is given in Appendix D.

6.2.3. Regional or country specific input

Four factors are chosen which can differ between countries or are expected to change in the future. Electric cars are becoming increasingly popular, thus the expectation is that in the future the share of electric cars increases. This can be accounted for by adjusting the car fleet, a percentage can be filled in for the share of petrol, diesel, electric and PHEV cars. The same goes for taxi's, although only diesel, petrol and electric cars are considered here thus PHEV are neglected. Battery production emissions in kg CO_2-eq/kWh are expected to decrease in the future, which the model can thus account for. The last factor which differs between countries and/or regions is the electricity emissions factor. The electricity emission factor influences the fuel emissions of electric vehicles, which are the metro, tram, train, electric car, electric bus, e-bike and e-moped here. In STREAM, fuel emissions for the average Dutch electricity mix, 100 % green generated electricity and electricity from 100 % gray energy sources is included. It is however only expected or desired that all electricity is generated by renewable sources from 2050. To account for future developments in the electricity emission factor - thus being able to represent the electricity mix between 2022 and 2050 - it is also possible to fill in a specific value.

6.3. Model assumptions

The previous chapter has already provided data assumptions. In addition certain model assumptions are made. The first assumption pertains to the conversion of modal shift from trip-level to km-level. To achieve this, the average trip distance per replaced transport mode are used but these these were not specifically specified for each individual city. Another assumption made is that maintenance emissions are constant and not affected by variations in lifespan. Thus, the total CO_2-eq emissions over the lifespan of the vehicle remain unchanged, while the GWP of the maintenance components may alter due to extended or shortened lifespan.

6.4. Verification and validation

Verification and validation are critical steps in ensuring the accuracy and credibility of a model. Section 6.4.1 first explains what verification is and how it is performed. This is followed by section 6.4.2, which explains validation and how it was conducted for this model specifically..

6.4.1. Verification

Modal verification is accomplished through testing, whereby parameters or inputs are modified, and the resultant outcomes are evaluated in terms of their direction of change and magnitude.

Trip-level to km-level modal shift

An experiment was conducted to verify the accuracy of the modal shift conversion from trip-level to km-level. The most straightforward approach involved assigning the same average trip distance value to all replaced modes of transportation. A correctly functioning model would yield the same km-level substitution percentages as the input trip-level modal shift percentages. This experiment was performed twice, using an average trip distance of 3.7 km for all replaced modes in the first test and 8.0 km for all modes in the second test. The resulting km-level substitution rates were found to be identical to the trip-level modal shift rates for both experiments, indicating the proper functioning of the model.

Service distance

The BSO emissions are determined by a combination of the service distance and the GWP of the service vehicle. The model is considered accurate when the service distance per shared e-moped kilometer is zero, the operational service emissions also become zero. Additionally, there must be a linear relationship between the service distance and BSO emissions. Both of these conditions have been tested, and the model performs as intended.

Electricity emission factor

The fuel emissions of all electric vehicles, including (shared) e-bikes, (shared) e-mopeds, trams, metros, trains, electric buses, electric cars, and electric taxis, should be affected by the electricity emission factor. To verify this, the electricity mix is specified for both 100 % fossil and renewable sources used to generate electricity. As a result, the fuel emissions for all electric transportation modes were found to have changed, indicating that the model is functioning properly.

Occupation

Higher occupation should translate to decreased GHG emissions per passenger kilometer.To be more specific, a doubling of occupancy should result in a halving of GWP in g CO_2-eq/pkt. Experiments were performed to evaluate this relationship by doubling the occupancy of various transportation modes. Results for three representative modes are presented in Table 6.2, demonstrating the model's accurate performance.

Table 6.2: Verification test: occupancy

Transport mode	Occupancy	GWP
Shared e-moped	1.3	34.93
	2.6	17.47
Car	1.31	231.2
	2.62	115.6
Private traditional bike	1.0	10.51
	2.0	5.26

6.4.2. Validation

Model validation involves assessing whether the outputs of a model match the actual observations or reality. In the case of most transportation modes assessed in this study, validation indirectly occurs in Appendix 1 by comparing the Global Warming Potential (GWP) results with those of other studies. The GWP determined for shared e-mopeds, which is the focus of this study, can be compared with the GWP value of a Dutch e-moped, which was determined by a third-party investigation - commissioned by the shared e-moped operator - to be 33 g CO_2-eq/pkt (Appendix B). The calculated GWP of a shared e-moped in this study is 34.9 g CO_2-eq/pkt, which is very similar to the that value.

The second method of validating the model involves comparing the environmental impact at the city level with the study conducted by CE Delft for Felyx in Rotterdam, which only considers fuel and BSO emissions (CE Delft, 2021). In this study, the model was adjusted by deselecting vehicle, battery, and maintenance emissions to align with the LCA approach. LCA emissions are still considered for the service van, which is corrected for by an own separate calculation. The Felyx study for Rotterdam assumed a total of 4.6 million shared e-moped kilometers in 2020. If a Felyx would not have been available, the other modes of transport would have emitted 568 ton CO_2-eq. Per shared e-moped kilometer approximately 123 g CO_2-eq was avoided. The use of Felyx e-mopeds resulted in 82 ton CO_2-eq emissions, which equals 17.8 g CO_2-eq per shared e-moped kilometer. The Felyx study used a different occupancy rate compared to this study, which is why the values were compared per shared e-moped kilometer and not per shared e-moped passenger kilometer. This study calculated emissions of 126 grams of CO_2-eq per shared e-moped kilometer for the replaced transport modes. Per shared e-moped kilometer, 17 g CO_2-eq emissions were calculated in this study. Comparison of the values from the two studies led to the conclusion that they are nearly similar, with a small difference that can be explained by the use of STREAM values from 2013 in the study by CE Delft (2021) (although corrected with the emissions factors from 2020) and the use of updated values from the STREAM 2023 study and consequently a different electricity emission factor in this study.

The final method of validity concerns face validity, which is a part of content validity. It refers to the extent to which people perceive the measure to be content-valid (ScienceDirect, 2023a). Specifically, it focuses on whether a measurement instrument appears relevant and appropriate for the intended construct at a surface level. Face validity plays a crucial role in quickly and easily assessing the usefulness of a measurement instrument at first glance. For this research, experts from CE Delft are used for face validity. In this study, experts from CE Delft were used to evaluate the validity of the model. A presentation was conducted, followed by a discussion on the methodology and the obtained results. The experts approved the validity of the model and acknowledged its relevance to the intended purpose. In addition, they provided suggestions for enhancing the usefulness of the results. As a result of the presentation, this study incorporated the relative impact at city level and marginal emissions.

7 Results

This chapter presents the results of the model used in this study. The model results are fourfold. Firstly, in section 7.1, the Global Warming Potential (GWP) for all transport modes - calculated using the developed model - are presented. These results are further analyzed to determine the contribution of each LCA component to the GWP of each vehicle. Secondly, an uncertainty analysis is conducted on the GWP of shared e-mopeds in section 7.2, using Monte Carlo simulation for all independent variables. The results are discussed in terms of uncertainty and the robustness of shared e-mopeds GWP. Thirdly, the environmental impact of shared e-mopeds is examined in section 7.3. Four case studies - Amsterdam, Groningen and Rotterdam - are applied to the model, one of which is an average Dutch city. The results are presented in terms of the environmental impact per shared e-moped pkt, as well as the absolute reduction in GHG emissions and the relative reduction in total transportation emissions in a city. Finally, in section 7.4, two future scenarios are created for 2030 and 2040 to gain insight into the future environmental impact of shared e-mopeds. An individual sensitivity analysis is conducted for each factor expected to change in the future, followed by a combination of these factors for the two scenarios. The scenario results are presented in terms of the environmental impact per shared e-moped pkt.

7.1. GWP results

This section presents the GWP results of the considered transport modes. Specifically, section 7.1.1 provides a comparison of GWP values across different transport mods, while section 7.1.2 breaks down the GWP for each transport mode to the LCA components and discusses their respective contributions.

7.1.1. GWP comparison between transport modes

Figure 7.1 illustrates the calculated GWP for all of the transport modes considered in this study. The results indicate that taxis have the highest GWP and therefore emit the most CO_2-eq per passenger kilometer traveled when taking into account life cycle emissions. This difference compared to passenger cars is due to lower occupancy (1.1 vs. 1.3), but this is partially offset by longer lifespan (300,000 km vs. 240,000 km) and different fleet distribution. Private and shared e-mopeds have almost the same environmental impact, with the shared version having a slightly higher GWP due to operational services. However, due to higher occupancy, this difference in GWP is almost negated. In comparison to other transport modes, only private e-bikes, private e-mopeds, and traditional bikes have a smaller environmental impact in terms of GHG-emissions than shared e-mopeds.

Shared e-bikes have a notably high GWP, which is higher than that of shared e-mopeds, mainly due to their short lifespan and lower occupancy. However, if the same lifespan as that of private e-bikes is applied, the GWP of shared e-bikes would significantly decrease to 32.3 g CO_2-eq/pkt. Nonetheless, this value is still higher than that of private e-bikes but lower than that of shared e-mopeds. The higher GWP compared to private e-bicycles is expected since extra operational service emissions and additional batteries are needed to ensure that fully charged batteries are always available in shared e-bikes.

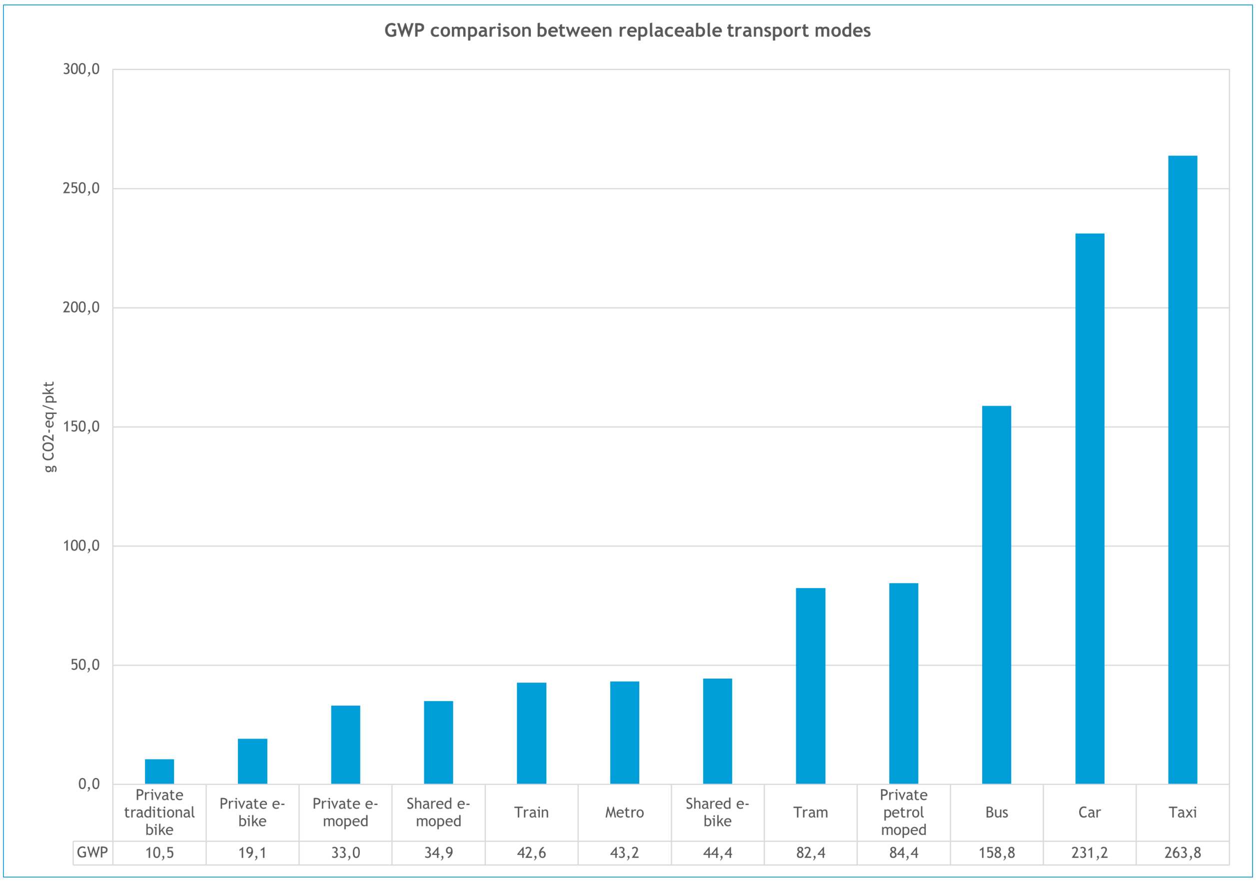


Figure 7.1: GWP comparison between replaceable transport modes

7.1.2. GWP considering LCA components

Figure 7.2 presents a breakdown of the GWP for all transport modes to each LCA component. Appendix E presents individuals enlarged figure for micromobility, urban rail, bus, car and taxi. Figure 7.3 further illustrates the relative contribution of each LCA component to the GWP of a given transportation mode. The results reveal that fuel emissions have the largest impact on the GWP of transport modes, except for (electric) micromobility. In the case of electric rail public transport, for instance, more than 95 % of the GWP comes from fuel emissions for regional trains and metros, and almost 80 % for trams. It is worth noting that the proportion of fuel emissions decreases for buses, cars, and taxis that have a higher degree of electrification, whereas the emissions resulting from vehicle production - including battery production - increase.

These findings underscore the importance of applying LCA methodology to evaluate the environmental impact of shared e-mopeds. Focusing solely on fuel and BSO emissions would decrease the GWP of e-mopeds by nearly 50 %, whereas for a private e-bike, the decrease would be around 85 %, and for a traditional private bike, it would be 100 % since there are no fuel emissions. However, neglecting vehicle production and maintenance emissions barely changes the GWP of metro and regional trains. The same trend applies to diesel and hybrid cars, buses, and taxis, where the GWP decreases between 10 and 20 % (for electric types, this is between 25 and 40 %). These findings demonstrate the importance of using LCA methodology for a fairer comparison between different transport modes.

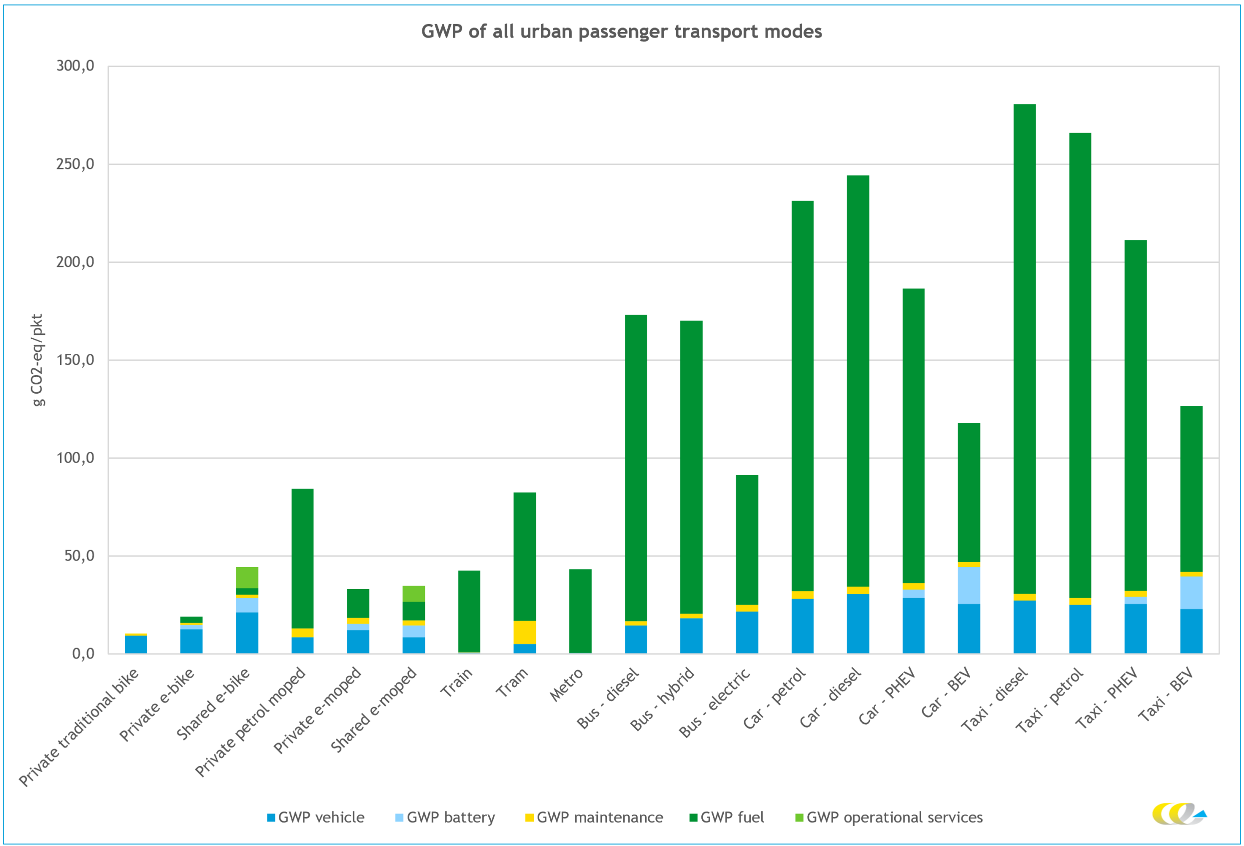


Figure 7.2: GWP transport modes to LCA components

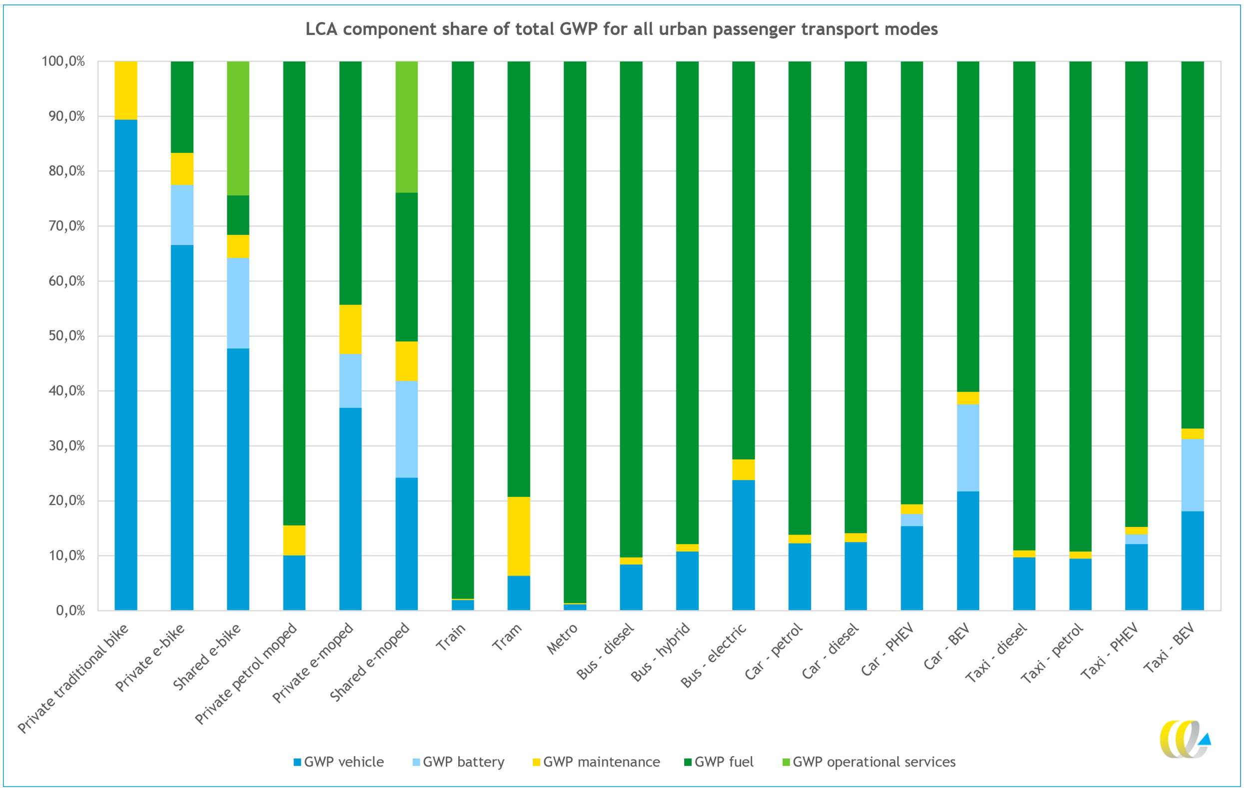


Figure 7.3: LCA contribution to GWP of all considered transport modes

7.2. Monte Carlo Analysis

Uncertainty analysis determines the accuracy of model outcomes due to the variability of input parameters (ScienceDirect, 2023b). Monte Carlo simulation is a commonly used method for uncertainty analysis in LCA. Combining LCA with Monte Carlo can effectively address the uncertainty problem in environmental impact assessment, providing a more scientifically and reasonable basis for decision-making (Sun & Ertz, 2020). The Monte Carlo method in this research consists of three steps, as outlined below and adapted from (IBM, 2023).

1. Set up the environmental impact model and identify the dependent variable to be predicted and the independent variables that will determine this outcome
2. Specify probability distribution of all independent variables. Historical data and the analyst's subjective judgement is used to define the range of likely values and to determine the probability distribution used
3. Run simulations repeatedly, generating random value of the independent variables until it results in a representative sample of all possible combinations.

The application of the Monte Carlo method is restricted to the calculation of the GWP for shared e-mopeds only, as it is the central focus of this study, and performing a Monte Carlo simulation for all transportation modes would be excessively time-consuming. Therefore, the GWP of shared e-mopeds is the sole dependent variable (separated into each LCA component). Table 7.1 presented below exhibits the independent variables along with their corresponding probability distributions and parameter value ranges.

Triangular probability distributions are selected for all independent variables. The notation for a triangular distribution is denoted as $X \sim T(a, b, c)$, where a represents the lower bound, b the upper bound and c an educated guess of the most likely value of the variable. In this case, c, represents the default value used in the research. a and b denotes the range of the value for the variable found in the literature.

Table 7.1: Monte Carlo Analysis input

Independent variable	Lower bound	Upper bound	Default value	Unit
Shared e-moped lifespan	30,000	60,000	50,000	km
Shared e-moped occupancy	1.1	1.4	1.3	persons
Vehicle production emissions	6.0	8.0	7.11	kg CO_2-eq/kg
Battery production emissions	45.0	85.0	72.4	kg CO_2-eq/kWh
Battery vehicle ratio	2	4	3	#
Battery range	40	60	50	km
Service distance per e-moped km	20	80	50	km/vkm

7.2.1. Monte Carlo results

A total of 10,138 simulations were conducted, resulting in a representative sample of all possible combinations. The distribution of the GWP for shared e-mopeds is presented in Figure 7.4, whereas Table 7.2 shows the average, minimum, and maximum values for each LCA component and the total GWP. The average GWP obtained from all 10,138 runs is 1.5 g CO_2-eq/pkt higher than the default value calculated in this study, 36.4 vs 34.9 g CO_2-eq/pkt. An interpretation of the results, combined with an explanation of the discrepancy between the average used in the study and that obtained from the Monte Carlo Analysis, is provided below. First, the histogram is interpreted, and the reason for its shape is explained.

Histogram shape

The bandwidths of triangular distributions are not always symmetrical. The maximum (b) possible value of an independent variable can be much further from the average (c) value than the minimum (a). This is exemplified by the lifespan and occupancy variables in this study, where the minimum values are farther away from the default value than the maximum values. In the case of lifespan and occupancy, a lower value has a negative impact on the GWP, causing it to increase. As a result, the histogram obtained from a Monte Carlo analysis using triangular distributions is not symmetrical, with a high peak on the left and a longer tail on the right, in contrast to a regular histogram. By adjusting the lower bound of lifespan and occupancy to 40,000 km and 1.2 persons respectively to achieve a symmetrical triangular distribution, the resulting histogram exhibits a normal shape with a peak in the middle, which decreases to a higher and lower GWP with smaller frequencies. The histogram shape dependence on these variables can be explained since they have the most significant impact on the GWP of shared e-mopeds. Occupancy affects all LCA components, while lifespan has a linear influence on maintenance, vehicle, and battery production. To put into perspective, battery production emissions solely (partially) impact the battery component. Additionally, independent variables can reinforce each other, resulting in interaction effects. Hence, the high peak on the left side of the histogram, which decreases to a high GWP, can be reasonably explained. This also clarifies why the average obtained from the Monte Carlo Analysis is not the same as the value used in this study.

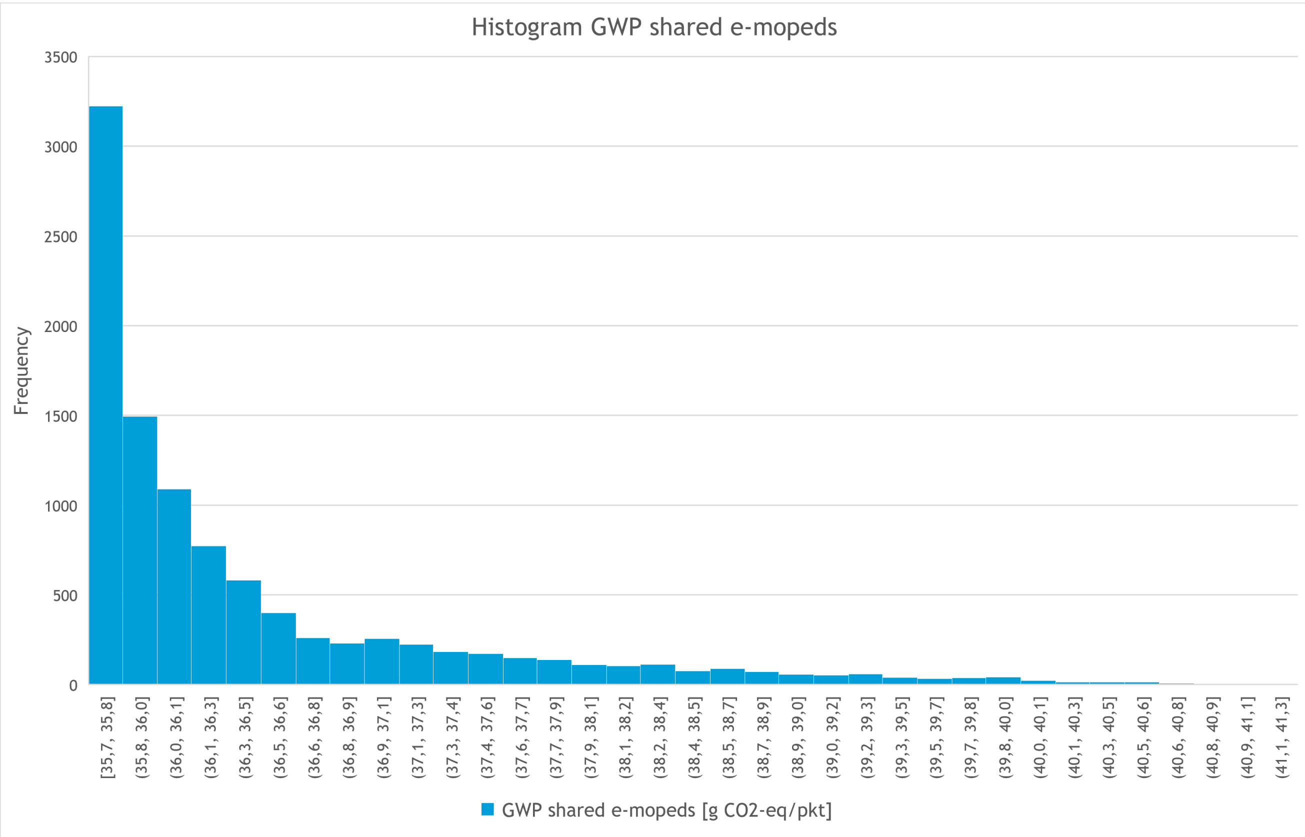


Figure 7.4: Histogram GWP shared e-mopeds - Monte Carlo analysis

Results interpretation
According to the parameter distribution presented in Table 7.1, there is a 90 % probability that the GWP of shared e-mopeds ranges from 35.7 to 37.9 g CO_2-eq/pkt. Additionally, it is noteworthy that the GWP calculated and used in this study is only 2.6 % lower than the mean value obtained from the Monte Carlo simulation. This low uncertainty can be attributed to the limited variance of the independent variable distributions.

Results from table 7.2 further show that the vehicle and maintenance component are the most sensitivity to input variable uncertainty, caused by the high dependency on the e-moped lifespan where the minimum value is further away from the average than the maximum value. The average value from the Monte Carlo analysis of the vehicle component is 9.6 % higher and of the maintenance 11.5 % higher than the value used in this research, while for the battery, fuel and BSO component this is respectively 1.5 %, 1.2 % and 0.5 % [1] .

[1]This percentage differs due to random component, but it still very small and approximately between 0.3 and 0.8 %

Further, it is striking that the distribution of especially BSO emissions is quite big (see table 7.3), which is caused by the wide dispersion of the independent variable *Service distance per e-moped km*.

	GWP	Vehicle	Battery	Maintenance	Fuel	BSO
Average	36.4	9.4	6.3	2.8	9.6	8.4
Minimum	35.7	7.4	5.1	1.9	7.2	3.7
Maximum	41.2	14.0	7.3	4.9	13.	12.8
Default value	34.9	8.5	6.2	2.5	9.5	8.4

Table 7.2: MC simulation results per LCA component in g CO_2-eq/pkt

	GWP	Vehicle	Battery	MTN	Fuel	BSO
Deviation of default value from average	-4.1 %	-9.7 %	-1.5 %	-11.7 %	-1.3 %	-0.5 %
Deviation of minimum from average	2.2 %	27.2 %	21.9 %	45.9 %	34.0 %	127.8 %
Deviation of maximum from average	-11.5 %	-32.9 %	-14.5 %	-41.9 %	-29.2 %	-34.5 %

Table 7.3: Monte Carlo results to LCA component

In summary, the results suggest that there is a low level of uncertainty associated with the GWP of shared e-mopeds. Therefore, it can be concluded that the GWP of shared e-mopeds is robust, and the model provides an accurate estimate of the GWP, despite the presence of uncertainty in the input parameters.

7.3. Shared e-mopeds environmental impact results

The environmental impact of e-moped sharing is three folded, and presented in three subsection. First, in section 7.3.1, the results are discussed in terms of the environmental impact per shared e-moped passenger kilometer travelled. Secondl in section 7.3.2, the results are presented in absolute terms at city level by incorporating the total number of shared e-moped kilometers travelled, resulting in CO_2-eq change per day, month, or year. Lastly, in section 7.3.3, the relative impact of shared e-mopeds at the city level is discussed by presenting the relative change in CO_2-eq transport emissions per city.

The findings are presented through case studies of three specific locations and an unspecified location, referred to as the *Dutch average city*, which employs average Dutch values for city-specific input parameters. The three specific locations are Amsterdam, Groningen, and Rotterdam. Substantiation for selecting these cities and background information regarding them can be found in Appendix D.

7.3.1. Environmental impact per shared e-moped pkt

The primary indicator for assessing whether shared e-mopeds have a positive or negative impact on GHG transportation emissions in a city is the environmental impact per shared e-moped passenger kilometer traveled. The following four factors determine this impact in a specific city.

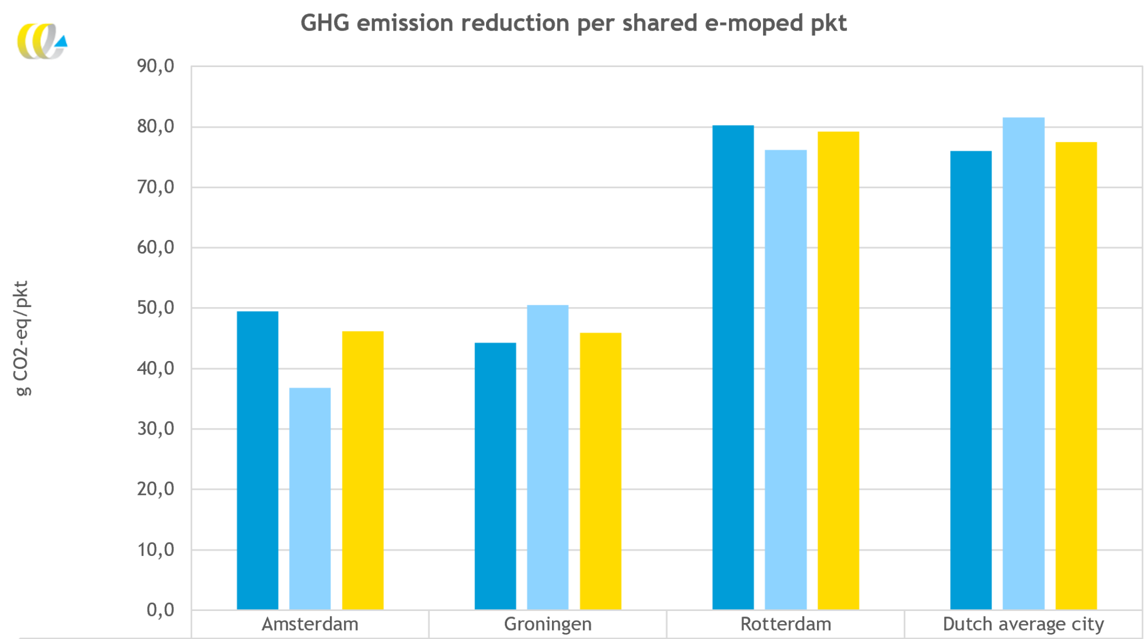
The following factors are considered:

- BTM distribution
- BTM occupation (rate)
- Bus fleet
- Modal shift

Figure 7.5 illustrates the environmental impact per shared e-moped pkt. The results indicate that shared e-mopeds have a positive environmental impact, regardless of the chosen city. To contextualize this impact, in Amsterdam and Groningen, for every 5.0 pkt travelled with a shared e-moped, the equivalent of 1 pkt CO_2-eq by car is saved. In Rotterdam, this is for every 2.9 pkt and in the average Dutch city this is for every 3.0 pkt. A lower value indicates that car passenger kilometers are saved faster with a shared e-moped, thus meaning the higher positive impact a shared e-mopeds has on the city.

Furthermore, the study found that if 100 % renewable sources are used to generate electricity, the environmental impact of shared e-mopeds per passenger kilometer decreases in Amsterdam and Rotterdam, resulting in a less positive impact. In contrast, the environmental impact per passenger kilometer increases in Groningen and the average Dutch city due to the high share of replaced BTM trips. In these cities, most BTM trips consist of metro and tram, which operate on electricity and benefit the most from sustainable electricity generation. In Groningen, where 44 % of buses are electric, the GWP of a bus decreases, but the GWP of shared e-mopeds also decreases (which has a greater impact), resulting in more avoided CO_2-eq emissions per passenger kilometer. The same explanation applies to the average Dutch city.

Additionally, it is interesting to see that if electricity is generated by 100 % renewable sources, the environmental impact of shared e-mopeds per pkt decreases in Amsterdam and Rotterdam (i.e., less positive impact), while in Groningen and the average Dutch city, the impact increases (i.e., more positive impact). his difference can be attributed to the high percentage of replaced public transport trips (BTM) in Amsterdam and Rotterdam, where the majority of BTM trips involve metro and tram, which operate on electricity and hence benefit the most from sustainable electricity generation. In contrast, in Groningen, 44 % of buses are electric, resulting in a decrease in the global warming potential (GWP) of a bus, but simultaneously, the GWP of shared e-mopeds decreases (which has a greater impact), leading to a greater reduction in avoided CO_2-eq per pkt. The same reasoning applies to the average Dutch city.



	Amsterdam	Groningen	Rotterdam	Dutch average city
100% grey/fossil	49,5	44,3	80,3	76,0
100% sustainable	36,8	50,5	76,2	81,6
Average mix NL	46,1	45,9	79,2	77,5

Figure 7.5: Environmental impact per shared e-moped pkt

There are two factors that differ between the cities, namely the GWP of BTM and the modal shift. These two characteristics are responsible for explaining why the environmental impact per shared e-moped pkt is higher in Rotterdam and the average Dutch city compared to Amsterdam and Groningen. The values of these two characteristics for all four cases are presented in Figures 7.6 and 7.7.

In Groningen, the GWP of a bus is lower than that of the average bus in the Netherlands, due to the high proportion of electric buses and the use of HVO-diesel as fuel. The GWP of a bus in Groningen is even lower than that of a tram in Rotterdam and an average Dutch city. This, along with the fact that 67 % of shared e-moped trips in Groningen replace active modes (walking and cycling), results in the lowest environmental impact per shared e-moped pkt compared to the other cases. The environmental

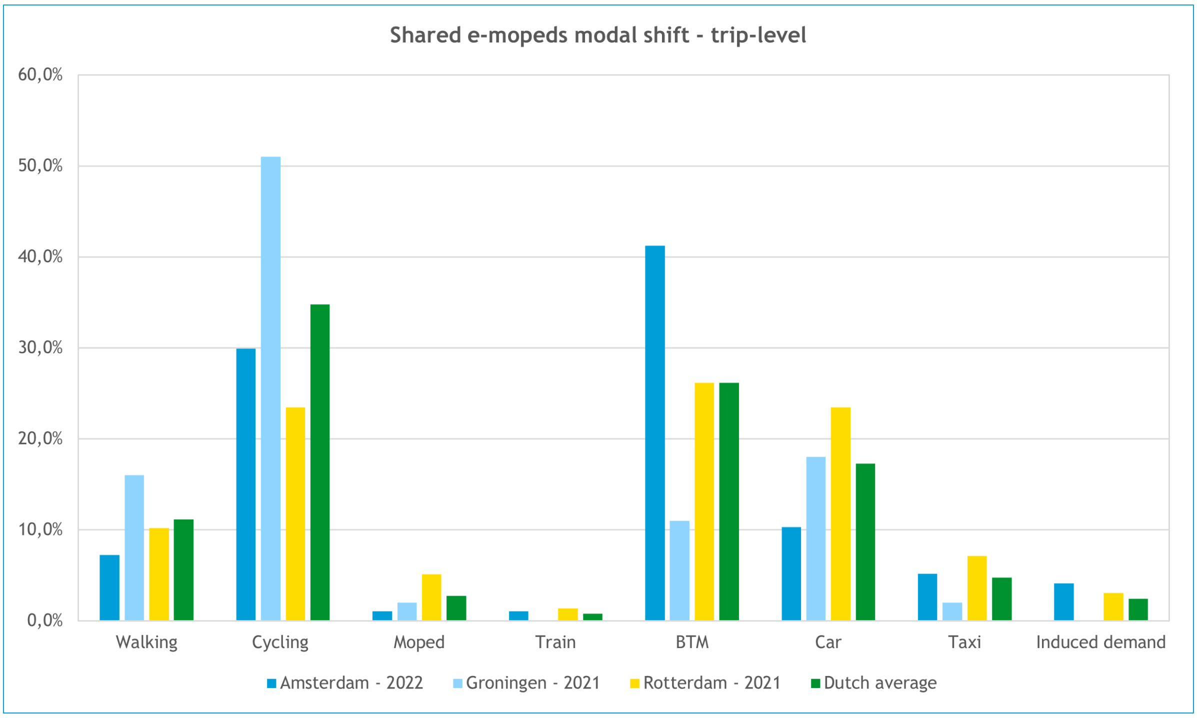
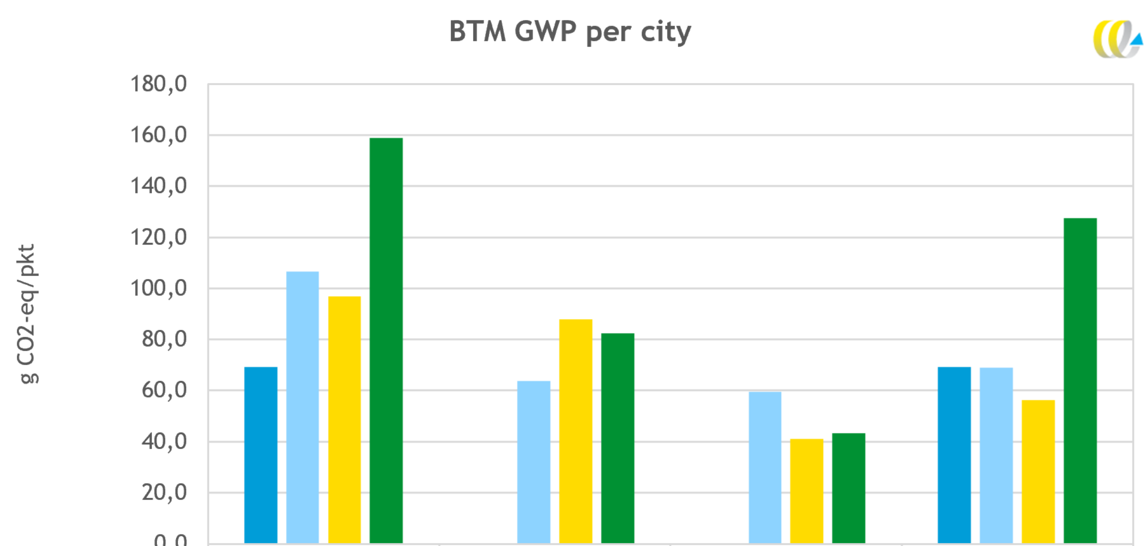


Figure 7.6: Modal shift for the four case studies



	GWP bus	GWP tram	GWP metro	GWP BTM
Groningen	69,2	0,0	0,0	69,2
Amsterdam	106,6	63,8	59,4	69,0
Rotterdam	96,9	87,9	41,2	56,4
Dutch average	158,8	82,4	43,2	127,5

Figure 7.7: GWP of bus, tram and metro and BTM combined for the four case studies

impact in Amsterdam is comparable to Groningen, with a 41.8 % lower impact than in Rotterdam and a 39.1 % lower impact than the average Dutch city.

BTM in Rotterdam has the lowest environmental impact compared to the other cases, due to the high share of metro in the BTM division (70 % vs 18.7 % in the Netherlands). In addition, the higher occupancy of the metro in Rotterdam results in lower GHG emissions per pkt than in Amsterdam. Furthermore, bus occupancy is higher in Amsterdam and Rotterdam than the national average, and these cities have a more sustainable bus fleet than the Dutch average, resulting in a higher GWP for buses in an average Dutch city compared to Amsterdam, Rotterdam, and Groningen.

When assessing a specific city, it is crucial to input its own value for BTM shares to account for the availability of a metro and/or tram network and the division of bus, tram, and metro passenger kilometers. This has a substantial impact on the GWP since the GWP of an average bus is almost twice that of a tram and 3.7 times higher than that of a metro in the Netherlands.

7.3.2. Absolute environmental impact at city-level

The absolute environmental impact of shared e-mopeds in a city is determined using the number of shared e-moped kilometers traveled in a city. However, whether shared e-mopeds have a positive or negative impact on the environment is already indicated above. Table 7.4 provides information on the number of shared e-moped kilometers traveled per day, month, and year for Amsterdam, Groningen, Rotterdam, and an average Dutch city. Additional information on the inputs used to calculate these values can be found in Appendix D.

	Day	Month	Year
Amsterdam	2,1000	640,500	7,665,000
Groningen	7,197	219,502	2,626,832
Rotterdam	28,339	864,338	10,343,720
Dutch average city	6,660	203130	2,430,900

Table 7.4: Shared e-moped kilometers per city

The avoided emissions in kg CO_2-eq per day, month and year for each city are presented in Table 7.5. Appendix D provides a visual representation of these values. Although Amsterdam, Groningen, and Rotterdam are all large cities in the Netherlands and have more shared e-moped kilometers driven than the Dutch average city, the impact on the environment per shared e-moped pkt is lower in Groningen than the average Dutch city. This results in a higher impact in the average Dutch city compared to Groningen.

	Day	Month	Year
Amsterdam	745	22,731	272,028
Groningen	249	7,604	90,995
Rotterdam	1,727	52,667	630,274
Dutch average city	389	11,827	141,535

Table 7.5: Avoided GHG-emissions in kg CO_2-eq using the Dutch average electricity mix

7.3.3. Relative environmental impact at city-level

To gain insight into the relative effect of introducing shared e-mopeds in a city, the avoided emissions per year are compared to the total transport emissions in that city. This analysis is conducted for Amsterdam, Rotterdam, and Groningen, but not for an average Dutch city due to the difficulty of estimating the total transport GHG emissions in such a case. Table 7.6 presents the total transportation GHG emissions per year for the three addressed cities.

	Transportation GHG-emissions	Avoided CO_2-eq emissions	Percentage
Amsterdam	688,000,000	300,765	0.044 %
Groningen	246,000,000	90,700	0.037 %
Rotterdam	651,000,000	627,277	0.096 %

Table 7.6: Relative impact of introducing shared e-moped, compared to the total transport GHG-emissions in a city. All numbers are expressed in kg CO_2-eq

When considering the city-wide passenger transportation emissions, the impact of introducing shared e-mopeds is found to be minimal, as shown in table 7.6. The largest impact is observed in Rotterdam, where the introduction of shared e-mopeds reduces transportation GHG emissions by 0.096 %, which is more than twice the reduction observed in Amsterdam and Groningen.

7.4. Scenario Analysis

Two scenario's are constructed, in which future prospects are implemented to gain insight in the environmental impact of shared e-mopeds in the future. The scenarios incorporates future developments for car fleet, bus fleet, taxi fleet, battery production emissions and the electricity mix and thus electricity emissions factor. This scenario is applied to the four cases, in which the previous results were also presented. First, the impact of each factor is assessed individually in section 7.4.1, where the future value of a factor/variable is compared to the base case value (current Dutch average value). Thereupon in section 7.4.2 , a 2030 and 2040 scenario is constructed in which the factors/variables are adjusted simultaneously. Results are discussed in terms of impact average replaced transport mode per pkt and consequently environmental impact per shared e-moped pkt.

7.4.1. Sensitivity analysis

Car fleet

Every year, the Climate and Energy exploration (in Dutch: Klimaat- en energieverkenning (KEV) provides a clear and comprehensive report on the expected effects of the climate and energy policy of the Dutch government (PBL, 2022). Until 2030, the electric car share in new sold cars keeps increasing relatively fast. However, the share in the total car fleet is still moderate, only 16 % in 2030. From 2035, EU policy prescribes that all new passenger cars must be emissions free at the exhaust, meaning no Tank-to-Wheel (TTW) are allowed. As a result, in 2040 more than half of the car fleet is expected to consists of electric cars. On yearly basis, new cars drive more kilometers, resulting in the fact that in 2040 - under current policy - in 2040 two third of all passenger and delivery van kilometers are electric. This is also the reason why in 2030 the electric passenger car kilometers make up 20 % of all passenger car kilometers. The impact of both car fleet divisions - 2030 and 2040 - on the GWP of the average car and subsequently also on the GWP of the average replaced transport mode and the impact per shared e-moped pkt is explored. The car fleet division used for calculation for 2030 and 2040 is shown below. Both scenario's are calculated keeping all the other parameters and variables on their base case.

Table 7.7: Car fleet division: current, 2030 and 2040

	Current	2030	2040
Petrol	71.6 %	60 %	25 %
Diesel	23.3 %	15 %	8 %
Electric	2.3 %	20 %	67 %
LPG	1.4 %	0 %	0 %
CNG	0.2 %	0 %	0 %
Plug-in hybrid	1.1 %	5 %	0 %

Car fleet - results

Results show that the increased share of electric cars in the car fleet decreases the GWP of a car with 9.9 % in 2030 and with 32.4 % in 2040 compared to the current situation. Consequently, in an average Dutch city, the average impact per replaced trip decrease with 4.3 % in 2030 and 14.2 % in 2040. The environmental impact per shared e-moped pkt decreases with the same amount as the average impact per replaced trip. The percentage change is however larger since the shared e-moped impact remained constant.

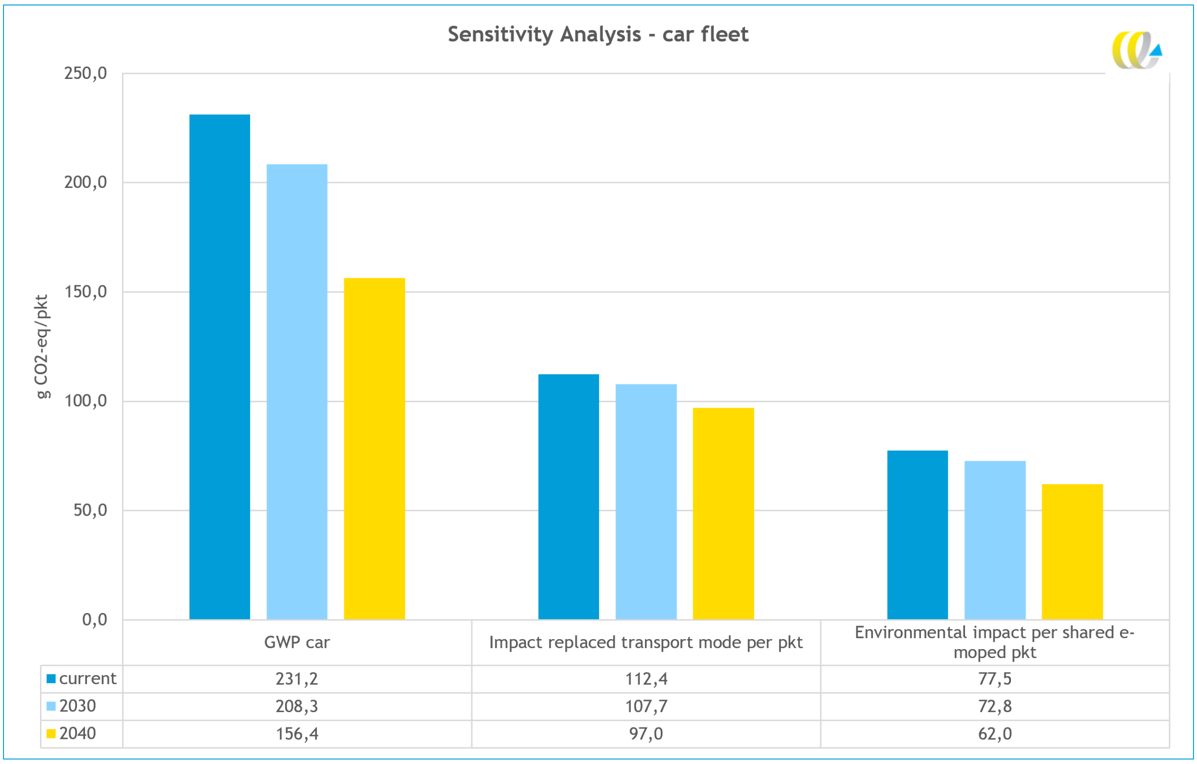


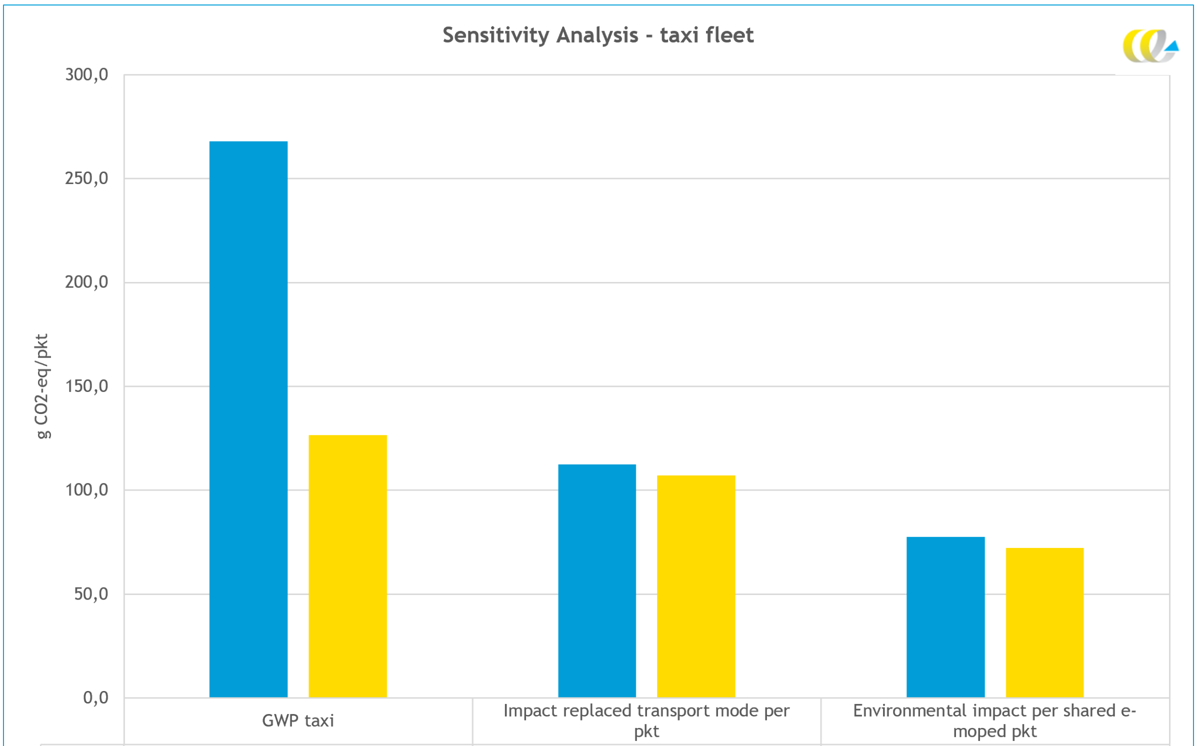
Figure 7.8: Sensitivity Analysis: car fleet future developments

Taxi fleet
In 2021, the Dutch government decided - in consultation with six large municipalities and representatives of the taxi industry - that in 2030 all (new) taxi's are required to be quiet and emissions free (Rijksoverheid, 2021b). For the six large municipalities - Amersfoort, Amsterdam, The Hague, Eindhoven, Rotterdam and Tilburg - who account for around 75 % of all taxi's, this requirement already applies from 2025. On average, the lifetime of a taxi is between three and five years (Rijksoverheid, 2021a). Therefore, it is assumed that for calculation of the 2030 scenario here, the taxi fleet solely consists of electric ones.

Table 7.8: Taxi fleet division: current and 2030

	Current	2030
Petrol	10 %	0 %
Diesel	80 %	0 %
Electric	10 %	100 %

Taxi fleet - results
Full electrification of the taxi fleet has a major impact on the GWP of a taxi. The GHG-emissions per passenger kilometer travelled are more than halved in 2030, whilst the electricity emission factor remains on the current value when this is expected to already decrease considerable in 2030 resulting in an even lower environmental impact. The eventual impact on the environmental impact per shared e-moped passenger kilometer is however much less, since the share of replaced car trips in the modal shift is limited (4.8 % on trip-level).



	GWP taxi	Impact replaced transport mode per pkt	Environmental impact per shared e-moped pkt
current	268,0	112,4	77,5
2030	126,6	107,3	72,3

Figure 7.9: Sensitivity Analysis: taxi fleet future developments

Bus fleet

In 2016, the Dutch public transport providers agreed that in 2025 the influx of new busses are required to be emissions free at the exhaust, meaning only hydrogen and electric busses are allowed (Zero-emissiebus, 2016). The administrative agreement further states that in 2030, the entire bus fleet must be emissions free at the exhaust, meaning no Tank-to-Wheel (TTW) emissions are allowed. In this research, no life-cycle emissions for a hydrogen bus are determined, resulting in the fact that here it is assumed that in 2030 the entire bus fleet consists of only electric ones.

Table 7.9: Bus fleet division: current and 2030

	Current	2030
Diesel	56 %	0 %
HVO	3 %	0 %
CNG	29 %	0 %
Electric	12 %	100 %

Bus fleet - results

A 100 % electric bus fleet reduces the GWP of an average bus in the Netherlands with 42.5% to 91.3 g CO_2-eq/pkt. This is however higher than the current GWP of a bus in Groningen (69 g CO_2-eq/pkt). The reason for this is that in Groningen more than half of the buses contain HVO-diesel as fuel, while the rest are electric buses. The emissions of HVO-diesel is currently 1.8 times lower than the emissions of an electric bus per kilometer. It must be noted that in 2030 it is expected that the fuel emissions on an electric bus decrease a lot due to more green energy in the electricity mix. In a scenario where 100 % of the generated electricity is from renewable sources, the bus GWP is only 31 g CO_2-eq/pkt. A complete zero-emission (ZE) bus fleet also decreases the BTM GWP (for the average Dutch case) with 36.7 %. The average impact of the replaced trip decreases with 14.7 g CO_2-eq/pkt, similar to the environmental impact per shared e-moped pkt.

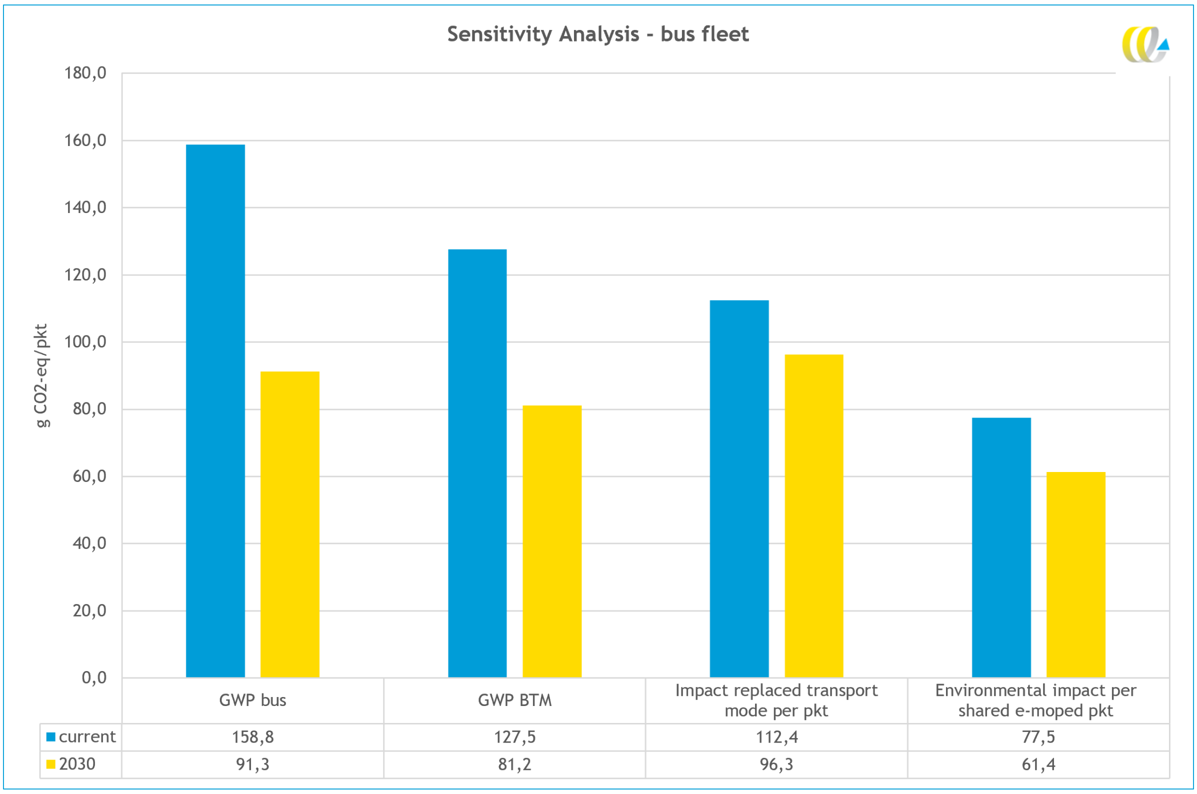


Figure 7.10: Sensitivity Analysis: bus fleet future developments

Battery production emissions

Battery production emissions are expected to decrease in the future. Prospects for 2030 are that these decrease to 55 g CO_2-eq/kWh, compared to 72.9 g CO_2-eq/kWh assumed currently. In a more optimistic scenario, where materials are extracted in a sustainable form using for example geothermal energy, they further decrease to 33 g CO_2-eq/kWh (CE Delft, 2023). The impact on the GWP of electric transport modes of both battery production emission values is explored.

Table 7.10: Future emissions values for battery production

	Battery production emissions
Current	72.9 g CO_2-eq/kWh
2030	55 g CO_2-eq/kWh
2040	33 g CO_2-eq/kWh

Battery production emissions - results

Sensitivity analysis for battery production emissions shown to only have a marginal impact of the GWP of battery electric transport modes. The largest decreases in GWP is observed at the shared e-moped itself, where the GWP decreases with 5.4 % in 2030 and 12.0 % in 2040. The GWP of a shared e-bike also decreases significantly with 2.2 g CO_2-eq/pkt in 2030 and 4.9 g CO_2-eq/pkt in 2040. The reason these two transport modes are more sensitive to a change in battery production emissions is that these emissions influence the GWP twice. First, the battery production on an e-moped or e-bike itself, and in addition also the battery production for the electric service van which influence the BSO emissions.

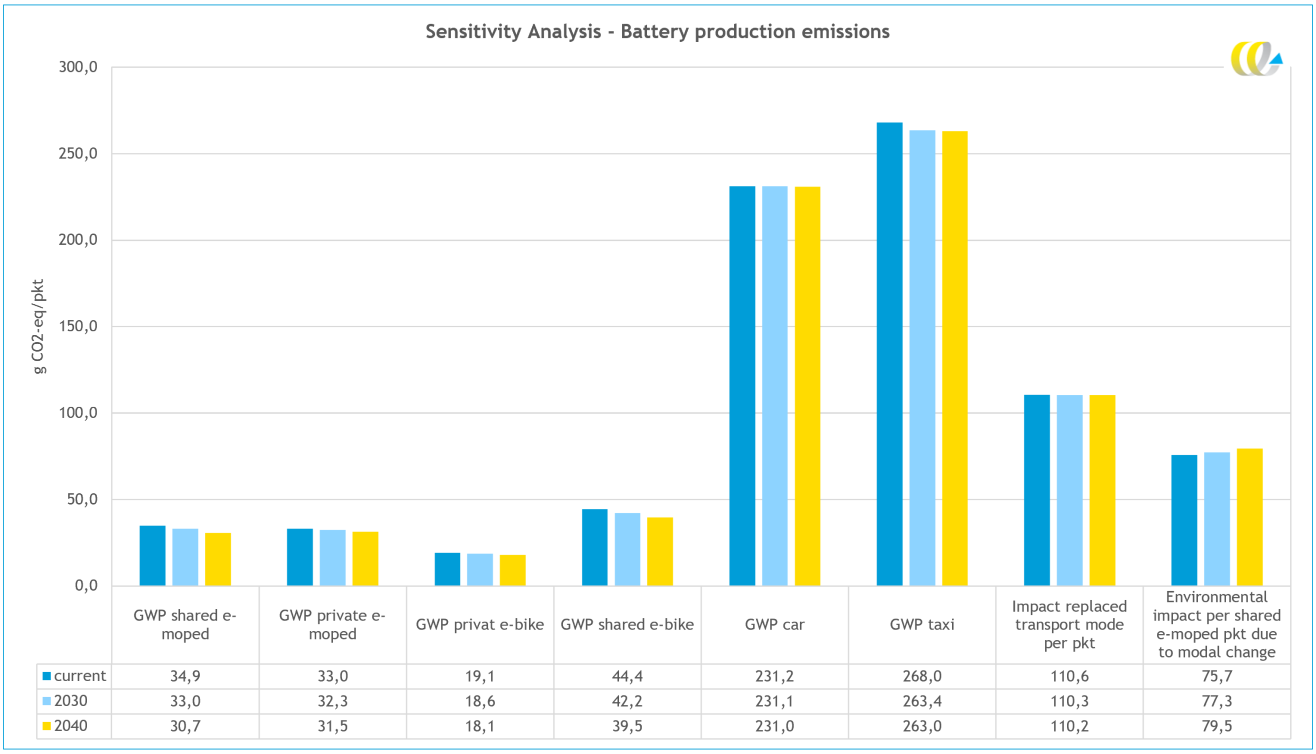


Figure 7.11: Sensitivity Analysis: battery production emission

Electricity mix

Currently, 26.7 % of the generated electricity is generated by renewable energy sources as wind and solar energy. Taking the CO_2-eq emissions required for energy-infrastructure into account, this results in an electricity emissions factor of 344 g CO_2-eq/kWh. The share of renewable sources in the electricity generation is expected to keep increasing in the future, resulting in a lower electricity emissions factor. If all electricity is generated using fossil sources, this would lead to an electricity emissions factor of 457 g CO_2-eq/kWh, while a complete green electricity mix leads to just 31 g CO_2-eq/kWh. The electricity emissions factor influence (the fuel emissions of) electric transportation modes as e-mopeds, e-bike, tram, metro, electric busses, electric car and electric taxi's.

Table 7.11: Sensitivity Analysis: electricity mix

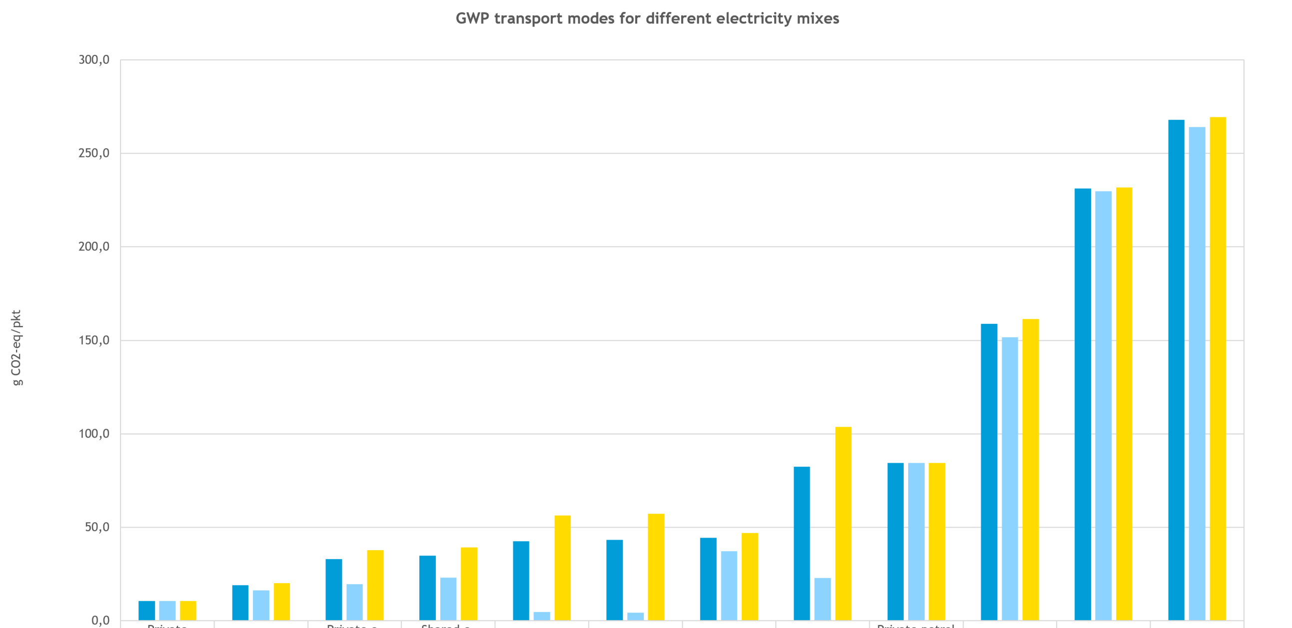
	Electricity emission factor
Average Dutch mix	344 g CO_2-eq/kWh
100 % green	31 g CO_2-eq/kWh
100 % gray/fossil	457 g CO_2-eq/kWh

Electricity mix - results

Results show that mainly train, metro and tram are highly influence by a 100 % green electricity mix. Their GWP reduces with respectively 89 &, 90 % and 72 %. This can be explained by the fact that fuel component has a very large share in the total GWP of these transport mode. Since they are electricified, using a 100 % green electricity mix thus has a significant impact.

The impact on shared and private e-bikes and e-mopeds is also substiantial. The impact is greater for the shared version, since the BSO emissions are also influenced by the electricity mix since they are served by electric vans. The GWP of shared e-mopeds reduces with 34 %, and for shared e-bikes with 16 %.

The impact on bus and car seems small. However, the impact on electric bus and car is significant, but due to fleet division, this is somewhat nullified in the average versions. The GWP of an electrc bus decreases with 66 %, from 61.7 to 21.0 g CO_2-eq/pkt. For an electric car this is 55 %, from 118.0 to 53.4 CO_2-eq/pkt.



	Private traditional bike	Private e-bike	Private e-moped	Shared e-moped	Train	Metro	Shared e-bike	Tram	Private petrol moped	Bus	Car	Taxi
Average NL mix	10,5	19,1	33,0	34,9	42,6	43,2	44,4	82,4	84,4	158,8	231,2	268,0
100% green	10,5	16,2	19,6	23,0	4,7	4,4	37,3	22,9	84,4	151,6	229,7	264,2
100% gray/fossil	10,5	20,2	37,9	39,2	56,3	57,2	47,0	103,8	84,4	161,4	231,8	269,4

Figure 7.12: Sensitivity Analysis: Electricity mix

Modal shift

Three city types are created by adjusting the modal shift. In active mode oriented city the majority of shared e-moped trips replace walking and cycling trips (80 % combined). The car oriented city has a large share of car trips, thus resulting in a large share of substituted car trips in the modal shift. Lastly, the public transport oriented city has a large share of substituted BTM trips (train trips are rarely replaced by shared e-mopeds), while the share of replaced cycle trips is also significant (20 %) since this is often used as first- and last-mile transport to public transportation. There is intentionally chosen for extreme substitution rate in the different city types, to gain insight in the maximum and minimum environmental impact of shared e-mopeds. The maximum and minimum substitution rates for transport modes are kept in mind when constructing the scenario's, however, sometimes the values here are a bit higher or lower than the Dutch maximum or minimum. This is however still realistic since the Dutch average is only based on three cities.

Modal shift percentages for the Dutch average city do not add up to 100%, since 5.9 % also replaced a private (e-)moped or train trip or is induced demand. The contribution of these substituted transport modes is limited, which is why these are not considered for the three constructed city types.

Modal shift - results

The positive environmental impact in a car oriented city is much higher than in an public transport or active modes oriented city, caused by a higher car GWP than that of BTM or walking/cycling, thus when more car trips are replaced this in-evidently results in more avoided GHG-emissions. Car oriented cities have almost 1.6 times the (positive) environmental impact per shared e-moped pkt than public transport oriented cities, while compared to an active mode oriented city the environmental impact per shared e-moped pkt is even 3.2 times higher.

Table 7.12: Substitution rates in the Netherlands (trip-level)

Vehicle category	Average	Minimum	Maximum
Walking	11.1 %	7.2 %	16.0 %
Cycling	34.8 %	23.5 %	51.0 %
Moped	2.7 %	1.0 %	5.1 %
Train	0.8 %	0.0 %	1.4 %
BTM	26.1 %	11.0 %	41.2 %
Car	17.3 %	10.3 %	23.5 %
Taxi	4.8 %	2.0 %	7.1 %
Induced demand	2.4 %	0.0 %	4.1 %

Table 7.13: Modal shift trip-level for three city types

	Public transport	Car	Active modes
Walking	10 %	10 %	25 %
Cycling	25 %	20 %	50 %
BTM	50 %	20 %	10 %
Car	10 %	40 %	10 %
Taxi	5 %	10 %	5 %

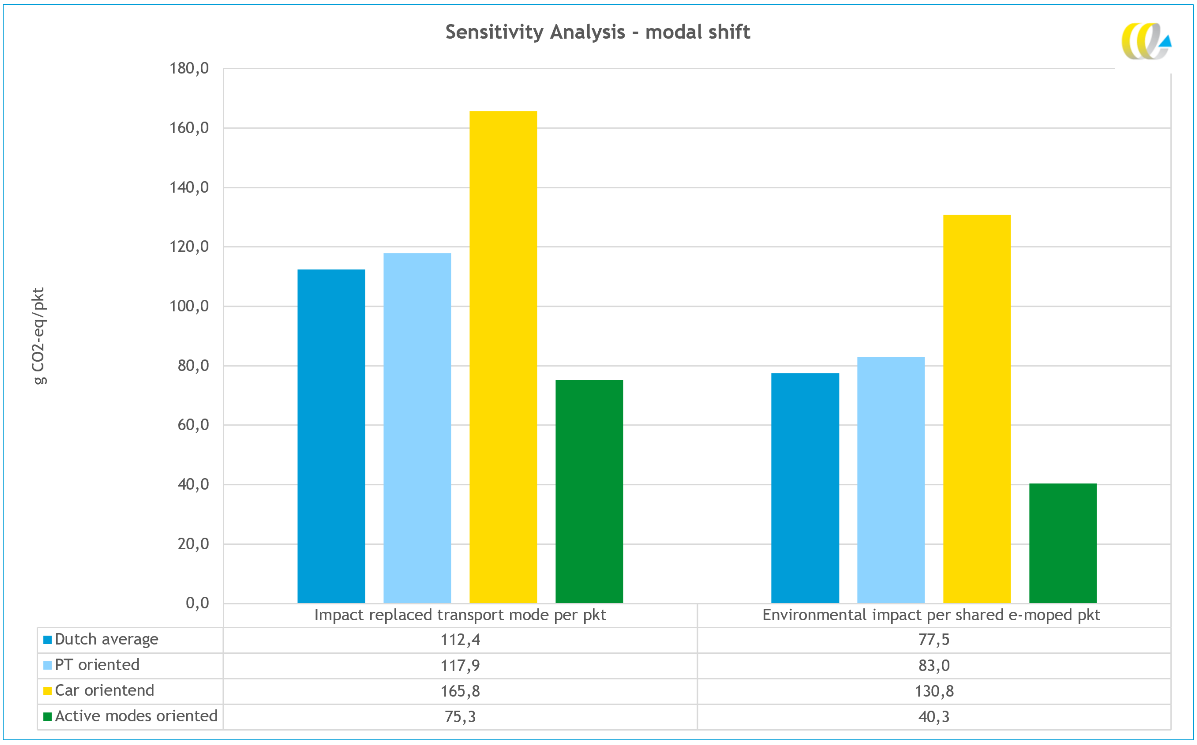


Figure 7.13: Sensitivity Analysis: modal shift

7.4.2. Scenario application

For both 2030 and 2040 a scenario analysis is performed. Both years are chosen, since the car fleet division is expected to change substantially between 2030 and 2040 due to EU policy. Next to a car fleet change in 2040 compared to 2030, the battery production emissions differ. Prospects for 2030 are that these decrease to 55 g CO_2-eq/kWh and in a more optimistic scenario to 33 g CO_2-eq/kWh. It can be expected that in the future materials are extracted in a more sustainable matter and the production process keeps improving in terms of efficiency. Therefore, battery production emissions are assumed to be 33 g CO_2-eq/kWh in the 2040 scenario. The used electricity emissions factor in 2030 and 2040 is explained and calculated below. The remaining variables explored above continue to have the same value or division for 2030 and 2040.

Electricity emission factor - 2030 and 2040
In addition, it is expected that in 2030 and 2040 the electricity emission factor is lower compared to the current emission factor, since more electricity is generated using green sources. The electricity emissions factor is expected to decrease to 70 g CO_2-eq/kWh in 2030 using the 'integral-method' [2] (PBL, 2022). The integral-method only considers direct-emissions, thus no chain emissions and emissions required for energy-infrastructure are taken into account. In STREAM and thus also here, these emissions are considered. In 2020, the direct emissions component in the electricity emissions factor are 290 g CO_2-eq/kWh and the chain emissions including energy-infrastructure emissions for the average Dutch electricity mix are 54 g CO_2-eq/kWh [3] (CE Delft, 2023).

Since the integral-method only considers direct emissions, these can all be attributed to electricity generation by gray energy sources. If the electricity mix consist of only gray energy sources, it would result in 396 g CO_2-eq/kWh for direct emissions (CE Delft, 2023). Since green energy sources do not have direct emissions, the direct emissions expected in 2030 thus all come from gray energy sources, this results in a share of 17.7 % of gray energy sources in 2030 (and thus 82.3 % green energy sources). These two percentages are used for determining the chain emissions including energy-infrastructure emissions. Calculating these, results in 36.3 g CO_2-eq/kWh. Adding this up to the direct emissions results in an electricity emissions factor of 106.3 g CO_2-eq/kWh in 2030. Applying an storage correction factor of around 2.7 % for energy-losses during the transformation from high-voltage power to low-voltage power results in an electricity emissions factor of 109.2 g CO_2-eq/kWh, which is used for calculations in the 2030 scenario (CE Delft, 2023).

The Dutch government desires that in 2050 all electricity is generated using renewable sources, thus having an electricity emissions factor of 31 g CO_2-eq/kWh (excluding transformation losses). In this research it is assumed that the generated electricity from fossil sources decreases gradually from 2030 to 2050, thus in 2040 the emission factor is the average of 2030 and 2050, namely 68.7 g CO_2-eq/kWh (70.6 g CO_2-eq/kWh when considering transformation losses).

Scenario results
Figure 7.14 shows the results in terms of average replaced transport mode impact and the environmental impact per shared e-moped passenger kilometer travelled for the four case studies. The current situation is compared to the 2030 and 2040 case. Table 7.14 shows the value related to the figure.

Table 7.14: 2030 and 2040 scenario results

	Impact replaced transport mode per pkt			Environmental impact per shared e-moped pkt		
	current	2030	2040	current	2030	2040
Amsterdam	81.1	43.4	29.4	46.1	19.3	9.1
Rotterdam	114.1	74.8	48.4	79.2	50.8	28.1
Groningen	80.8	65.7	44.1	45.9	41.6	23.8
Dutch average city	112.4	67.6	47.0	77.5	43.5	26.8

Initially, it is crucial to acknowledge that the various factors' impact reinforces one another. For instance, the influence of the electrification in the car fleet is strengthened by the lower electricity emission factor. The findings reveal that the positive environmental influence of shared e-mopeds diminishes over time. Nevertheless, shared e-mopeds still produce a favorable impact on CO_2-eq emissions in a city in all cases for both scenarios. In addition, it is noteworthy that, for Amsterdam, emissions decline rapidly by 2030, whereas, for instance, for Groningen, this reduction is much higher by 2040. This discrepancy can be explained by the fact that, in Amsterdam, numerous tram and metro journeys

[2] The integral method or average method is used for assigning CO_2-eq emissions to consumed or generated electricity. The 'referentiepark-method' or marginal-method is used for analysing the effect of changes in the deployment and construction of electricity production capacity (PBL, CBS, ECN, Agentschap NL, & Harmelink consulting, 2012)

[3] 73.3 % of the electricity mix consist of gray energy sources which require 61 g CO_2-eq/kWh for chain emissions including energy-infrastructure. The rest is generated by green energy sources which require 31 g CO_2-eq/kWh for chain emissions including energy-infrastructure

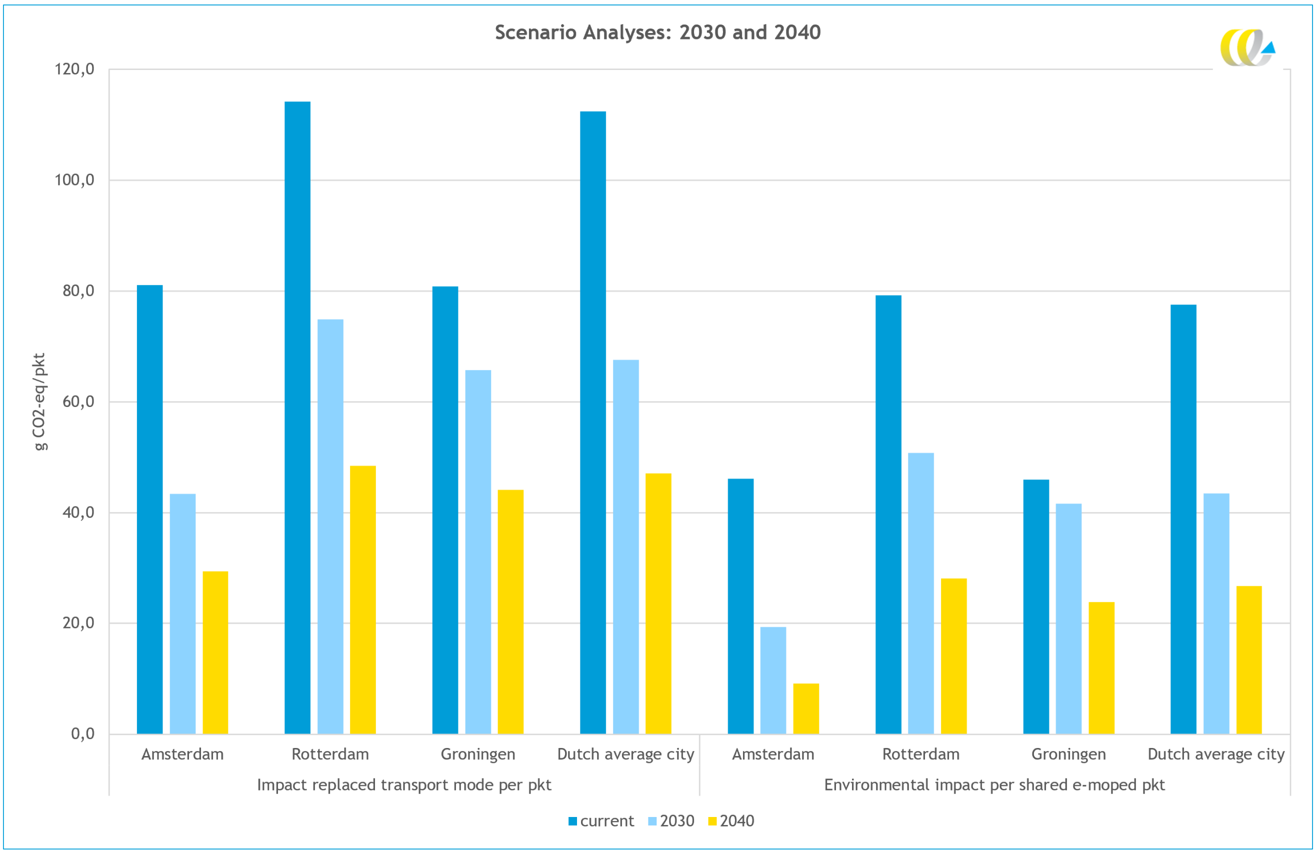


Figure 7.14: Scenario analysis: 2030 and 2040 for the four case studies

are substituted, which are electrified and hence significantly affected by the already considerably reduced electricity emission factor in 2030. On the other hand, in Groningen, a more substantial portion of car trips is replaced compared to Amsterdam; therefore, in 2040, there is a high reduction due to a more substantial share of electric cars in 2040.

8 Conclusion

Shared e-mopeds are a relative new mobility alternative that provides an on-demand, free-floating service, which increases flexibility and accessibility. E-moped sharing also brings implications for public health, safety, street scenes, congestion and greenhouse gas (GHG) emissions. The environmental impact, specifically the GHG emissions of shared e-mopeds is frequently debated in news articles, and the scientific literature lacks consensus whether it has a positive or negative environmental impact (within a city). This research puts a conclusion to this debate by providing a scientific answer to the following research question:

What is the environmental impact of e-moped sharing in a city in terms of GHG emissions?

In order to answer this main research question, five sub-questions were addressed. Initially, the factors that influence the environmental impact of e-moped sharing in a city were identified. Key factors that affect the environmental impact of a transportation mode are the vehicle's lifespan and occupancy.

By considering city-specific factors, such as modal shift, public transport availability, and bus fleet, the city-dependent environmental impact per shared e-moped pkt was calculated. It can be concluded that - independent of a city - shared e-mopeds bring positive impact on the GHG transportation emissions in a city. To contextualize this impact, the equivalent of 1.0 pkt CO_2-eq by car is saved for every 3.0 pkt travelled with a shared e-moped, based on average Dutch city values. Sensitivity analysis indicated that the difference in impact mainly depends on the city type (which determines the modal shift) and the average environmental impact of the present public transportation in that city. The relative impact of e-moped sharing on total GHG transportation emissions in a city is however very small. Introducing shared e-mopeds reduces total transportation emissions in a city by less than 0.01 %.

Future scenarios considering developments in the bus, car, and taxi fleet, electricity emissions factor, and battery production emissions show that the environmental impact of shared e-mopeds decreases over time but still has a positive impact in 2040, for all case studies. Future developments have a positive impact on the GWP of shared e-mopeds. However, the overall positive environmental impact of e-moped sharing is projected to decrease. This is because the positive impact on the GWP of the average transport mode replaced by shared e-mopeds is expected to be even greater because of the electrification of the replaced transport modes and the decreasing electricity emissions factor.

In conclusion, it can be stated that e-moped sharing has a positive impact on GHG transportation emissions in a city. Important factors that influence this impact are the transport it replaces and the electrification of replaced transport modes.

9

Discussion

This discussion first interpreted the results and discuses the implications in 9.1. Section 9.2 acknowledges limitations of the research. Last, section 9.3 gives recommendations for further research.

9.1. Result interpretation and implications

This section first provides insights in the results compared to other studies in 9.1.1. After that, in section 9.1.3 the research methodology used in the research is compared to solely considering fuel and BSO emissions. Third, the impact of solely considering marginal emissions is discussed in section 9.1.4. Last, policy implications are presented in section 9.1.5.

9.1.1. Results comparison with other studies

Compared to other studies (see table C.3 in Appendix C), the GWP of shared e-mopeds in this study is relatively low. This is attributed to the favorable inputs for the Dutch case used in the calculation, which include high occupancy compared to other studies and the usage of an electric van for operational services.

In Barcelona, the use of a shared e-moped results in an extra 8.54 g CO_2-eq on average per shared e-moped pkt. In this research, instead of extra CO_2-eq, 77.5 g CO_2-eq is avoided per shared e-moped pkt for the average Dutch city. Meaning that instead of a negative environmental impact in Barcelona, e-moped sharing has a positive environmental impact in a Dutch city.

There are two explanations for this difference. First, the replaced transport modes have a lower GWP, due to the higher public transport occupancy and a more green electricity mix compared to the Netherlands. Second, the GWP of shared e-mopeds is calculated to be much higher in Barcelona than in this study, approximately 74 g CO_2-eq/pkt versus 34.9 CO_2-eq/pkt [1]. As elaborated upon in section 5.2.3, this is due to the high BSO emissions, caused by a incorrect calculation in the Barcelona study. Therefore, this research is essential as it provides a different outcome and thus has different implications for the promotion of this new mobility alternative.

9.1.2. Shared e-moped GWP

In this study, a Monte Carlo uncertainty analysis was performed to address uncertainties in input variables used for calculating the GWP of shared e-mopeds. Results show that the uncertainty associated with the calculated GWP of shared electric mopeds is relatively low. There is a 90 % chance that the GWP of shared e-mopeds falls within the range of 35.7 to 37.9 g CO_2-eq/pkt. It was not initially expected that the uncertainty would be this low since the GWP depends on seven independent variables that exhibit significant variation. The low uncertainty is likely due to the negative impact of one variable offsetting the positive effect of another, resulting in consistent outcomes over more than 10,000 runs. Given the relatively low uncertainty, the results of this study provide a reliable estimate of the environ-

[1] In Barcelona, a occupancy of 1.07 is used, correcting to the same occupancy used here of 1.3, results in around 61 g CO_2-eq/pkt

mental impact of shared e-mopeds. This information can be used by shared e-moped operators and (local) policy makers to highlight the favorable environmental profile of shared e-mopeds compared to more harmful modes of transportation.

9.1.3. LCA approach impact

In this study, a LCA approach was used to determine the environmental impact of e-moped sharing. The developed calculation model can account for taking the different LCA components into account when calculating the GWP of shared e-moped and its replaced transport modes. Therefore, the impact of using a LCA approach as opposed to solely considering fuel emissions and BSO emissions is addressed here. The environmental impact per shared e-moped pkt is -77.5 g CO_2-eq/pkt for the average Dutch case. Solely considering fuel and operational service emissions [2], results in an environmental impact per shared e-moped pkt of -81.0 g CO_2-eq/pkt. This difference indicates that using a LCA approach results in a slightly less favorable environmental impact per shared e-moped pkt, than solely considering the emissions during the use phase. It is important to note that for Amsterdam the difference between the two approaches is more significant. Using an LCA approach results in 46.1 g CO_2-eq/pkt avoided emissions, while solely considering the emissions during the use phase results in 54.6 g CO_2-eq/pkt. This represents a decrease of 15.6 %, compared to only 4.3 % in the average Dutch case.

9.1.4. Marginal emissions

Considering marginal emissions only, means that emission from public transport are overlooked, since these transportation services are not affected by introducing shared e-mopeds. To determine the impact of the assumption that e-moped sharing has little impact on the mobility system, thus it does not affect public transport services, the difference is calculated here. In the case of the average Dutch city, neglecting the GWP of public transport results in a positive environmental impact of 32.7 g CO_2-eq/pkt. In the case of Amsterdam, the impact decreases most, but there is still a positive impact of 12.5 g CO_2-eq/pkt. Even in 2040, when most urban passenger transport modes are expected to be electrified and electricity generation from green sources is projected to increase, the environmental impact of e-moped sharing based on marginal emissions remains positive. For the worst-case scenario in Amsterdam, the impact is 4.6 g CO_2-eq/pkt.

9.1.5. Policy implications

To promote environmental sustainability in an urban e-moped sharing system, it may be beneficial to implement policies that require the use of electric service vans instead of diesel vans. Currently, many e-moped service providers use electric service vans, but they are not required to do so and very occasionally resort to diesel vans if electric ones are not available. In this study, we assume that all service vans are 100 % electric. To ensure that this assumption is valid, regulations mandating the use of electric service vans can be established, thereby maximizing environmental sustainability.

When evaluating the impact of e-moped sharing for policy purposes, it is crucial to consider more than the environmental impact in terms of GHG emissions. While it is true that e-mopeds have a positive impact on GHG emissions in cities, due to the small usage relative to other urban passenger transport, their overall impact is relatively small. Nevertheless, e-moped sharing can play an important role in introducing people to shared mobility which can be considered the future of urban mobility. In addition, it is expected to reduce the need of privately owned vehicles, and thus free up parking lots to help the current challenges regarding public space design.

Policy makers must consider several other implications when promoting e-moped sharing as a new environmental sustainable transport alternative. In addition to their impact on GHG emissions, policy makers must also consider safety, congestion, street scenes, air quality, transport poverty, and public health. For example, e-moped sharing may contribute to unsafe travel in busy urban areas, particularly if riders are inexperienced or unfamiliar with traffic laws for mopeds. Furthermore, e-moped sharing may have broader implications for transport poverty. For instance, individuals who are unable to afford a private vehicle may benefit from the availability of shared e-mopeds. However, high usage cost or limited availability in these areas may undermine this potential benefit.

[2] The operational service emissions are corrected for solely considering fuel emissions for the service van and not life cycle emissions. The GWP of shared e-mopeds then decrease from 17.8 to 14.2 g CO_2-eq/pkt

Overall, while e-moped sharing present promising benefits as a environmental sustainable transport alternative, policy makers must consider a range of implications beyond just their impact on GHG emissions. By carefully evaluating the potential risks and benefits of e-moped sharing and developing appropriate regulations and policies, cities can ensure that this mode of transport is sustainable from environmental, social and economic perspectives.

9.1.6. Model application for a specific city

The developed quantitative environmental impact model is applicable to cities worldwide. However, to obtain an accurate estimation, it is necessary to specify city and country specific information. The model comprises different types of data, including occupancy rates sourced from Dutch data, which are country-specific but expected to have low variation between countries. LCA data, except for fuel emissions, are derived from the Ecoinvent database and literature search, hence not country-specific, and not subjected to change for different countries, given the exclusion of transportation emissions. Fuel emissions originate from the same source as occupancy rates, hence specific to the Netherlands. However, fuel emissions for electric vehicles are anticipated to differ between countries due to varying electricity emission factors. The default value for the electricity emission factor is based on the Dutch value, and therefore, it is crucial to specify the relevant value for the area of interest when calculating the environmental impact of e-moped sharing.

Although the Monte Carlo analysis demonstrated low uncertainty surrounding the GWP of shared e-mopeds, a shared e-moped operator may require a more precise estimation based on data from a specific vehicle type. Currently, vehicle production emissions rely on a single source that conducted an LCA on one e-moped type. In the model, these emissions are scaled to the average e-moped weight and battery capacity. A more precise estimation can be made by inputting the corresponding weight and battery capacity of the specific type of e-moped, resulting in a more accurate estimation. Additionally, data on the service distance for that specific city and on the (electric) service vehicle used can be specified, leading to a more precise estimation of the operational service emissions. Currently, the same service distance value is used, and the LCA of the service vehicle is based on an electric car scaled to the weight of a van.

Furthermore, it is crucial to specify the BTM share and public transport occupancy, where the default value represents the Dutch average distribution and occupancy. The default occupancy value represents a Dutch average. It can be expected that the occupancy is higher in highly urbanized cities where shared e-mopeds are available. The same applies to the bus fleet, which differs between cities and countries, and thus must be specified according to the cities bus fleet.

Lastly, the shared e-moped usage characteristics such as modal shift, frequency of use, average trip distance, and fleet size must be specified for a city. Modal shift data can be obtained using surveys, but it is difficult to make a statement on modal shift before introduction in a city. Therefore, conducting multiple modal shift surveys in various cities would provide more insights into modal shift patterns related to city characteristics. The last three characteristics are used to calculate the shared e-moped kilometers in a city, and thus the absolute and relative citywide impact. Since this does not determine whether shared e-mopeds have a positive or negative impact on the transportation GHG-emissions in a city, it is not problematic that these are unknown when estimating the environmental impact of e-moped sharing before its introduction.

9.2. Limitations

This study acknowledges four limitations that are discussed in the following sections. The first limitation is related to the rebalancing assumptions and is elaborated on in section **??**. The second limitation concerns the occupancy and lifespan of the replaced transport modes, and is discussed in section 9.2.2. The third limitation concerns the lack of consideration for hydrogen vehicles, which is expounded upon in section 9.2.3. Finally, the fourth limitation relates to the assumption of equal service distance for each city, and is discussed in section 9.2.4.

9.2.1. Rebalancing

Rebalancing of shared vehicles is sometimes required as there could be a imbalance between demand and supply in different areas. The concept is not separately considered in this study, as shared e-moped service providers claim that rebalancing rarely takes place. f rebalancing were taken into account, the service distance per shared e-moped kilometer would increase, which currently only includes battery swap service kilometers. The literature already indicates a broad range of service distance per shared e-moped kilometer, varying from 20 to 80 meters. In most studies, vehicle repositioning is considered in the service distance value. The static value taken for calculation for all cities in this research in higher than the value calculated for Rotterdam, 50 m vs 41 m, it can be argued that rebalancing distance is already (partially) considered. Furthermore, the uncertainty analysis of the global warming potential of shared e-mopeds considers the entire range found in the literature for the service distance, yet the uncertainty around the GWP remains relatively low. Therefore, it can be concluded that the omission of explicit rebalancing considerations does not significantly affect the GWP of shared e-mopeds.

9.2.2. Data limitations replaced transport modes

Another limitations of this research concerns data on the lifespan and occupancy of the replaced transport modes. The lifespan and average occupancy are crucial factors that significantly influence the GWP of a transport mode. The occupancy of all replaced transport modes - except the taxi - is assumed to be accurate, since this is obtained from the STREAM study of CE Delft. However, the occupancy of a taxi is up for debate. In this study, a value of 1.1 is assumed, to the average of the value of STREAM and three scientific papers. The range between these four studies is quite large, from 0.54 to 2.4 passengers. Since the GWP of a vehicle has a linear relationship with occupancy, the assumed value has a considerable impact on the GWP of a taxi. However, it is not expected to have a significant effect on the environmental impact of e-moped sharing, as only 4-8 % of shared e-moped trips replace taxi trips.

The lifespan of the substituted transport modes is based on a literature study, which showed a large range in the lifespan of these modes. Obtaining data on the lifespan from public transport operators themselves would be more accurate in making a statement on the GWP. However, for transport modes where the GWP primarily consists of fuel emissions, such as rail, ICE bus, ICE car, and ICE taxi, the impact is expected to be limited, as the lifespan of a vehicle does not influence fuel emissions.

9.2.3. Hydrogen vehicles

It was beyond the scope of this study to examine the GWP of hydrogen vehicles (bus, car and taxi), which affects the results of the scenario analysis conducted. The zero-emission administrative agreement prescribes that all public transport buses must be emission-free by 2030. In this research, 100 % electric buses are assumed, while also hydrogen buses are also expected to play a role in the future. The same holds for hydrogen cars, although the share in the car fleet is expected to be less significant compared to the bus fleet.

Currently, fuel emissions from a hydrogen electric bus and car are 2.7 times higher compared to a battery electric version (CE Delft, 2023). Fuel emissions for a hydrogen vehicle (partially) depend on the electricity mix, and therefore decrease with a greener electricity mix in the future. However, the difference between a battery electric vehicle and a hydrogen electric vehicle increases for a 100 % green electricity mix. Specifically, the difference increases to approximately 4.2 times higher emissions for a full battery electric version compared to a full hydrogen electric version

In future scenarios, if it is assumed that there will also be hydrogen electric cars, buses and taxis, it is expected that the GWP of the average replaced transport modes will increase due to the higher fuel emissions of hydrogen vehicles compared to battery electric ones. However, it is expected that this will not affect the results in terms of the environmental impact per shared e-moped significantly. Nevertheless, further research is necessary to make a sound statement.

9.2.4. Service distance per city

The last limitations of this research comprises the service distance per shared e-moped kilometer. For each city, thus the cases of Amsterdam, Rotterdam and Groningen and the average Dutch city, the same value is used. This value is based on a literature review, where an average value is taken. There is however a wide range present. It ranges from 20 - 83 m per shared e-moped kilometer. The service distance has a significant, linear impact on the BSO, since multiplied with the GWP of the service van is determines the BSO emissions. The value depends on multiple factors like the warehouse location, city size and number of vehicles in the city. The lower the value, the less kilometer a service van must travel, the lower the BSO emissions are. Considering this wide range, it would thus be more accurate if specific city data is used for calculation of this service distance. Using the lowest value from the literature results in the fact that the GWP of shared e-mopeds decrease with 5 g CO_2-eq/pkt, while the same goes for the highest value, but then it increases with 5 g CO_2-eq/pkt.

9.3. Recommendations for further research

Further research is needed to establish the impact of e-moped sharing on air pollutant emissions. GHG emissions are global, while air pollution emissions have a local and direct impact on public health in urban areas. As these emissions are already considered in the STREAM study, it is feasible to include them in the model. It is also important to explore the various implications that shared electric mopeds may have in a city, beyond GHG emissions and air pollutant emissions. Research into safety, costs, and transport poverty - which is relevant to all forms of shared mobility - is crucial, as focusing solely on GHG emissions when evaluating shared electric mopeds is narrow in scope.

The results suggest that one of the main factors influencing the environmental impact of e-moped sharing is mode replacement. A significant proportion of shared e-moped trips replaced environmental friendlier modes. Especially for short distance trips which replace walking and cycling, shared e-moped do not impose a positive environmental impact. Additional research on usage patterns and operational systems in various cities is needed to make a more precise statement on the environmental impact of e-moped sharing. This would entail conducting surveys to collect modal shift data in different cities. If more modal shift data becomes available, data analysis can be performed on influencing factors of this modal shift, which could for instance be spatial city characteristics or city demographics. This way local authorities and shared e-moped operators could encourage modal change from more environmental harmful transport modes to shared e-mopeds instead of substituting of walking and cycling.

Additionally, it would be beneficial is access is gained to the *Dashboard shared mobility* of CROW (2023). The extensive version of the dashboard collects data on the position of shared vehicles every thirty seconds. As a result, data on the frequency of use during a specific period, as well as information on the origin and destination of rentals, are available. In combination with the fleet size per area or municipality, insight into the relationship between fleet size and frequency of use can be gained. This information could be used to determine the optimal fleet size and in addition determine usage patterns prior to the introduction of shared e-mopeds in a city. Moreover, since the dashboard collects data for a specified period of time, more precise shared e-moped usage patterns can be established, enabling more accurate assessments of the (environmental) impact of e-moped sharing, rather than relying on average shared e-moped usage data as was done in this study.

Overall, further research on the implications of shared electric mopeds in a city is needed. Safety, congestion, transport poverty and public health all are important aspects to investigate. More knowledge on all sort of implications will help policymakers and stakeholders better understand the impact of this emerging mode of transportation and develop strategies to minimize any negative consequences while maximizing benefits.

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A

Scientific papers on e-moped sharing

Figure A.1: Scientific papers on e-moped sharing part 1

Title	Author + year	Subject / findings
Exploring the adoption of moped scooter-sharing systems in Spanish urban areas	Álvaro Aguilera-Garcíaa, Juan Gomeza, Natalia Sobrino (2020)	Adoption shared e-mopeds: sociodemographic and travel-related variables play a main role, while personal opinions and attitudes were not found to be significant. Similar profiles for occasional and frequent users.
On the adoption of e-moped sharing systems	Fiorini et al. (2022)	Average daily flow (usage) directly proportional to the distance from the city center. Impact concentration of places and walkability on the adoption suggest that diversification of POIs and organization of roads play a central role in explaining mobility patterns. Increase in education index (share of graduates, proxy for socio-economic status on a area) leads to an increase in e-moped use
Moped Scooter Sharing: Citizens' Perceptions, Users' Behavior, and Implications for Urban Mobility	Aguilera-García et al. (2021)	Identifies the segment of the urban population that is more likely to adopt moped sharing. Key drivers determining the willingness to use moped sharing is analyzed and individuals opinions whether owning a private vehicle will not be needed in the future. The results indicate that age, occupation, income, and environmental awareness seem to be among the main reasons behind the potential use of these services in the future.
Exploring the spatio-temporal dynamics of moped-style scooter sharing services in urban areas	Arias-Molinares et al. (2021)	Mopeds location patterns over time and how different dynamics influence its usage level and self-balanced potential are analyzed. These insights are useful for operators to adjust and optimize vehicle distribution routes and maintenance/recharge tasks, decreasing congestion and increasing efficiency. The results may also be helpful for policy makers when planning and offering effective policies and infrastructure to encourage shared mobility.
Parking Places to Moped-Style Scooter Sharing Services Using GIS Location-Allocation Models and GPS Data	Pérez-Fernández and García-Palomares (2021)	A methodology is proposed for finding parking spaces for shared motorcycle services using GIS location-allocation models and GPS data. The results demonstrate how reserving a relatively small number of parking spaces for scooters makes it possible to capture over 70% of journeys in the catchment area. The daily variations in the distribution of demand slightly reduce the efficiency of the network of parking spaces in the morning and increase it at night, when demand is strongly focused on the most central areas.
A GIS-Based evaluation of the motorcycle sharing systems in Spain	Méndez-Manjón, Plasencia-Lozano and Pantiga-Facal (2021)	The current motorcycle sharing systems deployed in Spain were analyzed based on GIS tools. The study can therefore be useful for companies in the sharing sector interested in introducing the system in cities which do not yet have them, and for government administrations interested in this type of system. Furthermore, this research is a starting point for future comparative studies on Spain and other countries, or electric motorcycle and other e-vehicle-sharing systems.

Figure A.2: Scientific papers on e-moped sharing part 2

Title	Author + year	Subject / findings
Assessing Environmental Performance of Micromobility Using LCA and Self-Reported Modal Change: The Case of Shared E-Bikes, E-Scooters, and E-Mopeds in Barcelona	Felipe-Falgas, Madrid-Lopez and Marquet (2022)	LCA approach to calculate the impact of shared e-scooters, e-bikes, and e-mopeds in three categories: Global Warming Potential (GWP), Particulate Matter Formation, and Ozone Formation. Results show that shared e-mopeds and shared e-bicycles caused an increase in GHG emissions, while shared bicycles and personal electric scooter decreased GHG emissions. All micromobility modes except personal e-scooters increased particulate matter emissions, but decreased those which were emitted within the city, while they all decreased NOx
Analysis of Electric Moped Scooter Sharing in Berlin: A Technical, Economic and Environmental Perspective	Wortmann, Syré, Grahle and Göhlich (2021)	The study investigates the ability of an e-moped sharing system to substitute passenger car trips, and the resulting economic and environmental effects. he results indicate that a substantial part of all passenger car trips in Berlin can be substituted. The larger the fleet, the more and longer trips are replaced. Already with today's grid mix, the use of shared e-mopeds results in a significant reduction in environmental impact compared to conventional and battery-electric passenger cars.
Life Cycle Assessment on Electric Moped Scooter Sharing	Schelte et al. (2021)	A LCA is conducted for shared e-mopeds using the example of an electric moped scooter manufactured and used in sharing services in Germany, based on different operating scenarios. The results show that e-moped sharing has a similar environmental impact on global warming potential, in terms of passenger kilometers, as public transport, especially if long product lifetimes as well as efficient operation logistics are realized.
Environmental performance of shared micromobility and personal alternatives using integrated modal LCA	de Bortoli (2021)	LCA assessment is used to compare the environmental performance of shared micromobility compared to private alternatives relying on field data. Results show that Electric micromobility ranks between active modes and personal ICE modes. Its impacts are globally driven by the vehicle manufacturing. Ownership does not affect directly the environmental performance: the vehicle lifetime mileage does.
Consequential LCA for territorial and multimodal transportation policies: method and application to the free-floating e-scooter disruption in Paris	de Bortoli and Christoforou (2020)	The paper proposes a mathematical formalization of CLCA applied to a territorial mobility change. The method is applied to quantify the impact on climate change of the breakthrough of free-floating e-scooters (FFES) in Paris. Final results estimate that over one year, the FFES generated an extra thirteen thousand tons of CO2eq under an assumption of one million users, mainly due to major shifts coming from lower-emitting modes (60% from the metro and the RER, 22% from active modes).

B

Interviews

B.1. Teun Kolner - GO Sharing

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B.2. Nick Knoester - municipality of Utrecht

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B.3. Martijn Geervliet - municipality of Breda

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B.4. Kas Avedissian - Felyx

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B.5. Paul van Merrienboer - Check

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C

GWP calculations

C.1. Shared e-mopeds

Table C.1: LCA components per reviewed and used study

	LCA component						
Reference	Vehicle	EoL	Transportation	Servicing	Fuel	Infra	Maintenance
ITF (2020)	x	x	x	x	x	x	
Felipe-Falgas et al. (2022)	x	x	x	x	x	x	x
Schelte et al. (2021)	x	x	x	x	x		
de Bortoli (2021)	x	x		x	x	x	x
Wortmann et al. (2021)	x	x			x		
Christoforou et al. (2020)	x	x		x	x	x	x

Table C.2: Input data per reviewed study

Paper	Case location	Occupancy rate	E-moped lifespan	BSO vehicle type
ITF (2020)	Global	1.0	19,610	van ICE
Felipe-Falgas et al. (2022)	Barcelona	1.07	50,000	electric LCV
Schelte et al. (2021)	Germany	1.3	50,000	Diesel
de Bortoli (2021)	Paris	1.0	48,000	electric LCV
Christoforou et al. (2020)	Paris	1.0	50,000	electric vehicle
Wortmann et al. (2021)	Berlin	1.0	89,846 [1]	-

Table C.3: GWP of shared e-mopeds expressed in gCO_2-eq/pkt per research sorted by LCA component

	Vehicle component			*Use phase*			
Paper	**Production**	**End-of-life**	**Transport**	**Fuel**	**Infrastructure**	**Servicing**	**Total**
ITF (2020)		35.0		20.0	11.0	14.0	80
Felipe-Falgas et al. (2022)		29.6			8.8	35.0	74
Schelte et al. (2021)	14.4	0.0000741	0.000139	11.8	-	24.6	51
de Bortoli (2021)	23.1		-	2.4	6.1	2.40	34

C.2. Bicycle

C.2.1. Private traditional bicycle

Dutch people cycle on average 3.0 km per day (CBS, 2022b). This results in 1095 km per year. Assuming a bicycle last around 10 years (in decent working state), this results in a lifetime kilometreage of 10,950 km. This is lower than the lifetime used by multiple studies who performed a LCA on private

[1]For a fleet size of 2,500 e-mopeds. Lifetime mileage decreases to 84,732 for a fleet size of 10,000 and to 61,826 for a fleet size of 10,000 e-mopeds

Figure C.1: Vehicle production emissions per considered study

Study	Vehicle weight withou	Production emissions	Emissions per kg	Source
Wortmann et al. (2021)			6,97	Ecoinvent: "Electric scooter production, without battery, GLO"
Felipe-Falgas et al. (2022)	67	467,0	6,97	Ecoinvent: "Market for electric scooter, without battery, GLO"
de Bortoli (2021)	98	683,1	6,97	Ecoinvent: "Market for electric scooter, without battery, GLO"
Christoforou et al. (2020)	112	780,6	6,97	Ecoinvent: "Market for electric scooter, without battery, GLO"
Schelte et al. (2021)	92	655,0	7,12	GaBi software of Sphera Solutions GmbH
ITF (2020)	64,7	293,1	4,53	GREET2 supplemented with a few scientific papers
This study	**76,5**	**544**	**7,11**	**Schelte et al. (2021)**

Figure C.2: Battery production emissions per considered study

Study	Number of batteries	Battery weight	Battery capacity	Production emissions	Emissions per kg	Emissions per kWh	Source
de Bortoli (2021)	2	28	4	180,3	6,4	45,1	Ecoinvent: "Market for battery cell, Li-ion, GLO"
Christoforou et al. (2020)	2	16	4	103,0	6,4	25,8	Ecoinvent: "Market for battery cell, Li-ion, GLO"
Felipe-Falgas et al. (2022)	2	15,2		122,5	8,1		Ecoinvent: "Market for battery, Li-ion, rechargeable, prismatic GLO"
Wortmann et al. (2021)	2	23,9	3,4	192,6	8,1	56,7	Ecoinvent: "Battery production, Li-ion, rechargeable, prismatic"
Schelte et al. (2021)	1	10	1,5	146,0	14,6	99,3	GaBi software of Sphera Solutions GmbH
ITF (2020)	2	18,2	2,6	310,8	17,1	119,5	GREET2 supplemented with a few scientific papers
This study	**1**	**10**	**1,7**	**126**	**12,6**	**72,4**	**Dai et al. (2019)**

Figure C.3: Legend

Input from Ecoinvent database
Input from paper
Own calculation

bikes. Since it is plausible that Dutch bikes last longer and Dutch people cycle relatively often, a lifetime equal to the one used in those studies of 15,000 for private traditional bikes is assumed. The average occupancy on a bicycle is assumed to be 1.0 person, similar to STREAM and as used in all reviewed studies.

According to an own search in the Ecoinvent database, the production of a normal bicycle weighing 17 kg emits around 141 kg and the maintenance component a total of 16.7 kg CO_2-eq over the bicycles entire lifetime. Using a bicycles lifetime of 15,000 km, this would lead to a GWP of 10.5 g CO_2-eq/pkt, which is thus used as a default value.

Table C.4: GWP of a private traditional bicycle

Characteristics	Value
Vehicle lifetime	15,000 km
Average occupancy	1.0 persons
Vehicle emissions	9.4 g CO_2-eq/pkt
Maintenance emissions	1.1 g CO_2-eq/pkt
GWP private traditional bicycle	10.5 g CO_2-eq/pkt

Comparing the value with other studies
The research of ITF (ITF, 2020), calculated a GWP for the personal traditional bicycle of 16 g CO_2-eq/pkt (7 g for the vehicle component and 9 g for the infrastructure component). In their calculations, they used a vehicle lifetime mileage of 13440 km (average daily distance of 6.6 km and lifetime of 5.6 year). Neglecting the infrastructure component, this results in 94.1 kg CO_2-eq emissions for the vehicle component of a traditional bike. For a vehicle lifetime of 15,000 km this leads to 6.3 g CO_2-eq/pkt for the vehicle production part (no maintenance is considered).

Using Barcelona as a case study and a vehicle lifespan of 13200 km, Felipe-Falgas et al. (2022) found a GWP of around 15.5 g CO_2-eq/pkt, where the infrastructure wear component only accounted for a very small share, approximately 0.8 g CO_2-eq/pkt. Thus resulting in 14.7 g CO_2-eq/pkt for a vehicle lifespan of 13,200 km which is 12.9 g CO_2-eq/pkt for a lifetime of 15,000 used in this study.

Christoforou et al. (2020) used the Ecoinvent database to determine the GWP of of shared e-scooters and their replaceables in the Paris case, and found a GWP of 15.4 g CO_2-eq/pkt. 14.1 g can be attributed to the vehicle component and 1.3 g to infrastructure component. The lifespan of a private bicycle is in the same order of magnitude as the study of (ITF, 2020), at 15000 km, resulting in 211.5 kg CO_2-eq emissions for the vehicle production component, including maintenance.

de Bortoli (2021) used an integrated modal LCA to assess the environmental performance of shared micromobility and their personal alternatives and found a GWP for the personal bicycle of 10,6 g CO_2-eq/pkt, considering the vehicle component only. The vehicle lifetime mileage was estimated at 20,000 km, using 15,000 km leads to 14.1 g CO_2-eq/pkt, logically similar to the study of Christoforou et al. (2020) because they used the same Ecoinvent database.

C.2.2. Private electric bicycle

The literature review from Spreafico and Russo (2020) states private electric bicycles leads to an increase of 400 % of CO_2-eq/pkt compared to traditional private bicycles. Applying this to the default value for private traditional bike would result in a GWP of 42 g CO_2-eq/pkt for a private e-bike.

Huang, Jiang, Chen, Dave, and Parry (2022) compared e-bikes with a petrol car and a electric vehicle for commuting. Taking a vehicle lifetime of 15,000 for the e-bike, they found that a electric bicycle emits 497,100 g CO_2-eq during its lifetime. Dividing this over the vehicle lifetime mileage results in 33.14 g CO_2-eq/pkt.

ITF (2020) assumed a vehicle lifetime of 13440 km and average occupancy of 1.0. A private e-bike has a GWP of 34 g CO_2-eq/pkt. Made up of 13 g for the vehicle component, 12 g for the fuel component and, the same as for the traditional bicycle, 9 g CO_2-eq/pkt for the infrastructure component. 13 g CO_2-eq/pkt for the vehicle component is equal to 171.6 kg CO_2-eq emissions for vehicle production (no maintenance and only 1 battery over its lifetime is considered) using a lifetime of 13,200 km.

The research of Felipe-Falgas et al. (2022) estimated the life cycle emissions of a personal e-bike at about 24.5 g CO_2-eq/pkt using a vehicle lifespan of 15,000 km, of which 3.6 g CO_2-eq/pkt can be attributed to the use phase (fuel and infrastructure). This results in 20.9 g CO_2-eq/pkt emissions for the vehicle component, thus 313.5 kg CO_2-eq emissions for the production on an electric bicycle (including maintenance and 2.75 batteries).

The study of Weiss, Dekker, Moro, Scholz, and Patel (2015) calculated the fuel emissions for e-bikes on 15 g CO_2-eq/pkt. The vehicle component emissions were estimated at 25 g CO_2-eq/pkt. Together this results in a GWP of 40 g CO_2-eq/pkt.

Table C.5: GWP of a private electric bicycle

Characteristics	Value
Vehicle lifetime	15,000 km
Average occupancy	1.0 persons
Vehicle emissions	12.7 g CO_2-eq/pkt
Battery emissions	2.1 g CO_2-eq/pkt
Maintenance emissions	1.1 g CO_2-eq/pkt
Fuel emissions	3.2 g CO_2-eq/pkt
GWP private electric bicycle	19.1 g CO_2-eq/pkt

C.2.3. Shared electric bicycle

Vehicle and battery component emissions calculation are the same as for private electric bikes. However, using a lifespan of 9,000 km instead of 15,000 km and two batteries are required per bicycle.

There is a very wide range in lifespan used in the literature. ITF (2020) uses 5510 km, Christoforou et al. (2020) 4500 km, de Bortoli (2021) 12,250 km and Felipe-Falgas et al. (2022) uses 13,200 km. The first uses a shared correction factor of 0.4 to account for tampering and vandalism, which is also the reasoning of the second study to explain the low lifespan. de Bortoli (2021) does state that this lifespan must be underestimated due to theft and the bicycles second lives. The shared bicycle operator in Barcelona states that on yearly basis around 20 % of the bicycle must be replaced due to theft, vandalism and misuse. As a default value for the lifetime of shared e-bikes, the mean value of the four studies is used, which is around 9,000 km.

Furthermore, operational service is required for shared electric bicycles. The BSO emissions of shared e-mopeds are used, corrected for a lower occupancy.

Table C.6: GWP of a shared electric bicycle

Characteristics	Value
Vehicle lifetime	9,000 km
Average occupancy	1.0 persons
Vehicle emissions	21.2 g CO_2-eq/pkt
Battery emissions	17.3 g CO_2-eq/pkt
Maintenance emissions	1.9 g CO_2-eq/pkt
Fuel emissions	3.2 g CO_2-eq/pkt
BSO emissions	10.9 g CO_2-eq/pkt
GWP shared electric bicycle	44.4 g CO_2-eq/pkt

C.3. Moped

C.3.1. Private electric moped

The lifespan of an e-moped is assumed to be 50,000 km. A battery can be charged around 800 times during its lifetime. Multiplying this loading cycli with the average range results in a battery lifetime of 40,000 km. Over an e-moped lifetime, thus 1.25 batteries are required.

STREAM calculated the energy consumption of an electric moped at 0.16 MJ/km, resulting in 0.045 kWh/km. For shared e-mopeds, an energy consumption of 0.035 kWh/km was calculated here using battery capacity, electric potential and range data from shared e-moped operators. Since the type of e-moped and thus battery can influence the energy consumption of an electric moped, the value calculated by STREAM is used as default value for the fuel emissions for private e-mopeds. STREAM calculates an average value for all electric mopeds in the Netherlands, and not just for the particular types used by shared e-moped service providers. It is important to keep in mind that the fuel emissions per passenger kilometer travelled are still higher for private e-mopeds than for shared ones due to the lower occupancy rate.

The GWP of private e-mopeds calculated here is very similar to the one calculated by ITF (2020), where they used an occupancy of 1 and lifetime of 49,000 km, resulting in a GWP of 30 g CO_2-eq/pkt (excluding the infrastructure and maintenance emissions).

Table C.7: GWP of a private electric moped

Characteristics	Value
Vehicle lifetime	50,000 km
Average occupancy	1.1 persons
Vehicle emissions 12.9 g CO_2-eq/pkt	
Battery emissions 3.3 g CO_2-eq/pkt	
Maintenance emissions 3.0 g CO_2-eq/pkt	
Fuel emissions	14.6 g CO_2-eq/pkt
GWP private electric moped	33.0 g CO_2-eq/pkt

C.3.2. Private petrol moped

Petrol moped production costs 1104 kg CO_2-eq, which results in 22.1 g CO_2-eq/pkt for a vehicle lifespan of 50,000 km in the Paris case (Christoforou et al., 2020). Correcting for a occupancy of 1.1 results in 20.1 g CO_2-eq/pkt for the vehicle component.

According to de Bortoli (2021) the personal moped (petrol) in Paris has a GWP of 135 g CO_2-eq/pkt, where 80 % of the climate change impact comes from fuel component, 4 % from the infrastructure component and the last 16 % from vehicle maintenance and manufacturing. Thus 108 g CO_2-eq/pkt are fuel emissions and 21.6 g CO_2-eq are vehicle production and maintenance emissions. For a vehicle occupancy of 1.1 this is 19.6 g CO_2-eq/pkt for the vehicle component. In the research of ITF (2020), the vehicle component only has a GWP of 8 g CO_2-eq/pkt.

The difference in GWP for the vehicle component can be explained by the used moped weight. ITF (2020) assumed a vehicle weight of 94 kg, while Christoforou et al. (2020) used 180 kg and de Bortoli (2021) assumed an average of 127 kg.

The Ecoinvent database process "motor scooter 50 cc production" and "motor scooter 50 cc maintenance", for a petrol moped of 90 kg, results in 665 kg CO_2-eq emissions. The most popular 50 cc scooter in the Netherlands is the Paggio Zip, weighing 86 kg. Another popular model is the vespa primavera 50 cc, which weights 109 kg for both the 25 and 45 km/h version. An average weight of 97.5 kg is thus used for calculations. 430 kg CO_2-eq emissions per scooter production results in 7.8 g CO_2-eq/pkt. Maintenance emissions are 235 kg CO_2-eq. Considering the mopeds lifespan and occupancy leads to 4.3 g CO_2-eq/pkt. Scaling these values up to the average petrol moped weight results in 8.5 and 4.6 CO_2-eq emissions for production and maintenance of a petrol moped.

Combined with the fuel emissions of 71.3 g CO_2-eq/pkt leads to 84.4 g CO_2-eq/pkt.

Table C.8: GWP of a private petrol moped

Characteristics	Value
Vehicle lifetime	50,000 km
Average occupancy	1.1 persons
Vehicle emissions	8.5 g CO_2-eq/pkt
Maintenance emissions	4.6 g CO_2-eq/pkt
Fuel emissions	71.3 g CO_2-eq/pkt
GWP private petrol moped	84.4 g CO_2-eq/pkt

C.4. Urban passenger rail transport

Some studies combine the metro and urban train into one transport service when calculating the GWP ITF (2020), while other create one average urban train out of a metro, regional train and regional-mid distance train (Felipe-Falgas et al., 2022). Others address the three urban rail modes separately, although using the same Ecoinvent process for metro and train only scaling to the weight while also using the same vehicles lifespan (Christoforou et al., 2020).

These combinations make it hard to make an accurate statement about the GWP of each urban rail type individually, also because in the Ecoinvent database (used by the studies of Christoforou et al. (2020) and Felipe-Falgas et al. (2022)), no metro production and maintenance process is present.

The vehicle and maintenance emissions for tram and regional train from the Ecoinvent database and the combination of metro and urban train of ITF (2020) are shown in table C.10. Table C.9 shows the vehicles lifespan used in the three different studies, in combination with the lifespan stated in the Ecoinvent database.

When scaling down or up to the actual weight of a vehicle, you indirectly also already account for the capacity. It is logic that a heavier metro is also longer and thus has more seat and standing capacity than a lighter one. Following the same approach as Christoforou et al. (2020), the Ecoinvent process of regional train production and maintenance is used to address the GWP of a metro, scaling down to the actual metro weight. Furthermore, the same lifespans as stated in the Ecoinvent database are used, 1,120,000 km for a tram and 6,000,000 km for a metro and train. These however have a significant impact on the GWP per kilometer travelled, here a default value is given but in the model these factors will be parameters which can be changed.

The lifespan of urban passenger rail transport differs significantly between the reviewed studies. This however does not impose big issues since the studies and this study show that the majority of the GWP comes from fuel emissions (> 90 %). Therefore, no extensive research in done to gain a more accurate estimation of the lifespan of tram, metro and train in the Netherlands.

C.4.1. Tram

In Rotterdam, a tram weights 37.7 ton and has a capacity of approximately 180 passengers and is on average occupied by 19 persons (RET, 2023b) (ACM, 2021). In Amsterdam the average tram - from

Table C.9: Urban rail transport services lifespan used in reviewed studies

	Tram (streetcar)	Metro	Train (regional)
Christoforou et al. (2020)	1,120,000 km	6,000,000 km	6,000,000 km
Felipe-Falgas et al. (2022)	3,945,826 km	3,945,826 km	3,945,826 km
ITF (2020)	-	2,640,000 km	2,640,000 km
Ecoinvent database	1,120,000 km	-	6,000,000 km
This study	**1,120,000 km**	**4,000,000 km**	**6,000,000 km**

Table C.10: Vehicle and maintenance emissions from the different data sources

	Ecoinvent regional train	Ecoinvent tram	ITF metro/urban train
Weight	171,000 kg	21,000 kg	186,000 kg
Lifespan	6,000,000 km	1,120,000 km	2,640,000 km
Lifetime	40 years	30 years	40 years
VP emissions per vehicle	559,000 kg CO_2-eq	73,200 kg CO_2-eq	1,002,001 kg CO_2-eq
VP emissions per kg vehicle	3.27 kg CO_2-eq	3,49 kg CO_2-eq	5.39 kg CO_2-eq
MTN emissions per vehicle	72,800kg CO_2-eq	164,000 kg CO_2-eq	-
MTN emissions per kg vehicle	0,43 kg CO_2-eq	7,81 kg CO_2-eq	-

GVB - weights around 38 ton, has place for on average 145 passengers and is on average occupied with 25 passengers (GVB, 2023b) (ACM, 2021). In the Hague, the third city of the Netherlands, the Avenio tram has a weight of almost 51 ton but also a capacity of 238 passengers and is occupied with on average 24 persons (ACM, 2021). Combining these three average trams, shows that per passenger capacity, a train weights around 230 kg. Here, a tram is assumed to weight 38 ton, which thus leads to a capacity of around 168 passengers. The Ecoinvent process ”production tram ReR”, is scaled to this weight which results in 132 ton CO_2-eq emissions. For the maintenance the same approach is followed, which leads to 300 ton CO_2-eq emissions. Adding these to up results in 429,000 kg CO_2-eq emissions for the vehicle component. Using a vehicle lifetime of 1,120,000 and average occupancy of 23 passengers, results in 16.4 g CO_2-eq/pkt for the vehicle component.

The tram (also referred to as streetcar) in Paris has a GWP of 20.2 g CO_2-eq/pkt (Christoforou et al., 2020). 3.71 g CO_2-eq can be attributed to the electricity generation. 10.8 g CO_2-eq is related to the infrastructure emissions. The vehicle component emits 715,290 kg CO_2-eq per tram, using a vehicle lifespan of 1,120,000 and occupancy of 113 passengers this results in 5.65 g CO_2-eq/pkt for the vehicle component (Christoforou et al., 2020). The difference between the study mentioned above and the calculations here can be explained by a higher occupancy in Paris, but also a higher tram weight of 52 ton instead of 38 ton used here.

Table C.11: GWP of a tram / streetcar

Characteristics	Value
Vehicle lifetime	1,120,000 km
Average occupancy	35.8 % (stream) - 23.5 passengers (own sources/calculation)
Vehicle emissions	5.2 g CO_2-eq/pkt
Maintenance emissions	11.8 g CO_2-eq/pkt
Fuel emissions	66.9 g CO_2-eq/pkt
GWP tram / streetcar	82.4 g CO_2-eq/pkt

C.4.2. Metro

In 2019, the Rotterdam metro was on average occupied with 75 persons and the Amsterdam metro with 89 persons, resulting in an average Dutch occupancy of 82 passengers (ACM, 2021). For vehicle production and maintenance emissions, the total CO_2-eq emissions are divided by this value. A metro lifespan of 4,000,000 km is used for calculations, which is an average of the lifespan used in the reviewed studies.

As illustrated in table C.9, the metro lifespan lies between 2,640,000 and 6,000,000 in the literature.

Here, a value in the middle of 4,000,000 km is chosen as default value. As mentioned before, the chosen value does not have a big impact on the total GWP. The vehicle and maintenance emissions account for such a small percentage of the total GWP, which mainly consists of fuel emissions. If for example 6,000,000 km is used instead of 4,000,000 km, the GWP of the vehicle component (vehicle production, disposal and maintenance) decreases from 0.59 g CO_2-eq to 0.39 g CO_2-eq. The total metro GWP decreases thus from 43.2 to 43.0 g CO_2-eq/pkt, where the contribution of the vehicle component decreases from 1.4 % to 0.9 %.

Vehicle and maintenance emissions are obtained using the same Ecoinvent processes as for the regional train, but scaled down to the average Dutch metro weight. The average RET metro in Rotterdam weights 52 ton (RET, 2023a). This results in 170 ton CO_2-eq emissions for metro production and 22 ton CO_2-eq emissions for metro maintenance. Combining leads to around 192,000 kg CO_2-eq emissions for the vehicle component, which is 0.59 g CO_2-eq/pkt.

Calculation for fuel emissions is a bit more complex for the metro. According to STREAM, the metro has an average seat occupancy of 84.3 %. This seems relatively high, which is caused by the small number of seats compared to standing places in the metro. Line M5 of metro operator GVB in Amsterdam only has 18 % of the total capacity as seats. For the metro SG3 in Rotterdam this is 38 %. For an average Dutch city where a metro network is present, the fuel emissions of STREAM per passenger kilometer travelled can be used, which are 42.6 g CO_2-eq/pkt (CE Delft, 2023). However, for the case studies of Amsterdam and Rotterdam, the occupation is desired to be considered in the fuel emission calculation. To be as accurate as possible, data from the GVB and RET them self on total energy consumption, energy consumption per pkt and total passenger kilometers are used together with electricity emissions factor from STREAM. The complete calculation for both cases is given in section XX.

Table C.12: GWP metro

Characteristics	Value
Vehicle lifetime	4,000,000 km
Average occupancy	84.3 % (stream) - 82 passengers (own calculation)
Vehicle emissions	0.52 g CO_2-eq/pkt
Maintenance emissions	0.07 g CO_2-eq/pkt
Fuel emissions	42.6 g CO_2-eq/pkt
GWP metro	43.2 g CO_2-eq/pkt

Comparing the value with other studies
In Paris, the metro has a GWP of 7.55 g CO_2-eq/pkt. The vehicle emissions released by producing, maintaining and disposing are determined at 647,054 kg CO_2-eq (Christoforou et al., 2020). Using an average lifespan of 6,000,000 km and occupancy of 161 passengers, the vehicle component emissions per passenger kilometer travelled are only 0.67 g CO_2-eq. which is in the same order of magnitude as calculated here. Most of the emissions come from infrastructure (2.43 g CO_2-eq/pkt) and the fuel component (4.45 g CO_2-eq). The study of ITF (2020) sees the metro and urban train as one transport mode with a GWP of 66 g CO_2-eq/pkt. Only 2 g CO_2-eq/pkt can be attributed to the vehicle component, which is again in the same order of magnitude as the study here.

The main difference is between the calculation in this research and the two studies mentioned above are the fuel emissions. Here, the energy consumption of a metro is 0.12 kWh/pkt. In the study of ITF (2020), per metro kilometer this is 17.7 kWh, which is - assuming 190 passengers on average - 0.093 kWh/pkt. Since the study used a electricity emissions factor of 565 g CO_2-eq/kWh, the fuel emissions per passenger kilometer travelled roughly match. The fuel emissions in the study of Christoforou et al. (2020) are much smaller, 4.45 g CO_2-eq/pkt. This can be explained by the large share of green energy in France - Paris was used as a case study - which results in an electricity emissions factor of only 48 g CO_2-eq/pkt. The energy consumption of a Paris metro is 0.071 kWh/pkt, for an average occupancy of 161 passengers this results in an energy consumption of 14.9 kWh/km.

C.4.3. Train

In Barcelona, the average train (build out of three major rail transport services, metro as well as trains), has an assumed lifespan of 3,945,826 km (Felipe-Falgas et al., 2022). As mentioned before, ITF (2020) assumed a lifespan of 2,640,000 km for a combination of a metro and train. The Ecoinvent database however suggest this lifespan is much higher, namely 6,000,000 km. Since the first two studies made a combination of train and metro, and the metro is assumed to have a lower lifetime, a lifespan of 6,000,000 km for a (regional) train is assumed here.

Data from NS and not from regional carriers is used. It must be noted that still some diesel trains are in operation at regional carriers, there are however not considered here and thus the electric regional train from NS is taken as reference. NS currently has three sprinter train types in operation - Sprinter Flirt, Sprinter Lighttrain (SLT) and Sprinter New Generation (SNG) - weighting on average 135 ton for a 4 wagon train and having an average total capacity of 376 passengers (NS, 2023a) (NS, 2023c) (NS, 2023b). These are the default values used here to calculate the life cycle emissions of a train. The Ecoinvent database processess ”Maintenance, train, passenger, regional RoW” and ”Train production, passenger, regional RoW” are used. Emissions from these processes are shown in table C.10. Disposal is included in the train production process.

Table C.13: GWP stop train

Characteristics	Value
Vehicle lifetime	6,000,000 km
Average occupancy	23.8 % - 89 passengers
Vehicle emissions	0.8 g CO_2-eq/pkt
Maintenance emissions	0.1 g CO_2-eq/pkt
Fuel emissions	42.6 g CO_2-eq/pkt
GWP stop train	42.6 g CO_2-eq/pkt

Comparing the value with other studies

In Barcelona, the vehicle component only accounts for a very small percentage in the GWP for a train. Less than 5 % of the GWP, around 1.75 g CO_2-eq/pkt can be attributed to the train itself. The difference is logic, since a lifetime of almost 4,000,000 km was assumed instead of the 6,000,000 in this study. The rest of the emissions come from the use phase, which gives combined GWP for the two components of about 35 g CO_2-eq/pkt. This lower than the use phase emissions assumed here, but in Barcelona a train is on average occupied by 108.3 passengers instead of 89 passengers here. Furthermore, the electricity mix in Barcelona is lower than in the Netherlands, and only electric powered train are considered.

The RER in Paris, a regional train, is calculated to have a GWP of only 8.79 g CO_2-eq/pkt, where 7 g CO_2-eq/pkt can be attributed to the use phase thus energy consumption emissions. Compared to the Dutch case, there are much less emissions per passenger kilometer travelled, due to the higher average occupation of 441 passengers per vehicle and the France electricity emissions factor of 48 g CO_2-eq/kWh (Christoforou et al., 2020).

C.5. Bus

Vehicle lifetime mileage - bus

The average lifespan of a bus differs substantially between studies. The Ecoinvent database assumed a lifespan 12.5 years and kilometric performance of 1,000,000 km. The Paris bus operator states that the lifespan of a bus is 480,000 km (Christoforou et al., 2020). In Sweden, a lifespan of 12 years and a corresponding 780,000 km is assumed (Nordelöf et al., 2019). ITF (2020) assumes a lifetime of 396,000 km, calculated using a lifetime of 9 years and annual mileage of 44,000 km. The annual mileage is calculated by multiplying the average speed (in km/h) with 8 operation hours day, 6 days a week en 50 weeks in a year (two weeks of maintenance are considered). This is a plausible method to calculate the annual mileage, however, it underestimates the annual kilometers driven. It is plausible that a bus operates more than 8 hours a day. According to the CBS, a bus drives on average 74,800 km per year (CBS, 2022c). Assuming a lifespan of 12 years - used in most studies - result in a lifespan of

897,000 km, which is used as the default value.

Vehicle occupancy - bus
In Paris, a bus is on average occupied with 17 passengers. ITF (2020) assumed 17, which decreases to 15.3 passengers when correcting for deadheading. In Barcelona there are on average 13.6 passengers in a bus, while in Lund this is 16. In the Netherlands, this is a bit lower, only 7.19 passengers (CE Delft, 2023). An explanation for this is that it is the average for the entire Netherlands. Paris, Barcelona and Lund are big cities with a high population density, which logically results in a higher bus occupation. The average bus occupation is a parameter in the model, since it can thus differ substantially between cities and thus studies. It is furthermore important to keep in mind that shared e-mopeds tend to arise mostly in big cities, where there is a higher bus occupation rate. Still, since no other data is available and to be able to use the fuel emission value from stream in g CO_2-eq per passenger kilometer travelled, as a default value 7.19 passengers is used here, equal to the occupancy used in the stream study.

GWP calculation - bus
Vehicle component emissions for conventional and Hydrotreated Vegetable Oil (HVO) diesel bus are the same (Nordelöf et al., 2019). Consequently, the conventional and HVO-diesel only differ in terms of fuel emissions per pkt.

The Ecoinvent database - used for calculations in the studies of Felipe-Falgas et al. (2022) and Christoforou et al. (2020) - contains data for production of only one bus type, the traditional ICE bus. Since in this study it is desired to be able to account for future developments in bus division, the Ecoinvent database is useless for the busses vehicle component emissions.

End-of-life emissions differ significantly between studies. According to Gabriel et al. (2021), the total life cycle emissions for electric, CNG and diesel buses decrease with respectively 29 %, 37 % and 43 % when accounting for recycling. Emissions are reduced since no new material extraction is needed for new vehicles in the future. The end-of-life emissons from Nordelöf et al. (2019) are however taken as default value here, since for all transport modes disposal and no recycling is assumed. It is however important to keep in mind that the production emissions can decrease significantly when recycling emissions are considered.

Nordelöf et al. (2019) performed a detailed LCA on four bus types: diesel, electric, HEV and PHEV. In the study case specific data obtained from Volvo in combination with more general inventory data from Ecoinvent 3.3 is used. This can thus be considered as an accurate and reliable estimation of the GWP of different bus types. In the study, the GWP is splited to each LCA component. However, since no CNG bus is considered, it is only used as source for maintenance and end-of-life emissions. Bus production emissions are obtained from the study of Gabriel et al. (2021), where a diesel, CNG and electric bus are compared. Logically, these emissions are converted to the vehicle lifespan and occupancy stated above. Fuel emissions are - as for all transport modes - taken from STREAM.

(HVO-)Diesel bus
Diesel bus production emits 93,800 kg CO_2-eq (Gabriel et al., 2021). The bus maintenance and end-of-life emissions are respectively 1.3 and 1.0 g CO_2-eq/pkt for a conventional diesel bus (Nordelöf et al., 2019). Converting this to total kg CO_2-eq emissions over the buses lifetime, results in around 16,250 kg CO_2-eq for maintenance and 12,500 kg CO_2-eq for end-of-life.

Using a vehicle lifespan of 897,000 km and occupancy of 8.11 passengers, results in 14.6 g CO_2-eq/pkt for the vehicle component (production and end-of-life) and 2.2 g CO_2-eq/pkt for maintenance.

Fuel emissions are 1268 g CO_2-eq per bus kilometer on city roads (< 50 km/h), resulting in 156.3 g CO_2-eq per passenger kilometer travelled.

CO_2-eq emissions for HVO-diesel are much smaller than for conventional diesel, 144 g CO_2-eq per bus kilometer, resulting in 17.7 g CO_2-eq per passenger kilometer.

CNG bus
CNG bus production emits 121,000 kg CO_2-eq (Gabriel et al., 2021). The CNG bus maintenance and end-of-life emissions assumed to be the same as for a diesel bus, thus for maintenance a total of 16,250

kg CO_2-eq is released and for end-of-life a total 12,500 kg CO_2-eq.

Using a vehicle lifespan of 897,000 km and occupancy of 8.11 passengers, results in 18.3 g CO_2-eq/pkt for the vehicle component (production and end-of-life) and 2.2 g CO_2-eq/pkt for maintenance.

Fuel emissions are 1212 g CO_2-eq per bus kilometer on city roads (< 50 km/h), resulting in 149.4 g CO_2-eq per passenger kilometer travelled.

Electric bus
Electric bus production has the highest GWP of all bus types, namely 144,000 kg CO_2-eq (Gabriel et al., 2021). Furthermore, more maintenance is required according to Nordelöf et al. (2019), and end-of-life emissions are slightly higher than for a diesel bus. Maintenance emissions come down to 25000 kg CO_2-eq and end-of-life emissions to 13750 kg CO_2-eq.

Using a vehicle lifespan of 897,000 km and occupancy of 8.11 passengers, results in 21.7 g CO_2-eq/pkt for the vehicle component (production and end-of-life) and 3.4 g CO_2-eq/pkt for maintenance.

Fuel emissions are 536.5 g CO_2-eq per bus kilometer on city roads (< 50 km/h), resulting in 66.2 g CO_2-eq per passenger kilometer travelled. These are the values using the average Dutch electricity mix, when the bus is charged with 100 % green energy, the fuel emissions decrease to 6 g CO_2-eq/pkt. If charged with electricy generated using fossil fuels only, it increases to 87.9 g CO_2-eq/pkt.

Table C.14: GWP of different bus types and average busses

Characteristic	Value
Vehicle lifetime	897,000 km
Average occupancy	8.11 passengers
GWP electric bus	91.3 g CO_2-eq/pkt
vehicle emissions	21.7 g CO_2-eq/pkt
maintenance emissions	3.4 g CO_2-eq/pkt
fuel emissions	66.2 g CO_2-eq/pkt
GWP diesel bus	173.2 g CO_2-eq/pkt
vehicle emissions	14.6 g CO_2-eq/pkt
maintenance emissions	2.2 g CO_2-eq/pkt
fuel emissions	156.3 g CO_2-eq/pkt
GWP HVO-diesel bus	51.4 g CO_2-eq/pkt
vehicle emissions	14.6 g CO_2-eq/pkt
maintenance emissions	2.2 g CO_2-eq/pkt
fuel emissions	34.6 g CO_2-eq/pkt
GWP CNG bus	170.0 g CO_2-eq/pkt
vehicle emissions	18.3 g CO_2-eq/pkt
maintenance emissions	2.2 g CO_2-eq/pkt
fuel emissions	149.4 g CO_2-eq/pkt
GWP average bus	158.8 g CO_2-eq/pkt
vehicle emissions	16.5 g CO_2-eq/pkt
maintenance emissions	2.4 g CO_2-eq/pkt
fuel emissions	139.8 g CO_2-eq/pkt

ITF study comparison
According to ITF (2020), the GWP of a bus with a ICE is 91 g CO_2-eq/pkt. For a hybrid bus this is 70 g CO_2-eq/pkt and for an electric version its 68 g CO_2-eq/pkt. For all types, the majority of the emissions come from the fuel component. These values differ with the values used here, but that can be explained by the lower lifespan - 396,000 km vs 897,000 km here -, higher occupancy - 15.3 vs 8.11 - and for the fuel emissions of the electric bus a different electricity mix.

Table C.15 shows the CO_2-eq emissions related to each LCA component for the different bus types.

Table C.15: GWP of different bus types related to LCA components (ITF, 2020)

	Bus - ICE	Bus - HEV	Bus - BEV
Vehicle component	8	8	14
Fuel component	72	53	46
Infrastructure component	4	4	4
Operational services	8	6	5
Total	91	70	68

C.6. Car and taxi

The previous often used studies of Christoforou et al. (2020) and Felipe-Falgas et al. (2022) are not applicable to determine the GWP of the passenger car types individually, since they only calculated the GWP for an average passenger car. As a consequence, three studies are evaluated and compared to the general Ecoinvent database to obtain default values for vehicle production, disposal and maintenance emissions (ITF, 2020) (Puig-Samper Naranjo et al., 2021) (de Souza et al., 2018). These studies are selected based on among others the published year (electric vehicle adoption has seen a big increase in recent years due to technology improvements) and the fact that they compared and assessed ICE, hybrid and electric cars for their environmental impact in GWP using LCA methodology.

No study is found that calculated the GWP of all five car types. The study of Puig-Samper Naranjo et al. (2021) is used as a benchmark here for vehicle production, vehicle disposal en battery disposal emissions. For their calculations they used the Ecoinvent database V3.5 combined with other literature, which makes it plausible that it is more accurate than solely using the Ecoinvent database. No plug-in hybrid car was considered in the study. This car type is created here by adjusting BEV and HEV data from the study. For most component, the PHEV lies between a full electric car and a 'normal' hybrid car which has a lower battery capacity than a plug-in hybrid car. The PHEV weight is considered the same as the HEV weight. For the maintenance emissions and CO_2-eq emissions per produced kg vehicle the average of the BEV and HEV is used. Battery production emission values are retrieved from Dai et al. (2019), which is the source used in the Ecoinvent database. The study performed a cradle-to-gate LCA, excluding use and end-of-life emissions. End-of-life emissions are obtained from the same study used for vehicle component emissions.

'Normal' hybrid cars (HEV) are not considered by STREAM, thus no fuel emission data is available. Fuel emissions from all other transport modes come from the same source, which ensures a fair comparison. Using fuel emissions for a HEV from a different sources could thus lead to an unfair comparison, which is why a HEV is neglected here.

Study	Car type	Vehicle weight	VP + VD emissions	VP emissions	VD emissions	VP + VD emissions per kg vehicle	MTN emissions
ITF (2020)	ICE	1494 kg	5537 kg CO2			3.7 kg CO2	
ITF (2020)	HEV	1583 kg	5856 kg CO2			3.7 kg CO2	
ITF (2020)	PHEV	1662 kg	6149 kg CO2			3.7 kg CO2	
ITF (2020)	BEV	1393 kg	5383 kg CO2			3.89 kg CO2	
Ecoinvent database	ICE - diesel	1341 kg	9293 kg CO2			6.93 kg CO2	1075.7 kg CO2
Ecoinvent database	ICE - petrol	1234 kg	8453 kg CO2			6.85 kg CO2	1075.7 kg CO2
Ecoinvent database	BEV	1200 kg	8868 kg CO2			7.39 kg CO2	916.2 kg CO2
Puig-Samper Naranjo et al. (2021)	ICE - petrol	1280 kg	8333 kg CO2	7650 kg CO2	682 kg CO2	6.51 kg CO2	1095 kg CO2
Puig-Samper Naranjo et al. (2021)	ICE - diesel	1373 kg	8990 kg CO2	8312 kg CO2	678 kg CO2	6.55 kg CO2	1175 kg CO2
Puig-Samper Naranjo et al. (2021)	BEV	1296 kg	7558 kg CO2	6797 kg CO2	761 kg CO2	5.83 kg CO2	791 kg CO2
Puig-Samper Naranjo et al. (2021)	HEV	1339 kg	9325 kg CO2	8618 kg CO2	707 kg CO2	6.96 kg CO2	1124 kg CO2
de Souza et al. (2018)	ICE - petrol	1181 kg	11017 kg CO2	10167 kg CO2	850 kg CO2	9.3 kg CO2	
de Souza et al. (2018)	PHEV	1181 kg	11017 kg CO2	10167 kg CO2	850 kg CO2	9.3 kg CO2	
de Souza et al. (2018)	BEV	1181 kg	11017 kg CO2	10167 kg CO2	850 kg CO2	9.3 kg CO2	
This study	ICE - petrol	1280 kg	8333 kg CO2	7650 kg CO2	682 kg CO2		1095 kg CO2
This study	ICE - diesel	1373 kg	8990 kg CO2	8312 kg CO2	678 kg CO2		1175 kg CO2
This study	BEV	1296 kg	7558 kg CO2	6797 kg CO2	761 kg CO2		791 kg CO2
This study	HEV	1339 kg	9325 kg CO2	8618 kg CO2	707 kg CO2		1124 kg CO2
This study	PHEV	1339 kg	8556 kg CO2	7820 kg CO2	736 kg CO2		958 kg CO2

Figure C.4: Vehicle production, disposal en maintenance emissions compared between multiple studies and the Ecoinvent database

Vehicle lifetime mileage - car
Girardi, Brambilla, and Mela (2020) compared three Volkswagen Golf passenger car options - electric, diesel and petrol - using a LCA. A lifetime mileage of 230,000 km, 210,000 km and 240,000 km is assumed for respectively the electric, petrol and diesel version. Which on a first glance seems quite low, but is already higher than the lifetime of 150,000 used in most LCA studies (also stated in the Ecoinvent database). ITF assumed a lifespan of 181,500 km for all car types. Most studie consider a same lifespan for all car types, which is why this is also done here. A lifespan of 225,000 km for all car types is assumed here, which is approxiametly the average of the lifetime mileages used by Girardi et al. (2020), and corresponds to the lifespan used in STREAM for a small LCA calculation (CE Delft, 2023).

Furthermore, it is assumed that the batteries lifetime corresponds to the vehicles lifetime for all electric vehicles. Drivers would continue to use the electric car even though the battery has exceeded its commercial end-of-life (Saxena, Le Floch, Macdonald, & Moura, 2015). The degree of battery degradation is not considered significant, thus it is assumed that a secondary battery may not be required.

Vehicle occupancy - car
On average 1.31 passengers are present in a passenger car (CE Delft, 2023). This is quite similar to the value of 1.45 used by ITF (2020). In Paris, the average occupancy is 1.3 passengers, while in Barcelona this is 2.24 passenger per vehicle, which is relatively. Here, the value from STREAM is taken as a reference. STREAM also consists on data of occupancy rates per trip purpose. It would be accurate to use data on shared e-moped trip purpose and combine this with car occupancy rates per trip purpose. This is however out of scope and thus neglected here.

GWP calculation - car
Figure C.4 shows a small literature review on vehicle production, disposal and maintenance emissions from four different sources. Vehicle production emissions per kg vehicle show quite a large range, varying from 3.7 kg CO_2-eq to 9.3 kg CO_2-eq per kg car weight. The value of Puig-Samper Naranjo et al. (2021) lies in the middle of this range, and it also distinguishes emissions for the different vehicle types and thus vehicle weight. This is an important benefit of this study which is the reason why this study is chosen as basis for vehicle weight and vehicle production, disposal and maintenance emissions.

Battery production emissions
Battery production emissions are obtained from Dai et al. (2019), which is the source used in the Ecoinvent database and the same sources as used for e-moped and e-bike batteries. Resulting in 72.9 kg CO_2-eq/kWh as default value for producing one kWh of a Li-ion NCM111 battery [2] (Dai et al., 2019). Battery disposal emissions again are taken from Puig-Samper Naranjo et al. (2021), which are 1.35 kg CO_2-eq per kg battery. Considering the fact that 1 kWh battery weights around 7 kg, result in 9.45 kg CO_2-eq/kWh battery (Puig-Samper Naranjo et al., 2021) (Dai et al., 2019).

Volkswagen e-Golf contains a battery of 318 kg, leading to a battery capacity of around 45 kWh considering a battery weight of 7 kg per kWh (Dai et al., 2019) (Girardi et al., 2020). A battery capacity of 42.2 for BEV are used by Puig-Samper Naranjo et al. (2021). The average battery capacity of all full electric vehicles is 66.8 kWh (Electric Vehicle Database, 2023). This is an average value for all available BEV, thus more accurate than using the battery capacity of a single vehicle model. Therefore, for BEV a battery capacity of 66.8 kWh is assumed. For PHEV, the mean battery size is 14.9 kWh, which is thus used as a default value (evstatistics, 2022). Logically, more battery capacity results in a larger range. Thus it is plausible that in the future battery capacities increase to ensure a larger driven range.

Car fuel emissions per passenger kilometer travelled are obtained from stream (CE Delft, 2023). For PHEV, 50 % PHEV-diesel and 50 % PHEV-petrol is assumed, although there is only a small difference in emissions (191 vs 203 g CO_2-eq/pkt).

[2] NCM111 is one of the three Li-ion battery types used in electric vehicles. The others are NCA (nickel-cobalt-aluminum) and LFP (lithium-iron-phosphate)

Table C.16: Vehicle component emissions for different passenger cars in kg CO_2-eq. VP = vehicle production. VD = vehicle disposal. BP = battery production. BD = battery disposal. MTN. = maintenance

Car type	VP	VD	BP	BD	MTN	Total	GWP Vehicle component
Petrol	7650	682	-	-	1095	9427	32.0 g CO_2-eq/pkt
Diesel	8312	678	-	-	1175	10166	34.5 g CO_2-eq/pkt
PHEV	7708	734	1086	141	958	10627	36.0 g CO_2-eq/pkt
BEV	6796	761	4870	631	791	11642	47.0 g CO_2-eq/pkt

Table C.17: GWP car

Characteristics	Petrol	Diesel	PHEV	BEV	Average car
Vehicle lifetime	240,000 km	240,000 km	240,000 km	240,000 km	240,000 km
Average occupancy	1.31	1.31	1.31	1.31	1.31
Vehicle emissions	28.3	30.5	28.6	25.6	28.6
Battery emissions			4.2	18.7	0.5
Maintenance emissions	3.7	4.0	3.2	2.7	3.7
Fuel emissions	199.3	209.8	150.4	71.0	198.2
GWP car	**231.3**	**244.3**	**186.4**	**118.0**	**231.2**

C.6.1. Taxi

Vehicle lifetime - taxi

Only two studies considered the taxi as a transport mode which can be replaced by a shared e-moped. The assumed lifetime kilometer performance of the two studies are far apart. One used 200,000 km and the other 400,000 km (ITF, 2020) (Christoforou et al., 2020). Christoforou et al. (2020) assumed the same lifetime for taxi as for private cars (200,000 km). On the contrary, ITF (2020) assumed a lifetime for taxi more than twice as big as for private cars, 400,000 km against 181,500 km. Another research who performed a LCA on three car mobility services: taxi, carpooling and privately owned car assumed a vehicle lifespan on 283,624 km against 160,109 for its private counterpart (Fernando, Soo, & Doolan, 2020). According to CBS (CBS, 2021a), the annual mileage of a taxi is on average 39,401 km, lasting around 7 years results in a lifespan of 300,000 km, which is used as the default value (ITF, 2020).

Vehicle occupancy - taxi

The average taxi occupancy is less than 1 person because the taxi driver is not taking into account and 'empty' trips take place. In Berlin, the average taxi occupancy is 0.54 (Bischoff, Maciejewski, & Sohr, 2015). In Paris, the average taxi occupancy is 0.85 passengers (Christoforou et al., 2020). ITF (2020) assumed an occupancy of 0.73, which decreased to 0.62 when deadheading is taken into account. For calculation of the GWP of taxis, deadheading is considered and thus an occupancy of 0.62 is taken as reference. According to STREAM, the average taxi occupancy is 2.4 passengers. This is much higher than the other sources, which can be explained by the fact that also big taxi vans with a higher capacity are considered. For taxi occupancy rate here 1.1 people is taken, which is the average value of the four studies mentioned above.

Taxi fleet division

The GWP of a car is corrected for the higher lifetime mileage and lower occupancy. Table C.18 displays the GWP for all different taxi car types. No data is available on the taxi fleet division to fuel type. The taxi fleet in Paris consist of 82 % diesel powered cars, 7 % gasoline cars and 11 % electric cars (Christoforou et al., 2020). The taxi fleet in Madrid consist of 93.2 % diesel cars, 3.9 % natural gas cars and 2.9 % hybrid cars (Vedrenne, Pérez, Lumbreras, & Encarnación Rodríguez, 2013). ITF (2020) created an average taxi out of 91 % ICEV, 3 % HEV, 3 % PHEV and 3 % BEV cars. In this study, considering the data above mentioned, it is assumed that 80 % is diesel, 10 % petrol and 10 % an average electric car. Table C.18 shows the resulting GWP default value for all taxi types and the average taxi.

Table C.18: GWP taxi

Car type	Value
Petrol	265.9 g CO_2-eq/pkt
Diesel	280.7 g CO_2-eq/pkt
PHEV	211.3 g CO_2-eq/pkt
BEV	126.6 g CO_2-eq/pkt
GWP average taxi	**268.0 g CO_2-eq/pkt**

Comparing the value with other studies
Fernando et al. (2020) performed a LCA on three car mobility services: taxi, carpooling and own car. In the European case, an average taxi occupancy of 0.54 is assumed, to the Berlin case Bischoff et al. (2015). The study further assumed a vehicle lifespan for the taxi of 283,624 km, higher than the assumption for private cars which is 160,109 km. The LCA results in a GWP of 288 g CO_2-eq/pkt for taxis, and 120 g CO_2-eq/pkt for private cars (Fernando et al., 2020).

The study of ITF (2020) differentiated the taxi's to the same types as they did for the car: ICE, HEV, PHEV and BEV. For taxis, a lifetime mileage of 400,000 km is assumed, which is more than twice as big as for private cars (ITF, 2020). The average occupancy in a taxi is however more than twice as small, only 0.73 passenger on average. If deadheading is included this value decrease even more to 0.62 passengers on average. For the calculation of the emissions per passenger kilometer travelled, the effect of deadheading is included. Table C.19 shows the GWP per LCA component for the different taxi types.

Table C.19: GWP (CO_2-eq/pkt) of taxis with different power sources (ITF, 2020)

	Taxi ICE	Taxi PHEV	Taxi BEV
Vehicle component	29	37	50
Fuel component	158	108	90
Infrastructure component	27	27	26
Operational services [3]	145	99	83
Total	358	271	249

The research of Christoforou et al. (2020) also did a LCA on taxi service and ride-hailing. The taxi fleet in Paris consist of 82 % diesel powered cars, 7 % gasoline cars and 11 % electric cars. The same vehicle lifespan of 200,000 km is used as for private cars, but because the occupancy is only 0,85 instead of 1.3 for private cars, the vehicle component emissions are higher than for the private car, 49.7 g CO_2-eq/pkt. Most of the taxis still run on diesel or gasoline, which is why the use stage still contributes for almost 82 % of the total GWP, 244 g CO_2-eq/pkt. The total GWP is equal to 299 g CO_2-eq/pkt, which makes taxis the most damaging to the environment in the Paris case (Christoforou et al., 2020).

In a study into the environmental impact of taxis in the city of Madrid, a LCA is used to evaluate the impact of different taxi types (diesel, natural gas and hybrid) for different traffic management zones. These zones differ in size, mean speed, annual mileage and whether it has an urban or highway driving pattern. Table C.20 shows the GWP of each taxi type to three different zones (all zones have an urban driving pattern). The taxi fleet in Madrid consist of 93.2 % diesel cars, 3.9 % natural gas cars and 2.9 % hybrid cars.

Table C.20: Taxi GWP (g CO_2-eq/vkt) in Madrid (Vedrenne et al., 2013)

Zone	Mean speed	Annual mileage	Area	Diesel	Natural Gas	Hybrid	Average
3	21.0 km/h	6317 km	13.4 m2	206	189	102	202.3
5	27.1 km/h	6221 km	33.7 m2	185	185	99	182.5
7	51.9 km/h	10602 km	157.5 m2	136	136	95	134.8

D
Case studies

This Appendix provides background information and data for the three case studies which are used for result illustration. All information is retrieved from publicly available sources, evaluation reports or policy documents.

Substantiation for case study choices
Amsterdam, Rotterdam and Groningen are chosen as case studies due to the publicly availability of shared e-moped usage data in combination with their city characteristics. Amsterdam and Rotterdam and the only two cities in the Netherlands with a metro network. Furthermore, Rotterdam is the first Dutch city which adopted shared e-mopeds in 2019 and it has a very large fleet size compared to other cities where the fleet size is often restricted due to municipal permits. The usage per e-moped is (by far) the highest in Amsterdam, partially caused by the small fleet size relative to the city size compared to for example Rotterdam (700 vs 2300 e-mopeds). Groningen is on its turn an interesting city due to the high student population - which are shown to have a high share in the shared e-mopeds users - and high electrified/sustainable bus fleet and thus BTM fleet since no tram or metro network is present.

D.1. Amsterdam

Table D.1: Amsterdam shared e-moped usage characteristics. Fleet size is given in number of e-mopeds, frequency of use in number of rentals per e-moped per day and average trip distance in km (Gemeente Amsterdam, 2022)

Shared e-moped usage	Value
Fleet size	700
Frequency of use	7.5
Average trip distance	4

Table D.2: Public transport shares in Amsterdam (ACM, 2021)

PT-mode	Passenger kilometers	Share
Bus	181.7	18 %
Tram	301.9	29 %
Metro	549.3	53 %

Table D.3: Public transportation occupation in Amsterdam (ACM, 2021)

PT occupation	Persons
Bus	12 %
Tram	25 %
Metro	89 %

Table D.4: Bus fleet distribution Amsterdam (GVB, 2023a)

Bus type	Number	Share
Diesel	189	81 %
HVO-diesel	0	0 %
CNG	0	0 %
BEV	44	19 %
Hydrogen	0	0 %
Diesel-hybrid	0	0 %

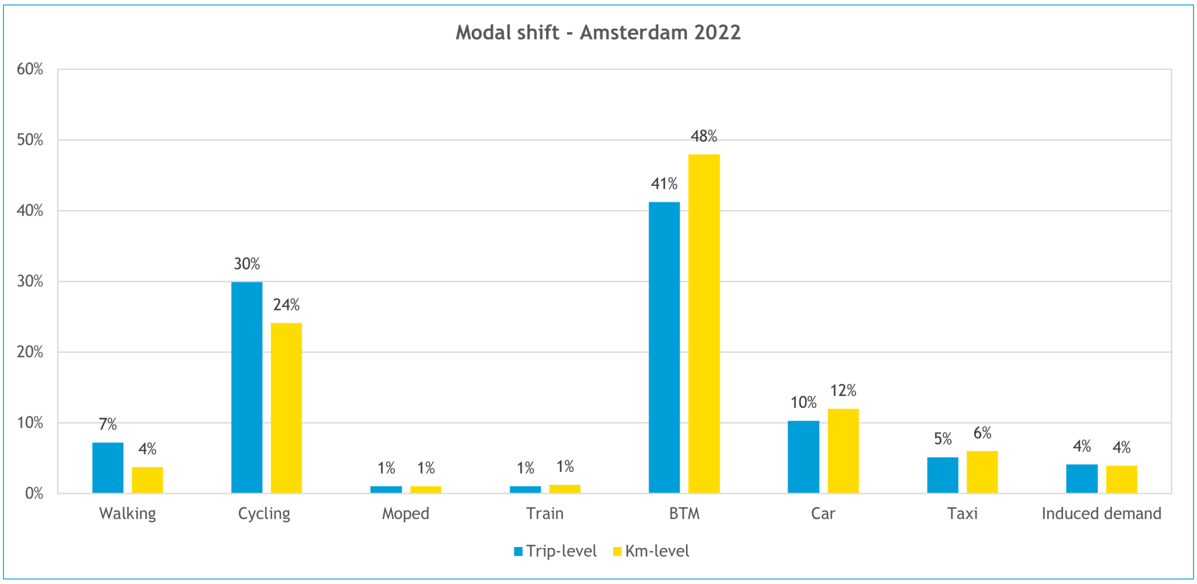


Figure D.1: Amsterdam modal shift trip-level to km-level (2022)

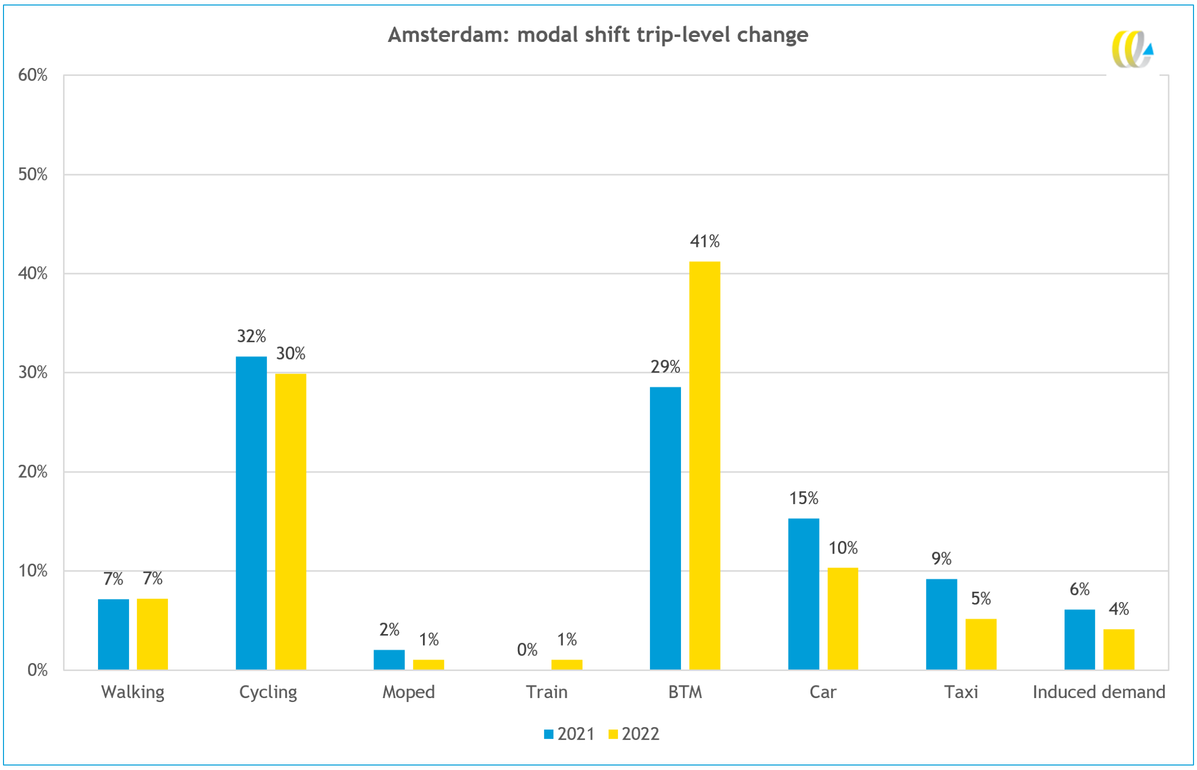


Figure D.2: Amsterdam modal shift change from 2021 to 2022 (Gemeente Amsterdam, 2022) (Gemeente Amsterdam, 2021)

D.2. Groningen

Table D.5: Groningen shared e-moped usage characteristics. Fleet size is given in number of e-mopeds, frequency of use in number of rentals per e-moped per day and average trip distance in km (Gemeente Groningen, 2022)

Shared e-moped usage	Value
Fleet size	400
Frequency of use	5.2
Average trip distance	3.46

Table D.6: Bus fleet distribution Groningen (Qbuzz, 2023)

Bus type	Number	Share
Diesel	189	81 %
HVO-diesel	0	0 %
CNG	0	0 %
BEV	44	19 %
Hydrogen	0	0 %
Diesel-hybrid	0	0 %

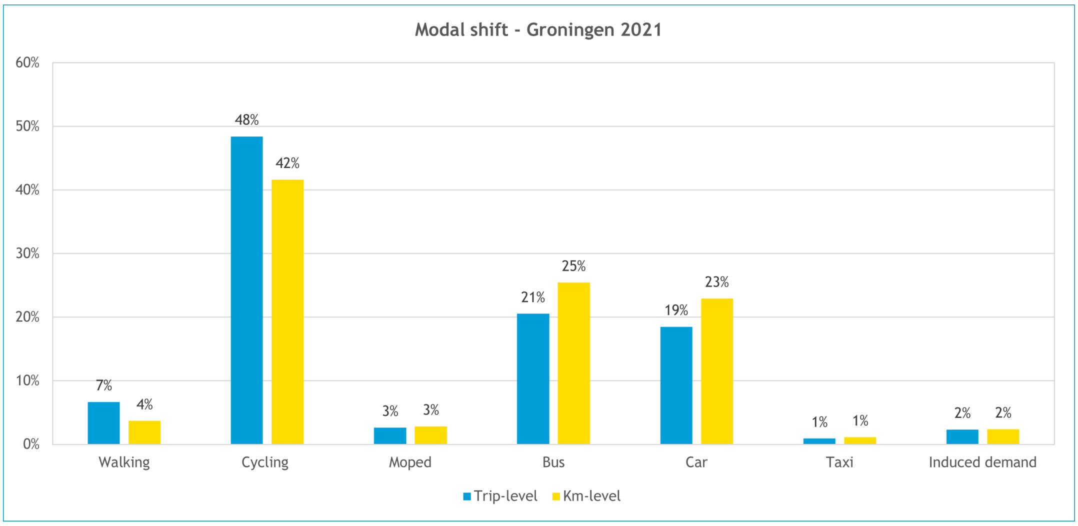


Figure D.3: Groningen modal shift trip-level to km-level (2022)

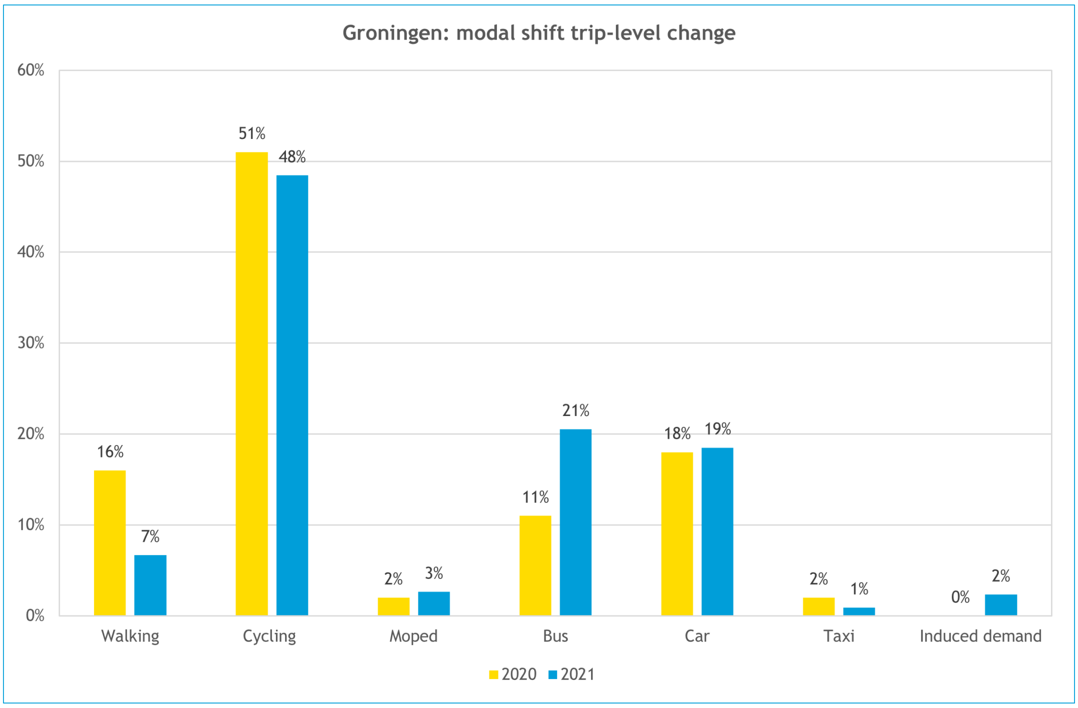


Figure D.4: Groningen modal shift change from 2020 to 2021 (Gemeente Groningen, 2022) (Gemeente Groningen, 2020)

D.3. Rotterdam

Table D.7: Rotterdam shared e-moped usage characteristics. Fleet size is given in number of e-mopeds, frequency of use in number of rentals per e-moped per day and average trip distance in km (Gemeente Rotterdam, 2021) (*Dashboard Deelmobiliteit | Een project van CROW*, n.d.)

Shared e-moped usage	Value
Fleet size	2344
Frequency of use	3.9
Average trip distance	3.1

Table D.8: Public transport shares in Rotterdam (ACM, 2021)

PT-mode	Passenger kilometers	Share
Bus	143	16 %
Tram	129	14 %
Metro	649	70 %

Table D.9: Public transportation occupation in Rotterdam (ACM, 2021)

PT occupation	Persons
Bus	10
Tram	19 %
Metro	75 %

Table D.10: Bus fleet distribution Rotterdam (RET, 2021)

Bus type	Number	Share
Diesel	189	81 %
HVO-diesel	0	0 %
CNG	0	0 %
BEV	44	19 %
Hydrogen	0	0 %
Diesel-hybrid	0	0 %

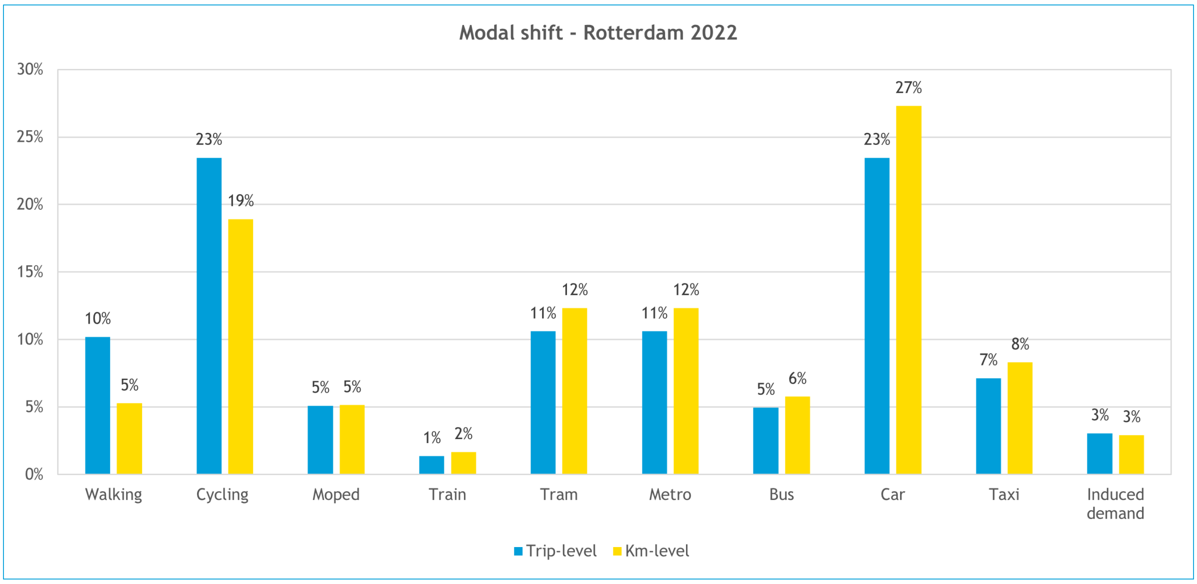


Figure D.5: Rotterdam modal shift trip-level to km-level (2022)

D.4. Non-specified location

The average fleet size for a Dutch city is derived by the total number of shared e-mopeds in the Netherlands and dividing this with all cities where shared e-mopeds operate (CROW, 2023) . Fleet size in Dutch cities - and thus also total number of shared e-mopeds in the Netherlands - can be found at a dashboard created by CROW (CROW, 2023). The average fleet size is calculated by dividing the total number of shared e-mopeds in the Netherlands by the number of cities where shared e-mopeds are available.

Table D.11: Average Dutch shared e-moped usage characteristics. Fleet size is given in number of e-mopeds, frequency of use in number of rentals per e-moped per day and average trip distance in km (*Dashboard Deelmobiliteit | Een project van CROW*, n.d.) (Appendix interviews B

Shared e-moped usage	Value
Fleet size	300
Frequency of use	6.0
Average trip distance	3.7

Table D.12: Public transport shares in the Netherlands (CE Delft, 2023)

PT-mode	Share
Bus	69 %
Tram	13 %
Metro	19 %

Table D.13: Public transportation occupation in the Netherlands (CE Delft, 2023)

PT occupation	Persons or occupation rate
Bus	8
Tram	35.8 %
Metro	84.3 %

Table D.14: Bus fleet distribution the Netherlands (CBS, 2021b)

Bus type	Share
Diesel	56 %
HVO-diesel	3 %
CNG	29 %
BEV	12 %
Hydrogen	0 %
Diesel-hybrid	0 %

E

Results extended

E.1. GWP results

Figure E.1: GWP transport modes to LCA components

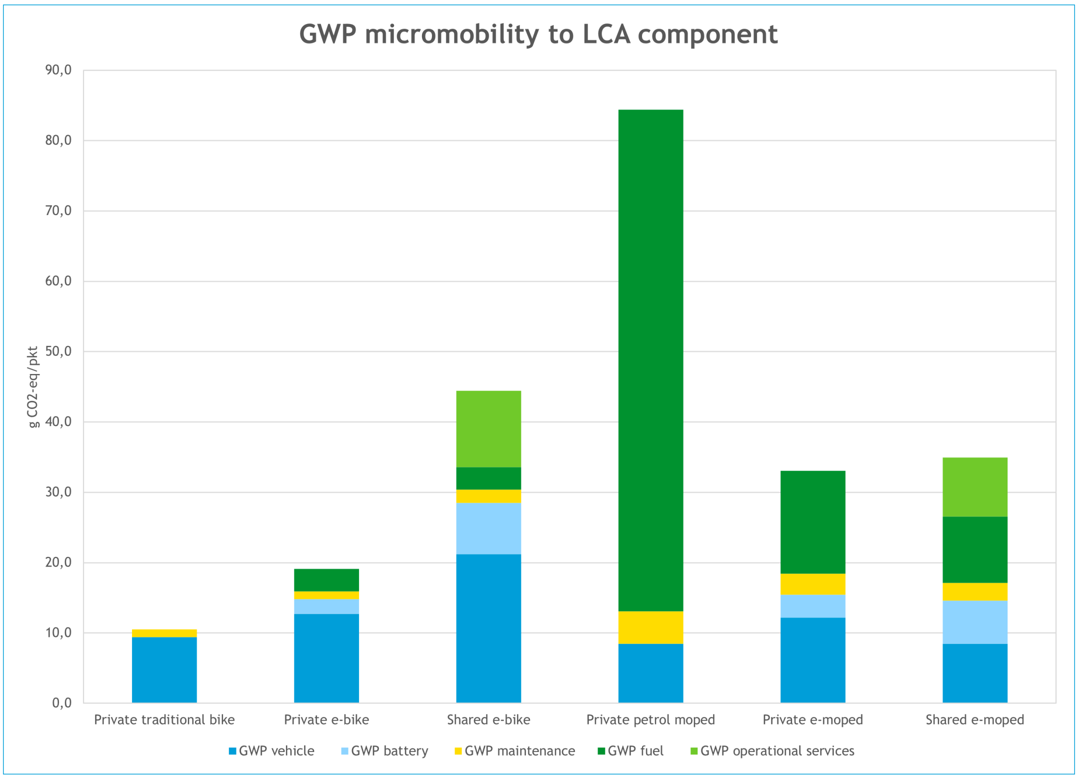


Figure E.2: GWP transport modes to LCA components

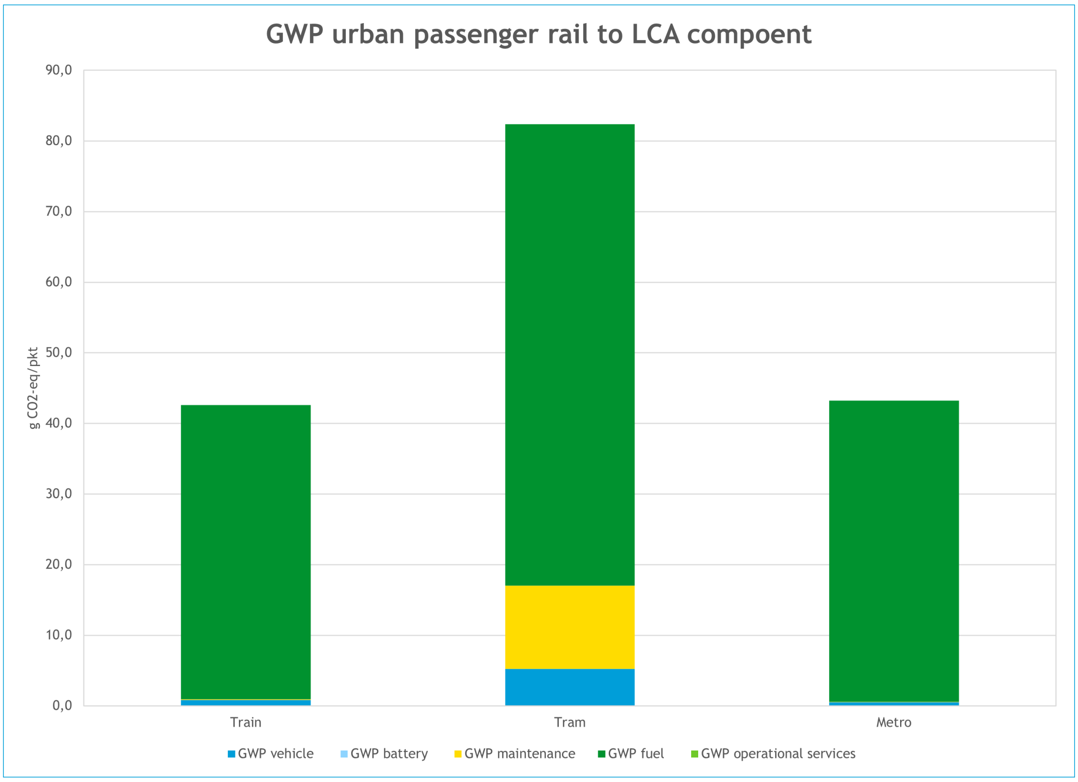


Figure E.3: GWP transport modes to LCA components

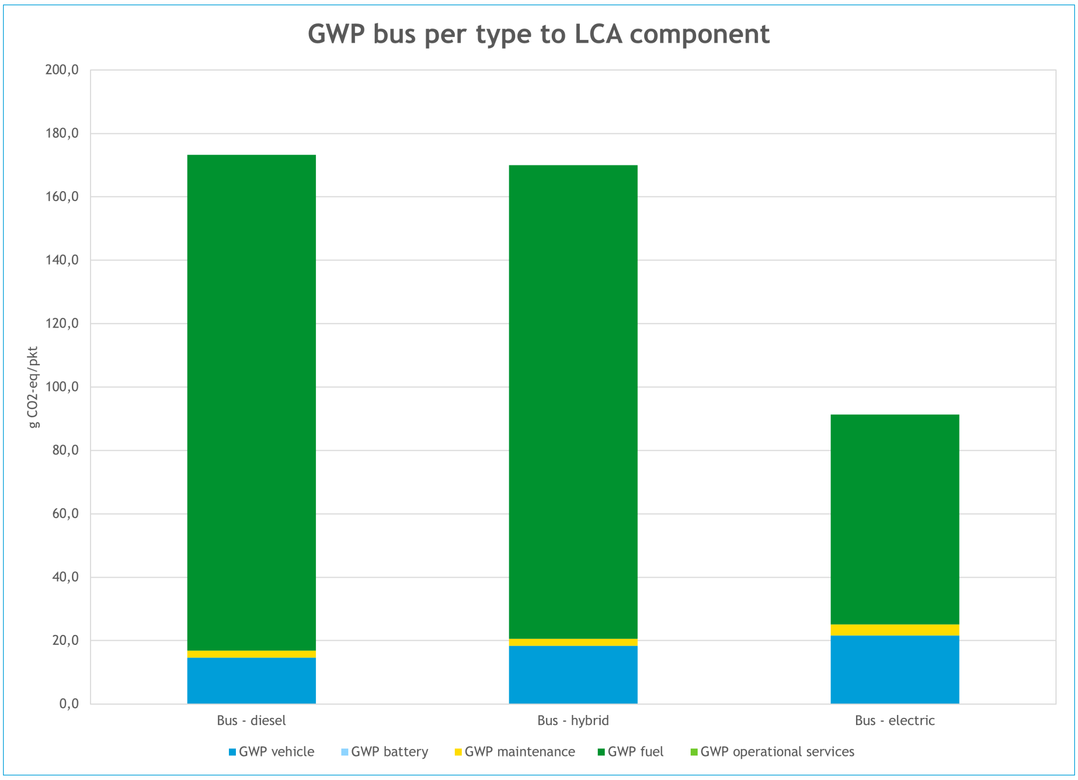


Figure E.4: GWP transport modes to LCA components

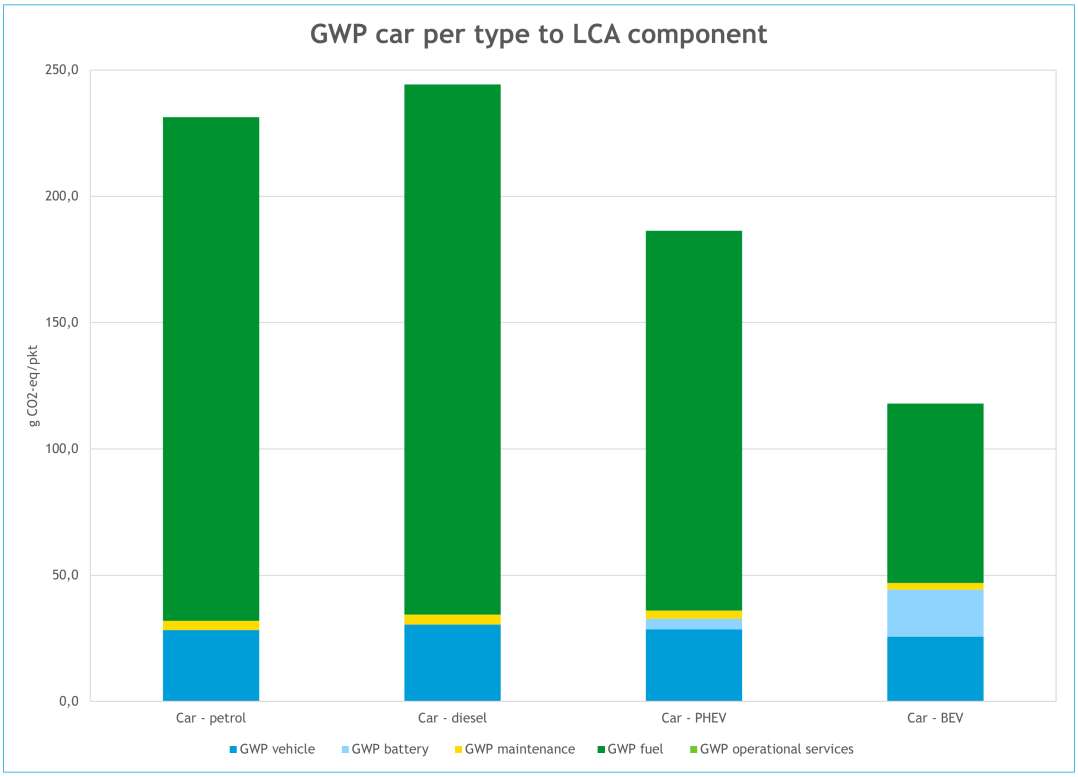


Figure E.5: GWP transport modes to LCA components

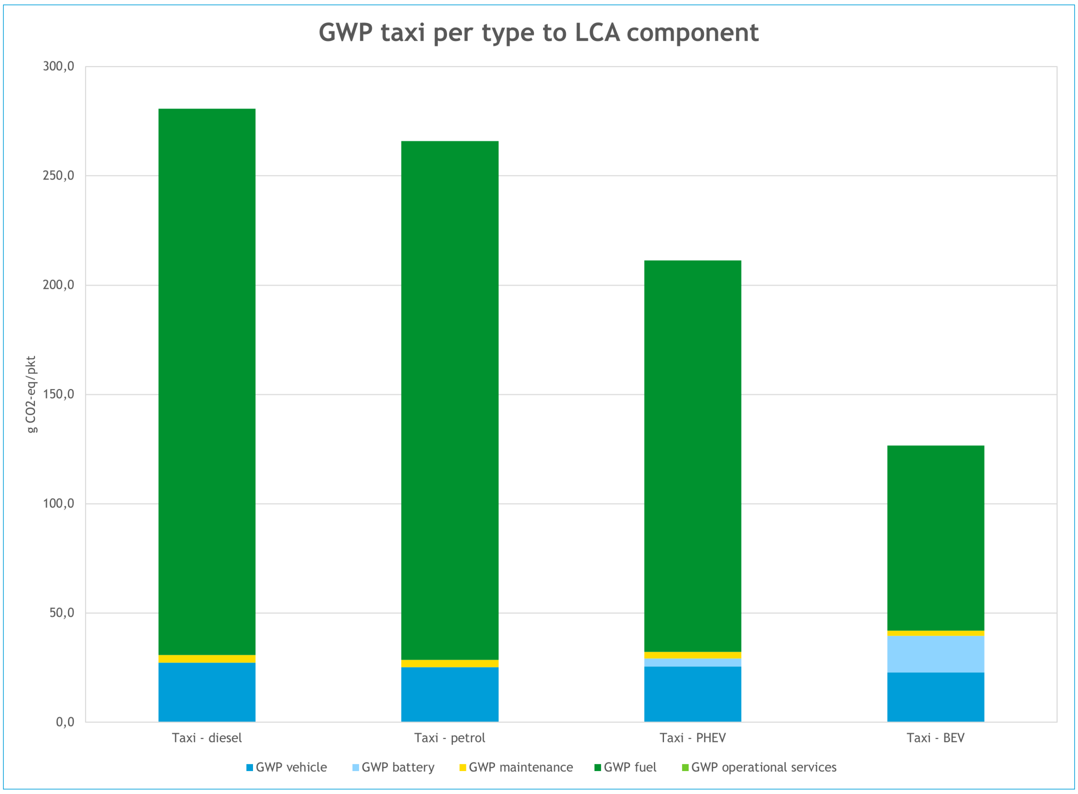


Figure E.6: Avoided CO2-eq emissions per day per city

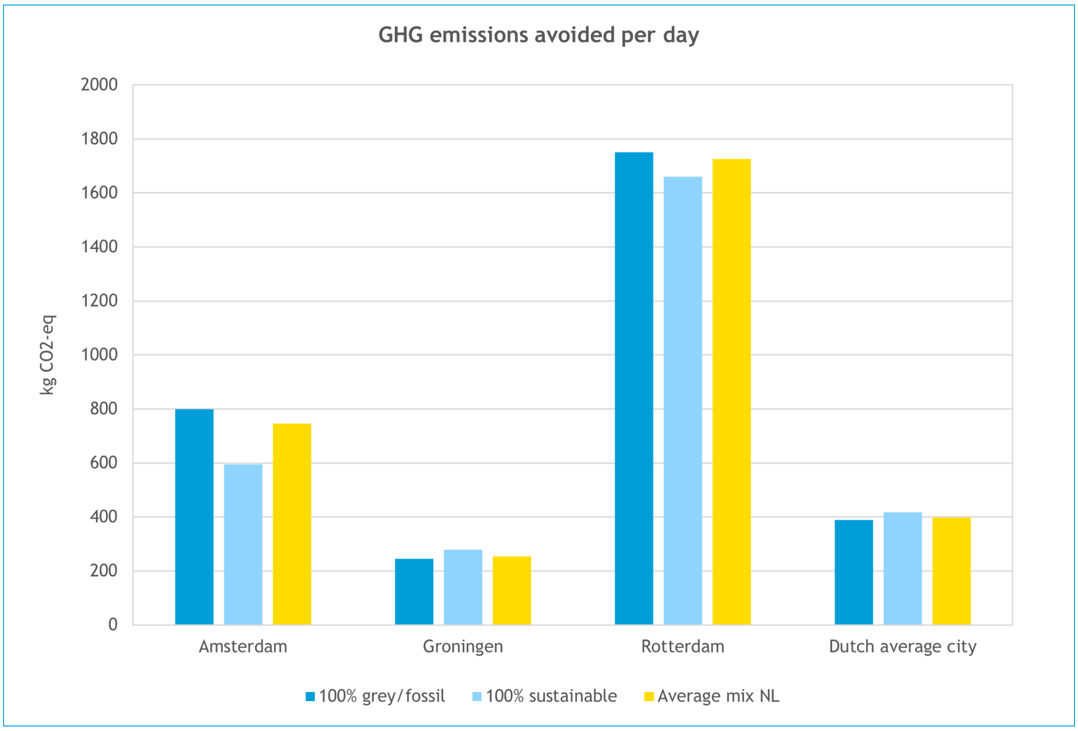


Figure E.7: Avoided CO2-eq emissions per month per city

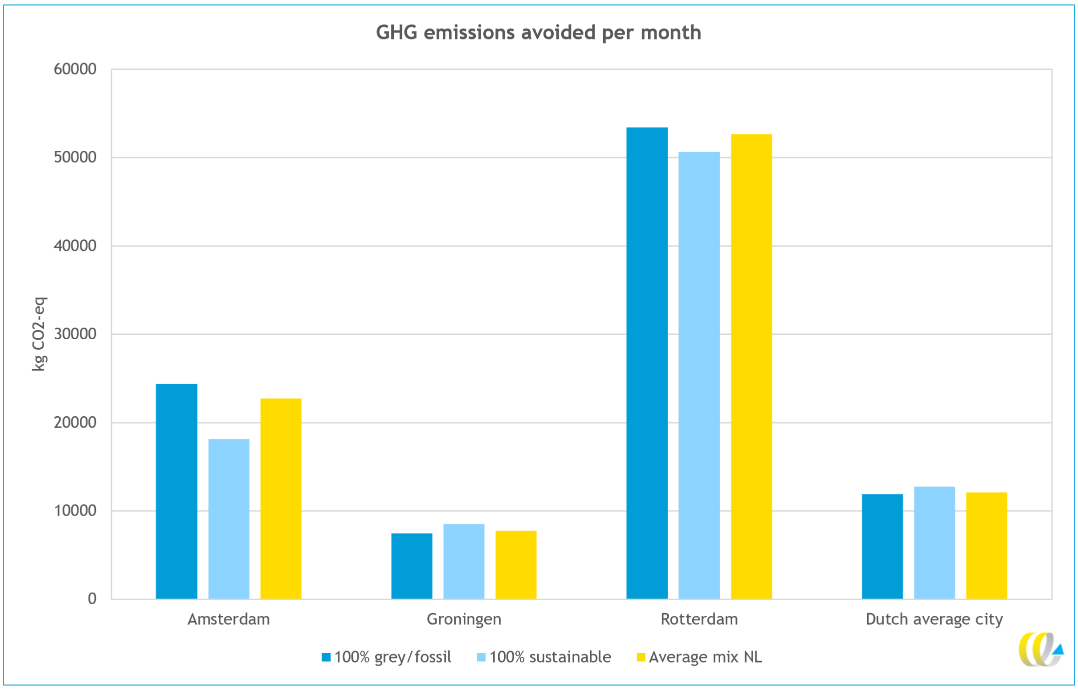
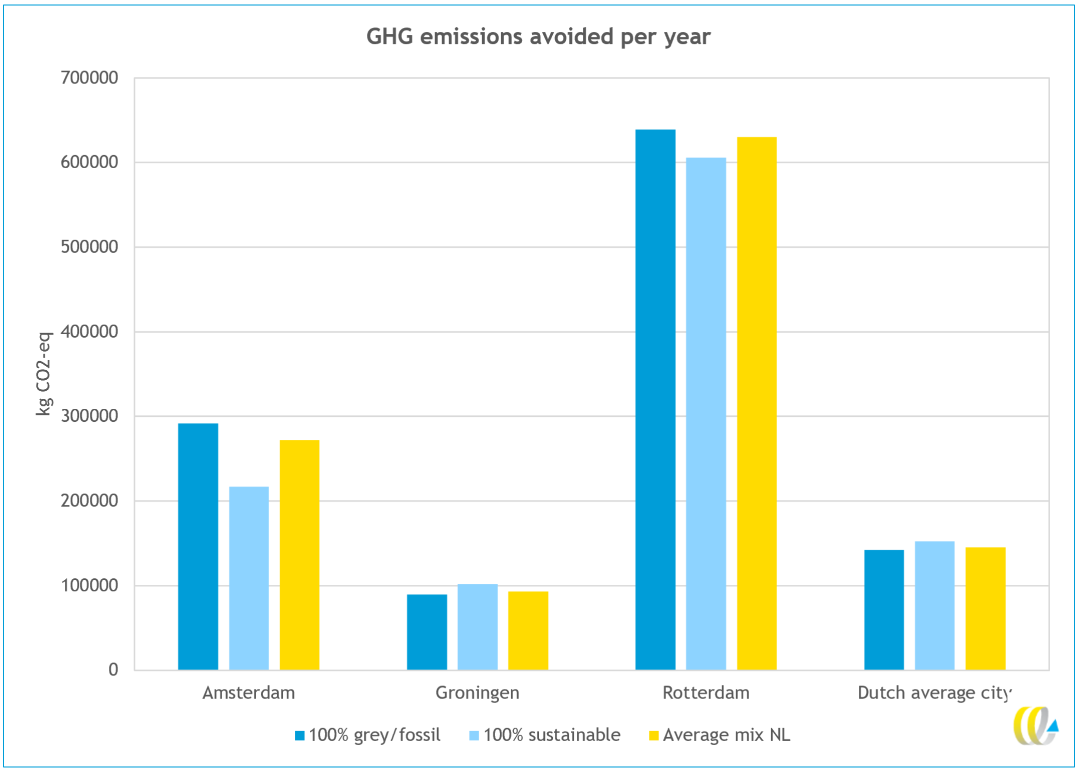


Figure E.8: Avoided CO2-eq emissions per year per city



City	KPI	Electricity mix	Value	Unit
Amsterdam	CO2-eq emissions reduction per day	Average mix NL	745,28	kg CO2-eq
Amsterdam	CO2-eq emissions reduction per month	Average mix NL	22731,13	kg CO2-eq
Amsterdam	CO2-eq emissions reduction per year	Average mix NL	272028,33	kg CO2-eq
Amsterdam	Environmental impact per shared e-moped pkt due to modal change	Average mix NL	-46,14	g CO2-eq/pkt
Amsterdam	Impact replaced transport modes per pkt	Average mix NL	81,07	g CO2-eq/pkt
Amsterdam	Impact shared e-moped per pkt	Average mix NL	34,93	g CO2-eq/pkt
Dutch average city	CO2-eq emissions reduction per day	Average mix NL	397,08	kg CO2-eq
Dutch average city	CO2-eq emissions reduction per month	Average mix NL	12111,01	kg CO2-eq
Dutch average city	CO2-eq emissions reduction per year	Average mix NL	144935,09	kg CO2-eq
Dutch average city	Environmental impact per shared e-moped pkt due to modal change	Average mix NL	-77,51	g CO2-eq/pkt
Dutch average city	Impact replaced transport modes per pkt	Average mix NL	112,44	g CO2-eq/pkt
Dutch average city	Impact shared e-moped per pkt	Average mix NL	34,93	g CO2-eq/pkt
Groningen	CO2-eq emissions reduction per day	Average mix NL	254,20	kg CO2-eq
Groningen	CO2-eq emissions reduction per month	Average mix NL	7753,08	kg CO2-eq
Groningen	CO2-eq emissions reduction per year	Average mix NL	92782,76	kg CO2-eq
Groningen	Environmental impact per shared e-moped pkt due to modal change	Average mix NL	-45,92	g CO2-eq/pkt
Groningen	Impact replaced transport modes per pkt	Average mix NL	80,85	g CO2-eq/pkt
Groningen	Impact shared e-moped per pkt	Average mix NL	34,93	g CO2-eq/pkt
Rotterdam	CO2-eq emissions reduction per day	Average mix NL	1726,78	kg CO2-eq
Rotterdam	CO2-eq emissions reduction per month	Average mix NL	52666,73	kg CO2-eq
Rotterdam	CO2-eq emissions reduction per year	Average mix NL	630273,94	kg CO2-eq
Rotterdam	Environmental impact per shared e-moped pkt due to modal change	Average mix NL	-79,21	g CO2-eq/pkt
Rotterdam	Impact replaced transport modes per pkt	Average mix NL	114,15	g CO2-eq/pkt
Rotterdam	Impact shared e-moped per pkt	Average mix NL	34,93	g CO2-eq/pkt

Figure E.9: Results in table format for the average Dutch electricity mix

City	KPI	Electricity mix	Value	Unit
Amsterdam	CO2-eq emissions reduction per day	100% gray / fossil	799,25	kg CO2-eq
Amsterdam	CO2-eq emissions reduction per month	100% gray / fossil	24377,11	kg CO2-eq
Amsterdam	CO2-eq emissions reduction per year	100% gray / fossil	291726,03	kg CO2-eq
Amsterdam	Environmental impact per shared e-moped pkt due to modal change	100% gray / fossil	-49,48	g CO2-eq/pkt
Amsterdam	Impact replaced transport modes per pkt	100% gray / fossil	88,72	g CO2-eq/pkt
Amsterdam	Impact shared e-moped per pkt	100% gray / fossil	39,24	g CO2-eq/pkt
Dutch average city	CO2-eq emissions reduction per day	100% gray / fossil	389,53	kg CO2-eq
Dutch average city	CO2-eq emissions reduction per month	100% gray / fossil	11880,82	kg CO2-eq
Dutch average city	CO2-eq emissions reduction per year	100% gray / fossil	142180,25	kg CO2-eq
Dutch average city	Environmental impact per shared e-moped pkt due to modal change	100% gray / fossil	-76,04	g CO2-eq/pkt
Dutch average city	Impact replaced transport modes per pkt	100% gray / fossil	115,27	g CO2-eq/pkt
Dutch average city	Impact shared e-moped per pkt	100% gray / fossil	39,24	g CO2-eq/pkt
Groningen	CO2-eq emissions reduction per day	100% gray / fossil	245,05	kg CO2-eq
Groningen	CO2-eq emissions reduction per month	100% gray / fossil	7474,09	kg CO2-eq
Groningen	CO2-eq emissions reduction per year	100% gray / fossil	89443,99	kg CO2-eq
Groningen	Environmental impact per shared e-moped pkt due to modal change	100% gray / fossil	-44,27	g CO2-eq/pkt
Groningen	Impact replaced transport modes per pkt	100% gray / fossil	83,50	g CO2-eq/pkt
Groningen	Impact shared e-moped per pkt	100% gray / fossil	39,24	g CO2-eq/pkt
Rotterdam	CO2-eq emissions reduction per day	100% gray / fossil	1750,41	kg CO2-eq
Rotterdam	CO2-eq emissions reduction per month	100% gray / fossil	53387,66	kg CO2-eq
Rotterdam	CO2-eq emissions reduction per year	100% gray / fossil	638901,47	kg CO2-eq
Rotterdam	Environmental impact per shared e-moped pkt due to modal change	100% gray / fossil	-80,30	g CO2-eq/pkt
Rotterdam	Impact replaced transport modes per pkt	100% gray / fossil	119,54	g CO2-eq/pkt
Rotterdam	Impact shared e-moped per pkt	100% gray / fossil	39,24	g CO2-eq/pkt

Figure E.10: Results in table format if electricity from 100 % fossil fuels

City	KPI	Electricity mix	Value	Unit
Amsterdam	CO2-eq emissions reduction per day	100% sustainable	594,82	kg CO2-eq
Amsterdam	CO2-eq emissions reduction per month	100% sustainable	18142,13	kg CO2-eq
Amsterdam	CO2-eq emissions reduction per year	100% sustainable	217110,69	kg CO2-eq
Amsterdam	Environmental impact per shared e-moped pkt due to modal change	100% sustainable	-36,82	g CO2-eq/pkt
Amsterdam	Impact replaced transport modes per pkt	100% sustainable	59,83	g CO2-eq/pkt
Amsterdam	Impact shared e-moped per pkt	100% sustainable	23,00	g CO2-eq/pkt
Dutch average city	CO2-eq emissions reduction per day	100% sustainable	417,92	kg CO2-eq
Dutch average city	CO2-eq emissions reduction per month	100% sustainable	12746,52	kg CO2-eq
Dutch average city	CO2-eq emissions reduction per year	100% sustainable	152540,32	kg CO2-eq
Dutch average city	Environmental impact per shared e-moped pkt due to modal change	100% sustainable	-81,58	g CO2-eq/pkt
Dutch average city	Impact replaced transport modes per pkt	100% sustainable	104,58	g CO2-eq/pkt
Dutch average city	Impact shared e-moped per pkt	100% sustainable	23,00	g CO2-eq/pkt
Groningen	CO2-eq emissions reduction per day	100% sustainable	279,47	kg CO2-eq
Groningen	CO2-eq emissions reduction per month	100% sustainable	8523,71	kg CO2-eq
Groningen	CO2-eq emissions reduction per year	100% sustainable	102005,10	kg CO2-eq
Groningen	Environmental impact per shared e-moped pkt due to modal change	100% sustainable	-50,48	g CO2-eq/pkt
Groningen	Impact replaced transport modes per pkt	100% sustainable	73,49	g CO2-eq/pkt
Groningen	Impact shared e-moped per pkt	100% sustainable	23,00	g CO2-eq/pkt
Rotterdam	CO2-eq emissions reduction per day	100% sustainable	1660,57	kg CO2-eq
Rotterdam	CO2-eq emissions reduction per month	100% sustainable	50647,33	kg CO2-eq
Rotterdam	CO2-eq emissions reduction per year	100% sustainable	606107,34	kg CO2-eq
Rotterdam	Environmental impact per shared e-moped pkt due to modal change	100% sustainable	-76,18	g CO2-eq/pkt
Rotterdam	Impact replaced transport modes per pkt	100% sustainable	99,18	g CO2-eq/pkt
Rotterdam	Impact shared e-moped per pkt	100% sustainable	23,00	g CO2-eq/pkt

Figure E.11: Results in table format if electricity from 100 % green sources

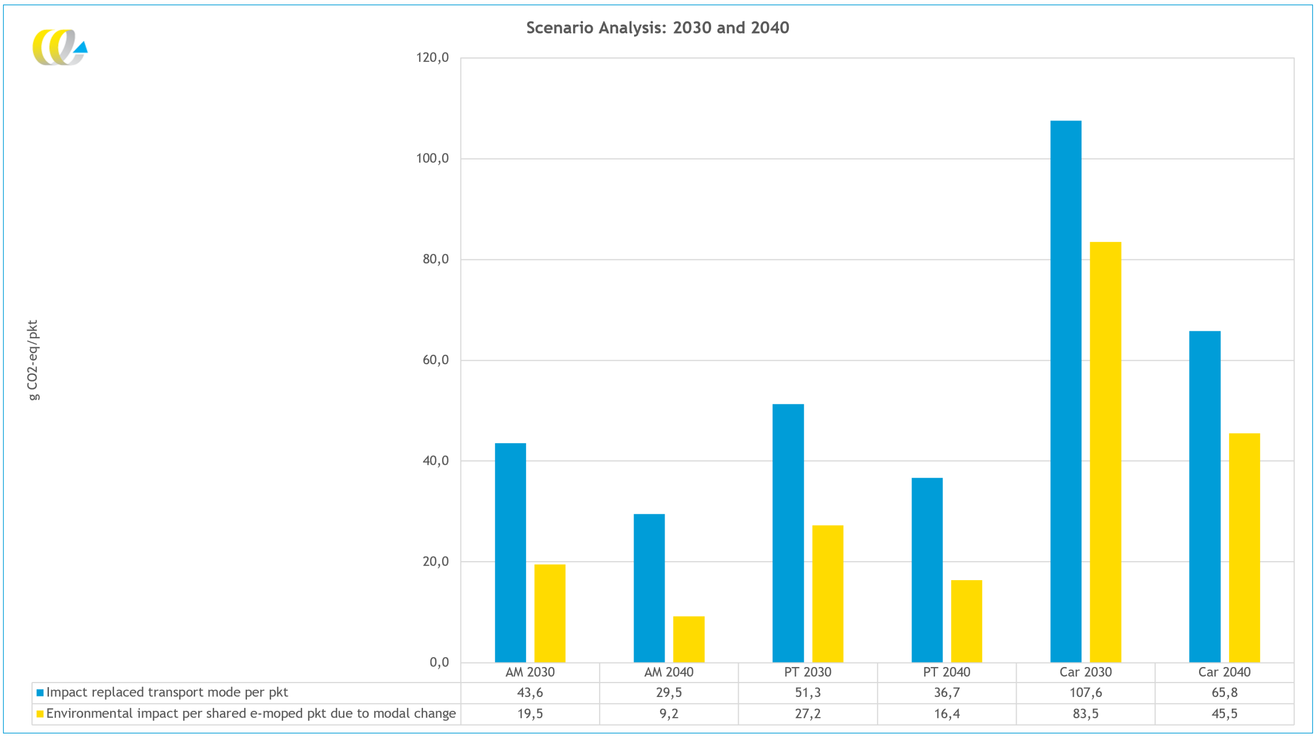


Figure E.12: Scenario analysis: 2030 and 2040 for three own created cities