

The influence of E-scooters on urban mobility and transport related emissions.

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**The influence of E-scooters on urban mobility
and transport related emissions.**

**El-skottrarnas inflytande på rörlighet i städer och
transportrelaterade utsläpp.**

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Abstract:

In the efforts made to reach a sustainability transportation system in large urban cities, shared micro mobility system (*SMMS*) appears in many countries including Sweden to solve the social, economic, and environmental challenges, and to promote this kind of transport instead of other transport modes.

Nowadays, the increasing demands coming from both population growth and urbanization lead to consider all available alternatives inside the transportation sectors. The invention of E-scooters in the last few years was a beginning of a new advanced shared mobility mode which takes place in the urban transport system in most large cities. The new innovative shared e-scooters are paying more attention to their environmental impacts and urban infrastructure by looking to their influences on other transport mobility modes.

The main purpose of this paper is to calculate the life cycle analysis (LCA) of climate change Greenhouse Gas (GHG) emissions which represents the biggest environmental impacts. Other challenges are depending on the social behaviour studies and survey analysis of mode substitution patterns to use E-scooters as a preferred option based on the mode choice models. To reach this goal, Life Cycle Analysis (LCA) of the Voyager model (*V5*) from VOI company has been made, and then the transaction data from both companies (Voi and Tier) have been handled to understand how to reduce the emissions in the urban transportation system and evaluate LCA results which contain more than 700 000 trips of shared e-scooters in Gothenburg city of Sweden.

The emission results from LCA analysis are calculated to be more than the average estimated emissions from previous literature which is equal to 151 (*g.CO₂ eq.*) compared to 70 (*g.CO₂ eq.*) per one e-scooter. These results are also compatible with the previous literature when the manufacturing stage of LCA contributes to more than fifty percent of the total LCA emissions. Other results from statistical analysis of data collected in Gothenburg city by using (Jupyter notebook, Python 3), find the highest probability of substituted transport mode by shared e-scooter is “Walk” while the lowest probability is “Car” in the inner city of Gothenburg which explain the negative environmental impacts of shared e-scooter occurred when e-scooter is replaced by the short trip distance of “Walk”. In addition to calculate the aggregated *GHG* reduction per unit area for each zone of Gothenburg and classify these zones according to their environmental impacts.

Keywords: Emissions, Micro mobility, E-scooter, Infrastructure, Transportation.

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List of abbreviations:

SMMS - shared micro mobility system

GHG - Green House Gas emission

CO₂ - carbon dioxide

E - Emission factor

E_{avg} - Average emission factor

*g.CO₂ eq./P * Km* - Amount of carbon dioxide (in gram) equivalents per (person*kilometer)

GWP - global warming potential

MNL - Multi Nominal Logit model

NL - Nested Logit model

U - Utility of transport mode

P - Probability calculated by *MNL*

LCA - Life Cycle Analysis

SESS - Shared Electric Scooter System

e-scooter - Electric scooter

e-van - Electric van

e-bike - Electric bike

PT - Public Transport

SEB - Shared Electric bike

Kg - Kilogram

t. - Ton

g - Gram

Km - Kilometer

Min. - Minute

V5 - Voyager model 5 from VOI company

KWh - KiloWatt-hour (energy unit)

MJ - Mega Joule (energy consumption unit)

KJ - Kilo Joule (energy consumption unit)

m² - Square meter (area unit)

g/cm³ - Density unit

m/s - Meter per second (Speed unit)

Std. – Standard Deviation

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1. Introduction:

More than fifty percent of population live in urban cities where the centre of human activities and transport systems. And when these cities are being occupied by more people and the distances to cities become longer, the need for developing alternative transport modes is getting higher to supply these increasing demands by finding more efficient transport utilities. (Blomgren, 2020)

But the transportation sector is still contributing to climate change and causing environmental impacts larger than 24% of the total global warming potential (GWP) in the whole world. This is happened because of using the fossil fuel source for energy and increasing the greenhouse gas emissions represented by carbon dioxide concentrations with 32% in the atmosphere from mainly the transportation roads. So, shifting to cleaner energy like electricity and using the advanced electric mobility instead are the main sustainable transportation goals. (Ishaq et al, 2022)

The micro mobility is the new transportation mode for short distance trip by using vehicles and devices up to 350 kg. It includes many tools such as bicycles, skateboards, e-scooters...etc. And when increasing the demands for this innovation, the private companies started supplying the urban cities with these e-scooters by renting them under the name of shared micro mobility. (Peci & Ali, 2022) The biggest micro mobility market is in Paris since 2018 considering it as the first and last mile solution for the traffic system. (Christoforou et al, 2021) While in the second place comes Italy of using e-scooter in Europe. (Ishaq et al, 2022)

This micro mobility system gets more interests in big cities of Europe after the share rate of using bicycles attains approximately forty percent of the total number of trips in Amsterdam and Copenhagen. The other factor of using micro mobility is to reduce the impacts of environmental emissions by modal splits from other transport modes. (Badia & Jenelius, 2021)

Shared E-Scooter System (*SESS*), as being one of these micro mobility systems, has low speed limit and includes both types of standing shared e-scooter and moped style shared e-scooter. The aim of this system is to serve different social groups and to avoid the extra transportation costs, congestion, parking spaces and accidents as low as possible. (Peci & Ali, 2022)

Shared e-scooter has achieved more increasing demands from users due to their extra advantages: smaller, lighter, and less maintenance. This solution comes between Cycling and Walk whereas the business model of e-scooter is business to customer (B2C) is characterised by three services: operation, way of use, and fare system. The operators get the benefits of swappable batteries to distribute only this component over the service area. In addition to the app system installed on smartphones which helps to get full information form clients about each type of trip, location, and payment. Other thing that e-scooter service is cheaper than other transport costs when the average time is ten minutes, the average speed is 10 *Km/hr*, and the average distance of trip is 1.5 *Km*. (Badia & Jenelius, 2021)

1.1. Background:

Shared e-scooter appeared in the US since 2017 to discuss its potential effects on transportation safety, user behaviours, mode choice and the substitution to other transport modes to estimate its (CO_2) emissions and evaluate the contribution of shared e-scooter in the total (CO_2) emissions. (Weschke et al, 2022) The transport sector in Sweden is responsible for about thirty percent of the

emissions that consist of carbon dioxide (CO_2). And Sweden undertakes the goal of zero net emissions in its agenda 2045. (Peci & Ali, 2022)

The electric two-wheeler vehicles include any two-wheel-vehicle provided by electricity for example e-scooter, e-bike, and e-motorbike. These vehicles have achieved successful steps when the price of electricity is getting low while the price of fuel is going up by the time, thus they could ensure transportation sustainability on the long term. (Weiss et al, 2015) other available types of e-scooters are electric-seated scooter and stand-up e-scooter. (Kazmaier et al, 2020) There are many companies have been entered the market of shared E-scooter in Sweden since 2018 such as LIME, VOI, TIER, and UFO. (Peci & Ali, 2022)

The implementation of bike sharing system services was the beginning of this big change supported by the regulation policies to promote this kind of transport such as bike lanes, bike parking and pro-bike spaces. One of the technological improvements in the fourth generation of bike sharing system is electric power assistance which its advantages are reducing the traffic congestion without any need to infrastructure, getting high accessibility from the origin to the destination, and providing flexibility movements when reducing the environmental impacts. (Badia & Jenelius, 2021)

1.2. Aim/Purpose:

The aim of this thesis is to check the influence of shared E-scooters, which can be organized in three aspects: first, estimate the lifecycle analysis (*LCA*) stages of shared E-scooter; second, estimate the replaced travel trips by shared e-scooter; and third, checking the environmental benefits of shared E-scooters to answer whether it is eco-friendly.

To reach this purpose, it is important to answer on the following research questions:

RQ1: What is the Life cycle Analysis of shared e-scooters in Sweden?

RQ2: What are the environmental emissions of replacing trips by using shared e-scooters?

RQ3: What are the potential benefits of shared e-scooters to be considered eco-friendly?

2. Literature review:

The previous literatures start to explain the modal substitution patterns of e-scooters, and their effecting Factors. After that they discuss the environmental impacts by *LCA* analysis and consider the expected environmental benefits when replacing other transport modes by shared e-scooter.

2.1. The modal substitution patterns of using e-scooter:

Most alternative transport modes include five patterns (if e-scooter doesn't exist): walk, car, ride-hailing, public transport, and bicycle. It has demonstrated that the substitution rate is more than fifty percent of patterns: Walk, public transport and cycling trips when using e-scooters in most cities. (Badia & Jenelius, 2021) The most dominant traffic mode among these patterns is the car in many locations such as Sweden where the car has 55% of the total trips, followed by 16% bike, 16% walk, and finally 13% public transport (Peci & Ali, 2022) The same thing in London where the car has 35% of trips, followed by 24% walk, 13% taxi, and finally 11% of trips by public transport. Also in

Amsterdam, the car has 35% followed by 24% walk, 13% taxi, and finally 11% public transport. (Cottell et al, 2021)

It has been found that the most substituted mode by shared e-scooter is car with more than 40% followed by public transport with 15% and then bike with 10%. (Badia & Jenelius, 2021) Another study has been found that Walk and Bike have the highest substitution rates among other transport modes by shared e-scooter because of many features such as the flexibility movement directly to the destination, lower time, and lower cost. (Weschke et al, 2022)

The modal substitution is estimating the number of trips based on local surveys where most involved people are young men, well-educated and have median income. The most common substituted mode is Walk with a range (30% - 60%) of the total trips since people in different cities have different patterns to use as shown in Appendix 1. Also, shared e-scooters are considered an intermediate mode between Walk and Bicycle, and more than 90% of e-scooters users ride on the sidewalks. (Wang et al, 2022)

Most of trips by shared e-scooters in Europe are replacing mainly Public Transport and Walk with different percentages for example, Christoforou et al (2021) showed in the survey of Paris that 37% of public transport trips and 35% of Walk trips are replaced by shared e-scooters. (Reck et al, 2022) Another survey (face to face) shows that 35% Walk, 27% public transport, 9% private car, and 6% of taxi trips are replaced by shared e-scooter. (Christoforou et al, 2021) While another study in Paris found that public transport is 26.4% and Walk is 60.3% are being replaced by shared e-scooter. (Badia & Jenelius, 2021) While another study done by Fearnley et al (2020) in Oslo results in 60% of Walk, 23% of public transport, and 8% of cars are being replaced. These substitution patterns are exposed to biased because different results of data survey come from different population and different areas. (Reck et al, 2022)

The mode choice of different substitution patterns represented in table (1) for the case of Zurich city are showing that shared e-scooter substitutes more trips of public transport and walk than the personal e-scooter. And shared e-scooter substitutes more walk trips than shared e-bikes. The substitution rates by shared e-scooters per trip level is higher than the corresponding rate per kilometer level because most of walk trips are made within a short distance. (Reck et al, 2022)

Table (1) Different substitution rates for (e-bike, e-scooters) for both personal and shared micro mobility. (Reck et al, 2022)

Mode	(person) E-bike		(shared) E-bike		(person) E - scooter		(shared) E - scooter	
	trip	Km	trip	Km	trip	Km	trip	Km
walk	26%	9%	24%	9%	35%	19%	51%	25%
PT	20%	29%	27%	43%	23%	27%	19%	38%
Car	37%	48%	11%	15%	17%	25%	12%	15%
Bike	17%	14%	33%	29%	24%	27%	13%	13%
E-Bike (person)			3%	5%	2%	1%	1%	2%
(shared) E-bike	0%	0%			0%	0%	4%	5%
(person) E-scooter	0%	0%	0%	0%			0%	0%
(shared) E-scooter	0%	0%	0%	0%	0%	0%		

Other studies show that shared e-scooters substitutes 43% of Walk trips, 22% of taxi trips, and 13% of private cars. And the most dominant replace mode is “walk” for short trip distance as it is illustrated in figure (1). And when the trip distance increases, both Public Transport (PT) and Car increase their shares. (Reck et al, 2022)

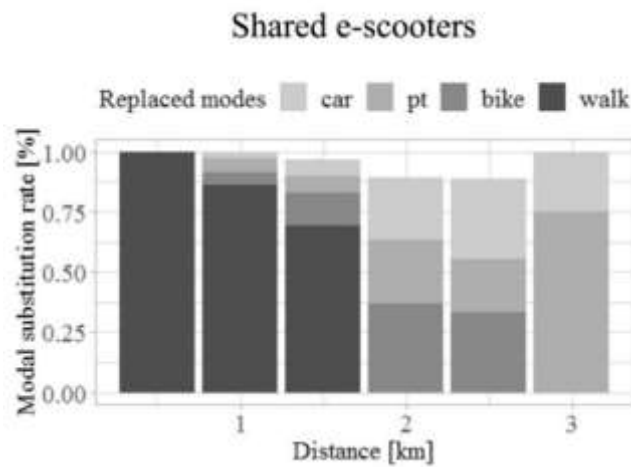


Figure (1) Different substitution rates by distance. (Reck et al, 2022)

Other surveys in Germany show that regular using of shared e-scooter in the last trip without any need for parking, results in negative impact on public transport. And encouraging individuals to use shared e-scooter as a feeder mode is significant important due to flexible shorter time and saving the costs during the congestion which are explained through (minimum - maximum) emission factors of each mode in table (2). In addition, the substitution rate of using shared e-scooter has reached 43% instead of Walk, 19% instead of public transport, and 11.5% instead of bicycles. (Weschke et al, 2022)

Table (2) Substitution rate of shared e-scooter and the emission factors of each mode. (Weschke et al, 2022)

Mode	Weighted average mode shift	<i>(g. CO₂ emission/p * Km)</i>	
		Minimum	Maximum
foot	42.23%	0	2
Private bicycle	11.48%	5	17
Public transport	19.41%	71	80
Private car	11.54%	147	257
Private motorbike	0.25%	73	143
Taxi	3.01%	276	299
Ride sourcing	0.24%	276	299
Bike sharing	2.88%	33	118
E-moped sharing	0.42%	28	79
Car sharing (emission data from private car)	0.94%	147	257
Induced demand	7.12%	0	0
Others (Median of other modes)	0.49%	71	96
Emission of substituted modes		43.23	64.73
Emission of shared e-scooter		42.8	131

The largest number of trips are in the centre of Gothenburg while the smallest number at the edges of the city because most of parking spaces and public transport hubs are near the inner city. More than fifty percent of trips are made by cars followed by 20% of trips by public transports. And the cars are the most traffic used mode for group age (45-54 years) while the group (16-24 years) uses the public transport more than other groups. (Peci & Ali, 2022)

According to VOI company zones, the use of e-scooter is limited to the inner-city of Gothenburg within the major roads E6, E20, and E45. And the parking spaces are allowed anywhere in 27 different zones of Gothenburg. The pilot program of shared e-scooter can control the speed in the densified zones automatically to adjust with the speed limit, in addition to the restricted regulations to drive e-scooters in the prohibited areas. (Peci & Ali, 2022)

Based on the statistical records in 2017 for Gothenburg inhabitants, around forty percent of the travels are made by an age group (25-44 years) for short distances distributed either inside Gothenburg city or to the suburb areas around the city as shown in table (3). (Västsvenska paketet, 2017)

Table (3) Travel distance survey in Gothenburg city. (Västsvenska paketet, 2017)

Reslängdsintervall	Kvinna	Man	Göteborgs-Regionen	Kommuner i omnejd
<2 Km	22%	17%	20%	19%
2- <5 Km	25%	22%	22%	25%
5 - <10 Km	18%	18%	19%	16%
10 - <20 Km	15%	19%	18%	14%
Minst 20 Km	20%	25%	21%	25%

The data from VOI company is collected and recorded from 14th may until 20th of July in 2018. It has 762565 trips of using e-scooter all weekdays over twenty-seven different zones of Gothenburg city where the trips are concentrated in the inner and middle of Gothenburg without any natural obstacles, and the substituted patterns of using e-scooter per travel distance are described in table (4). The modal distribution patterns are different by the travel distance in Gothenburg. If the distance is less than two kilometres, the most transport modes are Walk and Bike. Whereas for more than 2 Km the most used modes are the cars and public transport. (Peci & Ali, 2022)

Table (4) Substituted patterns per travel distance in Gothenburg on all weekdays. (Västsvenska paketet, 2017)

	Walking	Bike	Public Transport	Car	Others
< 2 km	58%	12%	5%	24%	1%
2 - < 5 km	12%	15%	21%	51%	1%
5 - < 10 km	3%	10%	29%	57%	2%
10 - < 20 km	0%	4%	25%	70%	1%
Minst 20 km	0%	0%	29%	70%	1%

2.2. The effecting Factors of using e-scooter:

The effecting factors extend in two directions, the first one is related to the travel data collected from the companies and the second one is based on the surveys from the social behaviours of users. (Weschke et al, 2022) Most of e-scooter trips concentrate in the high-density areas and downtown cities, and the purpose of most these trips is for leisure more than commuting. The social behaviour studies concern with the characteristics of users such as age, education, and income. The previous surveys focus on the young generation whether singles or married without children, high educated and the salary is above the average. It has been found that local riders spend half the time per trip when riding to specific locations compared to the visitors. And the average distance trip by e-scooter is doubled than the pedestrian trip and half than cycling trip, although the average speed of cycling is doubled the e-scooter speed. Whereas using e-scooter is related to weather conditions, length, and time of trip per day. (Badia & Jenelius, 2021)

Mode choice is the third step of transport planning to divide the total generated trips between the available attracted transport modes and to show the probability of choosing each mode. Mode choice has many factors in terms of spatial and temporal terms. Parking spaces, land use and population density are some spatial factors. While income, education, lifestyle, and having children are socio-demographic factors. (Blomgren, 2020)

Another mode choice of travellers is related to journey characteristics of origin and destination points, which is concerned with the highest utility, the lowest cost, and time spent. (Peci & Ali, 2022) The importance of mode choice is one of the four essential parts in transport planning which contributes to determine the environmental impacts more accurately than the surveys. But mode choice between shared micro mobility and other existing transport modes is limited because of less understanding the travel behaviours. (Reck et al, 2022)

The land use of Gothenburg affects on using shared e-scooters in all zones within the city as shown in figure (2) where housing density is very high in the south part of city and very low at the city centre. On the contrary, the commercial activities and traffic congestion is very high at the center of city. (Peci & Ali, 2022)

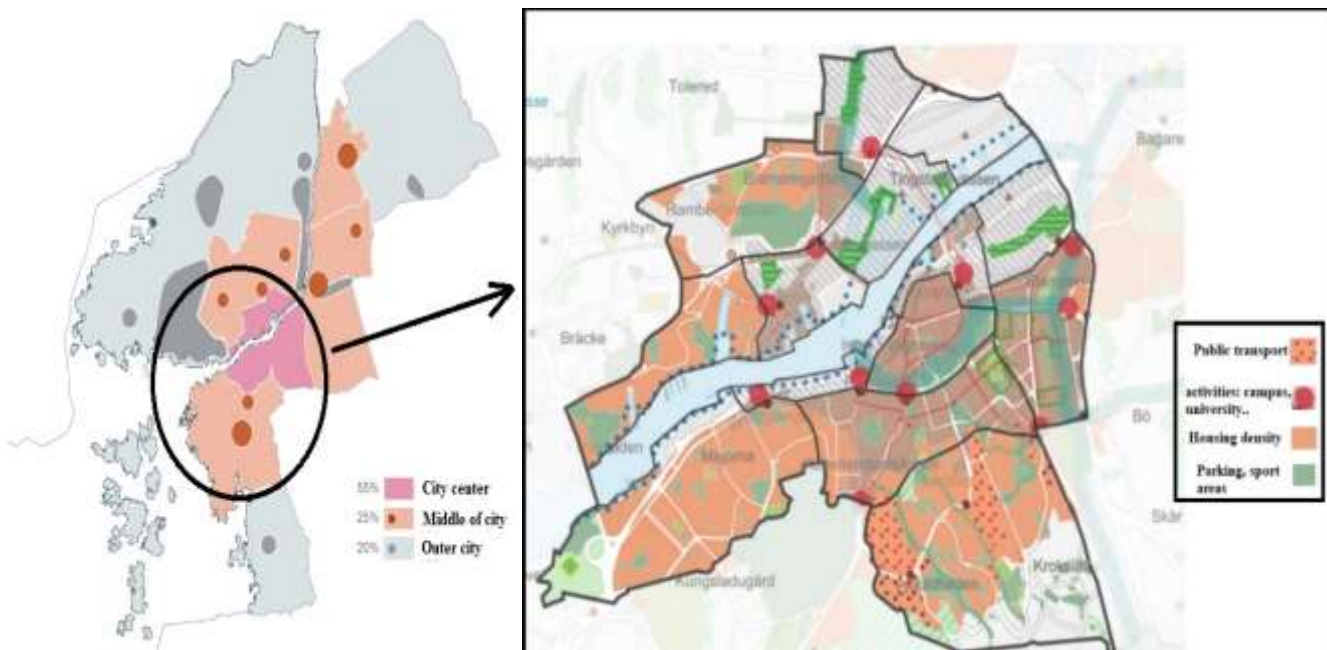


Figure (2) The land use of Gothenburg city. (Göteborgs stad., n.d.)

Gothenburg city extends on the area of 448Km^2 , and has 580 000 people living and commuting by the available transportation utilities. The city development is considered by the rapidly increasing population growth in few urban areas. (Peci & Ali, 2022) But the whole urban planning of Gothenburg is divided into three general regions which are described in table (5) by knowing that there are many connections between these regions. For example, in the eastern part of Gothenburg where the middle city connects with the city center by many regions such as Gamlestaden and Bergsjön. (Göteborgs stad., n.d.)

Table (5) The urban regions of Gothenburg city. (Göteborgs stad., n.d.)

Geographical regions	Description	Smaller zones (districts) within the urban regions
The inner city (City centre): (55% of Gothenburg area)	high population density.	Majorna_Linne, Annedal, Lunden, Stigberget Eriksberg, Johanneberg, Stampen, Vasastaden, Kungladugård, Krokslätt, Stigberget, Skår, Guldheden, Landala, Olivedal, Haga, Bagaregården, Kålltorp, Redberg.

	Less parking spaces. More public spaces and services.	Lindholmen, Hisingen, Backaplan, Frihamnen, Södra älvstranden, Biskopsgården.
	New parts of the city centre.	Älvstaden, Sjöfartstaden, Varvfartstaden.
The middle city: (25% of Gothenburg area)	Mixture of residential places with office places, with less facility for activities such as: sports..etc	Gamlestaden, Rymdtorget, Munkeback torget, Gräddsås torg, Delsjövägen, Bergsjön, Kortedala, Kviberg Bagaregården, Olskroken, Lunden, Östra sjukhuset, Gullbergsvass, Angered.
The outer city: (20% of Gothenburg area)	Suburb areas full of agricultural, natural, and recreational activities.	Torslanda, Kärra, Billdal, Olofstorp, Gunnilse, Säve, Björlanda, Älmhult, Hovås, Akism, Gerrebacka, Björlanda,

Multi Nominal Logit model (*MNL*) is the most common mode choice model and used to estimate shifting the mode behaviour of using shared e-scooter to other transport modes. *MNL* explains the reasons behind switching users to the new transport mode based on changes in behaviour, availability, and shorter time of accessibility according to the rational travellers. (Weschke et al, 2022)

When the substituted transport modes are only four (walk, bike, private car, and public transport), they need to conclude all variables of deterministic utility (*V*) from reality in terms of travel time and distance of explaining all these variables as shown in Appendix (3). (Bai, T. et al, 2017).

But the disadvantage of *MNL* is the assumption of Independence and Irrelevant Alternatives (IIA) between two or more options are not affected by other alternatives when the individual unmeasured attributes are changing. To overcome this disadvantage, the Nested Logit model (*NL*) is used instead to put similar alternative modes together on different levels and in different nests. (Blomgren, 2020)

2.3. The Environmental benefits of shared e-scooter:

Evaluating the environmental benefits of shared e-scooter is related to determine the most substituted transport mode which has been replaced for each trip used by the traveller. So, this needs to know which transport mode has been mostly substituted by shared e-scooter and how much the GHG emission reduction has been achieved in each trip.

Shared micro mobility such as mopeds, bikes, e-bikes, and e-scooters have shown reductions in the GHG emissions, and the energy use compared to other automobile modes (Wang et al, 2022) Shared E-Scooter System (SESS) also is used to reduce the travel time and cost and considered eco-friendly by consuming electricity during all stages of life cycle in related to the substituted transport mode. If the trips are made instead of taking public transport or cars, the environmental benefits are better, unless other modes like Walk and bicycle are not being substituted. (Peci & Ali, 2022)

The advantage of shared e-scooters is used for shorter distance than shared e-bike. (Reck et al, 2022) And the environmental benefit is achieved when correlating the total emission reduction with the built environment. (Li, A. et al, 2021) But increasing the demands in the densified cities by using vans for recharging or relocation will increase the negative environmental impacts. (Badia & Jenelius, 2021)

2.4. Estimating the environmental impacts by LCA analysis:

Life Cycle Assessment (*LCA*) is a systematic framework to evaluate the environmental impacts related to all stages from cradle to grave on different levels of transportation system. Different system boundaries, the size of cities, and user behaviours are some of factors to be considered when applying *LCA*. The transportation sector contributes to 14% of total Greenhouse Gas Emissions (GGE) which is the main cause to global climate change. The amount of greenhouse gas is calculated in terms of

carbon dioxide equivalent ($CO_2 eq.$) and unit ($g / p * Km$). (Cheng et al, 2022) In this report, the impact assessment method is the main step of evaluating the life cycle analysis in terms of gram ($g. CO_2 eq./person * Kilometre$), besides to the other three phases: objectives and scope, interpretation and analysing the stock. (Kazmaier et al, 2020)

The environmental impacts are related to many factors like: lifespan duration, frequently using e-scooter, travel distance, not/swappable battery, and electric source. The results show that shared e-scooter is better than cars and the same as both buses and bike sharing. But using vans to collect and distribute these devices over the proposed areas for recharging or relocation would increase the pressure on urban transport infrastructure and lead to more environmental impacts because of increasing the demands on transports modes in the densified cities. (Badia & Jenelius, 2021)

The interests of using sharing mobility for short distance travel are to reduce (GGE) and attain sustainable transportation. In addition to the successful experience of internet users, the bike sharing reached 200 cities in China in 2017 to reduce (GGE) in the urban transportation after considering the substitution effects of bike sharing. (Cheng et al, 2022) In a similar way, shared e-scooter is considered for the green environment of a sustainable transport mode to reduce cars and other fuel-based transport trips. But evaluating the environmental impacts is based on estimating the replacing trips of other transport modes by using e-scooters. (Peci & Ali, 2022)

So, the purpose of LCA is to analyse all the stages of e-scooter life cycle from extracting the raw materials until disposal the device at the end of life and evaluate the results of environmental impacts, in addition to energy source, energy consumption, and using battery. (Peci & Ali, 2022)

In the case study of Berlin, Germany, the aim is to calculate the life cycle analysis of shared e-scooter with a swappable battery as shown in figure (3) where LCA consists of four main stages: first production and manufacturing, second transportation to Germany, third: collection, distribution, charging, and fourth end of life. (Severengiz et al, 2020) The emission factors are calculated to estimate the emission impacts of shared e-scooter to other mode substitution patterns in terms of gram ($CO_2 eq./p * Km$). And the results show that shared e-scooter has negative net impact on the contrary to private e-scooter. (Weschke et al, 2022)

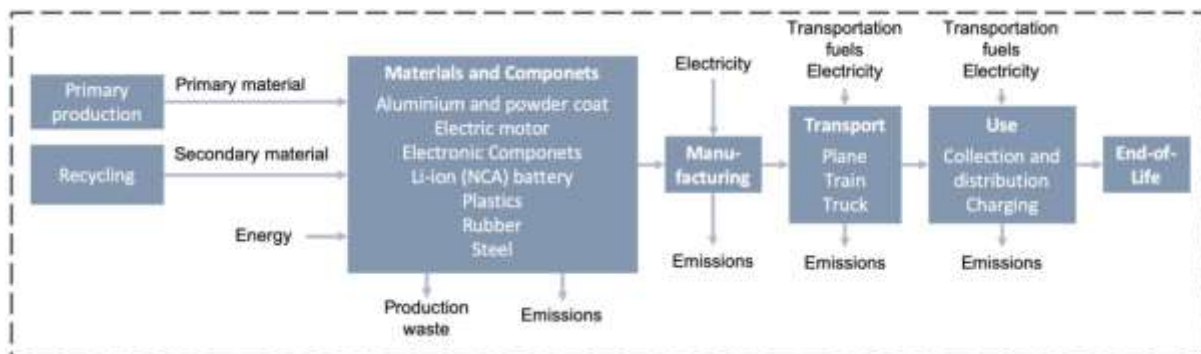


Figure (3) LCA Boundary system of shared e-scooter. (Severengiz et al, 2020)

The base case of finding the emissions from swappable battery e-scooter is calculated for two years lifespan and the average trip distance is equal to 10.2 (km/day). The resulting overall distance for the whole life cycle is 7500 (Km) (without considering maintenance service). The total GWP emission is equal to 77 ($g. CO_2 eq./p * Km$) distributed into the four phases: 63% (production and manufacturing), 1% (transportation), 35% (the third phase: 13% collecting and distributing plus 4% swapping battery, 11% charging (due to swappable battery)), 1% (end of life). (Severengiz et al, 2020) Another similar study in Berlin calculated the total emissions to be 58 ($g. CO_2 eq./p * Km$) when the average trip distance is equal to 20 (Km/day). (Badia & Jenelius, 2021) Furthermore, the final emissions of shared e-scooter have a negative environmental impact in Germany. (Weschke et al,

2022) and the calculated emissions of the second generation is 61 ($g. CO_2 eq./p * Km$). (Weschke et al, 2022)

In the scenario of not swappable battery in Berlin, collecting the whole e-scooter and charging it are done by using a van. So, each e-scooter requires only one battery per day and the average distance of van service is one kilometer per one e-scooter per day. So, the (GWP) emissions are 121 ($g. CO_2 eq./P * Km$) for an average distance of one Km per one e-scooter per day. And the difference with the base case is 58% for the third phase instead of 35% in the base case. (Severengiz et al, 2020)

The calculated LCA in Germany is shown in figure (4) for six-month services with a redistribution distance of 2 kilometre per scooter and the number of riding e-scooter is 4.9 times which means a total mileage of 2117 (Km). So, the total emissions for basic standardized case are calculated to be 165 ($g. CO_2 eq./Km$) distributed into 5 stages: material and manufacturing (73%), transport (9%), charging (3%), redistribution and collection (12%), and finally the end of life is only (3%) because of incineration process of recycling materials especially the batteries.

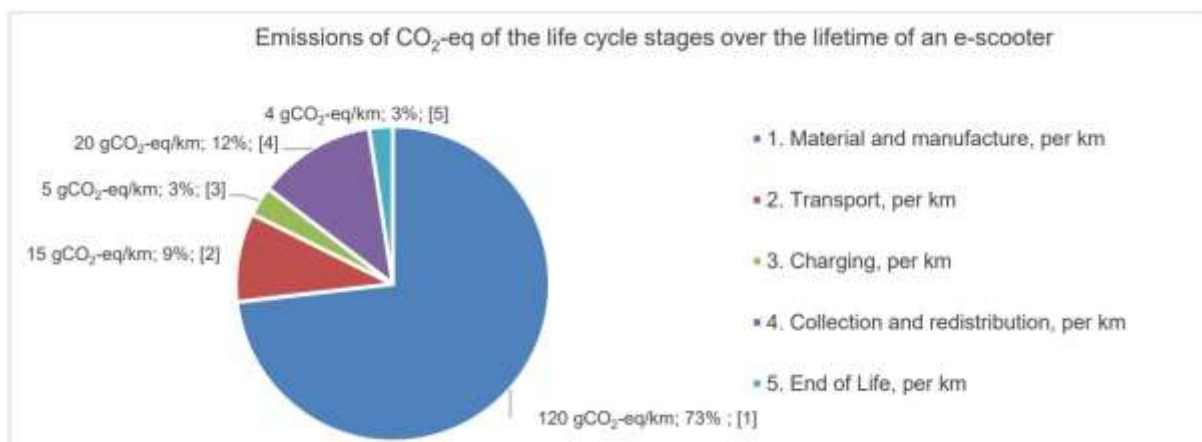


Figure (4) Total emissions calculated of the entire life cycle analysis. (Kazmaier et al, 2020)

Other scenarios are explained in figure (5) to show that increasing lifespan will reduce the total emissions per Km .

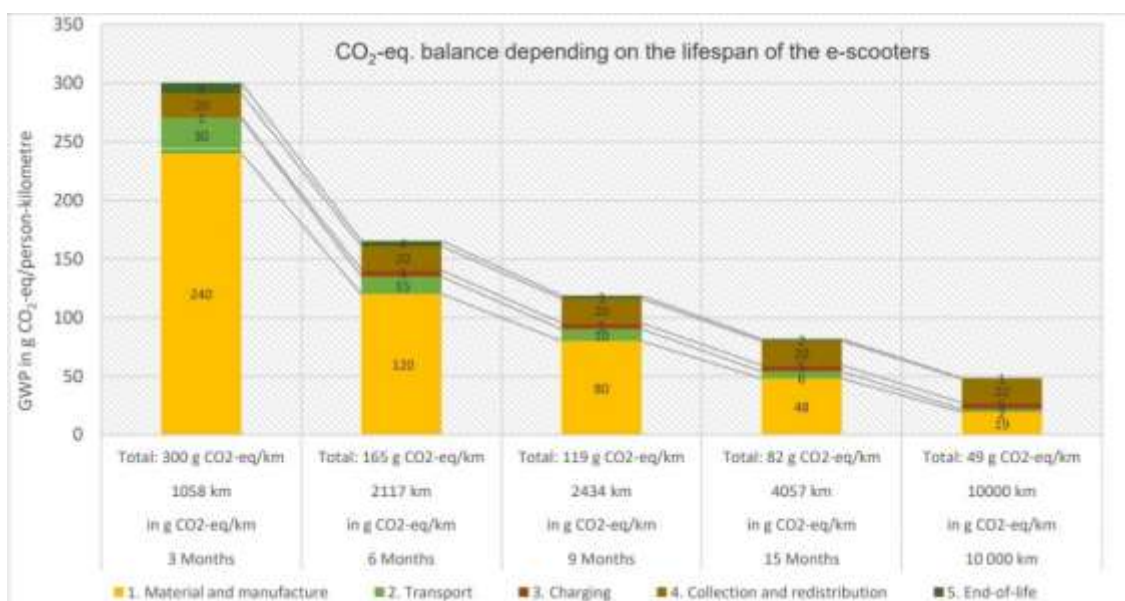


Figure (5) The distribution analysis of different stages LCA over lifespan. (Kazmaier et al, 2020)

Kazmaier et al. (2020) commented about the results in table (6) that the parameters are fixed for charging, redistribution, and collection stages while the changes in the material and manufacturing are big because of the high emissions coming from producing Aluminium and lithium battery during the material and production stages. (Kazmaier et al, 2020) while the carbon fiber material used in the bicycle manufacturing has caused least effect of emissions during production phase, but the acidification effect is very high which makes it not favourable material. (Ishaq et al, 2022)

Table (6) LCA stages in Germany for different scenarios. (Kazmaier et al, 2020)

Scenario	lifespan (months) or (Km)	LCA stages $g. (CO_2 eq./Km)$					total emissions $g. (CO_2 eq./Km)$
		material and manufacturing	Transport	Charging	redistribution and collection	end of life	
Basic case	6 months 2117 (Km)	120	15	5	20	5	165
Worst case	3 months 1058 (Km)	240	30	1	20	9	300
Best case	15 months 4057 (Km)	48	6	5	20	2	82
	9 months 2434 (Km)	80	10	5	20	3	119
	10000 (Km)	19	2	5	20	1	49

The best and worst scenarios of using shared e-scooter from above are depending on the transportation modes replaced by e-scooter. It was illustrated that in the worst scenario of shared e-scooter, the global warming potential (GWP) is 237 higher than all other modes as shown in figure (6). (Severengiz et al, 2020)

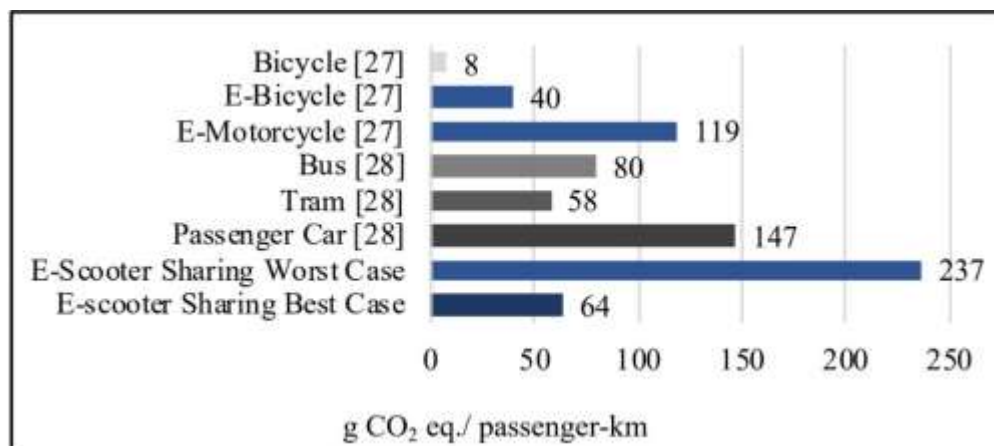


Figure (6) Comparing the global warming potential (GWP) to all available transport modes. (Severengiz et al, 2020)

Another study made by Hollingsworth in US (2019) shows that the emissions are in between (87.6 – 125.5) ($g. CO_2 eq./P * Km$). (Weschke et al, 2022) But if the lifespan extended to be two years, the emissions reduced from 126 to 88.1 ($g. CO_2 eq./P * Km$). The total GWP emission is distributed through production and manufacturing phase with 50% and the redistribution phase with 43%. (Kazmaier et al, 2020) For these emissions in US, the recommended solutions are to increase the lifespan products of Aluminium and lithium-ion battery during the manufacturing and recycling phases, and to reduce recharging during the collection and redistribution phase of e-scooters by

extending the lifespan of using shared e-scooter to be two years. Chester's research (2019) relates to Hollingsworth (2019) to show the feature of swappable battery system when increasing the travel distance of shared dockless e-scooter from 1200 (Km) to 6000 (Km) over the total life cycle by 57 ($g. CO_2 eq./P * Km$) emission reduction. Chester has also calculated the total life cycle emissions to be 200 ($g. CO_2 eq./P * Km$). (Severengiz et al, 2020) In Brussels the emissions are 131 ($g. CO_2 eq./P * Km$) and in Paris they are 109 ($g. CO_2 eq./P * Km$). (Weschke et al, 2022)

When Earnest and Young considered the swappable battery case in 2020 during the life cycle analysis of Voi company data in Paris, they found that the resulting emissions reached to 35 ($g. CO_2 eq./P * Km$) when expanding the lifespan of e-scooter to be two years. (Kazmaier et al, 2020)

According to international transport forum (2020) in Paris, the CO_2 emissions for shared e-scooter and shared e-bike are higher than other transport modes on the short term in figure (7). But the personal e-scooter and personal e-bike have lowest emissions than other modes which encourages the ownership of e-bike and e-scooter to reduce the CO_2 emissions on the long term. (Reck et al, 2022)

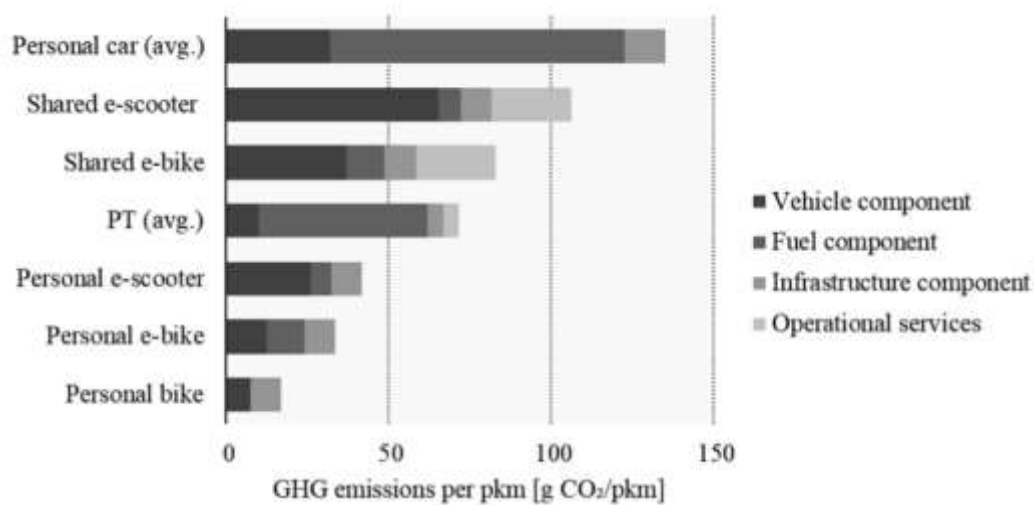


Figure (7) Life cycle of each transport mode ($g. CO_2 eq./P * Km$). (Reck et al, 2022)

While, the personal e-scooter in Italy has registered a total GWP emissions around 21 ($g. CO_2 eq./P * Km$) distributed by 14 ($g. CO_2 eq./P * Km$) in (production phase), 0.35 ($g. CO_2 eq./P * Km$) (transportation phase), and 6.7 ($g. CO_2 eq./P * Km$) (charging phase). (Ishaq et al, 2022) while using personal e-scooter in Spain has also achieved the least emissions among other vehicles with around 40 ($g. CO_2 eq./P * Km$). (Felipe-Falgas et al, 2022)

The CO_2 emission factors in Gothenburg for each transport mode are adapted according to table (7) for production and operation phases without considering the third disposal phase due to the lack of information. These mean values of emissions are retrieved from the article (Cottell, Connelly and harding, 2021) made in United Kingdom. (Peci & Ali, 2022)

Table (7) Mean values of emissions for each transport mode through production (E_p) and operation (E_0) phases. (Cottell, Connelly & harding, 2021)

Emission factors	Car	Bike	Public Transport	Shared e-scooter	Walk
Production (E_p)	29.45	18.75	7.14	35	0
Operation (E_0)	131.25	18.3	8.9	32.1	0
Total emission (E)	160.7	37.05	16.04	67.1	0

The European standards of Germany (14040/44) are used to calculate LCA emissions for shared e-scooter TIER company based on the data collected from Bill of Material (BoM) and GaBi software.

The study shows that manufacturing and production stages have the biggest shares of total emissions where Aluminium causes 61% of the total GHG emissions due to 12000 (Km) long lifespan distance from China to Europe. It also considers the case of swappable battery, (*GWP*), and the non-renewable primary energy demand (*PED*). The total *LCA* emissions of two scenarios of (*GWP*) are 42.8 (*g.CO₂ eq./P * Km*) for the green operations such as charging by wind power, and 46.7 (*g.CO₂ eq./P * Km*) for European average operation by non-renewable resources. The battery cells contribute in 11% of (*GWP*) emissions while they contribute in 13% of (*PED*) emissions. (Schünemann et al, 2021)

When substituting the trips of shared e-scooters with other transport modes (car, public transport, bike, Walk) by VOI company, the GHG emission reductions for different areas in Gothenburg are shown in figure (8). The lowest value in Annedal with -2 (*g.CO₂ eq.*) have a negative impact because Walk trips are substituted by e-scooter trips with increase GHG emissions. Whereas the highest value in Deljömrådet with 50 (*g.CO₂ eq.*) decreases the emissions instead because other public transports are not so many near the edges of city. (Peci & Ali, 2022)

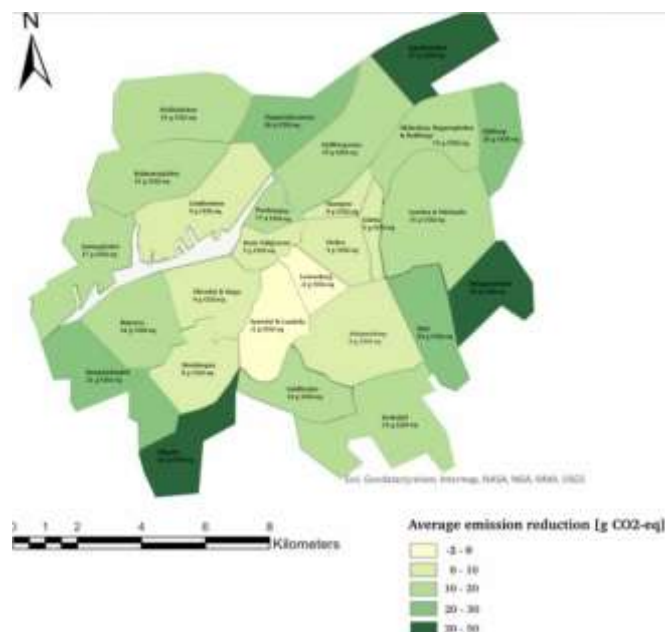


Figure (8) Average emission reductions per trip in different areas of Gothenburg. (Peci & Ali, 2022)

After finding the (*GHG*) emission reduction of each recorded trip, the aggregated (*GHG*) reduction of each analysis zone (*AZ*) is calculated by linear regressions to check about the environmental benefits of Dockless Bike sharing (*DLBS*). It contains two scenarios: the first one is to calculate the aggregated *GHG* emission when *DLBS* is used only, and the second one is to calculate the aggregated (*GHG*) of other alternative substituted modes when (*DLBS*) is not used. In this way the difference between the two previous cases represents the aggregated (*GHG*) reduction or “the environmental benefits”. (Li, A. et al, 2021)

This process of aggregated (*GHG*) reduction is important to see how the differences between urban areas could help in planning for the whole transport system. It affects by three factors: the number of travellers, the alternative transport modes used, and the distance travelled. The results will be shown through the cumulative (*GHG*) emission reductions for all zones to distinguish between them per unit area and the environmental benefit is achieved when correlating the total emission reduction with the built environment. (Li, A. et al, 2021)

2.5. The environmental impacts of e-scooter model Voyager 5 (V5) (Voi company):

Voi company tried to develop its environmental plannings and solve the life cycle impacts by producing more eco-friendly vehicles which have longer lifespan duration (more than 24 months or 2 years), such as the Model name: Voyager 5 (V5), with highly efficient swappable battery, lunched in 2022, and its expected lifespan is lasting for 60 months (5 years) as shown in figure (9). This strategy is made by Swedish national research centre and focused on many aspects of sustainability and durability by optimizing the vehicle utilization to the ultimate level and using both 30 % of recycled materials and 90% of recyclable materials and keeping the connections closer between the suppliers and Voi employees. (Voi report, 2022)



Figure (9) Specification of Model Voyager 5. (Voi report, 2022)

According to the similarities found between model Xiaomi M365 and Voyager 5, it has been assumed that they have approximately the same mass of 13 (kg) which helps in considering the coefficients used for Xiaomi M365 (Ishaq et al, 2022) in Voyager V5, and the components of Voyager 5 (V5) look like Voyager 4 in addition to easier repairment, simplified reusing, and twice the amounts of recycled materials. (Voi report, 2022) The model’s specifications are displayed in table (8). (Voi youtube, 2020)

Table (8) Voyager 5 (V5) specifications. (Voi youtube, 2020)

lifespan	wheels	reflectors	battery	Mechanical parts	Technical equipment
5 years	10 inches	360 degrees	Swappable with 90% charging efficiency	Frames, Brakes, handlebar, Lights.	Phone holder, Internet of things (IoT), and GPS.

2.6. The efficient usage of shared e-scooter:

The flexibility features of using shared e-scooter are higher than bike sharing which gives it more popularity in anywhere. But comparing shared e-scooter between different cities, needs to consider different criteria, for example the efficient utilities, unused time, and time consumed of e-scooter, the distance and time of urban characteristics of the temporal patterns. Li, Aoyong et al. (2022) explained the four main patterns used for this comparison: “spatio-temporal distribution”, “statistical distribution”, “efficient usage of shared e-scooter”, and “the electrical losses during the inactive usage time” of shared e-scooter. (Li, A. et al, 2022)

These patterns are limited to many factors such as the peak durations at all weekdays and how the average time is changing over the spatial distribution, which is also related to the availability of micro mobility services in each city. In addition to other factors like the land use, built environment, and demographical distribution of shared e-scooter based on the case of travel density from the surrounding areas to the centres of cities and vice versa, whereas calculating the electrical losses are based on the charging percentage state of e-scooter's battery. Other information such as the filtered trip number, service area, population, start date and end date are needed for each city to show the limitations of study, for example the number of populations in Lund is equal to 91940 but the smaller service area considered in Lund city (34.33 Km^2) leads to a smaller number of 45843 filtered trips. (Li, A. et al, 2022).

3. Methods Limitations:

This section includes the limitations to describe how the calculation limits are considered for Gothenburg city due to the available data, and it is conducted through the methodological section of coding in python and the formula of greenhouse gas emissions. These limitations are classified according to *LCA* analysis and Case study boundary.

3.1. *LCA* analysis limitations:

The lifespan of shared e-scooters depends on many factors, for example the longer travel distance per day has more lifespan and less weight of e-scooter design. (Badia & Jenelius, 2021) The life cycle emissions for shared e-scooter don't have any exhaust emissions like in combusted engines. When the previous studies calculate the full life cycle emissions, they conclude that fifty percent of (*GHG*) emissions are released during the production and manufacturing stages as long the lifespan design is shorter than the private e-scooter and consequently the emissions are higher. The lifespan of second-generation shared e-scooter is also better than the first generation when it lasts for at least one year and considering the minimum normal usage condition is one recharging per day. (Bozzi & Aguilera, 2021)

The emissions are calculated according to the Quick Results analysis among all types of *LCA* analysis, because this will give better understanding of the evaluation process when looking to the real emissions happening and their limitations. (Ishaq et al, 2022) The end-of-life stage will consider only the emissions calculated without any deeper details. (Ishaq et al, 2022)

Frequently using e-scooter and the lifespan are the main parameters which affect on the total environmental emissions. The impacts are high when lifespan and using rate are short, and the recommended lifespan is estimated to be two years in many companies like VOI company. (Badia & Jenelius, 2021) While (*GHG*) emissions during the distribution stage are related to both the development of swappable battery and the places of case study which varied between 20% as in Brussels and 50% as in the case of Paris. (Bozzi & Aguilera, 2021) Furthermore, expanding the lifespan service of e-scooter to be two years based on the swappable battery in previous study results in total emissions of $35 (g. CO_2 eq./P * Km)$. (Kazmaier et al, 2020)

The limitations of this paper are applied in the same manner from previous scenario of no-swappable battery which requires only one battery per scooter and the whole e-scooter is collected once for charging, the e-van serves an average of 100 e-scooters with travelling distance 100 (*km/day*). It means that each e-van serves and transports one e-scooter per *Km* per day. (Severengiz et al, 2020) and each person is using one e-scooter for each trip. (Peci & Ali, 2022).

The emission factor of Walk is considered zero because this transport mode does not require any tool to cause (*GHG*) emissions. (Li, A. et al, 2021) However, the value of emission factor is

considered from previous literatures of each transport mode in gram ($g. CO_2 eq.$) per kilometre to represent the quantities of CO_2 emissions per Km when using each transport mode separately.

When calculating greenhouse gas (GHG) emissions, they are represented by the amount of carbon dioxide (in gram) equivalents per person*kilometre or in the form of ($g. CO_2 eq./P * Km$). (Weschke et al, 2022) Also, the operating impacts and energy consuming are related to running the e-scooter and the auxiliary vehicles with collection and distribution tasks. (Badia & Jenelius, 2021)

3.2. Case study boundary limitations:

The estimated displacement mode of e-scooter is related to many things: number of trips, weight of trip frequency, travel length, and safety. Also, parking e-scooters is improperly in the absence of regulations which affect on the substitution percentage of shared e-scooters compared to other patterns. (Badia & Jenelius, 2021) By knowing that the main transport modes in this paper are Walk, Public Transport, Car, and Shared e-scooters.

On the other hand, filtering the transaction data from VOI and TIER companies have other limitations regarding to the maximum permitted speed is $20 Km/hr$, the maximum permitted distance is $10 Km$, and the maximum travel time is 45 minutes per trip when considering each person is using one e- scooter per each trip. (Peci & Ali, 2022)

4. Methodological approach:

Due to focusing on other substitution modes (Walk), (public transport) and (Car) to see the efficiency of replacing these modes by shared e-scooter according to previous literature, the methodological approach in figure (10) is performed on three steps.

First, analysing the previous literature results and handling the transaction data collected from VOI and TIER companies for each e-scooter trip in related to travel distance and time duration. Then estimating the modal substitution patterns of using e-scooter by applying a multinomial logit model (MNL), where the utility of e-scooter (U) is equal to the sum of deterministic utility (V) and random utility (ϵ) within Gumbel distribution (0,1) is shown in equation (1), while the choice probability of MNL is described in equation (2). (Weschke et al, 2022).

$$U_{i,q} = V_{i,q} + \epsilon_{i,q} \quad \text{eq. (1)}$$

$$P_{i,q} = \frac{e^{U_{i,q}}}{\sum_{j=1}^J e^{U_{j,q}}} \quad \text{eq. (2)}$$

Where, i : discrete alternative and q : individual transport mode. (Weschke et al, 2022)

After that calculating CO_2 emissions need to be made through two scenarios, one by using shared e-scooter only and the other one by the substituted alternative mode when shared e-scooter is not used as shown in figure (10).

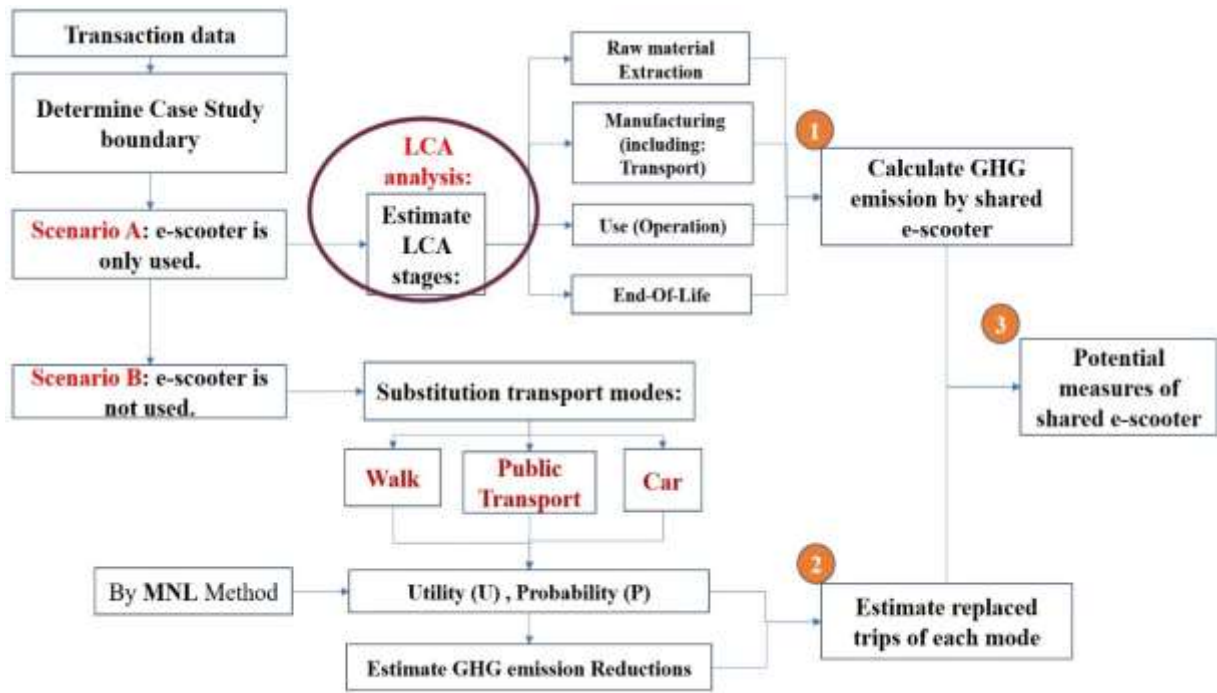


Figure (10) Methodological Framework.

Third, *LCA* analysis estimations which are explained briefly step by step in figure (11) through four *LCA* stages where transport stage is included in the second stage of manufacturing.

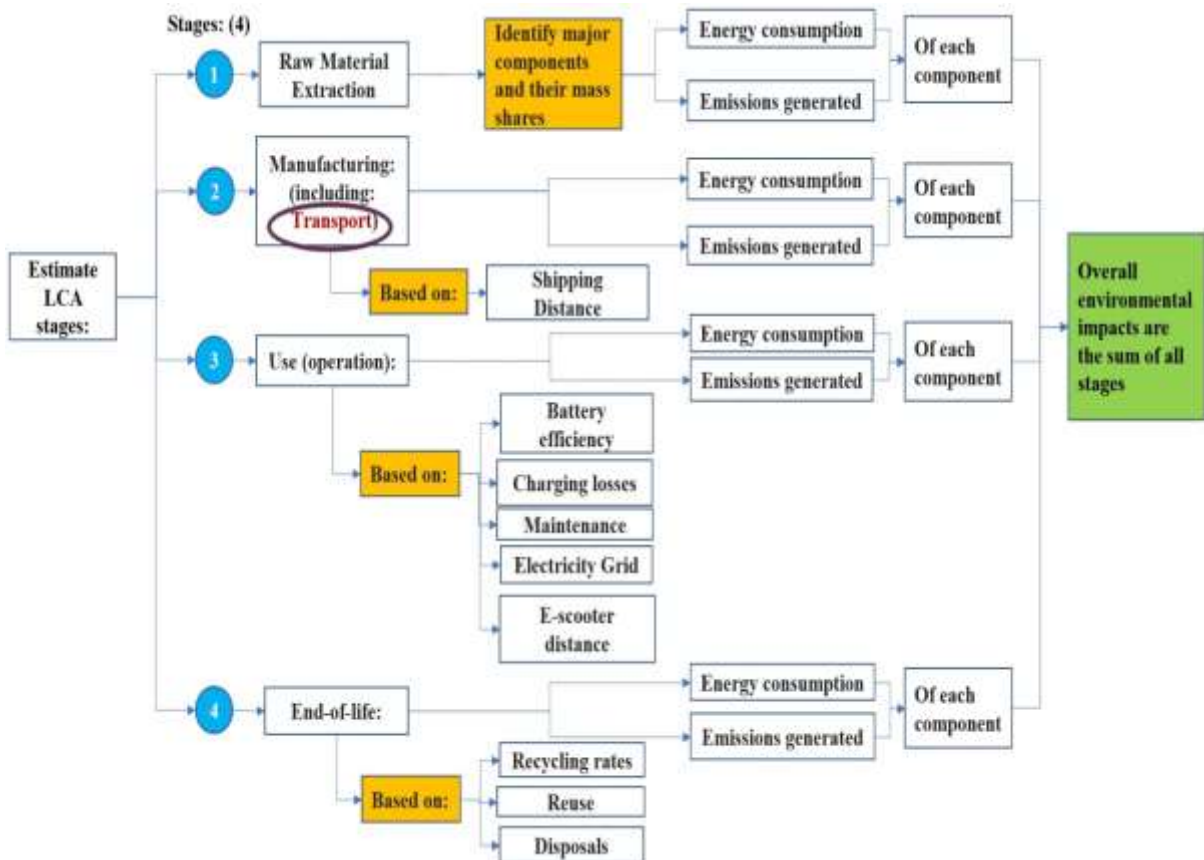


Figure (11) Life Cycle Analysis (*LCA*) framework methodology.

The emission factor (E) is the quantitative number of pollutants existing in the atmosphere. The idea of determining these values of emission factor (E) is to facilitate finding the effects of pollution on the long term. (EPA, 2022) The emission factor (E) of each transport mode per traveller per Km is related to different LCA stages and is calculated based on equation (3):

$$E_{final,j} = E_{production,j} + E_{operation,j} \quad eq. (3)$$

Where (j): refers to each transport mode. (Peci & Ali, 2022)

The Green House Gas emission ($GHG_{emission}$) is affecting on the atmosphere and global warming which needs to be estimated based on LCA analysis of each transport mode (j). (Peci & Ali, 2022) And the equation of ($GHG_{emission}$) of each transport mode (j) is given by equation (4):

$$GHG_{emission,j} = E_{final,j} * Distance_j \quad eq. (4)$$

Where (Distance j): refers to the total trip distance measured for each transport mode (j). (Peci & Ali, 2022)

To reduce the negative effect of (GHG emission) on the environment, it is important to determine GHG emission reduction ($GHG_{reduction}$) for each trip is being calculated from equation (5) between using e-scooter and the other substituted transport mode (Walk, public transport, and car). (Peci & Ali, 2022):

$$GHG_{reduction} = P_{walking} * GHG_{emission,walking} + P_{car} * GHG_{emission,car} + P_{public\ transport} * GHG_{emission,public\ transport} - GHG_{emission,e-scooter} \quad eq. (5)$$

Where the probability of using different transport modes ($P_{walking}, P_{car}, P_{public\ transport}$) are being calculated by using MNL function method. (Peci & Ali, 2022)

After that, filtering these data is based on the limitations from previous studies of maximum permitted speed is $20\ Km/h$, the maximum permitted distance is $10\ Km$, and the maximum travel time is 45 minutes per trip. (Peci & Ali, 2022) And by assuming that the emission unit is corresponding to ($g. CO_2 eq./P * Km$) considering each person is using one scooter per each trip.

4.1. LCA calculations for Model Voyager 5 (V5):

To calculate LCA for the Voyager model (V5), the four main stages “Raw material extraction”, “Manufacturing” (including transport stage), “Use”, and “End-of-life” are determined based on similar assumptions to the same case. The emissions of the model Voyager 5 are going to be calculated to see how its performance will be over its five-year-lifespan.

Making assumptions for Voyager 5 are being difficult due to lack of information, so these assumptions are being taken from different resources based on similar research studies by considering the high recycling materials during the production phase of this product in the same way as in the product Xiaomi M365 from table (9). (Ishaq et al, 2022) and it has been assumed that the additional plastic parts such as the phone holder and other technical components are approximately equal to 1.46% of the total mass.

Table (9) Material components of similar product “Xiaomi M365” e-scooter. (Ishaq et al, 2022).

Material components	Percentage shares	Material mass (kg)
Aluminium alloy	44.15%	5.73
Steel alloy	10.33%	1.33
rubber	8.74%	1.13
Polycarbonate	2%	0.26

lithium-ion battery pack	17.17%	2.23
electric motor	8.75%	1.13
e-scooter charger	3%	0.39
Wiring steel	1%	0.13
Electronic components	3.73%	0.49
Tap water + additional plastic parts	1.46%	0.19
Total	100%	13 (kg)

The mechanical properties of raw materials entering through producing this e-scooter model are illustrated in table (10) which retrieved from different resources.

Table (10) Energy and emissions generated from different resources (Stage 1).

Referenses	Material components	Embodied energy (MJ/kg)	Emissions generated during extraction. (Kg. CO ₂ eq./Kg)
(Energy Education, n.d.)	Aluminium alloy	190-230	8.24
(Energy Education, n.d.) (Materials., n.d.)	Steel alloy	20-25	2
(Materials., n.d.)	rubber	15-17	1.2–1.4
(Energy Education, n.d.)	Polycarbonate	38-47	2.3–2.8
(Materials., n.d.)	lithium-ion battery pack	31-34	2
(Materials., n.d.)	electric motor (steel)	31-34	2
(Materials., n.d.) (Materials., n.d.)	e-scooter charger (steel) e-scooter charger (copper)	31-34 57-63	2 3.7
(Materials., n.d.)	Wiring steel	31-34	2
(Energy Education, n.d.) (Materials., n.d.)	Electronic components	20-25	2
(Materials., n.d.)	additional plastic parts	127-140	6.8–7.5
(Zhu & Lu, 2023)	Tap water	---	0.91

The mechanical properties of components during manufacturing phase (Stage 2) are given in table (11) (Ishaq et al, 2022).

Table (11) The mechanical properties for some materials. (Ishaq et al, 2022).

Materials	Density (g/cm ³)	Stiffness (gpa)	Vibration Transfer speed (m/s)	Damping Capacity	Lifespan (year)	Embodied energy (MJ/kg)
Aluminium	2.7	69	5300	low	40-60	225
Steel	7.8	200	5000	Low	35-55	45
Magnesium	1.7	110	6310	Low	10-15	350
Carbon fiber	1.93			250	40-60	250
Timber	0.7	17	3600	high	10-20	1.2

Assuming that shipping is made by air for similar model Xiaomi M365 of 13 (kg) from the production unit which has a production capacity of 8000 products per month from Shenzhen airport in Hongkong, China to Reggio Calabria airport in Italy has a distance of 95000 (km) plus an additional distance to Milan hub 1000 (km) with a total weight of packaging 171 (ton * km) (plus an additional weight of 18 (ton * km) corresponding to this additional distance. So, the total emission by shipping for each one e-scooter is equal to 0.35 (g. CO₂ eq./Km). (Ishaq et al, 2022)

In this way, the emissions are considered the same when checking the distance per trip from Shenzhen airport to Gothenburg airport which is equal to 8565 (km) and it is close to the distance 9166 (km) by air from Shenzhen airport to Reggio Calabria airport (Air Miles Calculator, 2023).

The assumptions used to calculate both the energy and emissions for manufacturing (stage 1) are shown in table (12).

Table (12) Energy and emissions for manufacturing (Stage 2) from different resources.

Referenses	Material components	consumed energy. (MJ/kg)	Emissions generated. (kg. CO ₂ eq./kg)
(Ishaq et al, 2022) (Zhu & Lu, 2023)	Aluminium	225	18.3
(Ishaq et al, 2022)	Recycled Aluminium		0.5
(Bawden & Babbitt, 2016)	Steel alloy	(15 - 22)	(0.83–1.4)
(Zhu & Lu, 2023) (Chapman A., 2007)	rubber	(15-16)	2.73
(Duval & MacLean, 2007)	Polycarbonate	79	5.41
(Ishaq et al, 2022) (Severengiz et al, 2020)	lithium-ion battery pack	13.8/18 = 0.767	0.568 (kg. CO ₂ eq./KWh) (China)
(Ishaq et al, 2022) (Bawden & Babbitt, 2016)	electric motor (steel)	45	(0.83–1.4)
(Ishaq et al, 2022) (Zhu & Lu, 2023)	e-scooter charger (Steel and copper)	250	16.82
(Ishaq et al, 2022) (Bawden & Babbitt, 2016)	Wiring steel	45	(0.83–1.4)
(Ishaq et al, 2022) (Zhu & Lu, 2023)	Electronic components	250	16.82
(Duval & MacLean, 2007)	additional plastic parts	40	2.71

Assumptions for use stage (stage 3):

The power consumption per kilometre of (SEB) is equal to (0.014 KWh/km). (Zhu & Lu, 2023) So, it is assumed to be the same also for e-scooter Voyager 5.

Battery Efficiency is (90%). (Voi youtube, 2020)

Total distance travelled by e-scooter over lifespan:

Based on the e-scooter data collected (Voi and Tier data, 2022) in Gothenburg city, the average trip distance of each e-scooter is (256841 m) (282 days) according to figure (12).

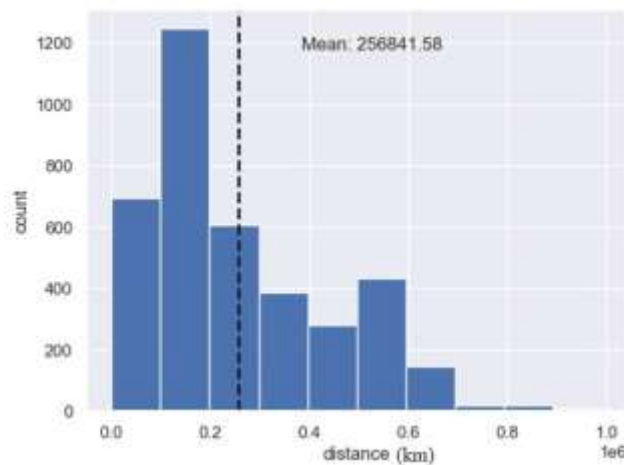


Figure (12) The average trip distance for each e-scooter (Voi and Tier data, 2022).

It means that the average trip for one e-scooter per year is equal to $\left(\frac{256841}{282} * 365\right) = 332436 m = 332.4 km$. So, it has been assumed that the five-year trip distance for one e-scooter is equal to $= 332.4 * 5 = 1662 km$.

Distribution by e-van:

This model has a similar scenario to the case of swappable battery with electric van (e-van) for distribution purposes as shown in table (13). (Severengiz et al, 2020) So, it is assumed that the electricity grid of Sweden to be mix with emission factor of 0.5 ($kg. CO_2 eq./KWh$) the same as in Italy. Another assumption is that the electric van serves an average of 100 e-scooters with travelling distance 100 Km/day when the whole e-scooter is collected once per day for charging and only one battery per scooter is needed.

Table (13) Swappable battery with e-van during distribution phase. (Severengiz et al, 2020)

	Base case	Shorter Lifespan	Not-swappable battery	E-vans
Energy demand per Km (kWh)	0.015			
Average distance per day (km)	10.2			
lifespan e-scooter (month)	24	6	24	24
Battery type	swappable	swappable	Non-swappable	swappable
Energy demand per lifespan (kWh)	115	29	115	115
Average distance per lifespan (km)	7500	1900	7500	7500
Vehicle for collecting broken scooter	Diesel-van	Diesel-van	Diesel-van	e-van
Distance per van and day (km)	50	50	100	50
Served e-scooter per van and day	200	200	100	200
Distance per van, scooter, and day (km)	0.25	0.25	1.00	0.25
Distance per cargo bike, and day (km)	-	-	-	-
Served e-scooter per cargo bike and day	-	-	-	-
Distance per cargo bike, scooter, and day (km)	-	-	-	-
Electricity Grid mix for charging of e-scooter	German mix, 0.568 ($Kg. CO_2 eq./KWh$)			

Charging losses:

The loss in charging caused more electricity to the actual power consumption per kilometre and it is equal to $(0.0169 Kwh/km)$ in the case for Shared electric bike (*SEB*). (Zhu & Lu, 2023).

Maintenance requirements:

The Additional factors for maintenance purposes are counted to be equal to $(5.53) (kg. CO_2 eq.)$ per one e-scooter as shown in table (14) from shared electric bike maintenance (*SEB*). (Zhu & Lu, 2023)

Table (14) (CO_2) emissions during maintenance of each component. (Zhu & Lu, 2023)

Coding	Part (Component)	maintenance (%)	Weight (kg)	GHG emission factor	Unit	GHG emission ($kg.$)
1	Brake (1)	0.7	0.392	2.3	($t. CO_2 eq./t$)	0.0063
2	chain	2.23	0.3	2.3	($t. CO_2 eq./t$)	0.0154
3	Foot support	2.97	0.4	2.3	($t. CO_2 eq./t$)	0.0273
4	saddle	4.4	1.5	2.73	($t. CO_2 eq./t$)	0.1802
5	Brake (2)	5.57	0.12	18.3	($t. CO_2 eq./t$)	0.1223
6	Pedal	5.63	0.33	3.12	($kg. CO_2 eq./kg.$)	0.058
7	Lock	58.13	0.78	2.3	($t. CO_2 eq./t$)	1.0429
8	Sign	61.73	0.08	3.12	($kg. CO_2 eq./kg.$)	0.1541
9	Tire	69.03	2	2.73	($t. CO_2 eq./t$)	3.769

10	Basket components	13.33	0.5	2.3	(t. CO ₂ eq./t)	0.1533
	total					5.5288

Assumptions for end-of-life (stage 4):

The recycling materials of all components are 90% and the disposal content is 10%. According to Voi report in 2022 the emissions of 26.7 (g. CO₂) are subtracted from production due to end-of-life measures for reuse and recycling. (Voi report, 2022) So, it will be assumed that reusing materials will be 26.7 (g. CO₂) for each one e-scooter.

At the end-of-life, the embodied energy of Aluminium is equal to 53 (MJ/Kg), while the emissions are 3 (kg. CO₂ eq./kg). This is related to 90% recycling rate of Aluminium. (Recycling Today, 2017) And this needs an energy consumption of 1.56 (MJ) or equivalent to 98.7 (g. CO₂). (Aluminium LCA, 2021) The electronic components like small IT products need for recycling 20.154 (ton. CO₂ eq./ton). (Elretur., 2022) Tables (15), (16), (17), (18), and (19) explain the energy consumption and emission factors used for each type of recycling and disposal material.

Table (15) Recycling plastics and rubber (resin). (Duval & MacLean, 2007)

references	Activity	Energy		GHG emissions	
		Energy requirement	Units	(CO ₂ eq.)	Units
C1	Virgin plastic resin production	40000	(KJ/kg)	2713	(g. CO ₂ eq./kg)
C5	Metal recovery /ASR separation	361	(KJ/kg)	75	(g. CO ₂ eq./MJ)
P6	Recycled Plastic resin production	4620	(KJ/kg)	75	(g. CO ₂ eq./MJ)
C2, C4, C6, P5, P7	Transportation (diesel operated tractor trailer)- operating at 60% and 85% capacity utilization	3.6	(KJ/kg * km)	0.125 (60%)	(g. CO ₂ eq./kg)
				0.103 (85%)	

Table (16) Recycling copper from electric motor. (Materials, n.d.)

Metal	Embodied energy (MJ/kg)	Carbon footprint (kg. CO ₂ /kg)	Water usage
Copper – pure:			
primary	57-63	3.7	293-324
recycled (40 to 45%)	12.9-14.3	1.07	
Copper alloys:			
primary	56-62	3.7	268-297
recycled (40 to 45%)	12-15	0.83	

Table (17) Recycling Steel alloy. (Materials, n.d.)

Metal	Embodied energy (MJ/kg)	Carbon footprint (Kg. CO ₂ /kg)	Water usage (L/kg)
Low steel alloy:			
primary	31-34	2	37-111
recycled (40 to 44%)	7.7-9.5	0.52	
Stainless steel:			
primary	81-88	5.0	112-336
recycled (35 to 40%)	11-13	0.73	

Table (18) (CO_2 eq.) emissions during disposal stage. (Zhu & Lu, 2023)

operation	Energy consumption	Weight	Unit	GHG emission factor	Unit	GHG ($Kg. CO_2$ eq./SEB)
Scenario 1	Solid waste incineration	6.77	(kg)	-124.3	(kg. CO_2 eq./t)	0.8415
	Diesel van average	0.04	(km)	0.6026	(kg. CO_2 eq./t * Km)	0.1447
	Electricity	0.11	(kwh)	0.53	(kg. CO_2 eq./KWh)	0.0583
	Total					0.6385
	Sewage	0.007	(m^3)	0.24	(kg. CO_2 eq./ m^3)	0.0064
	Diesel van average	0.015	(km)	0.6026	(kg. CO_2 eq./t * Km)	0.0309
	Mechanical energy consumption	2.0	(km)	0.285	(kg. CO_2 eq./Km)	0.57
Scenario 2	Natural degradation- plastic	3.21	(kg)	0.13	(Kg. CH_4 /Kg)	0.4176
	Natural degradation- rubber	3.5	(kg)	0.47	(Kg. CH_4 /Kg)	1.645
	Natural degradation- paper	0.06	(kg)	0.44	(Kg. CH_4 /Kg)	0.0264
	Total (for one (SEB))					52.8323

Table (19) Emissions of treated each type of waste. (Norden., 2015)

Material	Secondary production ($Kg. CO_2$ eq./kg.)	Primary production ($Kg. CO_2$ eq./kg.)
Glass	0.5	0.9
Aluminium	0.4	11.0
Steel	0.3	2.4
Plastics	1.3	2.1
Paper and cardboard	0.7	1.1
Organic waste (composting)	0.05	0.07
Organic waste (digestion)	0.01	0.09

4.2. Modal substitution transport patterns from Previous literature:

The previous literature review analyses are based on local surveys (excluding the Covid-19 surveys) from different locations for the substitution patterns of each alternative transport mode when replaced by shared e-scooter. These results are summarized in table (20) to show how these five basically transport modes are being replaced and considering only the case of travel distance is less than two kilometres.

Table (20) Results of substitution rates (%) by using shared e-scooter in different locations.

Reference	location	Substitution rate (%)				
		walk	Private bike	public transport	Private car	Shared e-scooter
(Badia & Jenelius, 2021)	Paris, France	60.3%	---	26.4%	---	0%
(Reck et al, 2022)	Paris, France	35%	----	37%	----	0%
(Christoforou et al, 2021) (Face to face survey)	Paris, France	35%	----	27%	9%	0%
(Wang et al, 2022) (online survey)	Paris, France	44%	----	30%	----	0%
(Weschke et al, 2022)	Berlin, Germany	42%	11.5%	20%	12%	0%
(Wang et al, 2022)	Munich, Germany	80%	----	59%	----	0%
(Wang et al, 2022)	Oslo, Norway	60%	----	23%	----	0%
(Reck et al, 2022)	Oslo, Norway	60%	----	23%	8%	0%
(Wang et al, 2022)	Zurich, Switzerland	52%	----	24%	---	0%
(Reck et al, 2022)	Zurich, Switzerland	51%	13%	19%	12%	0%
(Miller, 2020)	Stockholm, Sweden	47%	3%	33%	4%	0%
(Peci & Ali, 2022)	Gothenburg, Sweden: trip distance < 2 (km)	58%	12%	5%	24%	0%
(Peci & Ali, 2022)	Gothenburg, Sweden: trip distance > 20 (km)	0%	0%	29%	70%	0%
(Wang et al, 2022)	Tempe, Arizona	57%	----	4.5%	----	0%
(Wang et al, 2022)	Tucson, Arizona	36%	----	3%	---	0%
(Wang et al, 2022)	San Francisco, California	61%	----	34%	----	0%
(Wang et al, 2022)	Denver, Colorado	43%	----	7%	----	0%
(Wang et al, 2022)	Toronto, Canada	57%	----	53%	----	0%
(Wang et al, 2022)	Auckland, New Zealand	53%	----	7%	----	0%
(Badia & Jenelius, 2021)	All over the world	-----	10%	15%	40%	0%
(VOI report, 2021)	all cities provided by VOI service	----	----	63%	14%	0%

4.3. Emission factors (E) of replacing other transport modes (from previous literature):

This analysis is focusing on the substitution modes of both public transport and private car to see the environmental benefits of replacing these trips by shared e-scooter to reduce the emission impacts. The emissions are distributed with a range of values of each substituted transport mode as shown in table (21).

Table (21) Emission factors (E) of each substituted transport mode from previous literature.

reference	location	emissions ($g. CO_2 eq./p * Km$)				
		walk	Private bike	public transport	private Car	Shared e-scooter
(Weschke et al, 2022)	Germany	(0-2)	(5-17)	(71-80)	(147-257)	(43-131)
(Severengiz et al, 2020)	Germany	0	8	(58-80)	147	(64-237)
(Kazmaier et al, 2020) (Appendix A)	Germany	0	5	58	220.5	-----
(Cottell, Connelly & harding, 2021)	United Kingdom	0	37.05	16.04	160.7	67.1
The average values		0	15	54.7	170	101.53

In this way, the average emission factor of public transport ($E_{avg,PT} = 54.7 g. CO_2 eq./p * Km$) and the average emission factor of car ($E_{avg,car} = 170 g. CO_2 eq./p * Km$) are being used later when substituting both Public Transport and Car by shared e-scooter to calculate GHG emission reduction for the scenario (B) by using previous equation (5).

4.4. LCA analysis from previous literature:

The previous literature reviews the emission factors of LCA stages in different ways as shown in table (22) according to different locations.

Table (22) Results of emission factors (E) for each LCA stage (previous literature).

Reference	City, country	Lifespan (months) or (Km)	LCA stages ($g. CO_2 eq./p * Km$) or (%)					Total (E) ($g. CO_2 eq./p * Km$)
			material and manufacturing	Transport	Charging	redistribution and collection	end of life	
(Severengiz et al, 2020) (non-swappable battery)	Berlin, Germany	24 months	----	----	(Two into one stage): 58%	---	121	
The rest of cases are for swappable battery:								
(Severengiz et al, 2020)	Berlin, Germany	24 months	63%	1%	(Two into one stage): 35%	1%	77	
(Badia & Jenelius, 2021)	Berlin, Germany	20 Km/day	----	----	----	----	58	
(Kazmaier et al, 2020)	Berlin, Germany	6 months 2117 (km)	120	15	5	20	5	165

		3 months 1058 (km)	240	30	1	20	9	300
		15 months 4057(km)	48	6	5	20	2	82
		9 months 2434(km)	80	10	5	20	3	119
		10000 (km)	19	2	5	20	1	49
(Kazmaier et al, 2020)	Berlin, Germany	24 months	50%	---	---	---	---	88.1
(Schünemann et al, 2021)	Berlin, Germany	12000 (km)	61%	---	(With green operation - wind power)	----	---	42.8
	Berlin, Germany	12000 (km)	61%	----	(Without green operation)	----	---	46.7
(Weschke et al, 2022)	US	1200(km)						125.5
	US	6000(km)						87.6
(Weschke et al, 2022)	Paris, France	---	---	---	----	---	----	109
(Miller, 2020)	Paris, France	24 months	58.8	4.6	6.84		- 35.5	34.7
(Cottell, Connelly & harding, 2021)	United Kingdom	24 months	35	(Three stages into one): 32.1			0	67.1
(Miller, 2020)	Stockholm, Sweden	24 months	---	----			----	64
(Miller, 2020)	Brussels, Belgium	12 months	104	3	24		0	131
(Weschke et al, 2022)	Brussels, Belgium	---	----	---	---	----	---	131
(Miller, 2020)	Raleigh, North Carolina	12 months	61.5	1.86	62.1		0	126

As mentioned before that the changes of emissions during the material and manufacturing stage are very big comparing to other stages from previous table (22), the analysis will estimate the emission values for this stage after drawing the power curve in figure (13) between the crossing points of (emissions and months) based on the data from previous table (6) (Kazmaier et al, 2020). This curve equation helps in determining the expected value corresponding to 24 months which is 30 ($g. CO_2 eq./Km$) in Berlin. And this result is very close to the approximated value 35 ($g. CO_2 eq./p * Km$) in Gothenburg city (Peci & Ali, 2022).

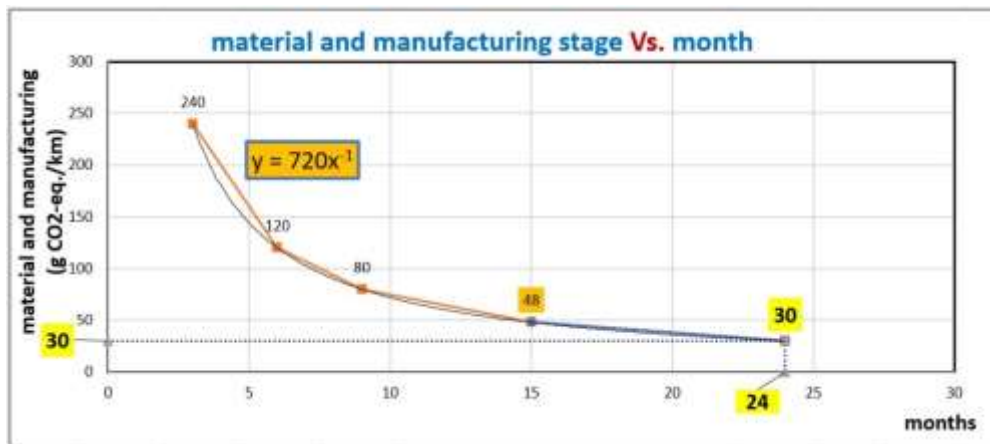


Figure (13) Estimating the emissions corresponding to material and manufacturing stage.

Thus, the concluded results from previous literature could be summarized in table (23) to show the average values for each *LCA* stage for 24 months lifespan.

Table (23) Summary results of *LCA* emission factors (*E*) from previous literature.

Reference	City, country	Lifespan (months)	<i>LCA</i> stages ($g. CO_2 eq./p * Km$)					Emission factor (<i>E</i>) ($g. CO_2 eq./p * Km$)
			material and manufacturing	Transport	Charging	redistribution and collection	end of life	
(Kazmaier et al, 2020)	Berlin, Germany	24	30	6	5	20	2	63
(Cottell, Connelly & harding, 2021)	United Kingdom	24	35	(Three stages into one): 32.1			0	67.1
(Severengiz et al, 2020)	Berlin, Germany	24	48.51	0.77	26.95		0.77	77
The average values		24	37.8	5.2	5	20	2	70

4.5. Determining the case study boundaries:

The VOI and TIER data have been recorded as daily trips of Gothenburg city and collected during the duration from 28th of December 2021 until 11th of January 2023, the total number of trips is counted to be 718761 trips.

Each trip includes full information in related to the longitudinal and latitude coordinates, starting, and ending points, The network distance (in meter), and the duration travel time (in seconds). (Voi and TIER data, 2022) By knowing that These data collected of “Car” mode is assumed to have the same emission factor of “private car” from table (21).

When using *MNL* equations (Weschke et al, 2022) to handle VOI and TIER transaction data are handled according to equations: (eq.7) for Walk, (eq.8) for Public Transport (*PT*), and (eq.9) for Car as follows:

$$V_{walk} = ASC_{walk} + \beta_{walk_distance} * Km_walk_dist + \beta_{walk_distance_2} \quad eq. (7)$$

$$V_{PT} = 2 + ASC_{PT} + \beta_{PT_time} * HR_transitTime + \beta_{PT_cost} * HR_waitingTime + \beta_{kids} * 0.5. \quad eq. (8)$$

$$V_{car} = 1 + ASC_{car} + \beta_{car_time} * HR_car_time + \beta_{car_cost} * CarCost + \beta_{lic} * 0.5 + \beta_{car_male} * 0.5 + \beta_{car_cons_cap} * cons_cap \quad eq. (9)$$

Where all parameters such as: *ASC*, β , and others are estimated for each substituted mode used from the above equations and are explained briefly in table (24) according to the case of Gothenburg city. (More details are also existed in Appendix (3)).

Table (24) Explanation of parameters related to *MNL* equations for Gothenburg city. (Bai, T. et al, 2017)

Mode	Parameter	explanation	value
Walk	V_{walk}	utility of Walk	Calculated from eq. (7)
	ASC_{walk}	alternative specific constant	1.45
	$\beta_{walk_distance}$	The coefficient of Walk distance related to (<i>MNL</i>)	-7.78
	$\beta_{walk_distance_2}$	The coefficient of Walk distance less than 2 (<i>km</i>)	1.08
	Km_walk_dist	Walk distance in (<i>km</i>)	$walk_distance_x/1000$
Public Transport	$walk_distance_x$	Walk transit distance (<i>m</i>)	(Voi and TIER data, 2022)
	V_{PT}	utility of public transport	Calculated from eq. (8)
	ASC_{PT}	alternative specific constant	0.611
	$HR_transitTime$	Total travel time by public transport (in hour)	$transit_time/3600$
	$transit_time$	travel time by public transport (in seconds)	(Voi and TIER data, 2022)
	$HR_waitingTime$	waiting time (in hour)	$waitingTime/3600$
	$waitingTime$	waiting time for public transport (in seconds)	(Voi and TIER data, 2022)
	β_{PT_time}	Coefficient of public transport time related to (<i>MNL</i>)	-0.968
Car	β_{PT_cost}	Coefficient of public transport travel cost related to (<i>MNL</i>)	-0.0471
	β_{kids}	If respondent is kid	0.469
	V_{car}	utility of driving car	Calculated from eq. (9)
	ASC_{car}	alternative specific constant	0.4
	β_{car_time}	Beta coefficient of driving time	-1.03
	β_{car_cost}	Beta coefficient of driving cost	-0.0215
	β_{car_male}	If the respondent is male	0.39
	$\beta_{car_cons_cap}$	Beta coefficient of Consumption capacity according to social norm.	0.2
	$cons_cap$	Consumption capacity (constant)	3
	Km_car_dist	Driving distance in (<i>km</i>)	$car_distance/1000$

	<i>car_distance</i>	Driving distance in (m)	(Voi and TIER data, 2022)
	<i>CarCost</i>	The cost of driving car in (SEK)	$61 + Km_car_dist * taxiprice$
	β_{lic}	If respondent has a driving licence	1.3
	<i>HR_car_time</i>	time of driving car (in hour)	$car_time/3600$
	<i>car_time</i>	time of driving car (in seconds)	(Voi and TIER data, 2022)
	<i>taxiprice</i>	The price of driving per one kilometre in (SEK)	17/1000

By using GIS opensource (DIVA-GIS, Sweden) to extract the maps of Gothenburg city and to define the boundary areas of all e-scooter trips needs to focus only on the inner city of Gothenburg while the islands of the city and the suburb areas are being excluded from the case study analysis because of the limited data collected there. And after applying the grids system available by GIS program (Arcmap 10.8.2 program) of each grid dimension (400 meter * 400 meter) , the data analysis is shown in figure (14).

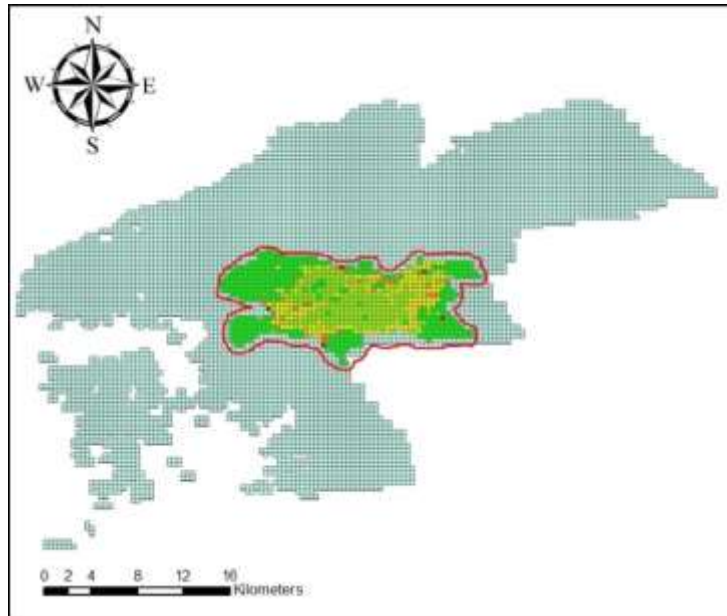


Figure (14) Boundary areas of trips in Gothenburg city. (Arcmap 10.8.2 program)

5. Results analysis and Discussion:

This section will browse the results of methods applied to compare them with results from similar studies and discuss the reasons of choosing shared e-scooter as an alternative substitution pattern among other micro mobility transport choices.

5.1. LCA results of model Voyager 5:

As been clarified before that *LCA* calculations contain four main stages (Extraction, Manufacturing (including Transport), Use, End-Of-Life). The energy consumption and emissions generated at each stage are estimated from previous section (4.1) for each component of e-scooter after multiplying its mass by the corresponding coefficient for each stage. The sum of all stages will give the total environmental emission factor by e-scooter ($kg. CO_2 eq.$) which needs to be calculated (per Km travelled) to find the environmental impact after dividing the emissions generated on the the average trip distance of one e-scooter per one year and then multiplied by five years (the expected lifespan

duration of 60 months for Voyager V5). These calculations are shown briefly for each stage in tables (25), (26), (27) and (28).

Table (25) Energy consumption and emissions of Stage 1.

Material Components	Percentage shares	Material mass	Embodied energy (MJ/kg)	Energy consumption (MJ)	Emissions generated during extraction. (kg. CO ₂ eq./kg)	Emissions generated. (kg. CO ₂ eq.)	References
Aluminium alloy	44.15%	5.73	230	1317.9	8.24	47.2152	(Energy Education, n.d.)
Steel alloy	10.33%	1.33	25	33.25	2	2.66	(Materials., n.d.)
Rubber	8.74%	1.13	17	19.21	1.4	1.582	(Materials., n.d.)
Polycarbonate	2%	0.26	47	12.22	2.8	0.728	(Energy Education, n.d.)
Lithium-ion battery pack	17.17%	2.23	34	75.82	2	4.46	(Materials., n.d.)
Electric motor	8.75%	1.13	34	38.42	2	2.26	(Materials., n.d.)
E-scooter charger	3%	0.39	63	24.57	3.7	1.443	(Materials., n.d.)
Wiring steel	1%	0.13	34	4.42	2	0.26	(Energy Education, n.d.)
Electronic components	3.73%	0.49	25	12.25	2	0.98	(Materials., n.d.)
Additional plastic parts	1.46%	0.19	140	26.6	7.5	1.425	(Zhu & Lu, 2023) (Materials., n.d.)
Total				1564.66		63.0132	

Table (26) Energy consumption and emissions of Stage 2.

Material Components	Percentage shares	Material mass	Embodied energy (MJ/kg)	Energy consumption (MJ)	Emissions generated during extraction. (kg. CO ₂ eq./kg)	Emissions generated. (kg. CO ₂ eq.)	References
Aluminium alloy	44.15%	5.73	225	128.93	18.3	104.86	(Ishaq et al, 2022) (Zhu & Lu, 2023)
Steel alloy	10.33%	1.33	22	29.26	1.4	1.862	(Bawden & Babbitt, 2016)
rubber	8.74%	1.13	16	18.08	2.73	3.0849	(Zhu & Lu, 2023) (Chapman A., 2007)
Polycarbonate	2%	0.26	79	20.54	5.41	1.4066	(Duval & MacLean, 2007)
lithium-ion battery pack	17.17%	2.23	0.767	1.71	0.568	1.26664	(Ishaq et al, 2022) (Severengiz et al, 2020)
electric motor (Steel)	8.75%	1.13	45	50.85	1.4	1.582	(Ishaq et al, 2022) (Bawden & Babbitt, 2016)
e-scooter charger (Steel +Copper)	3%	0.39	250	97.5	16.82	6.5598	(Ishaq et al, 2022) (Zhu & Lu, 2023)
Wiring steel	1%	0.13	45	5.85	1.4	0.182	(Ishaq et al, 2022) (Bawden & Babbitt, 2016)

Electronic components	3.73%	0.49	250	122.5	16.82	8.2418	(Ishaq et al, 2022) (Zhu & Lu, 2023)
additional plastic parts	1.46%	0.19	40	7.6	2.71	0.5149	(Duval & MacLean, 2007)
Total				1643.14		129.56	

Environmental impact for one e-scooter associated with manufacturing and transport to Sweden is equal to = $129.56 + (0.35 * 8565/1000) = 129.56 + 2.998$ (transport) = $132.558 \text{ kg. CO}_2 \text{ eq.}$

Table (27) Energy consumption and emissions of Stage 3.

Energy consumption of e-scooter (KWh/km) (Zhu & Lu, 2023)	Charging losses (KWh/km) (Zhu & Lu, 2023)	Total distance travelled by the e-scooter over Lifespan (Km) (Voi and Tier data, 2022)	Total energy consumed by e-scooter over 5 years. (KWh)	Charging efficiency (Voi youtube, 2020)	Energy required for e-scooter from electricity grid. over 5 years. (KWh)	Total Emissions (Electricity mix grid of Sweden) (0.5 kg. CO ₂ e /KWh)	Maintenance requirements (kg. CO ₂ eq. per one e-scooter) (Zhu & Lu, 2023)	Total Emissions of using one e-scooter (kg. CO ₂ eq.)
0.014	0.0169	1662	51.36	90%	57.06	28.53	5.53	34.06

Table (28) Energy consumption and emissions (recycling and disposal) of Stage 4.

All Material component	Recycling rate (90%)	Material mass recycled (kg)	Energy consumption (MJ/kg)	Energy consumption (MJ)	Disposal components (10%)	Material mass disposed (kg)	Emission factor from recycling. (kg. CO ₂ e /kg)	Emission factor from disposal. (kg. CO ₂ e /kg)	Overall Emissions per one e-scooter (kg. CO ₂ eq.)		Reference:
									Emission from recycling (Nord en., 2015)	Emission from disposal (Zhu & Lu, 2023)	
Aluminum alloy	39.74%	5.17	53	274	4.415%	0.573	3	0.4	15.51	0.2292	(Materials, n.d.)
Steel alloy	9.3%	1.21	9.5	11.495	1.033%	0.133	0.52	0.3	0.6292	0.0399	(Materials, n.d.)
rubber	7.9%	1.02	15	15.3	0.874%	0.113	1.2	3.6	1.224	0.4068	(Duval & MacLean, 2007)
Polycarbonate	1.8%	0.23	4.62	1.06	0.2%	0.026	0.075	0.8	0.01725	0.0208	(Materials, n.d.)
Lithium battery	15.45%	2.01	0.767	1.542	1.717%	0.223	0.568	0.568	1.14168	0.126664	(Materials, n.d.)
electric motor	7.88%	1.02	15	15.3	0.875%	0.113	0.83	1.07	0.8466	0.12091	(Materials, n.d.)
e-scooter charger	2.7%	0.35	9.5	3.33	0.3%	0.039	0.52	0.52	0.182	0.02028	(Materials, n.d.)
Wiring steel	0.9%	0.12	9.5	1.14	0.1%	0.013	0.52	0.52	0.0624	0.00676	(Materials, n.d.)

Electronic components	3.36%	0.43	3.6	1.55	0.373%	0.049	0.02	0.02	0.0086	0.00098	(Materials, n.d.)
Additional plastics	1.32%	0.17	15	2.55	0.146%	0.019	1.2	1.3	0.204	0.0247	(Duval & MacLean, 2007)
Total	90%	11.73		327.27	10%	1.30			19.826	0.997	

The emissions per one e-scooter of recycling, reuse, and disposals is equal to:
 $= 19.826 + 0.997 + 0.0267 (reuse) = 20.85 (kg. CO_2 eq.)$

Summary of all LCA stages (five -year-lifespan):

Table (29) summarizes the final calculations of energy consumption and emissions for each LCA stage.

Table (29) The total environmental impact for one e-scooter for five-year- lifespan.

Stage	Energy consumption of one e-scooter (MJ)	Emission factor of each stage (kg. CO ₂ eq.)	Sharing percentage of each stage
(1). Raw material extraction	1564.66	63.0132	25.16%
(2). Manufacturing: (including transport)	1643.14	129.56 (2.998)	51.72% (1.2%)
(3). Use:	0.057	34.06	13.6%
(4). End-OF-Life:	327.27	20.85	8.32%
Total	3535.127	250.481	

The total environmental impact for one e-scooter (per Km. travelled) is equal to:
 $= 250.481/1662 = 0.151 (kg CO_2 eq./km) = 151 (g. CO_2 eq./km)$. And the sharing percentage of manufacturing stage (51.72%) is the highest percentage whereas the sharing percentage of transport stage (1.2%) is the lowest one of the same LCA analysis.

The total travelled distance by e-scooter over the lifespan of five years is equal to 1662 km and it is affecting on the calculated emission factor of the current case compared to previous literature. Also, each LCA stage has a lot of details in terms of the coefficients used and the affecting factors used from similar case studies.

Thus, reducing the negative impact of e-scooter based on the calculations of each stage is mainly based on two things: the first one is the manufacturing percentage of the total life cycle emissions and the other important thing is the expected lifespan of e-scooter which has the biggest effect when dividing the total emissions of e-scooter by the travelled distance (per Km) in addition to the effects of lifespan on the Use stage.

5.2. Applying a Multinomial Logit model (MNL):

To estimate the alternative substitutional patterns by using multinomial logit model (MNL), two scenarios are being considered. The first one is when shared e-scooter is used only and the second one is when shared e-scooter is not existing which needs to calculate the modal splits of alternative substitution patterns: “walk”, “public transport” and “Car”.

Jupyter program is applied here to estimate the emissions of using the e-scooter based on the trip distance between the start and end points of each trip and calculate ($GHG_{emission,j}$) of each transport mode in different scenarios:

Scenario A:

Estimating $GHG_{emission,e-scooter}$ if shared e-scooter is the only used mode as shown in table (30).

Table (30) Estimating emissions for using only shared e-scooter mode (Scenario A).

Scenario	Total number of filtered trips	Total distance (km)	Real Lifespan (months)	shared e-scooter mode ($g.CO_2 eq./p * km$)	
				emission factor (E) from previous literature	$GHG_{emission,e-scooter}$
A	718761	861106	12	70	$70 * 861106 = 60,277,420$

Scenario B:

Estimating $GHG_{emission,j}$ for other substituted transport modes (if shared e-scooter mode doesn't exist) starts from finding the utilities of each mode ($U_{walking}, U_{car}, U_{public transport}$) and then finding the probabilities of using different transport modes ($P_{walking}, P_{car}, P_{public transport}$) by means of Jupyter program as shown in table (31). But when estimating $GHG_{emission,j}$, from equation (5), it has been considered the following:

- the estimated emissions of Walk mode $GHG_{emission,walking} = 0$
- the average emission factor of Public Transport ($E_{avg,PT} = 54.7 g.CO_2 eq./p * Km$)
- the average emission factor of Car ($E_{avg,car} = 170 g.CO_2 eq./p * Km$)
- the emission factor of shared e-scooter from previous literature case is ($E_{avg,E-scooter} = 70 g.CO_2 eq./p * Km$).

The results of the Green House Gas (GHG) reduction emissions are calculated from equation (5) for each trip and included in table (31). These values are going to be visualized later by the grid system and according to each zone of Gothenburg by means of Arcmap program (10.8.2).

Table (31) Utility and Probability (U_j, P_j) of each substituted transport mode (Scenario B). (Jupyter notebook, Python 3)

trip No.	trip distance (Km.)	trip duration (Min.)	Utility for each transport mode			Probability of each transport mode			(GHG) Emission Reduction ($g.CO_2 eq.$)
			Walk	Public Transport (PT)	Car	Walk	Public Transport (PT)	Car	Previous literature case
1	2.949414251	22.1666667	3.4577357	2.6841405	1.17850947	0.639503	0.295035536	0.06546167	-87.255
2	1.64108053	18.55	3.4168442	2.7325405	1.31941074	0.614548	0.310003365	0.075448733	-30.278
3	0.990788178	10.35	3.1681033	2.813207167	1.41046351	0.533704	0.374257954	0.092038007	-21.319
.....
718758	1.459956335	17.45	3.2526916	2.716407167	1.27474878	0.580292	0.339422811	0.080285431	5.502
718759	1.520978264	8.28333333	3.1628267	2.8455	1.42054847	0.525427	0.382559658	0.092013295	-72.403

718760	0.293548393	25.3	3.1843557	2.571207167	1.31710561	0.589556	0.319328928	0.09111479	123.262
718761	0.726861161	18.4666667	3.3199336	2.716407167	1.37905607	0.591556	0.323509855	0.084934339	29.867

5.3. Statistical analysis of VOI and TIER data:

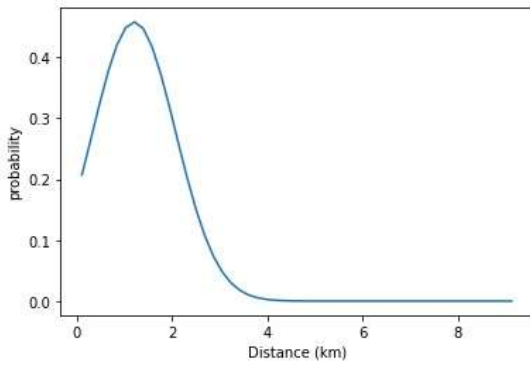
The statistical analysis has been made on Voi and Tier data to draw histograms for distance and duration analysis of each substituted transport mode in addition to (GHG) reduction analysis according to each zone within Gothenburg city.

5.3.1. distance analysis:

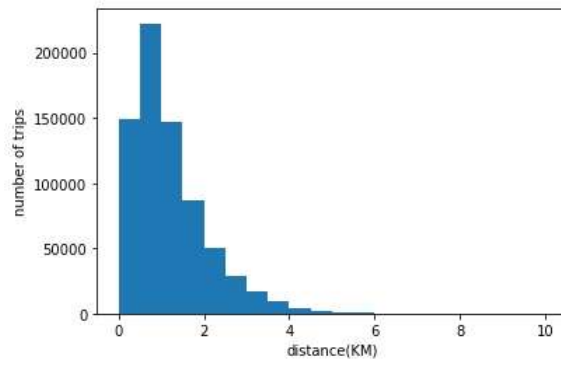
The number of trips is filtered according to the maximum distance of 10 kilometres as seen in table (32). And the common thing from figure (15) that most of trips have less than 6 Km. distance.

Table (32) Distance analysis results. (Jupyter notebook, Python 3)

	No. of trips	Mean distance (Km)	Std. (distance)	Maximum distance. (Km)	Minimum distance. (Km)
After filtering: (Maximum distance: 10 Km.)	718751	1.197	0.871	9.13	0.1



(a) Distance – probability distribution.



(b) Distance – Number of trips distribution.

Figure (15) Probability distribution according to: a) Distance, b) Number of trips. (Jupyter notebook, Python 3)

Distance Analysis with respect to each substituted transport mode is useful to show how the estimated substitution rate of each transport mode in terms of distance (Km) as shown in figure (16). In case (a) of “Walk” substituted distance, it has a peak probability more than 25% and most of substituted walk distance is less than 1.5 Km. While in case (b) of “public transport” substituted distance, it has a peak probability more than 60% and most of substituted distances by public transport are less than 6 Km distance. But, in case (c) of “Car” substituted distance, it has a peak probability more than 25% and most of substituted distance by Car is less than 8 Km.

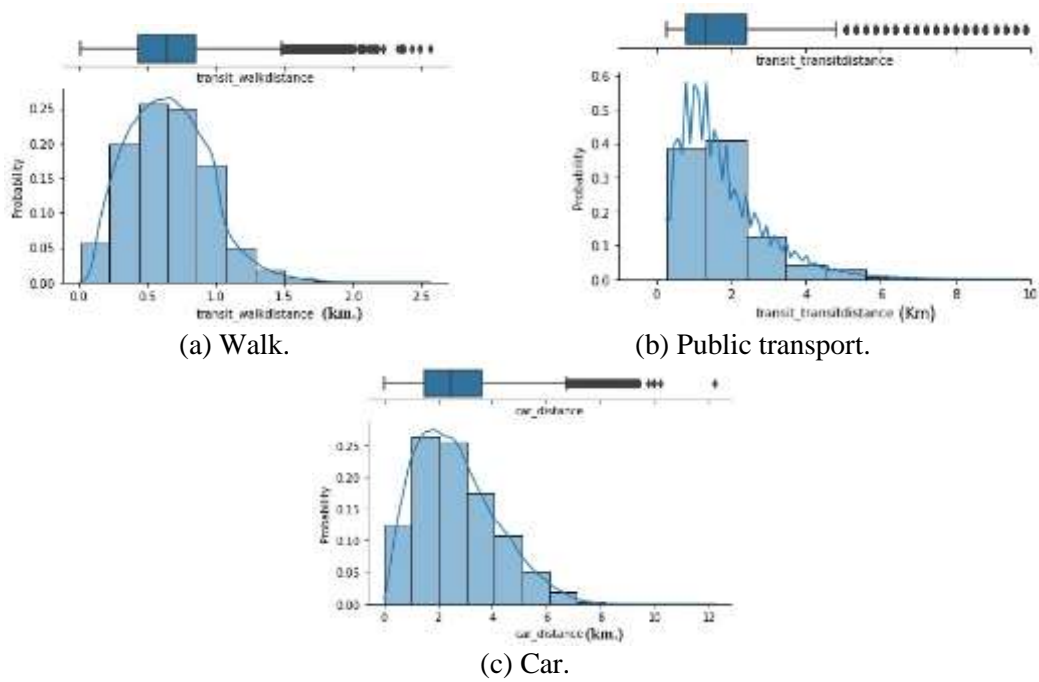


Figure (16) Distance-probability distribution of each substituted transport mode. (Jupyter notebook, Python 3)

All substituted modes (walk, public transport, Car) are visualized together to show the following results in figure (17), where the highest probability of substituted transport mode is “walk” between (40%-80%) of total trips. While the lowest probability of substituted transport mode is “Car” (less than 20%). The correlation between “walk” and “public transport” is explained by the free movement of travellers to reach to the nearest stations by Walk when shared e-scooter is not available.

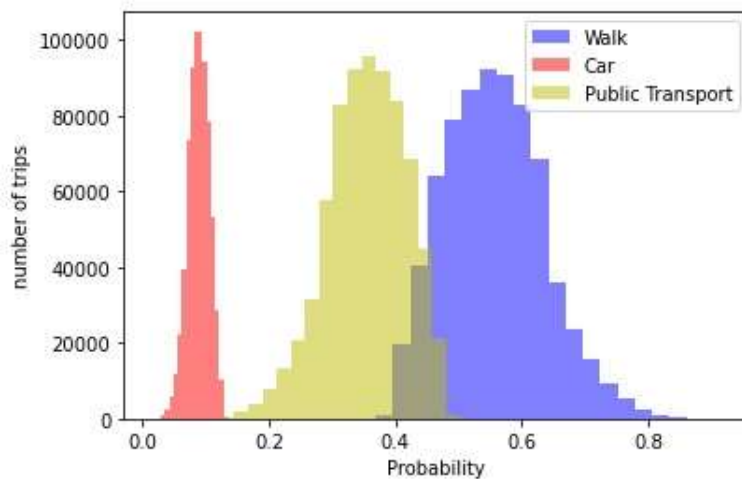


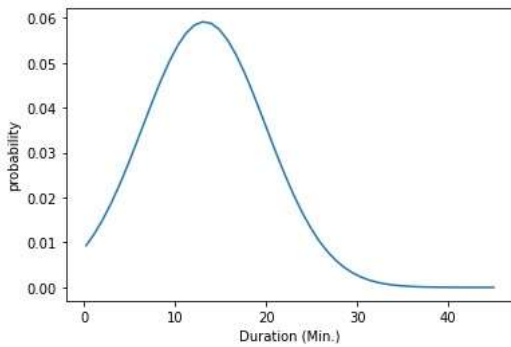
Figure (17) Probability distributions of all substituted modes from statical analysis. (Jupyter notebook, Python 3)

5.3.2. Duration analysis:

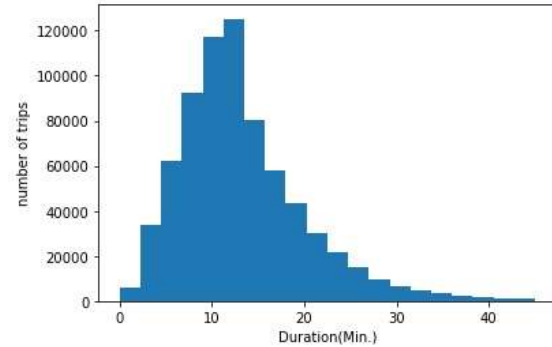
The number of trips is filtered according to the maximum duration of 45 minutes as seen in table (33). And the common thing from figure (18) that most of trips have less than 30 minutes duration.

Table (33) Duration analysis after filtering the data. (Jupyter notebook, Python 3)

	No. of trips	Mean duration (min.)	Std. (duration)	Maximum duration (min.)	Minimum duration (min.)
After filtering: (Maximum duration: 45 Min.)	716710	13.23	6.75	44.98	0.25



(a) Duration – probability distribution.



(b) Duration – Number of trips distribution.

Figure (18) Probability distribution according to: a) Duration, b) Number of trips. (Jupyter notebook, Python 3)

5.3.3. (GHG) reduction Analysis for Gothenburg based on both cases (previous literature and the current case):

Analysing the data of each trip by using (Jupyter notebook, Python 3) helps to calculate the GHG emission reduction in both cases: using the average emission factor ($E_{avg,e-scooter} = 70 \text{ g. CO}_2 \text{ eq.}$) from previous literature which is the average value of references (Kazmaier et al, 2020), (Cottell, Connelly & harding, 2021) and (Severengiz et al, 2020)), and the current case after calculating the emission factor ($E_{e-scooter} = 151 \text{ g. CO}_2 \text{ eq.}$) are illustrated in table (34).

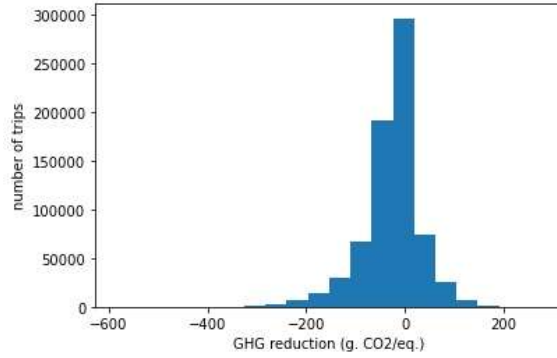
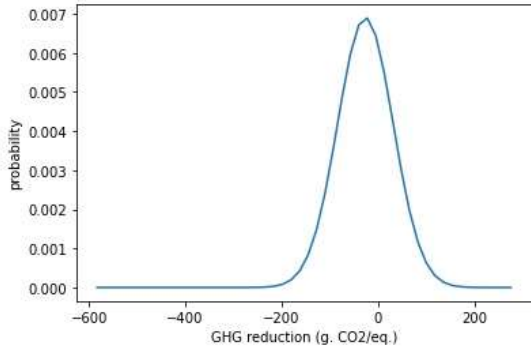
Table (34) (GHG) reduction Analysis of Gothenburg based on both cases. (Jupyter notebook, Python 3)

trip No.	(GHG) Emission Reduction ($\text{g. CO}_2 \text{ eq.}$)	
	Previous case	Current case
1	-87.255	-326.157
2	-30.278	-163.206
3	-21.319	-101.574
.....
718758	5.502	-112.754
718759	-72.403	-195.602
718760	123.262	99.485
718761	29.867	-29.009

After filtering the previous data according to the given limitations, the total number of filtered trips is counted to be 716710 trips and continue estimating the (GHG) emission reductions according to the parameters calculated in table (35). And the common thing from figure (19) that most of trips have GHG reduction between (-200) and (200) ($\text{g. CO}_2 \text{ eq.}$) when the peak value of probability reaches to 0.7%.

Table (35) Parameters of (GHG) emission reductions (previous case). (Jupyter notebook, Python 3)

No. of trips	mean GHG (g. CO eq.)	Std. (GHG)	Maximum (GHG) (g. CO eq.)	Minimum (GHG) (g. CO eq.)
716710	-25.77	57.77	276.32	-583.08



(a) GHG reduction – probability distribution. (b) GHG reduction – Number of trips distribution.

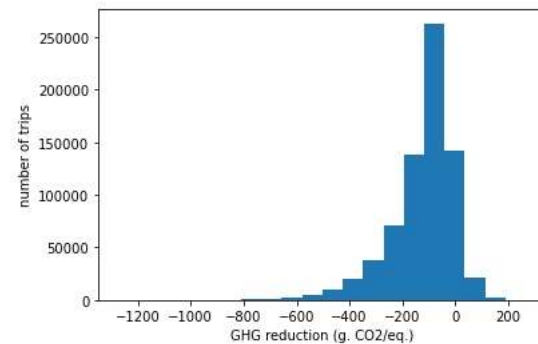
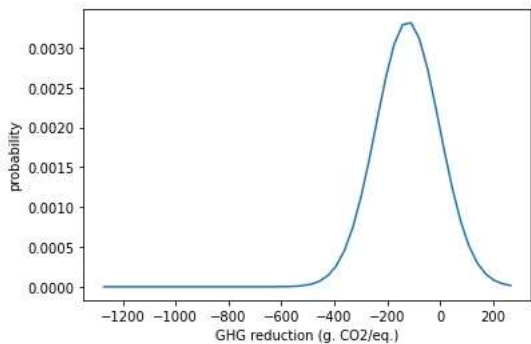
Figure (19) Probability distribution from previous case according to: a) GHG reduction, b) Number of trips. (Jupyter notebook, Python 3)

This analysis is also following the given limitations of filtering the data for the current case and is aimed to show the difference with the previous GHG reduction analysis when the real emissions of one e-scooter (per Km. travelled) is 151 (g. CO eq./km) is applied where all the parameters of GHG reduction are illustrated in table (36).

Table (36) GHG emission reductions in Gothenburg. (Jupyter notebook, Python 3)

No. of trips	mean GHG (g. CO eq.)	Std. (GHG)	Maximum (GHG) (g. CO eq.)	Minimum (GHG) (g. CO eq.)
716710	-122.47	119.8	266.191	-1270.785

On the other hand, the probability distributions according to both (GHG) reduction and the number of trips for the reality case are shown in figure (20) where most of trips have GHG reduction from (-400) to (200) (g. CO eq.).



(a) GHG reduction – probability distribution. (b) GHG reduction – Number of trips distribution.

Figure (20) Probability distribution from the current case according to: a) GHG reduction, b) number of trips. (Jupyter notebook, Python 3)

5.3.4. Visualizing the average (GHG) reductions for each zone of Gothenburg in both cases:

From the previous literature case, the analysis results of (GHG)emission reductions in Gothenburg city by grids system and the average GHG reduction according to the zones of Gothenburg is done by creating grids 400*400 meter are shown in figure (21).

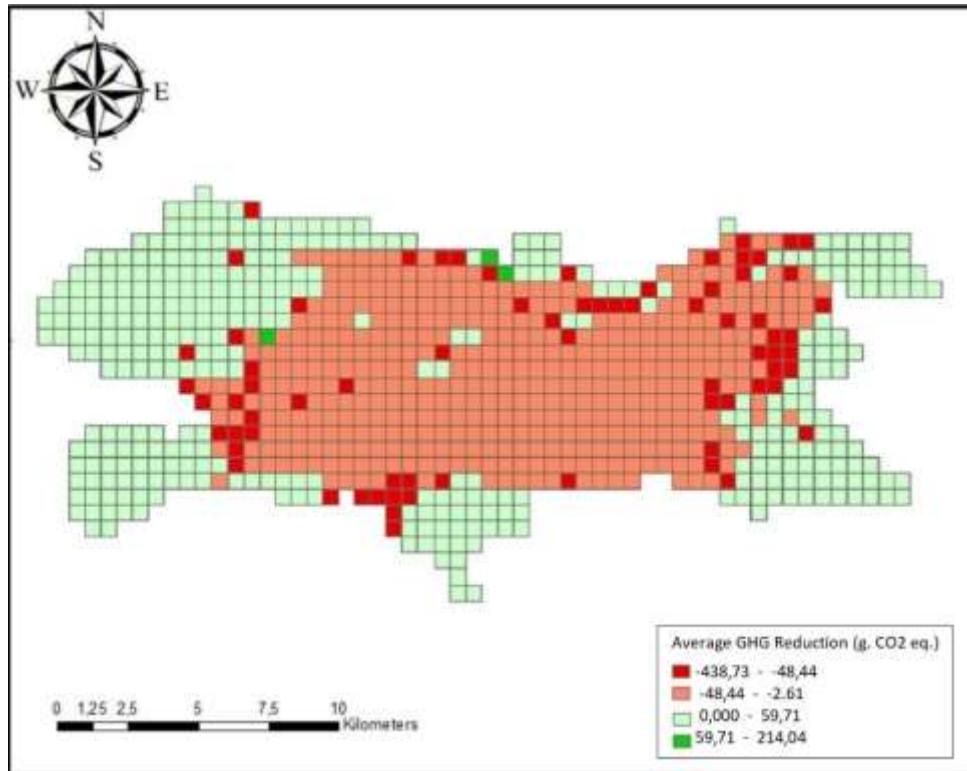


Figure (21) Average (GHG) emission reductions of Gothenburg (from previous case) by grids system based on ($E_{avg,e-scooter} = 70 \text{ g. CO}_2 \text{ eq.}$). (Arcmap 10.8.2 program)

While in the current case, the (GHG)emission reductions for Gothenburg city are shown by the concentrations of red-colour grids more on the edges of the city center and then decreasing gradually in the surroundings as shown in figure (22) compared to previous figure (21).

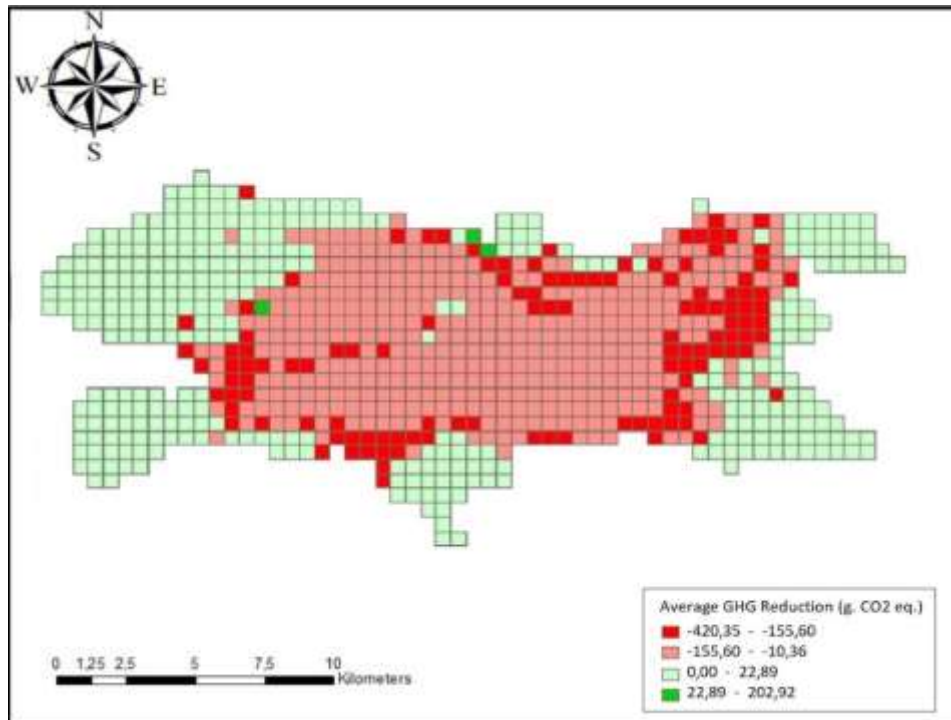


Figure (22) Average (GHG) emission reductions of Gothenburg (from the current case) by grids system based on ($E_{e-scooter} = 151 \text{ g. CO}_2 \text{ eq.}$). (Arcmap 10.8.2 program)

5.4. The environmental benefits by aggregated GHG reductions of each zone:

The idea of the aggregated GHG reduction in each area zone of Gothenburg city is to check the environmental benefits in terms of high or low values per unit area. There are 38 different zones in Gothenburg city are being visualized by using (Arcmap 10.8.2) program. According to figure (23) the zones in red colour show the negative impacts while the green ones have more neutral impacts with very small values. And when estimating the aggregated GHG reduction for each zone, the lowest Negative impact registered is equal to $-3930 \text{ (t. CO}_2 \text{ eq.)}$ in Skår whereas the neutral impact is close to $-5.97 \text{ (t. CO}_2 \text{ eq.)}$ in Hisingen.

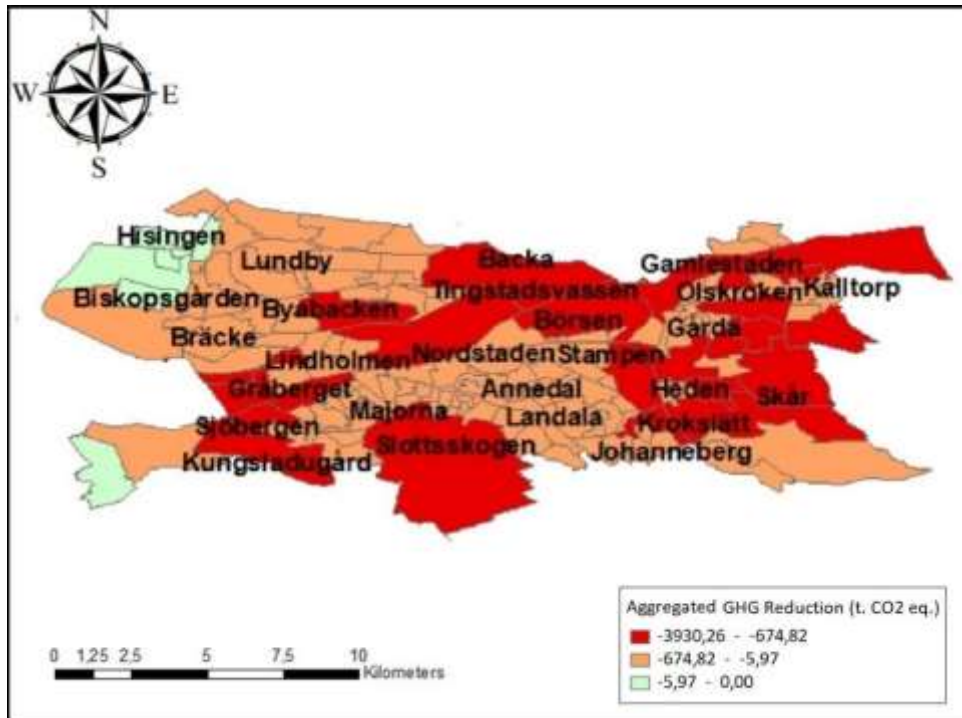


Figure (23) Aggregated (GHG) reduction of each zone in Gothenburg (from previous case) based on ($E_{e-scooter} = 70 \text{ g. CO}_2 \text{ eq.}$). (Arcmap 10.8.2 program)

During the current case, the aggregated GHG emissions of each zone of Gothenburg are shown in figure (24) and represent a lot of differences where All zones have negative environmental impacts.

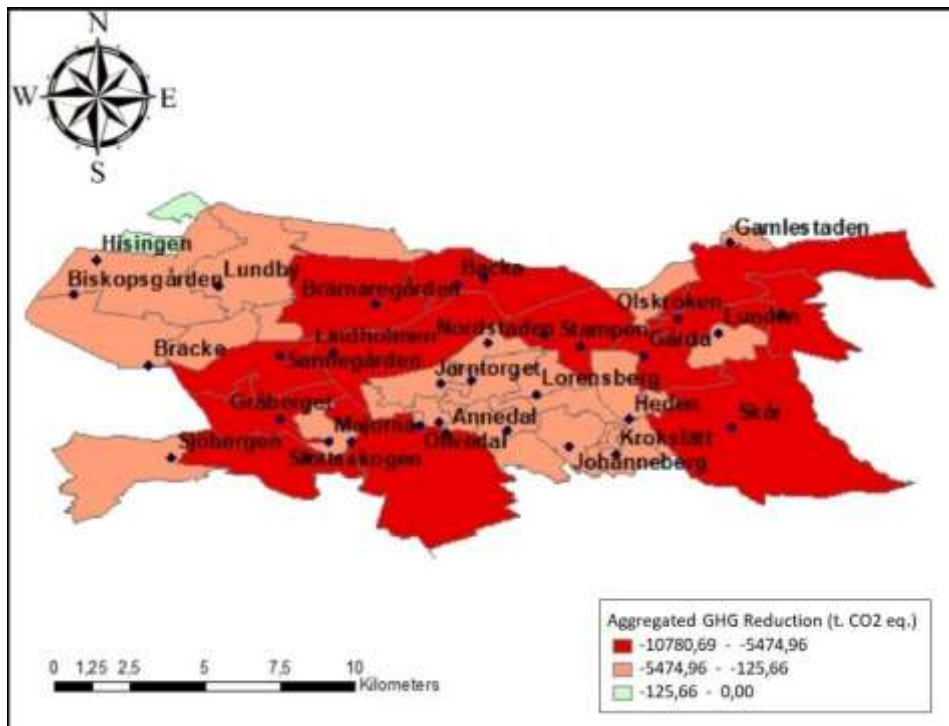


Figure (24) Aggregated (GHG) reduction of each zone in Gothenburg (for the current case) based on ($E_{e-scooter} = 151 \text{ g. CO}_2 \text{ eq.}$). (Arcmap 10.8.2 program)

5.5. Comparing the environmental benefit of Gothenburg in both cases (previous literature and current case).

This comparison is trying to reach the environmental benefits between previous and current cases by analysing the results of environmental impacts for each zone based on the aggregated GHG reductions per unit area as listed in table (37) for previous case and table (39) for the current case.

It has found from table (37) that the lower aggregated GHG reduction per unit area is noticed in Linneplatsen while the higher one is reached in Hisingen. The reason is related to the spatial distribution of aggregated GHG reduction over each area zone per unit area.

Table (37) The aggregated GHG reductions per unit area (previous literature) based on ($E_{avg,e-scooter} = 70 \text{ g. CO}_2 \text{ eq.}$). (Arcmap 10.8.2 program)

Zones	Area (m^2)	Aggregated GHG reduction ($ton. CO \text{ eq.}$)	GHG reduction per area ($kg. CO_2 \text{ eq./m}^2$)
Annedal	252 675	-796	-3.146
Backa	2 322 637	-1510	-0.65
Bagaregården	3 147 993	-3620	-1.15
Biskopsgården	3 410 165	-387	- 0.114
Bräcke	2 184 867	-297	- 0.14
Brämaregården	3 045 187	-3736	-1.23
Byabacken	1 046 763	-574	-0.55
Börsen	583423	-452	-0.77
Gamlestad	747844	-927	-1.24
Gråberget	1 704 941	-3619	-2.12
Grönebacken	398641	-390	-0.98
Guldhedskyrkan	681 246	-824	-1.21
Gårda	1 358 327	-2389	-1.76
Heden	997 254	-1217	-1.22
Hisingen	657 768	-5.97	- 0.01
Inom vallgraven	904 035	-1039	-1.15
Johanneberg	947 965	-1420	-1.5
Järntorget	734 787	-1397	-1.9
Korsvägen	556 754	-974	-1.75
Krokslätt	589 743	-1108	-1.88
Kungsladugård	2 085 880	-2404	-1.15
Kvillebäcken	1 144 840	-776	- 0.68
Källtorp	1 639 249	-3207	- 1.96
Landala	600 357	-1082	-1.8
Lindholmen	3 028 314	-2552	- 0.84
Linneplatsen	275 461	-1294	- 4.7
Lorensberg	183 890	- 475	-2.58
Lundby	2 415000	- 1041	-0.431
Lunden	727 206	-1420	-1.95
Majorna	578 430	-1606	-2.78
Mölnålsån	579 154	-1029	-1.78
Olivedal	298 470	-805	-2.7
Olskroken	1 085 152	- 2964	-2.73
Sannegården	1 933 772	-3057	-1.58
Sjöbergen	2 396 453	-139	-0.058
Skår	6 695 751	-3930	-0.59
Slottsskogen	5 163 114	-3148	-0.61
Stampen	2 104 319	-2276	-1.08

Analysing the previous results will give a broad classification of all Gothenburg zones in table (38), where some of these zones have neutral environmental benefit while others have very bad

environmental benefits, and the reason behind this classification is to find the possibility of achieving the environmental benefit by controlling the emissions inside each zone.

Table (38) Classifying Gothenburg zones from previous literature case based on ($E_{avg,e-scooter} = 70 \text{ g. CO}_2 \text{ eq.}$).

Zones	GHG reduction per area ($\text{kg. CO}_2 \text{ eq./m}^2$)	Classification
Lundby, Hisingen, Backa, Biskopsgården, Bräcke, Byabacken, Lindholmen, Kvillebäcken, Börsen, Grönebacken, Sjöbergen, Skår, Slottsskogen	> -1	Neutral
Järntorget, Landala, Källtorp, Krokslätt, Korsvägen, Kungsladugård, Inom vallgraven, Heden, Brämaregården, Bagaregården, Johanneberg, Gamlestaden, Guldhedskyrkan, Gårda, Lunden, Sannegården, Stampen, Mölndalsån	> -2	bad
Gråberget, Lorensberg, Majorna, Olivedal, Olskroken	> -3	bad
Annedal, Linneplatsen,	> -4	Very bad

The same way of analysis is done in table (39) for the current case, where the lower aggregated GHG reduction per unit area is recorded also in Linneplatsen and the higher one is found in Hisingen.

Table (39) The aggregated GHG reductions per unit area based on the current case of ($E_{e-scooter} = 151 \text{ g. CO}_2 \text{ eq.}$). (Arcmap 10.8.2 program)

Zones	Area (m^2)	Aggregated GHG reduction (ton. CO eq.)	GHG reduction per area ($\text{kg. CO}_2 \text{ eq./m}^2$)
Annedal	252 675	-1757.818	-6.95683
Backa	2 322 637	-5474.968	-2.35722
Bagaregården	3 147 993	-8686.748	-2.75946
Biskopsgården	3 410 165	-125.66	-0.03685
Bräcke	2 184 867	-251.549	-0.11513
Brämaregården	3 045 187	-9819.757	-3.22468
Byabacken	1 046 763	-1414.256	-1.35108
Börsen	583423	-1736.158	-2.97581
Gamlestaden	747844	-2437.867	-3.25986
Gråberget	1 704 941	-8488.665	-4.97886
Grönebacken	398641	-1289.873	-3.23568
Guldhedskyrkan	681 246	-2596.161	-3.8109
Gårda	1 358 327	-5905.731	-4.3478
Heden	997 254	-3264.873	-3.27386
Hisingen	657 768	0	0
Inom vallgraven	904 035	-3542.941	-3.91903
Johanneberg	947 965	-3836.289	-4.04687
Järntorget	734 787	-2648.388	-3.60429
Korsvägen	556 754	-2483.571	-4.4608
Krokslätt	589 743	-2979.942	-5.05295
Kungsladugård	2 085 880	-6351.917	-3.0452
Kvillebäcken	1 144 840	-2339.134	-2.0432
Källtorp	1 639 249	-7248.831	-4.42204
Landala	600 357	-2892.645	-4.81821
Lindholmen	3 028 314	-8002.58	-2.64259
Linneplatsen	275 461	-2328.78	-8.45412
Lorensberg	183 890	-1143.963	-6.22091
Lundby	2 415 000	-1611.094	-0.66712
Lunden	727 206	-3585.31	-4.93025

Majorna	578 430	-3548.901	-6.1354
Mölnålsån	579 154	-2619.458	-4.5229
Olivedal	298 470	-1417.085	-4.74783
Olskroken	1 085 152	-6120.51	-5.64023
Sannegården	1 933 772	-8017.548	-4.14607
Sjöbergen	2 396 453	-345.033	-0.14398
Skår	6 695 751	-10780.696	-1.61008
Slottsskogen	5 163 114	-9125.944	-1.76753
Stampen	2 104 319	-6705.346	-3.18647

The previous results can be also classified according to table (40) to show that some of these zones have neutral environmental benefits whereas others have very bad environmental impacts according to these values.

Table (40) Classifying Gothenburg zones for the current case based on ($E_{e-scooter} = 151 \text{ g. CO}_2 \text{ eq.}$)

Zones	GHG reduction per area ($\text{kg. CO}_2 \text{ eq./m}^2$)	Classification
Lundby, Hisingen, Biskopsgården, Bräcke, Sjöbergen,	> -1	Neutral
Byabacken, Kvillebäcken, Börsen, Skår, Slottsskogen,	> -2	bad
Backa, Lindholmen, Järntorget, Kungsladugård, Bagaregården,	> -3	bad
Grönebacken, Inom vallgraven, Heden, Brämaregården, Johanneberg, Gamlestaden, Guldhedskyrkan, Stampen, Olivedal	> -4	bad
Landala, Källtorp, Korsvägen, Gårda, Lunden, Sannegården, Gråberget,	> -5	bad
Krokslätt, Olskroken, Mölnålsån	> -6	bad
Lorensberg, Majorna, Annedal	> -7	bad
Linneplatsen	> -9	Very bad

Some of the corresponding zones from both tables (38) and (40) have registered neutral environmental impacts in terms of the values of aggregated GHG reduction per unit area such as (Lundby, Hisingen, Biskopsgården, Bräcke, and Sjöbergen) while others have registered bad impacts. And the worst environmental impact in both cases (the previous and current) is found in Linneplatsen.

5.6. Comparing Life Cycle Analysis (LCA) stages of shared e-scooter in different locations.

This kind of comparison between the case study of Sweden and other locations from previous literature will help to show the differences in calculating the life cycle stages according to different locations and which stages are affecting more on the final calculated emission factor as being illustrated in table (41).

Table (41) Comparing the Life Cycle Analysis used in different locations.

reference	City, country	Lifespan (months)	Emission factor ($E_{e-scooter}$) (g. CO ₂ eq.)	LCA analysis stages	Sharing percentage of each stage
(Kazmaier et al, 2020)	Berlin, Germany	24	63	five stages: 1. Material and manufacturing 2. Transport	47.62% 9.52%

				3.Charging 4.Redistribution and collection 5.End of life	7.94% 31.75% 3.17%
(Severengiz et al, 2020)	Berlin, Germany	24	77	four stages: 1. Manufacturing 2.Transport to Germany 3.Use phase 4.End of life	63% 1% 35% 1%
(Cottell, Connelly & harding, 2021)	United Kingdom	24	67.1	three stages: 1.Production 2.Operation 3.Disposal (is neglected)	52.16% 47.84% 0%
(Miller, 2020)	Brussels, Belgium	12	131	four stages: 1. Manufacturing 2.Transport to Belgium 3.Use phase 4.End of life (is neglected)	79.4% 2.29% 18.32% 0%
(Miller, 2020)	Raleigh, North Carolina	12	126	four stages: 1. Manufacturing 2.Transport to North Carolina 3.Use phase 4.End of life (is neglected)	48.81% 1.48% 49.29% 0%
The current case	Gothenburg, Sweden	60	151	five stages: 1. Raw material extraction 2.Manufacturing 3.Transport to Sweden 4.Use 5.End of life	25.16% 51.72% 1.2% 13.6% 8.32%

After checking the lifespan duration of e-scooter from table (40), the previous literature mentioned that the high emissions are happening when the lifespan of e-scooter and using rate are short. But it is not possible to be noticed here because each case study has different limitations and methodological approaches.

And when comparing *LCA* analysis of shared e-scooter between different locations, it has been shown that manufacturing stage has the biggest share while the transport stage has the lowest share by shipping the e-scooter product to the consumed country. Also, the highest emission factor is found in Gothenburg, Sweden while the lowest one is in Berlin, Germany.

Discussing the previous results is helping to answer on the three main research questions of this paper:

RQ1: What is the Life cycle Analysis of shared e-scooters in Sweden?

The methodological approach of Life Cycle Analysis (*LCA*) used here has the guideline of solution when it includes a lot of details through its stages and its processes from cradle to grave comparing to other (*LCA*) analysis used in previous literature. Also, the similarities between the two models of e-scooters: (Xiaomi M365) and (Voiaeger V5) help to consider some coefficients from (Xiaomi M365) into (Voiaeger V5) in addition to many other assumptions are being considered during the calculations.

The total travelled distance by e-scooter over the lifespan has the major effects on increasing or decreasing the final calculated emission factor per travelled distance of e-scooter (*Km*) and on the emissions during the use stage. But previous literature discussed the high emissions happening when the lifespan of e-scooter and using rate are short which is difficult to check about this issue here

because each case study from previous literature has followed different methodological approach when calculating the emission factor at each stage.

The calculated emission factor from *LCA* analysis is equal to 151 (*g. CO₂ eq.*) which is more than doubled the average estimated emission factor from previous literature 70 (*g. CO₂ eq.*) per one e-scooter because *LCA* analysis has considered all the effecting factors through all life cycle stages which have the most influence on the calculation processes whereas the estimated emissions from previous literature have referred only to the major factors when merging two or three stages into one stage.

The manufacturing stage from *LCA* analysis has the biggest percentage among all other stages with (51.72%) compared to the lowest percentage of transport stage (1.2%) for the current case of Gothenburg. This result has been found also in many cities according to table (41) to emphasize the importance of manufacturing stage on minimizing the emissions generated by e-scooter.

RQ2: What are the environmental emissions of replacing trips by using shared e-scooters?

The statistical analysis of data collected in Gothenburg city by using (Jupyter notebook, Python 3) program is the keyword of finding the emissions of replacing trips when using the average emission factors of replacing other transport modes by shared e-scooter from previous literature.

After handling and filtering the transaction data from Voi and Tier companies, the total number of trips have been reduced from 718761 trips to 716710 trips and the highest probability of substituted transport mode by shared e-scooter is “Walk” whereas the lowest probability is “Car” in the inner city of Gothenburg. These negative environmental impacts of shared e-scooter are mostly occurred because e-scooter is replaced by the short trip distance of “Walk” in the central areas of Gothenburg. These results are compatible with the previous literatures about the most substituted patterns for a travel distance less than 2 kilometers is Walk while for longer distances than 2 kilometers, both Public Transport and Car increase their shares. And the correlation between Walk and Public Transport are explained by the free movement of travellers to reach the nearest stations by walking when shared e-scooter is not used.

This analysis also shows that “Walk” mode is the most dominant one among other modes (Public Transport and Car), even though the previous literature considered the most dominant traffic mode is “Car” with more than fifty percent all over Sweden. On the other hand, most of substitution distances by “Walk” are found to be less than 1.5 Km whereas most of substitution distances by “Car” are less than 8 Km and most of substitution distances by Public Transport is less than 6 Km. Other results show that most of trips have less than 30 minutes duration and less than 6-kilometre distance while the average distance and duration of all trips in Gothenburg are accordingly (1.2 kilometre) and (13.23 minutes) which means that less distance and longer duration compared to previous literature in Gothenburg. This can be accounted for increasing the demands and congestions in the central areas of the city.

That is why the negative environmental impacts of getting high (*CO₂*) emissions of using shared e-scooter in cities are being discussed a lot in previous literature when shared e-scooter substituted by other alternative modes of zero emissions such as Walk. Also, most of trips have shown that (GHG reductions are between (-200) and (200) (*g. CO₂ eq.*)). But in the current case of Gothenburg, the results of (GHG reduction) are between (-400) and (200) (*g. CO₂ eq.*) which means that more negative impacts are happening by shared e-scooter compared to previous literature.

RQ3: What are the potential benefits of shared e-scooters to be considered eco-friendly?

The expected environmental benefits of shared e-scooter are found after making the comparison between the emission results of the previous literature and the current case of Gothenburg to monitor the locations of zones when they get more negative impacts than others.

Visualizing the aggregated GHG emission reductions per unit area between different zones of Gothenburg by means of (Arcmap 10.8.2) program has considered the two comparing cases of aggregated GHG emission reductions. The first case is from previous literature in table (37), and the second one is for the current case in table (39) where all zones of Gothenburg have negative environmental benefits except Hisingen which has a neutral impact in both cases. However, there are some areas have registered better impacts in terms of the values of aggregated GHG reduction per unit area such as in (Lundby, Biskopsgården, Bräcke, and Sjöbergen) while the worst environmental impact happened in Linneplatsen as shown in tables (38) and (40). On the other hand, the comparison among different cities has found that the highest emission factor is registered in Gothenburg whereas the lowest one is in Berlin.

6. Conclusions:

The negative environmental impacts of shared e-scooter occur after analysing the results of the calculated emission factors from LCA analysis and other replacing transport modes included in this paper (Walk, Public Transport, and Car). This research also explains the highest probability of substituted transport mode of “Walk” for most of the short trips inside Gothenburg city. Also, the calculated emission factor from LCA analysis is equal to 151 (*g. CO₂ eq.*) which is more than doubled the average estimated emission factor from previous literature 70 (*g. CO₂ eq.*) per one e-scooter.

The calculation processes of LCA analysis include a lot of details in terms of the coefficients used and the affecting factors of each stage. The total travelled distance over the lifespan of e-scooter is an important factor to be considered when calculating the final emission factor of e-scooter. On the other hand, LCA analysis has shown that the percentage of manufacturing stage contributes to more than fifty percent of the total LCA emissions and this is compatible with previous literature.

So, reducing the negative impact of e-scooter is based on minimizing the emissions during the manufacturing stage of LCA and controlling the expected lifespan of e-scooter which plays a major rule when dividing the total emissions of e-scooter by the travelled distance (per *Km*).

Other results shows that most of trips have less than 30 minutes duration and less than 6-kilometre distance while the average distance and duration of all trips in Gothenburg are accordingly (1.2 kilometre) and (13.23 minutes) which means that less distance and longer duration compared to previous literature of Gothenburg.

Shared e-scooter has showed many advantages through previous studies, and the results from life cycle analysis of shared e-scooter show the possibility of controlling the environmental impacts when focusing on the stages causing high emissions such as manufacturing and reducing the emissions depending on the related factors. But this becomes difficult to decide if shared e-scooter is eco-friendly or not because of its negative environmental impacts. The calculated emission factors and the highest probability of substituted transport mode of “Walk” for most of the short trips inside Gothenburg city have the biggest effects when considering the desirable environmental benefit of using shared e-scooter.

7. Recommendations:

Due to the limitations of thesis statement, MNL method is used here. But it is recommended for more research in future to follow the Nested Logit model (NL) instead because it gives more accurate results to analyse the similar alternative modes together on different levels. Another limitation is related to the size of grids which is (400 meter * 400 meter) to give a good visualization of the areas within the city but the recommended work in future is reduce the size of grids used which will help in reaching more results corresponding to the spatial distributions.

This study focuses on few transport modes to see how the modal substitution patterns are being affected by number of trips, origin and destination points, travel distance, travel time, longitudinal and latitudes coordinates...and other factors. But the substituted modes have the biggest effect on the results especially the emission factors of different substituted modes. It is not mentioned here the differences between private car or Taxi because the data collected from Voi and Tier companies are considered the substituted mode of Car in general. That is why it is recommended in future to extend the study to include all other kinds of transport modes even the personal e-scooter.

The recommended work in future is to analyse the substitution rates of different transport modes when replacing by shared e-scooter for travel distance is more than or equal to 20 Km based on previous literature when the most substitution modes are being replaced by public transport and cars to reduce the overall emissions from the transport sector on the long term. In addition, the comparison between different e-scooter models from different companies when applying LCA analysis is useful to see how these differences could affect on the final environmental impacts of shared e-scooter.

At the end, the transport planner must achieve the environmental benefits not only on the urban mobility level but also according to the condition of the current built environment and the accessibility of transport modes in different countries by considering the differences in regulations and legislations.

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9. Appendices:

9.1. Appendix 1:

Table (42) Substitution transport modes by shared e-scooter. (Wang et al, 2022)

No.	Study area	Driving alone	Taxi or TNC	Public transport	walk	Micro mobility
	North America					
1	Tempe city , Arizona	--	25%	4.5%	57%	8%
2	Tucson city , Arizona	24%	14%	3%	36%	8%
3	Los Anglos city , California	11%	22%	9%	48%	5%
4	Oakland city , California	14%	25%	9%	42%	12%
5	San Francisco city, California (Lime, 2018)	9%	51%	34%	61%	20%
6	San Francisco city, California (SFMTA, 2019)	5%	36%	11%	31%	9%
7	Santa Monica city , California	--	49%	4%	39%	7%
8	Denver city, Colorado	10%	22%	7%	43%	14%
9	Tampa city, Florida	21%	27%	1%	38%	6%
10	Atlanta, Gorgia	--	42%	2%	48%	4%
11	Bloomington, Indiana	25%	16%	7%	54%	--
12	Chicago city, Illionas	11%	32%	14%	30%	8%
13	St Louis Park city, Minnesota	34%	37%	5.5%	5%	8%
14	Hoboken, New Jersey	11%	37%	13%	51%	13%
15	Raliegh, North California	--	34%	11%	--	49%
16	Portland city, Oregon (2018)	19%	15%	10%	37%	5%
17	Portland city, Oregon (2019)	19%	23%	11%	39%	8%
	Portland city, Oregon (2020)	14%	23%	10%	41%	5%
18	Alexendria, Virginia	46%	41%	18%	50%	13%
19	Arlington County, Virginia	13%	19%	5%	37%	4%
20	Arlington County, Virginia (Rosslyn area)	7%	39%	7%	33%	12%
21	Blacksburg, Virginia (Campus)	--	6%	7%	77%	--
22	Milwaukee, Wisconsin	23%	22%	7%	40%	7%
23	Calgary, Canada	21%	12%	6%	56%	5%
24	Toronto, Canada	--	44%	53%	57%	36%
	Europe					
25	Paris, France (Face to face interview, 2019)	4%	6%	37%	35%	7%
26	Paris, France (Online questionnaire, 2019)	5%	8%	36%	37%	12%
27	Paris, Lyon, France (Online questionnaire, 2019)	3%	6%	30%	44%	12%
28	Munich, Germany	--	24%	59%	80%	59%
29	Thessanolyki, Greece	--	17%	33%	44%	7%
30	Oslo, Norway	3%	5%	23%	60%	6%
31	Zurich, Switzerland	--	10%	24%	52%	14%
	New Zealand					
32	Auckland, New Zealand		21%	7%	53%	6%
33	Christchurch, New Zealand	14%	9%	5%	52%	6%

9.2. Appendix 2:

Table (43) average *GWP* emissions for different transport modes in Germany. (Kazmaier et al, 2020)

Mode of Transport	Emissions (<i>g. CO₂ eq.</i>)	Source
Car	220.5	Umweltbundesamt (2019)
Public Transport	58	Umweltbundesamt (2019)
Bike	5	Weiss et.al (2015)
Other mode of transport	25 (assumption for e-bike)	Weiss et.al (2015)

9.3. Appendix 3:

Deterministic utility (V) equations of each transport mode: (Bai, T. et al, 2017)

$$V_{walk} = ASC_{walk} + \beta_{walk_distance} * Distance + \beta_{walk_dist < 2 km} * I_{dist < 2 km} \quad eq. (7)$$

$$V_{car} = ASC_{car} + \beta_{car_time} * Cartime + \beta_{Car_{cost}} * Carcost + \beta_{Car_{compar}} * I_{compar} + \beta_{Car_{male}} * I_{male} + \beta_{Car_{dist > 20 km}} * I_{dist > 20 km} + \beta_{Car_{own_driv_lic}} * I_{Car_{own_driv_lic}} + \beta_{Car_{cons_cap}} * Cons_cap + \beta_{Car_{cheappark}} * I_{Car_{cheappark}} + \beta_{Car_{housech-w-kid}} * I_{Car_{housech-w-kids}} + \beta_{Car_{flect}} * I_{Car_{flect}} \quad eq. (8)$$

$$V_{PT} = \beta_{PT} * PT_{time} + \beta_{PT_{cost}} * PT_{cost} + \beta_{PT_{noboard}} * PT_{noboard} + \beta_{PT_{male}} * I_{male} + \beta_{PT_{consCap}} * Cons_{cap} + \beta_{PT_{housech-w-kids}} * I_{housech_{wkids}} + \beta_{PT_{flect}} * I_{PT_{flect}} + \beta_{PT_{fwt}} * PT_{fwt} \quad eq. (9)$$

Table (44) Interpretations of utility variables. (Bai, T. et al, 2017)

Variable Name	Parameter	Description
ASC	Alternative specific constant	Take public transport as reference
Distance	Distance	Trip distance (in mile= 10 Km)
$I_{dist < 2 km}$	Distance	1 if distance less than 2 Km
$I_{dist > 20 km}$	Distance	1 if distance more than 20 Km
Income	Income	Monthly income SEK 1:0-7500, 2:7501-10000...etc
Cons_cap	Consumption capacity	According to social norm.
Car_time	Car time	Car driving time (in hour)
Car_cost	Car cost	Based on distance cost
PT_time	Public transport time	Total travel time by public transport
PT_cost	Public transport cost	Cost of public transport travel
PT_noboard	Public transport transfer	Public transport: number of boardings
PT_fwt	Public transport time	Public transport: first waiting time
I_{male}	male	1 if male
$I_{housech-w-kids}$	Children	1 if household with kids 0-12 years
$I_{own-driv-lic}$	Driving licence	1 if respondent has a driving licence
I_{flect}	Flex time working	1 if flexible working hours
$I_{compcar}$	Company car	1 if access to company car
β	Coefficient related to Multinomial logit Model (MNL)	The value of this coefficient is related to which model applied (MNL, NL, or Mixed Logit)

Table (45) Calculated variables based on Stockholm data for *MNL* method. (Bai, T. et al, 2017)

Parameters	Model specification	
	estimate	t-value
ASC_{walk}	1.45	4.27
ASC_{car}	-0.586	-2.3
$\beta_{walk_distance}$	-7.78	-14.4
$\beta_{walk_dist < 2 km}$	1.08	6.04
β_{car_time}	-1.03	-17.7
β_{PT_time}	-0.968	-3.27
β_{car_cost}	-0.0215	-3.84
β_{PT_cost}	-0.0471	-5.87
β_{car_male}	0.39	2.97
β_{PT_male}	-0.047	-0.352
$\beta_{car_conscap}$	-0.209	-3.87
$\beta_{PT_conscap}$	-0.114	-2.08
β_{car_flect}	-0.495	-3.75
β_{PT_flect}	-0.304	-2.27
$\beta_{PT_noboard}$	-0.0629	-0.986
β_{PT_fwt}	-1.3	-1.96

9.4. Appendix 4:

Coding by Jupyter programming notebook:

to estimate probabilities, utilities and GHG emission reductions by means of Python language, by defining parameters ASC and Beta...etc. for Gothenburg case.

```
import pandas as pd
```

```
df = pd.read_csv("final2.csv")
```

```
df.columns
```

```
df['km'] = df.escooter_distance/1000
```

```
df['km'].sum()
```

```
def U_walk(walkDistance_x):  
    KmWalkDist = walkDistance_x/1000  
    asc_walk = 1.45  
    b_walk_distance = -7.78  
    b_walk_distance_2 = 1.08  
    # v_walk = asc_walk + b_walk_distance_2*dwalk+b_walk_distance_2  
    v_walk = asc_walk + b_walk_distance_2*KmWalkDist + b_walk_distance_2  
    return v_walk
```

```
def U_PT (transit_time, waitingTime):  
    HR_transitTime= transit_time/3600  
    HR_waitingTime= waitingTime/3600  
    asc_pt = 0.611  
    b_pt_time = -0.968  
    b_lic = 1.3  
    b_pt_cost = -0.0471  
    b_kids = 0.469  
    v_pt = 2+ asc_pt + b_pt_time*HR_transitTime + b_pt_cost * HR_waitingTime + b_kids * 0.5  
    return v_pt
```

```
def U_car( car_time, car_distance, cons_cap=3):  
    HR_car_time= car_time/3600  
    asc_car = 0.4  
    b_car_time = -1.03  
    b_car_cost = -0.0215  
    b_car_male = 0.39  
    b_lic = 1.3  
    b_car_cons_cap = 0.2  
    KmCarDist = car_distance/1000  
    taxiprice = 17/1000  
    CarCost = 61 + KmCarDist*taxiprice
```

```
v_car = 1 + asc_car + b_car_time * HR_car_time + b_car_cost * CarCost + b_lic * 0.5 + b_car_male * 0.5 + b_car_cons_cap * cons_cap
return v_car
```

```
df['U_walk'] = df['walkDistance_x']. apply(U_walk)
df['U_PT'] = df.apply(lambda x: U_PT(x["transit_time"], x["waitingTime"]), axis=1)
df['U_car'] = df.apply(lambda x: U_car(x["car_time"], x["car_distance"]), axis=1)
```

```
def P_walk (U_walk, U_car, U_PT ):
    s = np.exp(U_walk) + np.exp(U_car) + np.exp(U_PT)
    return np.exp(U_walk)/s
```

```
def P_PT (U_walk, U_car, U_PT ):
    s = np.exp(U_walk) + np.exp(U_car) + np.exp(U_PT)
    return np.exp(U_PT)/s
```

```
def P_car (U_walk, U_car, U_PT ):
    s = np.exp(U_walk) + np.exp(U_car) + np.exp(U_PT)
    return np.exp(U_car)/s
```

```
df['P_walk'] = df.apply(lambda x: P_walk(x["U_walk"], x["U_car"], x["U_PT"]), axis=1)
```

```
df['P_PT'] = df.apply(lambda x: P_PT(x["U_walk"], x["U_car"], x["U_PT"]), axis=1)
```

```
df['P_car'] = df.apply(lambda x: P_car(x["U_walk"], x["U_car"], x["U_PT"]), axis=1)
```

```
import matplotlib.pyplot as plt
```

```
import scipy.stats
```

```
df['GHG_reduction'] = 0 * (df.P_walk * df.transit_walkdistance/1000) + 54.7 * (df.P_PT * df.transit_transitdistance/1000) + 170 * (df.P_car * df.car_distance/1000) - 151 * (df.escooter_distance/1000)
```

```
bins=20
plt.hist(df['P_walk'], bins=bins,color="b", alpha=0.5, label= "Walk")
plt.hist(df['P_car'],bins=bins,color="r", alpha=0.5, label= " Car")
plt.hist(df['P_PT'],bins=bins,color="y", alpha=0.5, label= "Public Transport")
plt.ylabel("number of trips")
plt.xlabel("Probability")
plt.legend(loc= "upper right")
plt.show()
```

9.5. Appendix 5:

Coding by Jupyter programming notebook:
to filter the transaction data for results analysis.

```
df_first = df[df["km"] < 10]
```

```
df_second = df_first[df_first["Duration_MIN"] < 45]
```

```
import seaborn as sns
```

```
x = df.transit_walkdistance/1000  
f, (ax_box, ax_hist) = plt.subplots(2, sharex=True, gridspec_kw={"height_ratios": (.15, .85)})  
sns.boxplot(x=x, ax=ax_box)  
sns.histplot(x=x, bins=12, kde=True, stat="probability", ax=ax_hist)  
ax_box.set(yticks=[])  
sns.despine(ax=ax_hist)  
sns.despine(ax=ax_box, left=True)
```

```
x = df.transit_transitdistance/1000  
f, (ax_box, ax_hist) = plt.subplots(2, sharex=True, gridspec_kw={"height_ratios": (.15, .85)})  
sns.boxplot(x=x, ax=ax_box)  
sns.histplot(x=x, bins=20, stat='probability', ax=ax_hist)  
ax_box.set(yticks=[])  
sns.despine(ax=ax_hist)  
sns.despine(ax=ax_box, left=True)
```

```
x = df.car_distance/1000  
f, (ax_box, ax_hist) = plt.subplots(2, sharex=True, gridspec_kw={"height_ratios": (.15, .85)})  
sns.boxplot(x=x, ax=ax_box)  
sns.histplot(x=x, bins=12, kde=True, stat='probability', ax=ax_hist)  
ax_box.set(yticks=[])  
sns.despine(ax=ax_hist)  
sns.despine(ax=ax_box, left=True)
```

```
x = df.transit_transitdistance/1000  
f, (ax_box, ax_hist) = plt.subplots(2, sharex=True, gridspec_kw={"height_ratios": (.15, .85)})  
sns.boxplot(x=x, ax=ax_box)  
sns.histplot(x=x, bins=20, kde=True, stat='probability', ax=ax_hist)  
ax_box.set(yticks=[])  
ax_box.set_xlim(-1, 10)  
sns.despine(ax=ax_hist)  
sns.despine(ax=ax_box, left=True)
```